

INTERNATIONAL STANDARD



Wind **turbines** energy generation systems –
Part 1: Design requirements

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INTERNATIONAL STANDARD



Wind **turbines** energy generation systems –
Part 1: Design requirements

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WIND ~~TURBINES~~ ENERGY GENERATION SYSTEMS –**Part 1: Design requirements****FOREWORD**

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International Standard IEC 61400-1 has been prepared by IEC technical committee 88: Wind energy generation systems.

This fourth edition cancels and replaces the third edition published in 2005 and Amendment 1:2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) general update and clarification of references and requirements;
- b) extension of wind turbine classes to allow for tropical cyclones and high turbulence;
- c) Weibull distribution of turbulence standard deviation for normal turbulence model (NTM);
- d) updated design load cases (DLCs), in particular DLC 2.1 and 2.2;
- e) revision of partial safety factor specifications;
- f) major revision of Clauses 8, 10 and 11;
- g) introduction of cold climate requirements, Clause 14;
- h) new Annex B on design load cases for site-specific or special class S wind turbine design or site suitability assessment;
- i) new Annex J on prediction of the extreme wind speed of tropical cyclones by using Monte Carlo simulation method;
- j) new Annex K on calibration of structural material safety factors and structural design assisted by testing;
- k) new Annex L on assessment and effects of icing climate;
- l) new Annex M on medium wind turbines.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
88/696/FDIS	88/701/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

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INTRODUCTION

This part of IEC 61400 outlines minimum design requirements for wind turbines and is not intended for use as a complete design specification or instruction manual.

Any of the requirements of this document may be altered if it can be suitably demonstrated that the safety of the system is not compromised. This provision, however, does not apply to the classification and the associated definitions of external conditions in Clause 6. Compliance with this document does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

This document is not intended to give requirements for wind turbines installed offshore, in particular for the support structure. ~~A future document dealing with offshore installations is under consideration.~~ For offshore installations, reference is made to the IEC 61400-3 series.

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WIND ~~TURBINES~~ ENERGY GENERATION SYSTEMS –

Part 1: Design requirements

1 Scope

This part of IEC 61400 specifies essential design requirements to ensure the ~~engineering~~ *structural* integrity of wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.

This document is concerned with all subsystems of wind turbines such as control and protection ~~mechanisms~~ functions, internal electrical systems, mechanical systems and support structures.

This document applies to wind turbines of all sizes. For small wind turbines, IEC 61400-2 ~~may~~ can be applied. IEC 61400-3-1 provides additional requirements to offshore wind turbine installations.

This document ~~should~~ is intended to be used together with the appropriate IEC and ISO standards mentioned in Clause 2.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60034 (all parts), *Rotating electrical machines*

IEC 60038, *IEC standard voltages*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2, *Insulation co-ordination – Part 2: Application guidelines*

IEC 60076 (all parts), *Power transformers*

IEC 60204-1:1997, *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*

IEC 60204-11:2000, *Safety of machinery – Electrical equipment of machines – Part 11: Requirements for HV equipment for voltages above 1 000 V AC or 1 500 V DC and not exceeding 36 kV*

IEC 60364 (all parts), *Low voltage electrical installations*

IEC 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 60664-1, *Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*

IEC 60664-3, *Insulation coordination for equipment within low-voltage systems – Part 3: Use of coating, potting or moulding for protection against pollution*

IEC 60721 (all parts), *Classification of environmental conditions*

~~IEC 60721-2-1:1982, Classification of environmental conditions – Part 2: Environmental conditions appearing in nature. Temperature and humidity~~

~~IEC 61000-6-1:1997, Electromagnetic compatibility (EMC) – Part 6: Generic standards – Section 1: Immunity for residential, commercial and light industrial environments~~

IEC 61000-6-2:1999, *Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity standard for industrial environments*

~~IEC 61000-6-4:1997, Electromagnetic compatibility (EMC) – Part 6: Generic standards – Section 4: Emission standard for industrial environments~~

~~IEC 61024-1:1990, Protection of structures against lightning – Part 1: General principles~~

~~IEC 61312-1:1995, Protection against lightning electromagnetic impulse – Part 1: General principle~~

IEC 61400-3, *Wind turbines – Part 3: Design requirements for offshore wind turbines*

IEC 61400-4, *Wind Turbines – Part 4: Design requirements for wind turbine gearboxes*

~~IEC 61400-21:2001, Wind turbine generator systems – Part 21: Measurement and assessment of power quality characteristics of grid-connected wind turbines~~

IEC 61400-24:2002, *Wind turbines generator systems – Part 24: Lightning protection*

IEC 61439 (all parts), *Low-voltage switchgear and controlgear assemblies*

IEC 61800-4, *Adjustable speed electrical power drive systems – Part 4: General requirements – Rating specifications for AC power drive systems above 1 000 V AC and not exceeding 35 kV*

IEC 61800-5-1, *Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy*

IEC 62271 (all parts), *High-voltage switchgear and controlgear*

IEC 62305-3, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

IEC 62477-1:2012, *Safety requirements for power electronic converter systems and equipment – Part 1: General*

ISO 76:1987, *Rolling bearings – Static load ratings*

ISO 281:1990, *Rolling bearings – Dynamic load ratings and rating life*

ISO 2394:~~1998~~, *General principles on reliability for structures*

ISO 2533:~~1975~~, *Standard Atmosphere*

ISO 4354:~~1997~~, *Wind actions on structures*

~~ISO 6336 (all parts), Calculation of load capacity of spur and helical gears~~

ISO 6336-2, *Calculation of load capacity of spur and helical gears – Part 2: Calculation of surface durability (pitting)*

ISO 6336-3:2006, *Calculation of load capacity of spur and helical gears – Part 3: Calculation of tooth bending strength*

~~ISO 9001:2000, Quality management systems – Requirements~~

ISO 12494:2001, *Atmospheric icing on structures*

ISO 13850, *Safety of machinery – Emergency stop function – Principles for design*

ISO/TS 16281, *Rolling bearings – Methods for calculating the modified reference rating life for universally loaded bearings*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

annual average

mean value of a set of measured data of sufficient size and duration to serve as an estimate of the expected value of the quantity

Note 1 to entry: The averaging time interval should be a whole number of years (e.g. 10) to average out non-stationary effects such as seasonality.

3.2

annual average wind speed

V_{ave}
wind speed averaged according to the definition of annual average

3.3

auto-reclosing cycle

event with a time period, varying from approximately 0,01 s to a few seconds, during which a breaker released after a grid fault is automatically reclosed and the line is reconnected to the network

3.4

blocking

<wind turbines> use of a mechanical pin or other device (other than the ordinary mechanical brake) that cannot be released accidentally to prevent movement, for instance of the rotor shaft or yaw mechanism

3.5**brake**

<wind turbines> device capable of reducing the rotor speed or stopping rotation

Note 1 to entry: The brake may operate on, for example, aerodynamic, mechanical or electrical principles.

3.6**characteristic value**

value having a prescribed probability of not being attained (i.e. an exceedance probability of less than or equal to a prescribed amount)

3.7**complex terrain**

surrounding terrain that features significant variations in topography and terrain obstacles that may cause flow distortion

3.8**control functions**

<wind turbines> functions of the control ~~and protection~~ system that, based on information about the condition of the wind turbine and/or its environment, adjust the turbine in order to maintain it within its operating limits

3.9**control system**

<wind turbines> system implementing the turbine control functions, including sensors, logic elements, actuators, communication networks, and power supplies

Note 1 to entry: The intent of the control system is to control operation of the turbine by active and passive means and keep the operating parameters within the limits assumed in the structural design. The control system is likely to include control loops for normal operation as well as alarms and shutdown mechanisms to ensure that limits are not exceeded.

3.10**cut-in wind speed**

V_{in}

lowest 10 min average wind speed at hub height at which the wind turbine starts to produce power in the case of steady wind without turbulence

3.11**cut-out wind speed**

V_{out}

highest 10 min average wind speed at hub height at which the wind turbine is designed to produce power in the case of steady wind without turbulence

3.12**design limits**

maximum or minimum values used in a design

3.13**dormant failure**

failure of a component or system which remains undetected during normal operation

3.14**downwind**

in the direction of the main wind vector

3.15**electrical power network**

particular installations, substations, lines or cables for the transmission and distribution of electricity

Note 1 to entry: The boundaries of the different parts of this network are defined by appropriate criteria, such as geographical situation, ownership, voltage, etc.

3.16

emergency shutdown stop

<wind turbines> rapid shutdown of the wind turbine triggered ~~by a protection function or~~ by manual intervention

3.17

environmental conditions

characteristics of the environment (wind, altitude, temperature, humidity, etc.) which may affect the wind turbine behaviour

3.18

external conditions

<wind turbines> factors affecting operation of a wind turbine, including the environmental conditions (temperature, snow, ice, etc.) and the electrical network conditions

3.19

extreme wind speed

value of the highest wind speed, averaged over t in seconds, with an annual probability of exceedance of $1/N$ ("~~recurrence~~ return period": N years)

Note 1 to entry: In this document ~~recurrence~~ return periods of $N = 50$ years and $N = 1$ year and averaging time intervals of $t = 3$ s and $t = 10$ min are used. In popular language, the less precise term, survival wind speed, is often used. In this document, however, the turbine is designed using extreme wind speeds for design load cases.

3.20

fail-safe

design property of an item which prevents its failures from resulting in critical faults

3.21

gust

temporary change in the wind speed

Note 1 to entry: A gust may be characterized by its rise time, its magnitude and its duration.

3.22

horizontal axis wind turbine

wind turbine whose rotor axis is substantially horizontal

3.23

hub

<wind turbines> fixture for attaching the blades or blade assembly to the rotor shaft

3.24

hub height

z_{hub}
<wind turbines> height of the centre of the swept area (3.57) of the wind turbine rotor above the terrain surface

3.25

idling

<wind turbines> condition of a wind turbine that is rotating slowly and not producing power

3.26

inertial sub-range

frequency interval of the turbulence spectrum, where eddies – after attaining isotropy – undergo successive break-up with negligible energy dissipation

Note 1 to entry: At a typical 10 m/s wind speed, the inertial sub-range is roughly from 0,2 Hz to 1 kHz.

3.27

limit state

state of a structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirement

~~[ISO 2394, modified]~~

Note 1 to entry: The purpose of design calculations (i.e. the design requirement for the limit state) is to keep the probability of a limit state being reached below a certain value prescribed for the type of structure in question (see ISO 2394).

3.27

~~logarithmic wind shear law~~

~~see 3.62~~

3.28

mean wind speed

statistical mean of the instantaneous value of the wind speed averaged over a given time period which can vary from a few seconds to many years

3.29

medium wind turbine

wind turbine with a rotor swept area or, in the case of a ducted or shrouded turbine, the larger of the duct or shroud entry and exit areas greater than 200 m² and less than or equal to 1 000 m²

3.30

nacelle

housing which contains the drive-train and other elements on top of a horizontal axis wind turbine tower

3.31

network connection point

<wind turbines> cable terminals of a single wind turbine or, for a wind power station, the connection point to the electrical bus of the site power collection system

3.32

network loss

loss of electrical network (grid) for a period exceeding any ride through provision in the turbine control system

3.33

normal shutdown

<wind turbines> shutdown in which all stages are under the control of the control system

3.34

operating limits

set of conditions defined by the wind turbine designer that governs the activation of the turbine control functions ~~and protection system~~

3.35

parked wind turbine

turbine being either in a standstill or an idling condition, depending on the design of the wind turbine, ~~parked refers to the turbine being either in a standstill or an idling condition~~

3.36 performance level PL

discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions

~~3.36
power law for wind shear
see 3.62~~

3.37 power collection system

<wind turbines> electric system that collects the power from one or more wind turbines

Note 1 to entry: It includes all electrical equipment connected between the wind turbine terminals and the network connection point.

3.38 power output

power delivered by a device in a specific form and for a specific purpose

Note 1 to entry: For a wind turbine, it is the electric power it delivers.

3.39 primary layer protection function

protection function (3.40) in a protection system with two or more independent layers which may be implemented as a part of the wind turbine control system and is separate from a secondary layer protection function (3.52) with a similar purpose

3.40 protection functions

<wind turbine> functions of the control and protection system which ensure that a wind turbine remains within the design limits

3.41 rated power

quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment

Note 1 to entry: For a wind turbine, it is the maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating and external conditions.

3.42 rated wind speed

V_r

minimum wind speed at hub height at which a wind turbine's rated power is achieved in the case of steady wind without turbulence

3.43 Rayleigh distribution

P_R

probability distribution function

Note 1 to entry: See 3.68.

3.44 reference wind speed

V_{ref}

basic parameter for wind speed used for defining wind turbine classes

Note 1 to entry: Other design related climatic parameters are derived from the reference wind speed and other basic wind turbine class parameters (see Clause 6).

Note 2 to entry: A turbine designed for a wind turbine class with a reference wind speed V_{ref} is designed to withstand climates for which the extreme 10 min average wind speed with a ~~recurrence~~ return period of 50 years at turbine hub height is lower than or equal to V_{ref} .

3.45

resistance partial safety factor

γ_M

factor which takes account of possible unfavourable deviations/uncertainties of the material strength parameters and of the resistance model including bias in the resistance model

3.46

rotationally sampled wind velocity

wind velocity experienced at a fixed point of the rotating wind turbine rotor

Note 1 to entry: The turbulence spectrum of a rotationally sampled wind velocity is distinctly different from the normal turbulence spectrum. While rotating, the blade cuts through a wind flow that varies in space. Therefore, the resulting turbulence spectrum will contain sizeable amounts of variance at the frequency of rotation and harmonics of the same.

3.47

rotor speed

<wind turbines> rotational speed of a wind turbine rotor about its axis

3.48

roughness length

z_0

extrapolated height at which the mean wind speed becomes zero if the vertical wind profile is assumed to have a logarithmic variation with height

3.49

safe-life

design property for a critical system which is either very difficult to repair or may cause severe damage to life and property

Note 1 to entry: Such systems are designed to work for the full system lifetime without requirement of any repairs or inspections.

3.50

safety integrity level

SIL

discrete level (one out of a possible four), corresponding to a range of safety integrity values for the control functions, where 4 and 1 belong to the highest and lowest levels, respectively

Note 1 to entry: Target failure measures for the four safety integrity levels are defined in Tables 2 and 3 of IEC 61508-1:2010. These levels can be used for specifying safety integrity requirements of safety functions allocated to the systems. A SIL is not a property of a system, subsystem, element or component. As defined in IEC 61508-1, the phrase "SIL n safety-related system" (where n is 1, 2, 3, or 4) means that the system is potentially capable of supporting safety functions with a safety integrity level up to n .

3.51

scheduled maintenance

preventive maintenance carried out in accordance with an established ~~time~~ schedule

3.52

secondary layer protection function

dedicated protection function which operates using a layer of monitoring and logic separate from a primary layer protection function (3.39) with a similar purpose

3.53

site data

environmental, seismic, soil and electrical network data for the wind turbine site

Note 1 to entry: Wind data shall be the statistics of 10 min samples unless otherwise stated.

3.54

standstill

condition of a wind turbine that is stopped

3.55

support structure

<wind turbines> part of a wind turbine comprising the tower and foundation

3.56

survival wind speed

~~popular name for the~~ maximum wind speed that a construction is designed to withstand

Note 1 to entry: This is a popular expression that is not used in this document. Design conditions instead refer to extreme wind speed (3.19).

3.57

swept area

projected area perpendicular to the wind direction that a rotor will describe during one complete rotation

3.58

turbulence intensity

I

ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified period of time

3.59

turbulence scale parameter

λ_1

wavelength where the non-dimensional, longitudinal power spectral density is equal to 0,05

Note 1 to entry: The wavelength is thus defined as $\lambda_1 = V_{\text{hub}}/f_0$, where $f_0 S_1(f_0)/\sigma_1^2 = 0,05$.

3.60

turbulence standard deviation

σ_1

standard deviation of the longitudinal component of the turbulent wind velocity at hub height

3.61

ultimate limit state

limit states which generally correspond to maximum load carrying capacity

[ISO 2394, modified]

3.62

unscheduled maintenance

maintenance carried out, not in accordance with an established time schedule, but after ~~reception~~ receipt of an indication regarding the state of an item

3.63

upwind

in the direction opposite to the main wind vector

3.64**vertical axis wind turbine**

wind turbine whose rotor axis is vertical

3.65**Weibull distribution**

P_W

probability distribution function

Note 1 to entry: See 3.68.

3.60**wind farm**

see 3.61

3.66**wind power station**

wind farm

group or groups of wind turbines, ~~commonly called a wind farm~~

3.67**wind profile****wind shear law**

mathematical expression for assumed wind speed variation with height above ground

Note 1 to entry: Commonly used profiles are the logarithmic profile (Equation (1)) or the power law profile (Equation (2)).

$$V(z) = V(z_r) \cdot \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \quad (1)$$

$$V(z) = V(z_r) \cdot \left(\frac{z}{z_r} \right)^\alpha \quad (2)$$

where

$V(z)$ is the wind speed at height z ;

z is the height above ground;

z_r is a reference height above ground used for fitting the profile;

z_0 is the roughness length;

α is the wind shear (or power law) exponent.

3.68**wind speed distribution**

probability distribution function, used to describe the distribution of wind speeds over an extended period of time

Note 1 to entry: Often used distribution functions are the Rayleigh, $P_R(V_0)$, and the Weibull, $P_W(V_0)$, functions.

$$\begin{aligned} P_R(V_0) &= 1 - \exp \left[-\pi (V_0 / 2V_{ave})^2 \right] \\ P_W(V_0) &= 1 - \exp \left[-(V_0 / C)^k \right] \end{aligned} \quad (3)$$

$$\text{with } V_{\text{ave}} = \begin{cases} C \Gamma(1 + \frac{1}{k}) \\ C \sqrt{\pi} / 2, \text{ if } k = 2 \end{cases} \quad (4)$$

where

$P(V_0)$ is the cumulative probability function, i.e. the probability that $V < V_0$;

V_0 is the wind speed (limit);

V_{ave} is the average value of V ;

C is the scale parameter of the Weibull function;

k is the shape parameter of the Weibull function;

Γ is the gamma function.

Both C and k can be evaluated from real data. The Rayleigh function is identical to the Weibull function if $k = 2$ is chosen and C and V_{ave} satisfy the condition stated in Equation (4) for $k = 2$.

The distribution functions express the cumulative probability that the wind speed is lower than V_0 . Thus $(P(V_1) - P(V_2))$, if evaluated between the specified limits V_1 and V_2 , will indicate the fraction of time that the wind speed is within these limits. Differentiating the distribution functions yields the corresponding probability density functions.

3.69

wind shear

variation of wind speed across a plane perpendicular to the wind direction

3.65

wind shear exponent

α

~~also commonly known as power law exponent, see 3.62~~

3.70

wind speed

V

~~at a specified point in space it is the~~ speed of motion of a minute amount of air surrounding ~~the~~ a specified point in space

Note 1 to entry: It is also the magnitude of the local wind velocity (vector) (see 3.73).

3.71

wind turbine generator system

<wind turbine> system which converts kinetic energy in the wind into electrical energy

3.72

wind turbine site

location of an individual wind turbine either alone or within a wind farm

3.73

wind velocity

vector pointing in the direction of motion of a minute amount of air surrounding the point of consideration, the magnitude of the vector being equal to the speed of motion of this air "parcel" (i.e. the local wind speed)

Note 1 to entry: The vector at any point is thus the time derivative of the position vector of the air "parcel" moving through the point.

3.74

wind turbine electrical system

~~all~~ electrical equipment internal to the wind turbine, up to and including the wind turbine terminals, including equipment for earthing, bonding and communications

Note 1 to entry: Conductors local to the wind turbine, which are intended to provide an earth termination network specifically for the wind turbine, are included.

3.75

wind turbine terminals

point or points identified by the wind turbine supplier at which the wind turbine may be connected to the power collection system

Note 1 to entry: This includes connection for the purposes of transferring energy and communications.

3.76

yawing

rotation of the rotor axis about a vertical axis

Note 1 to entry: For horizontal axis wind turbines only.

3.77

yaw misalignment

horizontal deviation of the wind turbine rotor axis from the wind direction

4 Symbols and abbreviated terms

4.1 Symbols and units

C	scale parameter of the Weibull distribution function	[m/s]
C_{CT}	turbulence structure correction parameter	
C_T	thrust coefficient	[-]
Coh	coherence function	[-]
D	rotor diameter	[m]
$D_{TV,i}$	standard deviation of terrain variation Δz in i th 30° sector	[m]
$D_{TV,360}$	standard deviation of terrain variation Δz of the 360° circle area	[m]
f	frequency	[s ⁻¹]
f_d	design value for material strength	[-]
f_k	characteristic value for material strength	[-]
F_d	design value for loads	[-]
F_k	characteristic value for loads	[-]
I_{ref}	~~expected value hub height turbulence intensity at a 10 min average wind speed of 15 m/s~~ reference value of the turbulence intensity corresponding to the 70 % quantile at 15 m/s	[-]
I_{eff}	effective turbulence intensity	[-]
k	shape parameter of the Weibull distribution function	[-]
k_1	empirical adjustment factor for TSI360, $k_1 = 5/3$	[-]
k_2	empirical adjustment factor for TVI360, $k_2 = 3$	[-]
K	modified Bessel function	[-]
L	isotropic turbulence integral scale parameter	[m]
L_e	coherence scale parameter	[m]
L_k	velocity component integral scale parameter	[m]
m	Wöhler curve exponent	[-]

n_i	counted number of fatigue cycles in load bin i	[-]
$N(.)$	number of cycles to failure as a function of the stress (or strain) indicated by the argument (i.e. the characteristic S-N curve)	[-]
N	~~recurrence~~ return period for extreme situations	[years]
p	air pressure	[N/m ²]
$P(V_0)$	probability distribution, i.e. the probability that $V < V_0$	[-]
$P_R(V_0)$	Rayleigh probability distribution, i.e. the probability that $V < V_0$	[-]
P_s	survival probability	[-]
$P_W(V_0)$	Weibull probability distribution	[-]
r	magnitude of separation vector projection	[m]
R	radius of circle segment	[m]
R_0	gas constant	[J/(kg·K)]
S	load function	[-]
s_i	the stress (or strain) level associated with the counted number of cycles in bin i	[-]
$S_1(f)$	power spectral density function for the longitudinal wind velocity component	[m ² /s]
$S_{F,min}$	minimum value of safety factor for tooth breakage	[-]
$S_{H,min}$	minimum value of safety factor for pitting	[-]
$S_k(f)$	one-sided power spectral density function for wind velocity component ~~spectrum~~ k : $k = 1$ longitudinal component $k = 2$ lateral component $k = 3$ vertical component	[m ² /s]
T	gust characteristic time	[s]
t	time	[s]
V	wind speed	[m/s]
$V(z)$	wind speed at height z	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_{cg}	extreme coherent gust magnitude over the whole rotor swept area	[m/s]
V_{eN}	expected extreme wind speed (averaged over three seconds), with a recurrence time interval of N years. V_{e1} and V_{e50} for 1 year and 50 years, respectively	[m/s]
V_{gust}	largest gust magnitude with an expected ~~recurrence~~ return period of 50 years	[m/s]
V_{hub}	wind speed at hub height	[m/s]
V_{in}	cut-in wind speed	[m/s]
V_0	limit wind speed in wind speed distribution model	[m/s]
V_{50}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 50 years	[m/s]
V_{100}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 100 years	[m/s]
V_{out}	cut-out wind speed	[m/s]

V_r	rated wind speed	[m/s]
V_{ref}	reference wind speed	[m/s]
$V_{ref,T}$	reference wind speed for tropical-like conditions	[m/s]
$V(y,z,t)$	longitudinal wind velocity component to describe transient horizontal wind shear	[m/s]
$V(z,t)$	longitudinal wind velocity component to describe transient variation for extreme gust and shear conditions	[m/s]
x, y, z	co-ordinate system used for the wind field description; along wind (longitudinal), across wind (lateral) and height respectively	[m]
Z_{NT}	life factor for contact stress for reference test conditions	[-]
z_{hub}	hub height of the wind turbine	[m]
z_r	reference height above ground	[m]
z_0	roughness length for the logarithmic wind profile	[m]
α	wind shear power law exponent	[-]
β	parameter for extreme direction change model	[-]
δ	coefficient of variation	[-]
Γ	gamma function	[-]
γ_f	partial safety factor for loads	[-]
γ_M	partial safety factor for ~~materials~~ resistances	[-]
γ_n	partial safety factor for consequences of failure	[-]
$\theta(t)$	wind direction change transient	[deg]
θ_{cg}	angle of maximum deviation from the direction of the average wind speed under gust conditions	[deg]
θ_{eN}	extreme direction change with a ~~recurrence~~ return period of N years	[deg]
θ_i	slope of fitted plane for i th 30° sector	[deg]
θ_{360}	slope of the fitted 360° plane	[deg]
$\theta_{1year,min}$	minimum ambient temperature to be expected in hourly average	[K]
$\theta_{min,operation}$	minimum allowable ambient temperature for wind turbine operation	[K]
Λ_1	turbulence scale parameter defined as the wavelength where the non-dimensional, longitudinal power spectral density, $fS_1(f)/\sigma_1^2$, is equal to 0,05	[m]
ρ	air density	[kg/m ³]
$\hat{\sigma}$	estimated ~~turbulence~~ wind speed standard deviation	[m/s]
$\hat{\sigma}_c$	representative ambient turbulence standard deviation	[m/s]
$\hat{\sigma}_{eff}$	effective estimated ~~turbulence~~ wind speed standard deviation	[m/s]
σ_{wake}	~~wake turbulence~~ wind speed standard deviation in the wake	[m/s]
$\hat{\sigma}_T$	maximum centre-wake ~~turbulence~~ wind speed standard deviation	[m/s]
$\hat{\sigma}_\sigma$	standard deviation of estimated ~~turbulence~~ wind speed standard deviation $\hat{\sigma}$	[m/s]

$\hat{\sigma}_{1\text{ETM}}$	extreme ambient turbulence standard deviation	[m/s]
σ_1	hub-height longitudinal wind velocity standard deviation	[m/s]
σ_2	hub-height ~~vertical~~ lateral wind velocity standard deviation	[m/s]
σ_3	hub-height ~~transversal~~ upward wind velocity standard deviation	[m/s]
Φ	standardized normal probability function	[-]
$E[]$	expected value of parameter inside brackets	[-]
$\text{Var}[]$	variance of parameter inside brackets	[-]

4.2 Abbreviated terms

A	abnormal (for partial safety factors)
AC	alternating current
DC	direct current
CC	cold climate
COV	coefficient of variation
DLC	design load case
DWM	dynamic wake meandering
ECD	extreme coherent gust with direction change
EDC	extreme wind direction change
EOG	extreme operating gust
ETM	extreme turbulence model
EWM	extreme wind speed model
EWS	extreme wind shear
F	fatigue
FMEA	failure mode and effect analysis
HV	high voltage
IAC	internal arc classification
IC	icing climate
LTC	low temperature climate
LVRT	low voltage ride through
N	normal and extreme (for partial safety factors)
NWP	normal wind profile model
NTM	normal turbulence model
S	special IEC wind turbine class
T	transport and erection (for partial safety factors)
TSI	terrain slope index
TVI	terrain variation index
U	ultimate
ULS	ultimate limit state

5 Principal elements

5.1 General

The engineering and technical requirements to ensure the safety of the structural, mechanical, electrical and control systems of the wind turbine are given in the following clauses. This specification of requirements applies to the design, manufacture, installation and manuals for operation and maintenance of a wind turbine and the associated quality management process. In addition, safety procedures, which have been established in the various practices that are used in the installation, operation and maintenance of wind turbine, are taken into account.

5.2 Design methods

This document requires the use of ~~a structural~~ an aeroelastic dynamics model to predict design loads. Such a model shall be used to determine the loads over a range of wind speeds, using the turbulence conditions and other wind conditions defined in Clause 6 and design situations defined in Clause 7. All relevant combinations of external conditions and design situations shall be analysed. A minimum set of such combinations has been defined as load cases in this document.

Data from full scale testing of a wind turbine ~~may~~ shall be used to increase confidence in predicted design values and to verify structural dynamics models and design situations as specified in 7.2.

Verification of the adequacy of the design shall be made by calculation and/or by testing. If test results are used in this verification, the external conditions during the test shall be shown to reflect the characteristic values and design situations defined in this document. The selection of test conditions, including the test loads, shall take account of the relevant safety factors.

5.3 Safety classes

A wind turbine shall be designed according to one of the following two safety classes:

- a normal safety class which applies when a failure results in risk of personal injury or other social or economic consequence;
- a special safety class that applies when the safety requirements are determined by local regulations and/or the safety requirements are agreed between the manufacturer and the customer.

Partial safety factors, for normal safety class wind turbines, are specified in 7.6.

Partial safety factors for special safety class wind turbines shall be agreed between the manufacturer and the customer. A wind turbine designed according to a special safety class ~~is~~ shall be classified as a class S wind turbine, as defined in 6.2.

5.4 Quality assurance

Quality assurance shall be an integral part of the design, procurement, manufacture, installation, operation and maintenance of the wind turbines and all their components.

It is recommended that the quality system comply with the requirements of ISO 9001.

5.5 Wind turbine markings

The following information, as a minimum, shall be prominently and legibly displayed on the indelibly marked turbine nameplate:

- wind turbine manufacturer and country;
- model and serial number;
- production year;
- rated power;
- reference wind speed, V_{ref} ;
- hub height operating wind speed range, $V_{in} - V_{out}$;
- operating ambient temperature range;
- IEC wind turbine class (see Table 1);
- rated voltage at the wind turbine terminals;
- frequency at the wind turbine terminals or frequency range in the case that the nominal variation is greater than 2 %.

6 External conditions

6.1 General

The external conditions described in Clause 6 shall be considered in the design of a wind turbine.

Wind turbines are subjected to environmental and electrical conditions that may affect their loading, durability and operation. To ensure the appropriate level of safety and reliability, environmental, electrical and soil parameters shall be taken into account in the design and shall be explicitly stated in the design documentation.

The environmental conditions are further divided into wind conditions and other environmental conditions. The electrical conditions refer to the electrical power network conditions. Soil properties are relevant to the design of wind turbine foundations.

The external conditions are subdivided into normal and extreme categories. The normal external conditions generally concern recurrent structural loading conditions, while the extreme external conditions represent rare external design conditions. The design load cases shall consist of potentially critical combinations of these external conditions with wind turbine operational modes and other design situations.

Wind conditions are the primary external conditions affecting structural integrity. Other environmental conditions also affect design features such as control system function, durability, corrosion, etc.

The normal and extreme conditions, which are to be considered for design according to wind turbine classes, are prescribed in 6.2 to 6.4.

6.2 Wind turbine classes

The external conditions to be considered for design are dependent on the intended site or site type for a wind turbine installation. Wind turbine classes are defined in terms of wind speed, wind turbine class I, II and III, and turbulence parameters, turbulence category A+, A, B, and C. The intention of the classes is to cover most applications. The values of wind speed and turbulence parameters are intended to represent many different sites and do not give a precise representation of any specific site, see 11.3. The wind turbine classification offers a range of robustness clearly defined in terms of the wind speed and turbulence parameters. In order to allow the use of wind turbine classes for areas, which may experience very high extreme winds in an otherwise moderate wind climate, a T class reference wind speed is included. Such conditions may be found in areas subject to tropical cyclones. This reference wind speed may be used with the average wind speed in class I to III and turbulence

categories A+ to C¹. Table 1 specifies the basic parameters, which define the wind turbine classes.

Table 1 – Basic parameters for wind turbine classes²

Wind turbine class	I	II	III	S
V_{ref} (m/s)	50	42,5	37,5	Values specified by the designer
A $I_{ref}(-)$	0,16			
B $I_{ref}(-)$	0,14			
C $I_{ref}(-)$	0,12			

In Table 1, the parameter values apply at hub height and

V_{ref} is the reference wind speed average over 10 min,

A designates the category for higher turbulence characteristics,

B designates the category for medium turbulence characteristics,

C designates the category for lower turbulence characteristics, and

I_{ref} is the expected value of the turbulence intensity³ at 15 m/s.

Wind turbine class		I	II	III	S
V_{ave} (m/s)		10	8,5	7,5	Values specified by the designer
V_{ref}	(m/s)	50	42,5	37,5	
	Tropical (m/s) $V_{ref,T}$	57	57	57	
A+	I_{ref} (-)	0,18			
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			
The parameter values apply at hub height and					
V_{ave} is the annual average wind speed;					
V_{ref} is the reference wind speed average over 10 min;					
$V_{ref,T}$ is the reference wind speed average over 10 min applicable for areas subject to tropical cyclones;					
A+ designates the category for very high turbulence characteristics;					
A designates the category for higher turbulence characteristics;					
B designates the category for medium turbulence characteristics;					
C designates the category for lower turbulence characteristics; and					
I_{ref} is a reference value of the turbulence intensity (see 6.3.2.3).					

Class T assumes all wind model parameters to be the same and allows the combination of $V_{ref,T}$ with all turbulence categories. It does not cover all the areas prone to tropical cyclones.

¹ A turbine class using for example the annual average wind speed of class II and turbulence category B together with the T class reference wind speed is designated class IIB,T.

² The annual average wind speed no longer appears in Table 1 as a basic parameter for the wind turbine classes in this edition of the standard. The annual average wind speed for wind turbine designs according to these classes is given in equation (9).

³ Note that I_{ref} is defined as the mean value in this edition of the standard rather than as a representative value.

A site assessment based on Clause 11 is needed, as a minimum assessing that V_{50} is below V_{ref} of class T ($V_{ref,T}$).

An optional wind turbine class CC, which may be used for areas with cold climate, is defined in Clause 14. The optional wind turbine class specifies additional requirements and parameters to what is given in Clause 6.

A further wind turbine class, class S, is defined for use when special wind or other external conditions or a special safety class, see 5.3, are required by the designer and/or the customer. The design values for the wind turbine class S shall be chosen by the designer and specified in the design documentation. For such special designs, the values chosen for the design conditions shall reflect an environment at least as severe as is anticipated for the use of the wind turbine.

~~The particular external conditions defined for classes I, II and III are neither intended to cover offshore conditions nor wind conditions experienced in tropical storms such as hurricanes, cyclones and typhoons. Such conditions may require wind turbine class S design.~~

Wind turbines to be designed for site-specific or very extreme conditions may require wind turbine class S design.

In addition to the basic parameters showed in Table 1, several other important parameters are required to completely specify the external conditions to be used in wind turbine design. In the case of the wind turbine classes I_{A+} through III_C, later referred to as the standard wind turbine classes, the values of these additional parameters are specified in 6.3, 6.4 and 6.5.

The design lifetime for wind turbine classes I to III shall be at least 20 years.

For the wind turbine class S the manufacturer shall, in the design documentation, describe the models used and values of design parameters. Where the models in Clause 6 are adopted, statement of the values of the parameters will be sufficient. The design documentation of wind turbine class S shall contain the information listed in Annex A. Guidance on turbine class S design load cases is given in Annex B.

The abbreviations added in parentheses in the subclause headings in ~~the remainder of this clause~~ 6.3.2.2 to 6.3.3.7 are used for describing the wind conditions for the design load cases defined in 7.4.

6.3 Wind conditions

6.3.1 General

A wind turbine shall be designed to safely withstand the wind conditions defined by the selected wind turbine class.

The design values of the wind conditions shall be clearly specified in the design documentation.

The wind regime for load and safety considerations is divided into the normal wind conditions, which will occur frequently during normal operation of a wind turbine, and the extreme wind conditions that are defined as having a 1-year or 50-year ~~recurrence~~ return period.

The wind conditions include a constant mean flow combined, in many cases, with either a varying deterministic gust profile or with turbulence. In all cases, the influence of an inclination of the mean flow with respect to a horizontal plane of ~~up to~~ 8° shall be considered. This flow inclination angle shall be assumed to be invariant with height.

The expression "turbulence" denotes random variations in the wind velocity from 10 min averages. The turbulence model, when used, shall include the effects of varying wind speed, shears and direction and allow rotational sampling through varying shears. The three vector components of the turbulent wind velocity are defined as

- longitudinal – along the direction of the mean wind velocity,
- lateral – horizontal and normal to the longitudinal direction, and
- upward – normal to both the longitudinal and lateral directions, i.e. tilted from the vertical by the mean flow inclination angle.

For the standard wind turbine classes, the random wind velocity field for the turbulence models shall satisfy the Kaimal model together with the coherence model described in Annex C. This model satisfies the following requirements.

- a) The turbulence standard deviation, σ_1 , with values given in the following subclauses, shall be assumed to be invariant with height. The components normal to the mean wind direction shall have the following minimum standard deviations⁴:
 - lateral component: $\sigma_2 \geq 0,7 \sigma_1$;
 - upward component: $\sigma_3 \geq 0,5 \sigma_1$;
- b) The longitudinal turbulence scale parameter, A_1 , at hub height z shall be given by

$$A_1 = \begin{cases} 0,7z & z \leq 60m \\ 42m & z \geq 60m \end{cases} \quad (5)$$

The power spectral densities of the three orthogonal components, $S_1(f)$, $S_2(f)$, and $S_3(f)$ shall asymptotically approach the following forms as the frequency in the inertial sub-range increases:

$$S_1(f) = 0,05 \sigma_1^2 (A_1 / V_{hub})^{-2/3} f^{-5/3} \quad (6)$$

$$S_2(f) = S_3(f) = \frac{4}{3} S_1(f) \quad (7)$$

- c) A recognized model for the coherence, defined as the magnitude of the co-spectrum divided by the auto-spectrum for the longitudinal velocity components at spatially separated points in a plane normal to the longitudinal direction, shall be used.

~~The recommended turbulence model that satisfies these requirements is the Mann uniform shear turbulence model in Annex B. Another frequently used model that satisfy these requirements is also given in Annex B. Other models should be used with caution, as the choice may affect the loads significantly.~~

As an alternative, the corresponding Mann model may be applied as described in Annex C.

Other turbulence models may be applied; however, for the standard wind turbine classes (I to III), the turbulence model shall satisfy the requirements a) to c) and also result in fatigue loads that are higher or equal to the fatigue loads generated using the models in Annex C. For Class S, a validated turbulence model may be applied.

⁴ The actual values can depend on the choice of turbulence model and the requirements in b).

6.3.2 Normal wind conditions

6.3.2.1 Wind speed distribution

The wind speed distribution is significant for wind turbine design because it determines the frequency of occurrence of individual load conditions for the normal design situations. The mean value of the wind speed ~~over a time~~ for an averaging period of 10 min shall be assumed to follow a Rayleigh distribution at hub height given by

$$P_R(V_{hub}) = 1 - \exp\left[-\pi(V_{hub}/2V_{ave})^2\right] \quad (8)$$

where, in the standard wind turbine classes, V_{ave} shall be chosen ~~as~~

$$V_{ave} = 0,2 V_{ref} \quad (9)$$

from Table 1.

6.3.2.2 Normal wind profile model (NWP)

The wind profile, $V(z)$, denotes the average wind speed as a function of height, z , above the ground. In the case of the standard wind turbine classes, the normal wind speed profile shall be given by the power law:

$$V(z) = V_{hub} (z/z_{hub})^\alpha \quad (9)$$

The power law exponent, α , shall be assumed to be 0,2.

The assumed wind profile is used to define the average vertical wind shear across the rotor swept area.

6.3.2.3 Normal turbulence model (NTM)

For the normal turbulence model, the representative value of the turbulence standard deviation, σ_1 , shall be given by the 90 %⁵ quantile for the given hub height wind speed. This value for the standard wind turbine classes shall be given by

$$\sigma_1 = I_{ref} (0,75V_{hub} + b); \quad b = 5,6 \text{ m/s} \quad (10)$$

Values for the turbulence standard deviation σ_1 and the turbulence intensity σ_1/V_{hub} are shown in Figure 1.

⁵ ~~Note, if other quantiles are desired for additional optional load calculations, they may be approximated for the standard classes by assuming a log-normal distribution and~~

$$E\langle\sigma_1|V_{hub}\rangle = I_{ref} (0,75V_{hub} + c); \quad c = 3,8 \text{ m/s}$$

$$Var\langle\sigma_1|V_{hub}\rangle = (I_{ref} (1,4 \text{ m/s}))^2$$

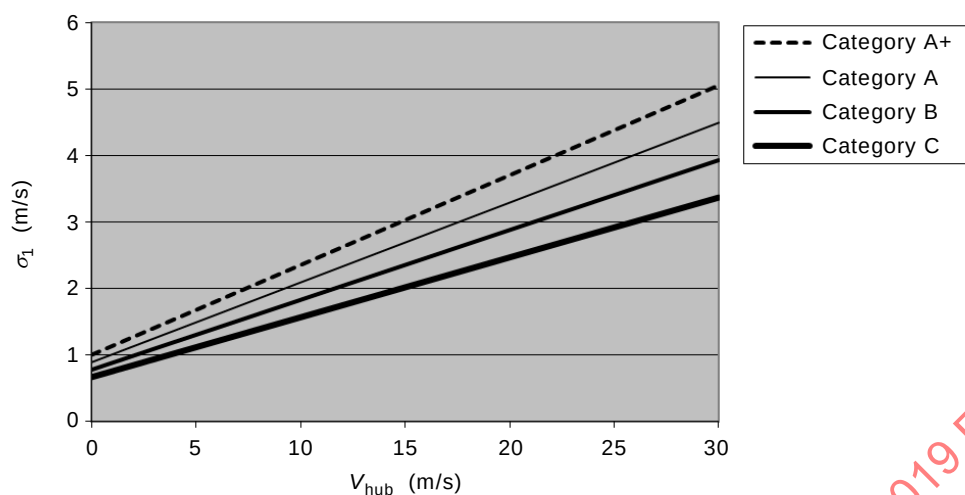


Figure 1a – Turbulence standard deviation

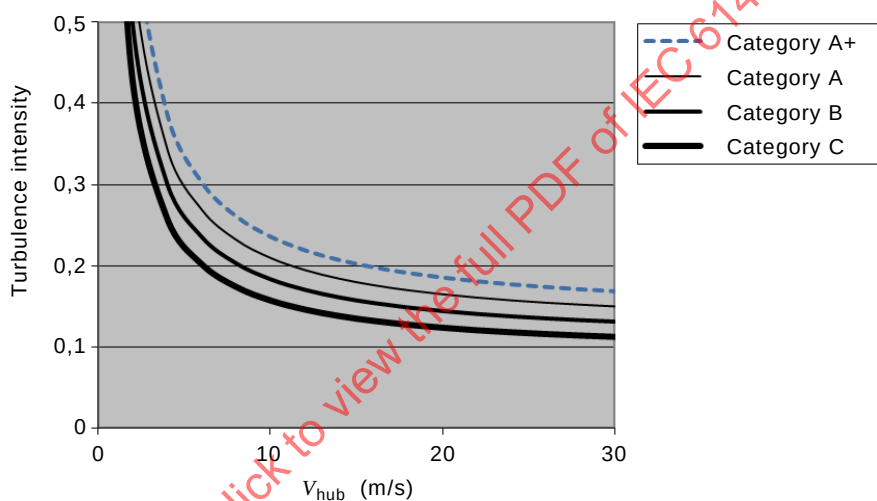


Figure 1b – Turbulence intensity

Figure 1 – Turbulence standard deviation and turbulence intensity for the normal turbulence model (NTM)

Values for I_{ref} are given in Table 1.

As an alternative to Equation (10), a Weibull distribution shall be assumed for σ_1 with Weibull scale and shape parameters:

$$P_W(\sigma_1 < \sigma_0) = 1 - \exp \left[- \left(\frac{\sigma_0}{C} \right)^k \right] \quad (11)$$

where

$$k = 0,27 V_{hub} (s/m) + 1,4$$

$$C = I_{ref} (0,75 V_{hub} + 3,3 \text{ m/s}) \quad (12)$$

6.3.3 Extreme wind conditions

6.3.3.1 General

The extreme wind conditions include wind shear events, as well as peak wind speeds due to storms and rapid changes in wind speed and direction.

6.3.3.2 Extreme wind speed model (EWM)

The EWM shall be either a steady or a turbulent wind model. The wind models shall be based on the reference wind speed, V_{ref} , and a fixed turbulence standard deviation, σ_1 . If the wind turbine type is designed for a T class reference wind speed, V_{ref} shall be replaced by $V_{ref,T}$ in the extreme wind speed model while keeping other parameters.

For the steady extreme wind model, the extreme wind speed, V_{e50} , with a ~~recurrence~~ return period of 50 years, and the extreme wind speed, V_{e1} , with a ~~recurrence~~ return period of 1 year, shall be computed as a function of height, z , using the following equations:

$$V_{e50}(z) = 1,4 V_{ref} \left(\frac{z}{z_{hub}} \right)^{0,11} \quad (13)$$

and

$$V_{e1}(z) = 0,8 V_{e50}(z) \quad (14)$$

In the steady extreme wind model, allowance for short-term deviations from the mean wind direction shall be made by assuming constant yaw misalignment in the range of $\pm 15^\circ$.

For the turbulent extreme wind speed model, the 10 min average wind speeds as functions of z with ~~recurrence~~ return periods of 50 years and 1 year, respectively, shall be given by

$$V_{50}(z) = V_{ref} \left(\frac{z}{z_{hub}} \right)^{0,11} \quad (15)$$

$$V_1(z) = 0,8 V_{50}(z) \quad (16)$$

The longitudinal turbulence standard deviation⁶ shall be

$$\sigma_1 = 0,11 V_{hub} \quad (17)$$

6.3.3.3 Extreme operating gust (EOG)

The hub height gust magnitude V_{gust} ⁷ shall be given for the standard wind turbine classes by the following relationship:

⁶ The turbulence standard deviation for the turbulent extreme wind model is not related to the normal (NTM) or the extreme turbulence model (ETM). The steady extreme wind model is related to the turbulent extreme wind model by a peak factor of approximately 3,5.

⁷ The gust magnitude is calibrated, together with the probability of an operation event such as starts and stops, to give a return period of 50 years.

$$V_{\text{gust}} = \text{Min} \left\{ 1,35(V_{e1} - V_{\text{hub}}); 3,3 \left(\frac{\sigma_1}{1 + 0,1 \left(\frac{D}{A_1} \right)} \right) \right\} \quad (18)$$

where

σ_1 is given in Equation (10);

A_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The wind speed shall be defined by Equation (19):

$$V(z,t) = \begin{cases} V(z) - 0,37V_{\text{gust}} \sin(3\pi t/T)(1 - \cos(2\pi t/T)) & \text{for } 0 \leq t \leq T \\ V(z) & \text{otherwise} \end{cases} \quad (19)$$

where

$V(z)$ is defined in Equation (9);

$T = 10,5$ s.

An example of the extreme operating gust ($V_{\text{hub}} = 25$ m/s, Class I_A, $D = 42$ m) is shown in Figure 2.

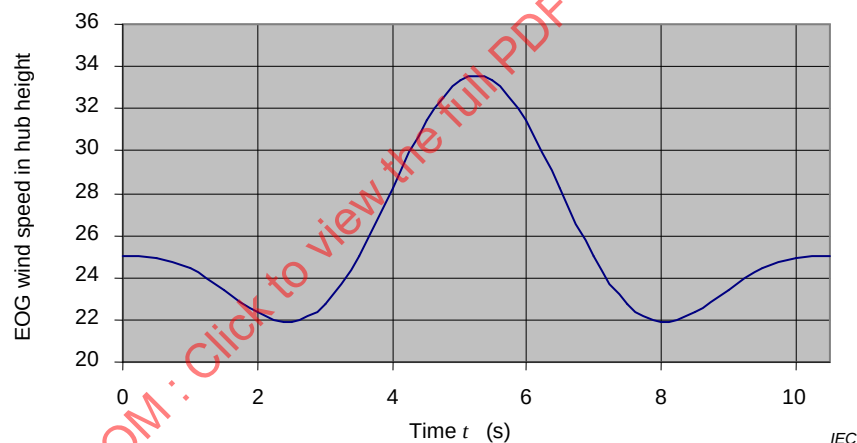


Figure 2 – Example of extreme operating gust

6.3.3.4 Extreme turbulence model (ETM)

The extreme turbulence model shall use the normal wind profile model in 6.3.2.2 and turbulence with longitudinal component standard deviation given by

$$\sigma_1 = c \cdot I_{\text{ref}} \left(0,072 \left(\frac{V_{\text{ave}}}{c} + 3 \right) \left(\frac{V_{\text{hub}}}{c} - 4 \right) + 10 \right); \quad c = 2 \text{ m/s.} \quad (20)$$

6.3.3.5 Extreme direction change (EDC)

The extreme direction change magnitude, θ_e , shall be calculated using the following relationship:

$$\theta_e = \pm 4 \arctan \left(\frac{\sigma_1}{V_{hub} \left(1 + 0,1 \left(\frac{D}{A_1} \right) \right)} \right) \quad (21)$$

where

σ_1 is given by Equation (10) for the NTM;

θ_e is limited to the interval $\pm 180^\circ$;

A_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The extreme direction change transient, $\theta(t)$, shall be given by

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0,5\theta_e(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ \theta_e & \text{for } t > T \end{cases} \quad (22)$$

where $T = 6$ s is the duration of the extreme direction change. The sign shall be chosen so that the worst transient loading occurs. At the end of the direction change transient, the direction is assumed to remain unchanged. The wind speed shall follow the normal wind profile model in 6.3.2.2.

As an example, the magnitude of the extreme direction change with turbulence category A, $D = 42$ m, $z_{hub} = 30$ m is shown in Figure 3 for varying V_{hub} . The corresponding transient for $V_{hub} = 25$ m/s is shown in Figure 4.

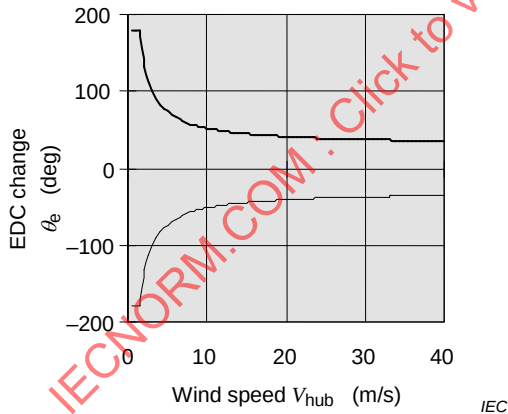


Figure 3 – Example of extreme direction change magnitude

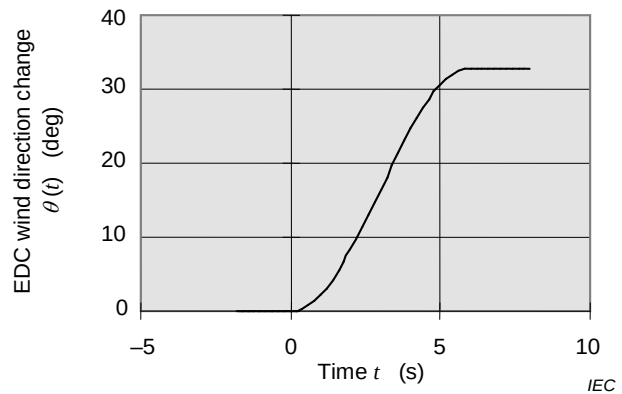


Figure 4 – Example of extreme direction change transient

6.3.3.6 Extreme coherent gust with direction change (ECD)

The extreme coherent gust with direction change shall have a magnitude of

$$V_{cg} = 15 \text{ m/s} \quad (23)$$

The wind speed shall be defined by

$$V(z,t) = \begin{cases} V(z) & \text{for } t \leq 0 \\ V(z) + 0,5V_{cg}(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ V(z) + V_{cg} & \text{for } t \geq T \end{cases} \quad (24)$$

where $T = 10$ s is the rise time and the wind speed $V(z)$ is given by the normal wind profile model in 6.3.2.2. The rise in wind speed during the extreme coherent gust is illustrated in Figure 5 for $V_{hub} = 25$ m/s.

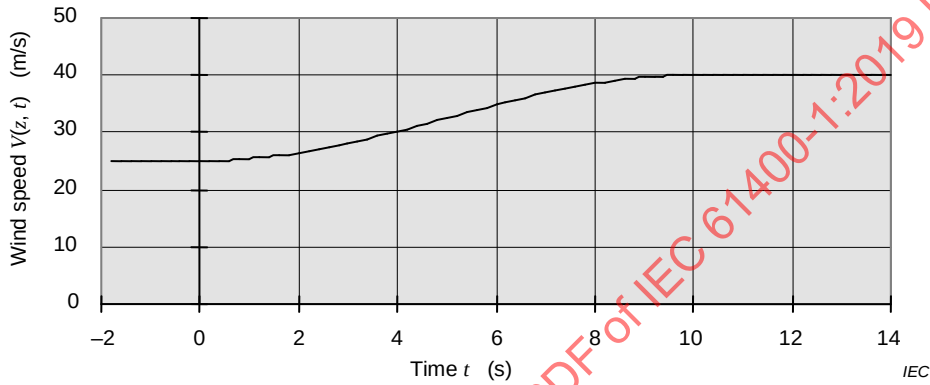


Figure 5 – Example of extreme coherent gust amplitude for ECD

The rise in wind speed shall be assumed to occur simultaneously with the direction change θ from 0° up to and including θ_{cg} , where the magnitude θ_{cg} is defined by

$$\theta_{cg}(V_{hub}) = \begin{cases} 180^\circ & \text{for } V_{hub} < 4 \text{ m/s} \\ \frac{720^\circ (m/s)}{V_{hub}} & \text{for } 4 \text{ m/s} < V_{hub} < V_{ref} \end{cases} \quad (25)$$

The simultaneous direction change is then given by

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0,5\theta_{cg}(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ \pm\theta_{cg} & \text{for } t > T \end{cases} \quad (26)$$

where $T = 10$ s is the rise time.

The direction change magnitude, θ_{cg} , and the direction change $\theta(t)$ are shown in Figures 6 and 7, as a function of V_{hub} and as a function of time for $V_{hub} = 25$ m/s, respectively.

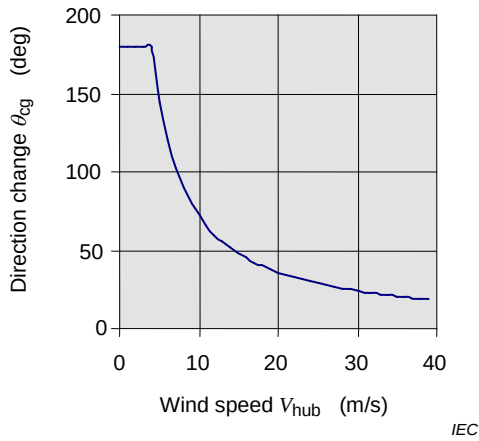


Figure 6 – Direction change for ECD

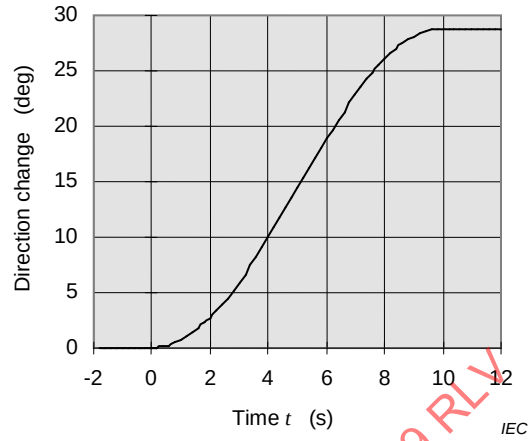


Figure 7 – Example of direction change transient

6.3.3.7 Extreme wind shear (EWS)

The extreme wind shear shall be accounted for using the following wind speed transients.

Transient (positive and negative) vertical shear:

$$V(z,t) = \begin{cases} V_{hub} \left(\frac{z}{z_{hub}} \right)^\alpha \pm \left(\frac{z - z_{hub}}{D} \right) \left(2,5[m/s] + 0,2\beta\sigma_1 \left(\frac{D}{A_1} \right)^{1/4} \right) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V_{hub} \left(\frac{z}{z_{hub}} \right)^\alpha & \text{otherwise} \end{cases} \quad (27)$$

Transient horizontal shear:

$$V(y,z,t) = \begin{cases} V_{hub} \left(\frac{z}{z_{hub}} \right)^\alpha \pm \left(\frac{y}{D} \right) \left(2,5[m/s] + 0,2\beta\sigma_1 \left(\frac{D}{A_1} \right)^{1/4} \right) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V_{hub} \left(\frac{z}{z_{hub}} \right)^\alpha & \text{otherwise} \end{cases} \quad (28)$$

where for both vertical and horizontal shear:

$\alpha = 0,2$; $\beta = 6,4$; $T = 12$ s;

σ_1 is given by Equation (10) for the NTM;

A_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The sign for the horizontal wind shear transient shall be chosen so that the worst transient loading occurs. The two extreme wind shears are not applied simultaneously.

As an example, the extreme vertical wind shear (turbulence category A, $z_{hub} = 30$ m, $V_{hub} = 25$ m/s, $D = 42$ m) is illustrated in Figure 8, which shows the wind profiles before onset

of the extreme event ($t = 0$ s) and at maximum shear ($t = 6$ s). Figure 9 shows the wind speeds at the top and the bottom of the rotor, to illustrate the time development of the shear (assumptions as in Figure 8).

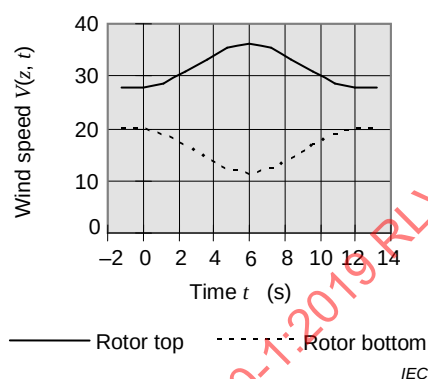
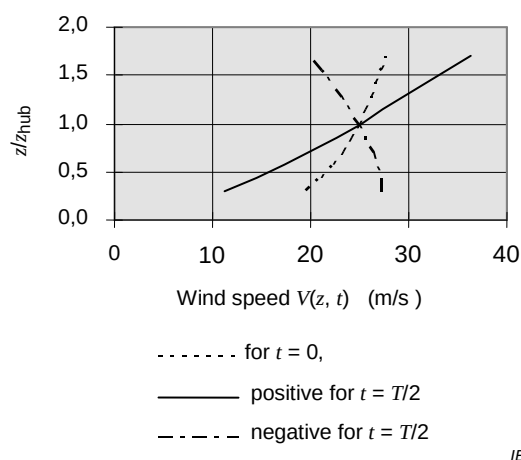


Figure 8 – Examples of extreme positive and negative vertical wind shear, wind profile before onset ($t = 0$, dashed line) and at maximum shear ($t = 6$ s, full line)

Figure 9 – Example of wind speeds at rotor top and bottom, respectively, which illustrate the transient positive wind shear

6.4 Other environmental conditions

6.4.1 General

Environmental (climatic) conditions other than wind can affect the integrity and safety of wind turbines, by thermal, photochemical, corrosive, mechanical, electrical or other physical action. Moreover, combinations of climatic conditions may increase their effects.

The following other environmental conditions, at least, shall be taken into account and the resulting action stated in the design documentation:

- temperature;
- humidity;
- air density;
- solar radiation;
- rain, hail, snow and ice;
- chemically active substances;
- mechanically active particles;
- salinity;
- lightning;
- earthquakes.

An offshore environment requires additional consideration, as per IEC 61400-3.

An optional cold climate class is defined in Clause 14.

The climatic conditions taken into account shall be defined in terms of either representative values or limits of the variable conditions. The probability of simultaneous occurrence of climatic conditions shall be taken into account when the design values are selected.

Variations in climatic conditions within the normal limits corresponding to a 1-year ~~recurrence~~ **return** period shall not interfere with the designed normal operation of a wind turbine.

Unless correlation exists, other extreme environmental conditions according to 6.4.3 shall be combined with normal wind conditions according to 6.3.2. **A general description on how to combine design situations with external conditions is given in 7.4.**

6.4.2 Normal other environmental conditions

The normal other environmental condition values that shall be taken into account are **the following**:

- ambient temperature range of -10 °C to $+40\text{ °C}$;
- relative humidity up to 95 %;
- atmospheric content equivalent to that of a non-polluted inland atmosphere (see IEC 60721-2-1);
- solar radiation intensity of $1\,000\text{ W/m}^2$;
- air density of $1,225\text{ kg/m}^3$.

When additional external conditions are specified by the designer, the parameters and their values shall be stated in the design documentation and shall conform to the requirements of IEC 60721-2-1.

6.4.3 Extreme other environmental conditions

6.4.3.1 General

The extreme other environmental conditions that shall be considered for wind turbine design are temperature, lightning, ice and earthquakes (see 11.6 for assessment of earthquake conditions).

6.4.3.2 Temperature

The extreme temperature range for the standard wind turbine classes shall be at least -20 °C to $+50\text{ °C}$.

6.4.3.3 Lightning

The provisions of lightning protection required in 10.7 may be considered as adequate for turbine designs for the standard wind turbine classes.

6.4.3.4 Ice

No minimum ice requirements are given for the standard wind turbine classes. **For cold climate, ice requirements are given in Clause 14 and Annex L.**

6.4.3.5 Earthquakes

No minimum earthquake requirements are given for the standard wind turbine classes. For consideration of earthquake conditions and effects, see 11.6 and Annex D.

6.5 Electrical power network conditions

The normal conditions at the wind turbine terminals to be considered are listed below.

Normal electrical power network conditions apply when the following parameters fall within the ranges stated below.

- Voltage – nominal value (according to IEC 60038) $\pm 10\%$.
- Frequency – nominal value $\pm 2\%$.
- Voltage imbalance – the ratio of the negative-sequence component of voltage not exceeding 2% .
- Auto-reclosing cycles – auto-reclosing cycle periods of 0,1 s to 5 s for the first reclosure and 10 s to 90 s for a second reclosure shall be considered.
- Outages – electrical network outages shall be assumed to occur 20 times per year. An outage of up to 6 h⁸ shall be considered a normal condition. An outage of up to 1 week shall be considered an extreme condition.

7 Structural design

7.1 General

The integrity of the load-carrying components of the wind turbine structure shall be verified and an acceptable safety level shall be ascertained. The ultimate and fatigue strength of structural members shall be verified by calculations ~~and/or~~, tests ~~or~~ both to demonstrate the structural integrity of a wind turbine with the appropriate safety level.

The structural analysis shall be based on ISO 2394.

Calculations shall be performed using appropriate methods. Descriptions of the calculation methods shall be provided in the design documentation. The descriptions shall include evidence of the validity of the calculation methods or references to suitable verification studies. The load level in any test for strength verification shall correspond to the safety factors appropriate for the characteristic loads according to 7.6.

Tower, rotor, and drive train resonances shall be identified for the frequency range up to and including 2 times the blade passing frequency excitation. Possible resonances shall be investigated at turbulence levels of 30 % of the NTM category C design turbulence for DLC 1.2, see 7.4.2. If high resonant loads are found at low turbulence, means shall be taken to avoid the resonances or they shall be included in the design loads.

7.2 Design methodology

It shall be verified that limit states are not exceeded for the wind turbine design. Model testing and prototype tests may also be used as a substitute for calculation to verify the structural design, as specified in ISO 2394.

The design calculations shall be based on validated methods and recognized codes.

The design methodology assumes that the aeroelastic simulation model used for the specific design calculations is subsequently validated by measurements. Such measurements shall be made on a wind turbine that is dynamically and structurally similar to, but may differ in detail (such as alternative tower designs) from the turbine designed. Requirements for load measurements can be found in IEC 61400-13.

7.3 Loads

7.3.1 General

Loads described in 7.3.2 through 7.3.5 shall be considered for the design calculations.

⁸ Six hours of operation is assumed to correspond to the duration of the severest part of a storm.

7.3.2 Gravitational and inertial loads

Gravitational and inertial loads are static and dynamic loads that result from gravity, vibration, rotation and seismic activity.

The allowable tolerances in tower verticality shall be stated in the design documentation and shall include initial and long term effects due to permanent soil subsidence. The effect of tower verticality on gravitational loads shall be taken into account separately during the structural analysis of tower and foundation.

7.3.3 Aerodynamic loads

Aerodynamic loads are static and dynamic loads that are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.

The airflow is dependent upon the average wind speed and turbulence across the rotor plane, the rotational speed of the rotor, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including aeroelastic effects.

It is not required in the aerodynamic load calculations to account for geometric tolerances in tower verticality of less than or equal to 3°.

7.3.4 Actuation loads

Actuation loads result from the operation and control of wind turbines. They are in several categories including torque control from a generator or inverter or both, yaw and pitch actuator loads and mechanical braking loads. In each case, it is important in the calculation of response and loading to consider the range of actuator forces available, including friction. In particular, for mechanical brakes, the range of friction, spring force or pressure as influenced by temperature, and ageing shall be taken into account in checking the response and the loading during any braking event.

7.3.5 Other loads

Other loads such as wake loads, impact loads, ice loads, ~~etc.~~, tower loads resulting for example from vortex-induced vibrations ~~may~~ might occur and shall be ~~included~~ considered where appropriate, ~~see 11.4~~. For other loads associated with cold climate, see Clause 14 and Annex L.

7.4 Design situations and load cases

7.4.1 General

Subclause 7.4 describes the design load cases for a wind turbine and specifies a minimum number to be considered.

For design purposes, the life of a wind turbine can be represented by a set of design situations covering the most significant conditions that the wind turbine may experience.

The load cases shall be determined from the combination of operational modes or other design situations, such as specific assembly, erection or maintenance conditions, with the external conditions. All relevant load cases with a reasonable probability of occurrence shall be considered, together with the behaviour of the control ~~and protection~~ system. The design load cases used to verify the structural integrity of a wind turbine shall be calculated by combining the following:

- normal design situations and appropriate normal or extreme external conditions;
- fault design situations and appropriate external conditions;
- transportation, installation and maintenance design situations and appropriate external conditions.

If correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a design load case.

Within each design situation, several design load cases shall be considered. As a minimum, the design load cases in Table 2 shall be considered. In that table, the design load cases are specified for each design situation by the description of the wind, electrical and other external conditions.

If the wind turbine controller ~~could~~ **can**, during design load cases with a deterministic wind model, cause the wind turbine to shut down prior to reaching maximum yaw angle and/or wind speed, then it ~~must~~ **shall** be shown that the turbine can reliably shut down under turbulent conditions with the same deterministic wind condition change.

Other design load cases shall be considered, if relevant to the structural integrity of the specific wind turbine design.

For each design load case, the appropriate type of analysis is stated by "F" and "U" in Table 2. "F" refers to analysis of fatigue loads, to be used in the assessment of fatigue strength. "U" refers to the analysis of ultimate loads, with reference to material strength, blade tip deflection and structural stability.

The design load cases indicated with "U" are classified as normal (N) or abnormal (A), ~~or transport and erection (T)~~. Normal design load cases are expected to occur frequently ~~within the lifetime of a turbine~~. The turbine is in a normal state or may have experienced minor faults or abnormalities. Abnormal design situations are less likely to occur. They usually correspond to design situations with severe faults that result in the activation of system protection functions. The type of design situation, N or A, ~~or T~~, determines the partial safety factor γ_f to be applied to the ultimate loads. These factors are given in Table 3.

Table 2 – Design load cases (DLC)

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM $V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD $V_{hub} = V_r - 2 \text{ m/s}, V_r, V_r + 2 \text{ m/s}$		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Normal control system fault or loss of electrical network or primary layer control function fault (see 7.4.3)	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	~~Protection system or preceding internal electrical fault~~ Abnormal control system fault or secondary layer protection function related fault (see 7.4.3)	U	A
	2.3	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	~~Control, protection, or electrical system faults including~~ system fault, electrical fault or loss of electrical network	F	*
	2.5	NWP $V_{in} < V_{hub} < V_{out}$	Low voltage ride through	U	N
3) Start-up	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
	3.3	EDC $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
4) Normal shutdown	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
5) Emergency shut down stop	5.1	NTM $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM 50-year ~~recurrence~~ return period		U	N
	6.2	EWM 50-year ~~recurrence~~ return period	Loss of electrical network connection	U	A
	6.3	EWM 1-year ~~recurrence~~ return period	Extreme yaw misalignment	U	N
	6.4	NTM $V_{hub} < 0,7 V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM 1-year ~~recurrence~~ return period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM V_{maint} to be stated by the manufacturer		U	~~F~~ N
	8.2	EWM 1-year ~~recurrence~~ return period		U	A

Key	
DLC	Design load case
ECD	Extreme coherent gust with direction change (see 6.3.3.6)
EDC	Extreme direction change (see 6.3.3.5)
EOG	Extreme operating gust (see 6.3.3.3)
EWM	Extreme wind speed model (see 6.3.3.2)
EWS	Extreme wind shear (see 6.3.3.7)
NTM	Normal turbulence model (see 6.3.2.3)
ETM	Extreme turbulence model (see 6.3.3.4)
NWP	Normal wind profile model (see 6.3.2.2)
$V_r \pm 2$ m/s	Sensitivity to all wind speeds in the range shall be analysed
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
~~T~~	~~Transport and erection~~
*	Partial safety for fatigue (see 7.6.3)

When a wind speed range is indicated in Table 2, wind speeds leading to the most adverse condition for wind turbine design shall be considered. The range of wind speeds may be represented by a set of discrete values, in which case the resolution shall be sufficient to assure accuracy of the calculation⁹. In the definition of the design load cases, reference is made to the wind conditions described in Clause 6.

In the further specifications of design load cases (DLCs) in 7.4.2 to 7.4.9, some DLCs allow alternative formulations. Where alternatives are mentioned, the party designing to this document shall decide which alternative shall be used throughout the analysis of the DLC.

7.4.2 Power production (DLC 1.1 to 1.5)

In this design situation, a wind turbine is running and connected to the electric load. The assumed wind turbine configuration shall take into account rotor imbalance. The maximum mass and aerodynamic imbalances (e.g. blade pitch and twist deviations) specified for rotor manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating situations such as yaw misalignment and control system tracking errors shall be taken into account in the analyses of operational loads.

Design load cases (DLCs) 1.1 and 1.2 embody the requirements for loads resulting from atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime (NTM). DLC 1.3 embodies the requirements for ultimate loading resulting from extreme turbulence conditions. DLC 1.4 and 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine.

The statistical analysis of DLC 1.1 simulation data, see 7.6.2.2 and Annex G, shall include at least the calculation of extreme values of the blade root in-plane moment and out-of-plane moment and tip deflection. If the extreme design values of ~~these parameters~~ the blade root moments derived from DLC 1.1 are exceeded by the extreme design values derived for DLC 1.3, the further analysis of DLC 1.1 may be omitted.

⁹ In general, a resolution of 2 m/s is considered sufficient. However, in the wind speed range where the power curve rises quickly, 2 m/s steps may be too large to assure accuracy.

If the extreme design values of ~~these parameters~~ the blade root moments derived from DLC 1.1 are not exceeded by the extreme design values derived for DLC 1.3, the factor c in Equation (20) for the extreme turbulence model used in DLC 1.3 may be increased until the extreme design values of the blade root moments computed in DLC 1.3 are equal to or exceed ~~the extreme design values of these parameters computed in DLC 1.1~~ the relevant extremes. The characteristic values of the loads relevant for other turbine components may be determined from this analysis based on DLC 1.3 with the increased c value. As an alternative to this analysis, the appropriate characteristic values of all load components relevant for each specific turbine component may be directly determined or extrapolated from the simulation.

7.4.3 Power production plus occurrence of fault or loss of electrical network connection (DLC 2.1 to ~~2.4~~ 2.5)

7.4.3.1 General

This design situation involves a transient event triggered by a fault or by the loss of electrical network connection while the turbine is producing power. Any fault in the control ~~and protection~~ system, or internal fault in the electrical system, significant for wind turbine loading (such as generator short circuit) shall be considered. ~~For DLC 2.1 the occurrence of faults relating to control functions or loss of electrical network connection shall be considered as normal events. For DLC 2.2, rare events, including faults relating to the protection functions or internal electrical systems shall be considered as abnormal. For DLC 2.3 the potentially significant wind event, EOG, is combined with an internal or external electrical system fault (including loss of electrical network connection) and considered as an abnormal event. In this case, the timing of these two events shall be chosen to achieve the worst loading. If a fault or loss of electrical network connection does not cause an immediate shutdown and the subsequent loading can lead to significant fatigue damage, the likely duration of this situation along with the resulting fatigue damage in normal turbulence conditions (NTM) shall be evaluated in DLC 2.4.~~

This design situation is considered to be relevant for fatigue analysis as well, see DLC 2.4.

A failure mode and effect analysis (FMEA) or equivalent fault analysis shall be carried out to determine fault events relevant for the wind turbine loading.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random.

Faults in the control system shall be considered in DLC 2.1 and DLC 2.2 as described in 7.4.3.2. For architectures where turbine safety is ensured by two independent sets of functions (via primary layer control functions and secondary layer protection functions, respectively) the method described in 7.4.3.3 may be used. See Clause 8 for guidance on identification of failure modes, assessment of failure mode return periods, fault exclusions, and measures to avoid common-cause failures.

7.4.3.2 Control system failure (DLC 2.1 and DLC 2.2) – Quantitative approach

For DLC 2.1, the following shall be considered as normal events:

- control system failure related events that have an expected failure mode return period that is equal to or less than 50 years;
- control system failure related events where the expected failure mode return period cannot be obtained;
- loss of electrical network connection.

For events with expected failure mode return periods between 10 and 50 years, the partial load factor applied is found as function of the failure mode return period as stated in Table 3.

For DLC 2.2, control system failure events or internal electrical and mechanical system faults with expected failure mode return period greater than 50 years shall be considered as abnormal.

Fault events with a return period in excess of 2000 years and fault events that are not relevant for wind turbine loading may be disregarded. The fault event return period is based on the statistical calculation of the probability of an event whereby a control or internal electrical system part is in or enters a failed state such that a structural failure could occur.

7.4.3.3 Control system failure (DLC 2.1 and DLC 2.2) – Two-layer approach

This approach can be used for control system architectures consisting of two or more independent layers. Within this approach,

- a) primary layer control and protection functions aim to keep the turbine operating parameters within their normal operating limits and their design limits, respectively, and
- b) secondary layer protection functions aim to keep the turbine operating parameters within their design limits. These shall be activated as a result of failure of the primary layer control functions or as a result of the effects of an internal or external failure or dangerous event.

For DLC 2.1, primary layer control function faults, activation of primary layer protection functions or loss of electrical network connection shall be considered as normal events. Control function faults which lead to exceedance of the limits and the activation of the secondary layer protection functions shall be included in DLC 2.2.

Primary layer control function faults considered in DLC 2.1 typically include faults relating to rotor speed, yaw angle, and blade pitch angles.

For DLC 2.2, rare events that have relevance for the wind turbine loading, including faults relating to activation of secondary layer protection functions, shall be considered as abnormal. Such faults may include erroneous activation of actuators, non-activation of braking systems, and blocking of the pitch system. This load case shall at least address the following: independent overspeed protection, generator overload/fault protection, uncontrolled blade pitch protection (blade pitch runaway), uncontrolled yaw protection and excessive vibration or shock protection.

7.4.3.4 Other power production plus occurrence of fault or loss of electrical network connection (DLC 2.3 to 2.5)

For DLC 2.3, the potentially significant wind event, the extreme operating gust (EOG), is combined with loss of one or more phases in a multiphase electrical network connection and considered as an abnormal event. In this case, the timing of these two events shall be chosen to achieve the worst loading.

As an alternative to the specification of DLC 2.3 above and in Table 2, DLC 2.3 may instead be considered as a normal event (i.e. a partial safety factor for load of 1,35) to be analysed using stochastic wind simulations ($NTM - V_{in} < V_{hub} < V_{out}$) combined with an internal or external electrical system fault (including loss of electrical network connection). In this case, 12 response simulations shall be carried out for each considered mean wind speed. For each response simulation, the extreme response after the electrical fault has occurred is sampled. The fault shall be introduced after the effect of initial conditions has become negligible. For each mean wind speed, a nominal extreme response is evaluated as the mean of the 12 sampled extreme responses plus three times the standard deviation of the 12 samples. The characteristic response value for DLC 2.3 is determined as the extreme value among the nominal extreme responses.

If a fault or loss of electrical network connection does not cause an immediate shutdown and the subsequent loading can lead to significant fatigue damage, the likely duration of this situation along with the resulting fatigue damage in normal turbulence conditions (NTM) shall

be evaluated in DLC 2.4. The manufacturer shall estimate the expected frequency/duration for the events¹⁰.

For DLC 2.5, the event of low voltage ride through (LVRT)¹¹ is considered as normal. The design low voltage ride through event shall be specified by voltage drop and duration.

7.4.4 Start-up (DLC 3.1 to 3.3)

This design situation includes all the events resulting in loads on a wind turbine during the transients from any standstill or idling situation to power production. The number of occurrences shall be estimated based on the control system behaviour.¹²

For DLC 3.2, at least four different timing events between the EOG and the start-up event shall be considered for each wind speed. The first timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 50 % of maximum power. The last timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 95 % of maximum power. At least two additional timings shall be chosen, evenly distributed within the interval from 50 % to 95 % of maximum power.

For each wind speed, the characteristic value of the load may be computed as the average value of the extreme computed transient value for the four defined distinct points of time.

As an alternative to the EOG gust, the DLC 3.2 may instead be analysed using at least 12 stochastic wind simulations for each mean wind speed with the ETM. For each mean wind speed, a nominal extreme response is evaluated as the mean of the simulated extremes.

7.4.5 Normal shutdown (DLC 4.1 to 4.2)

This design situation includes all the events resulting in loads on a wind turbine during normal transient situations from a power production situation to a standstill or idling condition. The number of occurrences shall be estimated based on the control system behaviour.¹³

For DLC 4.2, the timing of the gust and the shutdown event shall be chosen such that the EOG gust starts at different times relative to the shutdown, with minimum six events evenly

¹⁰ If there is no relevant data/information available, the following frequency/duration can be applied for the below listed events:

- 10 shut-downs per year for overspeed event;
- 24 hours per year of operation for events with yaw error;
- 24 hours per year of operation for events with pitch error;
- 20 times per year with loss of electrical network connection.

¹¹ Low voltage ride through situations are normally defined by the electrical utilities as situations with grid disturbances or failures the wind turbine should be able to handle without shutting down. The reason for a demand for riding through these situations is that if the wind turbines (especially in wind farms) shut down it can result in a collapse of the grid.

¹² If historical data on start-ups for similar wind turbines are unavailable, the following annual frequencies for DLC 3.1 can be assumed:

- 1000 start-up procedures at V_{in} ;
- 50 start-up procedures at V_r ;
- 50 start-up procedures at maximum start-up wind speed.

¹³ If historical data on shutdowns for similar wind turbines are unavailable, the following annual frequencies for DLC 4.1 can be assumed:

- 1000 shut-down procedures at V_{in} ;
- 50 shut-down procedures at V_r ;
- 50 shut-down procedures at V_{out} .

distributed from 10 s before the beginning of the shutdown, till the power reaches 50 % of the initial power production level.

At least four evenly distributed rotor azimuth positions shall be applied for each distinct point of time. For each wind speed, the characteristic value of the load may be computed as the mean value of the extreme computed loads among all timings and azimuth positions considered.

If, due to the safety and control system, a shutdown event is automatically triggered during the EOG gust, that event shall also be considered in the analysis.

As an alternative to the EOG gust, the DLC 4.2 may instead be analysed using at least 12 stochastic wind simulations for each mean wind speed with the ETM. For each mean wind speed, a nominal extreme response is evaluated as the mean of simulated extremes.

7.4.6 Emergency ~~shut-down~~ stop (DLC 5.1)

Loads arising from activation of the emergency ~~shut-down~~ stop button shall be considered.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random.

7.4.7 Parked (standstill or idling) (DLC 6.1 to 6.4)

In this design situation, the rotor of a parked wind turbine is either in a standstill or idling condition. In DLC 6.1, 6.2 and 6.3, this situation shall be considered with the extreme wind speed model (EWM). For DLC 6.4, the normal turbulence model (NTM) shall be considered.

For design load cases, where the wind conditions are defined by EWM, either the steady extreme wind model or the turbulent extreme wind model may be used. If the turbulent extreme wind model is used, the response shall be estimated using either a full dynamic simulation or a quasi-steady analysis with appropriate corrections for gusts and dynamic response using the formulation in ISO 4354. If the steady extreme wind model is used, the effects of resonant response shall be estimated from the quasi-steady analysis above. If the ratio of resonant to background response (R/B) is less than 5 %, a static analysis using the steady extreme wind model may be used. If slippage in the wind turbine yaw system can occur at the characteristic load, the largest possible unfavourable slippage shall be added to the mean yaw misalignment. If the wind turbine has a yaw system where yaw movement is expected in the extreme wind situations (e.g. free yaw, passive yaw or semi-free yaw), the turbulent wind model shall be used and the yaw misalignment will be governed by the turbulent wind direction changes and the turbine yaw dynamic response. Also, if the wind turbine is subject to large yaw movements or change of equilibrium during a wind speed increase from normal operation to the extreme situation, this behaviour shall be included in the analysis.

In DLC 6.1, for a wind turbine with an active yaw system, a yaw misalignment of up to $\pm 15^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 8^\circ$ using the turbulent extreme wind model shall be imposed, provided restraint against slippage in the yaw system can be assured.

In DLC 6.2, a loss of the electrical power network at an early stage in a storm containing the extreme wind situation shall be assumed. Unless power back-up is provided for the control and yaw system with a capacity for yaw alignment for a period of at least 6 h, the effect of a wind direction change of up to $\pm 180^\circ$ shall be analysed.

The partial safety factors for loads for DLC 6.1 and DLC 6.2 in Table 3 are derived by assuming that the coefficient of variation of the annual maximum wind speed is smaller than 15 %; for other COV, see footnote 31 in 11.3.2.

In DLC 6.3, the extreme wind with a 1-year ~~recurrence~~ return period shall be combined with an extreme yaw misalignment. An extreme yaw misalignment of up to $\pm 30^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 20^\circ$ using the turbulent wind model shall be assumed.

If for the cases DLC 6.1 with steady extreme wind model, DLC 6.2 and DLC 6.3, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades.

In DLC 6.4, the expected number of hours of non-power production time at a fluctuating load appropriate for each wind speed where significant fatigue damage can occur to any components (e.g. from the weight of idling blades) shall be considered.

7.4.8 Parked plus fault conditions (DLC 7.1)

Deviations from the normal behaviour of a parked wind turbine, resulting from faults on the electrical network or in the wind turbine, shall require analysis. ~~If any fault other than a loss of electrical power network produces deviations from the normal behaviour of the wind turbine in parked situations, the possible consequences shall be the subject of analysis.~~ As a minimum, failures in the following systems shall be evaluated: brake system, pitch system, and yaw system. The fault condition shall be combined with EWM for a ~~recurrence~~ return period of one year. Those conditions shall be either turbulent or quasi-steady with correction for gusts and dynamic response.

In case of a fault in the yaw system, yaw misalignment of $\pm 180^\circ$ shall be considered. If for the cases DLC 7.1 with fault in the yaw system, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades. For any other fault, yaw misalignment shall be consistent with DLC 6.1.

If slippage in the yaw system can occur at the characteristic load found in DLC 7.1, the largest unfavourable slippage possible shall be considered.

7.4.9 Transport, assembly, maintenance and repair (DLC 8.1 and 8.2)

For DLC 8.1, the manufacturer shall state all the wind conditions and design situations assumed for transport, assembly on site, maintenance and repair of a wind turbine. The maximum stated wind conditions shall be considered in the design if they can produce significant loading on the turbine. The manufacturer shall allow sufficient margin between the stated conditions and the wind conditions considered in design to give an acceptable safety level. Sufficient margin may be obtained by adding 5 m/s to the stated wind condition.

In addition, DLC 8.2 shall include all transport, assembly, maintenance and repair turbine states which may persist for longer than one week. This shall, when relevant, include a partially completed tower, the tower standing without the nacelle and the turbine without one or more blades. ~~It may be assumed that all blades are installed simultaneously.~~ In the case of a tower standing without a nacelle, appropriate means shall be taken to avoid critical wind speeds for vortex generated transverse vibrations, or the appropriate fatigue design load case shall be added¹⁴. It shall be assumed that the electrical network is not connected in any of these states. Measures may be taken to reduce the loads during any of these states as long as these measures do not require the electrical network connection.

Blocking devices shall be able to sustain the loads arising from relevant situations in DLC 8.1. Non-redundant blocking devices shall be designed in component class 3. In particular, application of maximum design actuator forces shall be taken into account. It is recommended

¹⁴ Guidance for tower loads from vortex-induced vibrations can be found in IEC 61400-6 (under preparation; stage at the time of publication: IEC CDV 61400-6:2017).

that standards for lifting appliances including safety factors/influence factors are additionally applied when relevant. Unless permanently installed, the lifting appliance itself is not covered by this document and should be designed and tested according to relevant standards for lifting appliances.

7.5 Load calculations

Loads as described in 7.3.2 through 7.3.5 shall be taken into account for each design load case. Where relevant, the following shall also be taken into account:

- wind field perturbations due to the wind turbine itself (wake induced velocities, tower shadow, etc.);
- the influence of three dimensional flow on the blade aerodynamic characteristics (e.g. three dimensional stall and aerodynamic tip loss);
- unsteady aerodynamic effects;
- structural dynamics and the coupling of vibration modes;
- aeroelastic effects;
- the behaviour of the control ~~and protection~~ system of the wind turbine.

Dynamic simulations utilizing a structural dynamics model are usually used to calculate wind turbine loads. Certain load cases have a turbulent wind input. The total period of load data, for these cases, shall be long enough to ensure statistical reliability of the estimate of the characteristic load. At least six 10-min stochastic realizations (or a continuous 60 min period) shall be required for each mean, hub-height wind speed used in the simulations. However, for DLC 2.1, 2.2 and 5.1, at least 12 simulations shall be carried out for each event at the given wind speed. Since the initial conditions used for the dynamic simulations typically have an effect on the load statistics during the beginning of the simulation period, the first 5 s of data (or longer if necessary) shall be eliminated from consideration in any analysis interval involving turbulent wind input.

It shall be ensured that during application of a cycle count on the load time series, the remaining residuals from each time series shall be taken into consideration by half-cycles for fatigue failure mode evaluation. Furthermore, the discretization of the load range shall ensure a sufficient resolution.

When turbulent winds are used for dynamic simulations, attention should be given to the grid resolution regarding the spatial¹⁵ and time resolution.

In many cases, the local strains or stresses for critical locations in a given wind turbine component are governed by simultaneous multi-axial loading. In this case, time series of orthogonal loads that are output from simulations are sometimes used to specify design loads. When such orthogonal component time series are used to calculate fatigue and ultimate loads, they shall be combined to preserve both phase and magnitude. Thus, the direct method is based on the derivation of the significant stress as a time history. Extreme and fatigue prediction methods can then be applied to this single signal, avoiding load combination issues.

Ultimate load components may also be combined in a conservative manner assuming the extreme component values occur simultaneously. In case this option is pursued, both minimum and maximum extreme component values shall be applied in all possible combinations to avoid introducing non-conservatism.

¹⁵ Concerning the spatial resolution, the maximum distance between adjacent points should be smaller than 25 % of λ_1 (Equation (5)) and no larger than 15 % of the rotor diameter. This distance is meant to be the diagonal distance between points in each grid cell defined by four points. In the case of a non-uniform grid, an average value over the rotor surface of the distance between grid points can be considered as the representative spatial resolution, but this distance typically decreases towards the blade tip.

Guidance for the derivation of extreme design loads from contemporaneous loads taken from a number of realizations is given in Annex I.

7.6 Ultimate limit state analysis

7.6.1 Method

7.6.1.1 General

Partial safety factors account for the uncertainties and variability in loads and ~~materials resistances~~, the uncertainties in the analysis methods and the importance of structural components with respect to the consequences of failure.

For the ultimate limit state analysis of the wind turbine, the following four types of analysis shall be performed where relevant:

- analysis of ultimate strength (see 7.6.2);
- analysis of fatigue failure (see 7.6.3);
- stability analysis (e.g. buckling) (see 7.6.4);
- critical deflection analysis (mechanical interference between blade and tower, etc.) (see 7.6.5).

Each type of analysis requires a different formulation of the limit state function and deals with different sources of uncertainties through the use of safety factors.

7.6.1.2 Partial safety factors for loads and ~~materials~~ resistance

~~To assure safe design values for~~ The uncertainties and variability in loads and ~~resistances~~ (including variability in materials) are taken into account by partial safety factors as defined in Equations (29) and (30) ~~in order to assure safe design values.~~

$$F_d = \gamma_f F_k \quad (29)$$

where

F_d is the design value for the aggregated internal load or load response to multiple simultaneous load components from various sources for the given design load case;

γ_f is the partial safety factor for loads;

F_k is the characteristic value for the load.

$$R_d = \frac{1}{\gamma_M} R_k \quad (30)$$

where

$f_d R_d$ are the design values for ~~materials~~ resistances, see Annex K;

γ_M are the partial safety factors¹⁶ accounting for ~~materials~~ uncertainties in the material parameters and resistance models, see Annex K;

$f_k R_k$ are the characteristic values of ~~material properties~~ resistances including load duration effects, scale effects, etc. accounted for by a conversion factor, see Annex K.

¹⁶ Alternatively, the partial safety factor for resistance γ_M can be included as a partial safety factor related to uncertainty in material parameters and a partial safety factor related to uncertainty in the resistance model, see Annex K.

The partial safety factors for loads used in this document take account of

- a) possible unfavourable deviations/uncertainties of the load from the characteristic value, and
- b) uncertainties in the loading model.

The partial safety factors for ~~materials~~ resistances γ_M used in this document, as in ISO 2394, take account of

- possible unfavourable deviations/uncertainties of the strength of material from the characteristic value,
- possible inaccurate assessment of the resistance of sections or load-carrying capacity of parts of the structure,
- uncertainties in the geometrical parameters,
- uncertainties in the relation between the material properties in the structure and those measured by tests on control specimens, and
- uncertainties in conversion factors.

These different uncertainties are sometimes accounted for by means of individual partial safety factors; but in this document, as in most others, the load related factors are combined into one factor, γ_f , and the material and resistance related factors into one factor, γ_M . Values of γ_f and γ_M are given in 7.6.2 to 7.6.5. However, these values may be replaced if it can be documented that assumptions leading to these values are conservative, in which case a calibration of load and resistance safety factors may be performed to meet the intended safety level in this document¹⁷.

7.6.1.3 Partial safety factor for consequence of failure and component classes

A consequence of failure factor, γ_n , is introduced to distinguish between:

- a) component class 1: used for "fail safe" structural components whose failure does not result in the failure of a major part of a wind turbine, for example replaceable bearings with monitoring;
- b) component class 2: used for "~~non fail~~ safe-life" structural components whose failures may lead to the failure of a major part of a wind turbine;
- c) component class 3: used for "~~non fail~~ safe-life" mechanical components that link actuators and brakes to main structural components for the purpose of implementing non-redundant wind turbine protection functions ~~described in 8.3~~. Regarding blocking devices, see 7.4.9.

Partial safety factors for consequences of failure:

- component class 1: $\gamma_n = 0,9$;
- component class 2: $\gamma_n = 1,0$;
- component class 3: $\gamma_n = 1,2$.

The consequences of failure factor shall be included in the test load when performing tests such as, for example, full scale blade testing.

Other values of γ_n apply for critical deflection analysis, see 7.6.5.

7.6.1.4 Application of recognized material codes

When determining the structural integrity of elements of a wind turbine, national or international design codes for the relevant material may be employed. Special care shall be

¹⁷ Annex K provides a guideline for calibration of material partial safety factors.

taken when partial safety factors from national or international design codes are used together with partial safety factors from this document. It shall be ensured that the resulting safety level is not less than the intended safety level in this document.

Different codes subdivide the partial safety factors for ~~materials resistance~~, γ_M , into several material factors accounting for separate types of uncertainty, for example inherent variability of material strength, extent of production control or production method. ~~The material factors given in this standard correspond to the so-called "general partial safety factors for materials" accounting for the inherent variability of the strength parameters.~~ If the code gives partial safety factors or uses reduction factors on the characteristic values to account for other uncertainties, these shall also be taken into account.

Individual codes may choose different factorizations of partial safety factors on the load and the material parts of the design verification. The division of factors intended here is the one defined in ISO 2394. If the division of factors in the code of choice deviates from that of ISO 2394, the necessary adjustments in the code of choice shall be taken into account in verifications according to this document.

7.6.2 Ultimate strength analysis

7.6.2.1 General

The limit state function can be separated into load and resistance functions S and R so that the condition becomes

$$\gamma_n \cdot S(F_d) \leq R_d \quad (31)$$

~~The resistance R generally corresponds with the maximum allowable design values of material resistance, hence $R(f_d) = f_d$, whilst~~ The function S for ultimate strength analysis is usually defined as the highest value of the structural response, hence $S(F_d) = F_d$. The equation then becomes

$$\gamma_n \gamma_f F_k \leq \frac{1}{\gamma_M} R_k \quad (32)$$

Note that γ_n is a consequence of failure factor and shall not be treated as a safety factor on materials.

For each wind turbine component assessed and for each load case in Table 2 where ultimate strength analysis is appropriate, the limit state condition in Equation (32) shall be verified for the most critical limit state, identified on the basis of having the least margin.

7.6.2.2 Partial safety factors for loads

~~In load cases involving turbulent inflow where a range of wind speeds is given, the exceedance probability for the characteristic load shall be calculated considering the wind speed distribution given in 6.3.1.1. Because many load calculations will involve stochastic simulations of limited duration, the characteristic load determined for the required recurrence period may be larger than any of the values computed in the simulation. Guidance for the calculation of characteristic loads using turbulent inflow is given in Annex F.~~

~~For DLC 1.1 the characteristic value of load shall be determined by a statistical load extrapolation and correspond to an exceedance probability, for the largest value in any 10-min period, of less than or equal to $3,8 \times 10^{-7}$, (i.e. a 50-year recurrence period) for normal design situations. For guidance see Annex F.~~

~~For load cases with specified deterministic wind field events, the characteristic value of the load shall be the worst case computed transient value. When turbulent inflow is used, the mean value among the worst case computed loads for different 10-min stochastic realisations shall be taken, except for DLC 2.1, 2.2 and 5.1, where the characteristic value of the load shall be the mean value of the largest half of the maximum loads.~~

For DLC 1.1, a characteristic value of load shall be determined by a statistical analysis of the extreme loading that occurs for normal design situations and shall correspond to one of the following alternatives.

- a) The characteristic value is obtained as the largest (or smallest) among the average values of the 10 min extremes determined for each wind speed in the given range, multiplied by 1,35. This method can only be applied for the calculation of the blade root in-plane moment and out-of-plane moment and tip deflection.
- b) The characteristic value is obtained as the largest (or smallest) among the 99th percentile (or 1st percentile in the case of minima) values of the 10 min extremes determined for each wind speed in the given range, multiplied by 1,2.
- c) The characteristic value is obtained as the value corresponding to a 50 year return period, based on load extrapolation methods, considering the wind speed distribution given in 6.3.2.1 and the normal turbulence model in 6.3.2.3. Guidance about load extrapolation is given in Annex G.

The design load will be then obtained by multiplying the characteristic loads according to any of these alternatives by the partial safety factor for DLC 1.1 defined in Table 3.

For all three alternatives above, data used in the statistical analysis shall be extracted from time series of turbine simulations of at least 10 minutes in length over the operating range of the turbine for DLC 1.1. A minimum of 15 simulations is required for each wind speed from ($V_r - 2$ m/s) to cut-out, and six simulations are required for each wind speed below ($V_r - 2$ m/s). When extracting data, the designer shall consider the effect of independence between peaks on the statistical analysis and minimize dependence when possible. For guidance on dependency checks, see Annex G.

For load cases with specified deterministic wind field events, the characteristic value of the load shall be the worst case computed transient value. If more simulations are performed at a given wind speed, representing the rotor azimuth, the characteristic value for the load case is taken as the average value of the worst case computed transient values at each azimuth. Guidance for the derivation of the contemporaneous load can be found in Annex I. When turbulent inflow is used, the mean value among the worst case computed loads for different 10 min stochastic realizations shall be taken, except for DLC 2.1, 2.2 and 5.1, where the characteristic value of the load shall be the mean value of the largest half of the maximum loads.

Partial safety factors for loads shall be at least the values specified in Table 3.

The approach in 7.6.1.2, where the partial safety factor for loads is applied to the load response, assumes that a proper representation of the dynamic response is of prime concern. Where a proper representation of non-linear material behaviour or geometrical nonlinearities (such as, for example, for foundations) or both are of primary concern, the design load response S_d shall be obtained from a structural analysis for the combination of the design loads F_d , where the design load is obtained by multiplication of the characteristic loads F_k by the specified partial load factor γ_f for favourable and unfavourable loads:

$$F_d = \gamma_f F_k \quad (33)$$

The load responses in the tower at the interface (shear forces and bending moments) factored with γ_f from Table 3 shall be applied as boundary conditions.

Table 3 – Partial safety factors for loads γ_f

Unfavourable loads		Favourable loads ¹⁸	
Type of design situation (see Table 2)		All design situations	
Normal (N)	Abnormal (A)	Transport and erection (T)	
1,35 ^a	1,1	1,5	0,9
^a For design load case DLC 1.1, ~~given that loads are determined using statistical load extrapolation at prescribed wind speeds between V_{in} and V_{out}~~, the partial load factor ~~for normal design situations~~ shall be $\gamma_f = 1,25$. If for normal design situations the characteristic value of the load response $F_{gravity}$ due to gravity can be calculated for the design situation in question, and gravity is an unfavourable load, the partial load factor for combined loading from gravity and other sources may have the value $\gamma_f = 1,1 + \varphi \zeta^2 \text{ and } \varphi = \begin{cases} 0,15 & \text{for DLC 1.1} \\ 0,25 & \text{otherwise} \end{cases}$ $\zeta = \begin{cases} 1 - \left \frac{F_{gravity}}{F_k} \right ; & F_{gravity} \leq F_k \\ 0; & F_{gravity} > F_k \end{cases}$ For design load case DLC 2.1, the partial load factor may be calculated from the following expression if the mean time between failures (MTBF), in years, for the considered failure mode has been evaluated (see 7.4.3.2): $\gamma_f = \begin{cases} 1,35 & \text{MTBF} \leq 10 \\ 1,71 - 0,155 \ln(\text{MTBF}) & 10 < \text{MTBF} \leq 50 \\ 1,10 & \text{MTBF} > 50 \end{cases}$ For design load case DLC 2.5, the partial load factor shall be 1,2.			

Use of the partial safety factors for loads for normal and abnormal design situations specified in Table 3 requires that the load calculation model is validated by load measurements. These measurements shall be made on a wind turbine that is similar to the wind turbine design under consideration with respect to aerodynamics, control and dynamic response.

7.6.2.3 Partial safety factors for gravity foundations

For gravity foundations, the limit states considering overall stability (rigid body motion with no failure in soil) and bearing capacity of soil and foundation shall be regarded and calculated according to a recognized standard. In general, a partial safety factor of $\gamma_f = 1,1$ for unfavourable gravity loads and $\gamma_f = 0,9$ for favourable gravity loads shall be applied for foundation load, backfilling and buoyancy. If it can be demonstrated by respective quality management and surveillance that the foundation material densities specified in the design documentation are met on site, a partial safety factor for gravity foundation load $\gamma_f = 1,0$ can be used for the limit states regarding bearing capacity of soil and foundation. If buoyancy is calculated equal to a terrain water level, a partial safety factor for buoyancy $\gamma_f = 1,0$ can be applied.

Alternatively, the check of capacity of soil and foundation can be based on a partial safety factor $\gamma_f = 1,0$ for both favourable and unfavourable gravity loads, and the check of overall

¹⁸ Pretension and gravity loads that significantly relieve the total load response are considered favourable loads. In the case of both favourable and unfavourable loads, Equation (32) becomes

$$\gamma_n S(\gamma_{f,unfav} F_{k,unfav}, \gamma_{f,fav} F_{k,fav}) \leq R(f_d)$$

stability can be based on a partial safety factor of $\gamma_f = 1,1$ for unfavourable gravity loads and $\gamma_f = 0,9$ for favourable gravity loads, using in all cases conservative estimates of weights or densities defined as 5 %/95 % fractiles. The lower fractile is to be used when the load is favourable. Otherwise the upper fractile is to be used.

7.6.2.4 Partial safety factors for ~~materials~~ resistances where recognized design codes are not available

~~Partial safety factors for materials shall be determined in relation to the adequacy of the available material properties test data. The value of the general partial safety factor for materials, γ_m , and accounting for the inherent variability of the strength parameter shall be~~

$$\gamma_m \geq 1,1 \quad (32)$$

~~when applied to characteristic material properties of 95 % survival probability, p , with 95 % confidence limit¹⁹. This value applies to components with ductile behaviour²⁰ whose failure may lead to the failure of a major part of a wind turbine, for example welded tubular tower, tower flange connection, welded machine frame or blade connections. Failure modes may comprise:~~

- ~~• yielding of ductile materials;~~
- ~~• bolt rupture in a bolt connection with sufficient number of bolts to provide $1/\gamma_m$ of the strength following the failing of a single bolt.~~

~~For “non fail safe” mechanical/structural components with non ductile behaviour whose failures lead rapidly to the failure of a major part of a wind turbine, the general safety factor for materials shall be not less than:~~

- ~~• 1,2 for global buckling of curved shells such as tubular towers and blades, and~~
- ~~• 1,3 for rupture from exceeding tensile or compression strength.~~

~~To derive the global partial safety factors for materials from this general factor it is necessary to account for scale effects, tolerances and degradation due to external actions, for example ultraviolet radiation or humidity and defects that would not normally be detected.~~

~~Partial safety factors for consequences of failure:~~

~~Component class 1: $\gamma_R = 0,9$~~

~~Component class 2: $\gamma_R = 1,0$~~

~~Component class 3: $\gamma_R = 1,3$~~

Partial safety factors for resistances shall be selected in relation to the adequacy of the available material properties test data. The safety level in this document corresponds to a partial safety factor for resistances, $\gamma_M = 1,2$ when applied to characteristic material properties of 95 % survival probability.²¹ This value assumes no bias (typically systematic conservatism in the resistance model) and small uncertainty related to the resistance model (coefficient of variation less than 5 %), see Annex K; and applies to components with ductile behaviour whose failure may lead to the failure of a major part of a wind turbine.

¹⁹ ~~The characteristic strength parameters should be selected as the 95 % fractile (determined with 95 % confidence) or the certificate value for materials with established routines for testing of representative samples.~~

²⁰ ~~Ductile behaviour includes not only ductile materials but also components which behave like ductile materials due to, for example internal redundancy.~~

²¹ Alternatively, the characteristic strength parameters can be selected as the 95 % fractile using the Bayesian approach, see Annex K and ISO 2394. The characteristic strength parameters should be selected as the 95 % fractile (determined with 75 % confidence) or the certificate value for materials with established routines for testing of representative samples.

To derive the design values for resistances, it is necessary to account for scale effects, tolerances and degradation due to external actions, for example, ultraviolet radiation or humidity. These effects can be taken into account through additional factors on the partial safety factor for resistance or through a conversion factor used to obtain the characteristic value of the resistance, see Annex K.

In the following cases with ductile failure modes, the partial safety factor for resistance, γ_M , shall be not less than

- 1,1 for materials with a well-defined elastic limit (yield strength is 90 % or less of the ultimate strength), and
- 1,1 for bolt rupture in a connection with sufficient number of bolts to ensure a ductile failure mode.

For "safe-life" mechanical/structural components with non-ductile behaviour whose failures lead rapidly to the failure of a major part of a wind turbine, the partial safety factor for resistance, γ_M , shall be not less than

- 1,3 when materials with no well-defined elastic limit (yield strength is more than 90 % of the tensile or compression strength) are used, and
- 1,2 for global buckling of curved shells such as tubular towers and blades.²²

7.6.2.5 Partial safety factors for materials where recognized design codes are available

The combined partial safety factors for loads, γ_F , materials resistance and the consequences of failure, γ_M , and γ_n , shall be not less than those specified in 7.6.1.3, 7.6.2.2 and 7.6.2.4.

7.6.3 Fatigue failure

7.6.3.1 General

Fatigue damage shall be estimated using an appropriate fatigue damage calculation. For example, in the case of Miner's rule, the limit state is reached when the accumulated damage exceeds 1. Thus, in this case, the accumulated damage over the design lifetime of a turbine shall be less than or equal to 1. Fatigue damage calculations shall consider the formulation, including effects of both cyclic range and mean strain (or stress) levels. All partial safety factors (load, material and consequences of failure) shall be applied to the cyclic strain (or stress) range for assessing the increment of damage associated with each fatigue cycle. An example formulation is given for Miner's rule in Annex H.

7.6.3.2 Partial safety factor for loads

The partial safety factor for loads, γ_F , shall be 1,0 ~~for all normal and abnormal design situations.~~

7.6.3.3 Partial safety factors for materials resistances where recognized codes are not available

The partial safety factor for materials resistances, γ_M , shall be at least ~~1,5~~ 1,7 provided that the SN-curve is based on 50 % survival probability and coefficient of variation < 15 %. For components with large coefficient of variation for fatigue strength²³, i.e. 15 % to 20 % (such as for many components made of composites, for example reinforced concrete or fibre

²² The parametric formulas based on membrane theory in Eurocode 3 Part 6 (EN 1993-1-6:2007) for shell buckling applicable to tubular steel towers with $D/t < 300$ include a bias that can be accounted for by reducing γ_M for buckling to 1,1.

²³ Fatigue strength is defined here as stress ranges associated with given numbers of cycles.

composites), ~~the partial safety factor γ_M must~~ shall be increased accordingly and at least to ~~1,7~~ 2,0.

The fatigue strengths shall be derived from a statistically significant number of tests and the derivation of characteristic values shall account for scale effects, tolerances, degradation due to external actions, such as ultraviolet radiation, and defects that would not normally be detected.

For welded and structural steel, traditionally the 97,7 % survival probability is used as basis for the SN-curves. In this case, γ_M may be taken as ~~1,1~~ 1,25, ~~corresponding to a safe-life assessment approach, see Annex K.~~ In cases where it is possible to detect critical crack development through introduction of a periodic inspection programme, a lower value of γ_M may be used, ~~corresponding to a damage tolerant assessment approach, see Annex K.~~ In all cases, γ_M shall be larger than ~~0,9~~ 1,0.

For fibre composites, the strength distribution shall be established from test data for the actual material. The 95 % survival probability ~~with a confidence level of 95 %~~ shall be used as a basis for the SN-curve. In that case, γ_M may be taken as ~~1,2~~ 1,35. The same approach may be used for other materials.

~~Partial safety factors for consequences of failure:~~

~~Component class 1: $\gamma_R = 1,0$~~

~~Component class 2: $\gamma_R = 1,15$~~

~~Component class 3: $\gamma_R = 1,3$~~

7.6.3.4 Partial material factors where recognized design codes are available

The combined partial safety factors for loads, materials and consequences of failure shall not be less than those specified in 7.6.3.2 and 7.6.3.3, with due consideration of the quantiles specified in the code.

7.6.4 Stability

The load-carrying parts of "non fail-safe" components shall not buckle under the design load. For all other components, elastic buckling under the design load is acceptable. Buckling shall not occur in any component under the characteristic load.

A minimum value for the partial safety factor for loads, γ_F , shall be chosen in accordance with 7.6.2.2 to obtain the design value. The material partial safety factors shall be not less than those specified in 7.6.2.4.

7.6.5 Critical deflection analysis

7.6.5.1 General

It shall be verified that no deflections affecting structural integrity occur in the design conditions detailed in Table 2. ~~One of the most important considerations is to verify that no mechanical interference between blade and tower will occur.~~

The maximum elastic deflection in the unfavourable direction shall be determined for the load cases detailed in Table 2 ~~using the characteristic loads.~~ A characteristic value for the resulting deflections is determined in a manner consistent with the other load components. The resulting characteristic deflection is then multiplied by the combined partial safety factor for loads, materials and consequences of failure.

7.6.5.2 Partial safety factor for loads

The values of γ_f shall be chosen from Table 3.

7.6.5.3 Partial safety factor for the elastic properties of materials

The value of γ_M shall be 1,1 except when the elastic properties of the component in question have been determined by ~~full-scale~~ testing and monitoring, in which case it may be reduced to ~~1,0~~. Particular attention shall be paid to geometrical uncertainties and the accuracy of the deflection calculation method.

7.6.5.4 Partial safety factor for consequences of failure

~~Component class 1: $\gamma_n = 1,0$~~

~~Component class 2: $\gamma_n = 1,0$~~

~~Component class 3: $\gamma_n = 1,3$~~

The partial safety factor for consequences of failure, γ_n , shall be 1,0.

The elastic deflection shall then be added to the un-deflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference.

~~Direct dynamic deflection analysis may also be used. In this case, the characteristic deflection is determined in a manner consistent with the characteristic loads determined for each load case in Table 2. The exceedance probability in the most unfavourable direction shall be the same for the characteristic deflection as for the characteristic load. The characteristic deflection is then multiplied by the combined safety factor and added to the un-deflected position as described above.~~

7.6.5.5 Blade (tip) deflection

One of the most important considerations is to verify that no mechanical interference between blade and tower will occur. The combined safety factor, $\gamma_f \gamma_n \gamma_m$, for blade-tower clearance shall be at least 1,15.

In general, blade deflections have to be calculated for the ultimate load cases. The deflections caused by the ultimate load cases can be calculated based on beam models, finite element models or the like. All relevant load cases from Table 2 have to be taken into account with the relevant partial load safety factors.

Moreover, for DLC 1.1 a statistical analysis of maximum tip deflection or minimum tower clearance is mandatory according to 7.4.2. Here, direct dynamic deflection or tower clearance analysis can be used. The probability in the most unfavourable direction shall be the same for this characteristic value as for the characteristic blade loading. For a deflection analysis, the characteristic deflection is then to be multiplied by the combined partial factors for loads, materials and consequences of failure and be added to the undeflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference. In the case of direct dynamic tower clearance analysis, the minimum allowable clearance is determined by multiplying the nominal undeflected tower clearance by the ratio of the combined partial factors for loads, materials and consequences of failure minus one to the

combined partial factor (i.e. $\frac{\gamma_f \gamma_n \gamma_m - 1}{\gamma_f \gamma_n \gamma_m}$).

7.6.6 Special partial safety factors

Lower partial safety factors for loads may be used where the magnitudes of loads have been established by measurement or by analysis confirmed by measurement to a higher than

normal degree of confidence. The values of all partial safety factors used shall be stated in the design documentation.

8 ~~Control and protection~~ system

8.1 General

Wind turbine operation ~~and safety~~ shall be governed by a control ~~and protection~~ system that meets the requirements of Clause 8.

~~Manual or automatic intervention shall not compromise the protection functions. Any device allowing manual intervention must be clearly visible and identifiable, by appropriate marking where necessary.~~

~~Settings of the control and protection system shall be protected against unauthorised interference.~~

The scope of Clause 8 is limited to ensuring that the control system provides an appropriate level of protection against structural failure of the turbine main components.²⁴

For special cold climate requirements, see 14.6.

8.2 Control functions

The control functions of a wind turbine shall control the operation by active or passive means and keep the operating parameters within ~~their normal limits~~ the envelope assumed in the structural design. ~~Where selection of control mode can be exercised, for example for maintenance, each mode shall override all other control, with the exception of the emergency stop button. Mode selection shall be governed by a selector, which can be locked in each position corresponding with a single mode. When certain functions are controlled numerically, access codes shall be provided to appropriately select the function.~~

The control functions may govern or otherwise limit functions or parameters such as

- power,
- rotor speed,
- connection of the electrical load,
- start-up and shutdown procedures,
- cable twist,
- excessive vibrations,
- alignment to the wind, and
- blade pitch angle.

The ability of the control functions to control the turbine during failure-free operation of the control functions shall be demonstrated in the design load cases (but excluding the DLC 2.1 and 2.2 load cases).

When a control function failure occurs, the wind turbine must maintain a safe mode of operation, which may include maintaining operation or bringing the wind turbine to a shutdown.

²⁴ Risk assessments may result in requirements for additional control system functionality needed for ensuring personnel safety. These functions should be designed and evaluated according to recognized methods and design principles, such as those specified in ISO 13849 or IEC 62061.

Turbine behaviour following a fault in the control functions shall be clearly defined, including any procedures for automatic or manual restart, see 8.7.

8.3 Protection functions

~~The protection functions shall be activated as a result of failure of the control function or of the effects of an internal or external failure or dangerous event. The protection functions shall maintain the wind turbine in a safe condition. The activation levels for the protection functions shall be set in such a way that the design limits are not exceeded.~~

~~The protection functions shall have higher priority than control functions, but not higher than the emergency stop button, in accessing the braking systems and equipment for network disconnection when triggered.~~

~~The protection functions shall be activated in such cases as~~

- ~~• overspeed;~~
- ~~• generator overload or fault;~~
- ~~• excessive vibration;~~
- ~~• abnormal cable twist (due to nacelle rotation by yawing).~~

~~The protection functions shall be designed for fail-safe operation. The protection functions shall in general be able to protect the wind turbine from any single failure or fault in a power source or in any non safe life component within the systems implementing the protection functions. Any single failure in the sensing or non safe life structural parts of the systems implementing the control functions shall not lead to malfunction of the protection functions.~~

~~If two or more failures are interdependent or have a common cause, they shall be treated as a single failure.~~

~~Measures shall be taken to reduce the risk from dormant failures. Non safe life components within the systems implementing protection functions shall fail to a safe condition or their condition shall be automatically monitored; in either case their failure shall result in a machine shutdown. Safe life designed components shall be inspected at adequate intervals.~~

~~All non fail safe components required for implementation of non redundant protection functions shall be considered in component class 3 with an appropriate consequences of failure partial safety factor defined in 7.6. All such protection system critical components shall be analysed for ultimate strength, fatigue, buckling and critical deflection.~~

~~In cases of conflict, the protection function shall overrule the control function.~~

~~The automatic or remote restart of a wind turbine shall not be possible where the shutdown was initiated by an internal fault or trip that is critical to the turbine safety. If such a fault or trip is followed by electrical network interruption or loss of load, automatic restart shall not be possible after return of electrical network or load.~~

~~An emergency stop button, which will override the control functions, shall bring the rotor to a complete stop in any wind speed less than the wind speed limit defined for maintenance and repair, see 7.4.8, and as a minimum to idling mode from any operation condition. In addition, activation of the emergency stop button shall de-energise the medium and the high voltage systems. Emergency stop buttons shall be provided at every major working place (e.g. nacelle and tower bottom). Disengagement of any emergency stop button following its use shall require an appropriate action. Following disengagement, automatic restart shall only be possible after manual clearance.~~

The control system shall make use of protection functions in order to prevent turbine structural overloading due to failure modes. These protection functions may be implemented as either control functions that apply inherently safe design measures²⁵, or as separate secondary layer protection functions.

Where a secondary layer protection function is used to bring the turbine to a safe mode of operation, it shall overrule the primary layer control function.

Functions protecting against structural overloading shall be implemented by means of multi-channel architectures²⁶ with diagnostic coverage to yield sufficiently high mean time between failure.

The ability of protection functions to protect against structural overloading shall be demonstrated in design load cases DLC 2.1 and 2.2, cf. 7.4.3.

8.4 Control system failure analysis

8.4.1 General

Faults or errors in the systems implementing the control and protection functions may lead to a number of failure modes, where the failure mode is defined as the behaviour of the control system in case of a fault or error. Such failure modes may lead to events affecting the turbine structure.

EXAMPLE A sensor fault may lead to erroneous pitch action (the failure mode), which may lead to excessive rotor speed (the event).

Failure modes of the control system shall be identified according to the requirements in this clause and evaluated according to the requirements given in 7.4.3.

FMEA or equivalent fault analysis shall be carried out to determine fault events relevant for wind turbine loading. This may include fault-tree analysis or similar methods to identify any common cause failures.

The set of events addressed in the fault analysis shall include at least the following:

- a) excessive rotor speed;
- b) excessive vibrations;
- c) excessive power production;
- d) actuator faults, e.g. pitch and yaw actuation faults.

8.4.2 Independence and common-cause failures

It may be assumed that independent faults do not occur simultaneously. If independent faults are assumed, measures against common-cause failures shall be implemented, and there shall be sufficient diagnostic coverage to protect against dormant failures.²⁷

²⁵ ISO 12100:2010, 6.2.11 and 6.2.12 provides guidance on applying inherently safe design measures to control systems.

²⁶ Multichannel architectures include but are not limited to the use of redundancy. A single functional channel with high diagnostic coverage provided by a separate test channel may suffice if the resulting mean time to dangerous failure is sufficiently high. The designated architecture for Category 2 systems as per ISO 13849-1 constitutes such architecture.

²⁷ ISO 13849-1 may be used to judge whether the measures against common cause failures are sufficient.

8.4.3 Fault exclusions

Control system failures subject to fault exclusions²⁸ as described in recognized standards can be omitted.

All mechanical components of the control system where fault exclusions are applied shall be considered in component class 3 with an appropriate consequences-of-failure partial safety factor (as defined in 7.6). All such critical components shall be analysed for ultimate strength, fatigue, buckling and critical deflection.

8.4.4 Failure mode return periods

If failure mode return periods are claimed in the load calculations (see 7.4.3.2) then these shall be demonstrated by recognized methods.²⁹

For mechanical components, failure mode return periods need only to be established if fault exclusions do not apply.

8.4.5 Systematic failures

For protection functions and for control functions where failure mode return periods higher than 10 years are claimed, measures for avoiding systematic failures³⁰ (including software failures) described by recognized standards shall be applied.

8.5 Manual operation

Manual or automatic intervention shall not compromise the control system's ability to keep the turbine within limits. Any device allowing manual intervention shall be clearly visible and identifiable, by appropriate marking where necessary.

Where selection of control mode can be exercised, for example for maintenance, the mode selection shall be governed by a selector, which can be locked in each position corresponding with a single mode.

Settings of the control system shall be protected against unauthorized interference.

8.6 Emergency stop button function

An emergency stop button function shall be implemented using recognized methods and design principles, such as those specified in ISO 13850, which gives guidance on emergency stop button availability, location, choice of stop functionality, and reset behaviour.

It shall be specified which stop category is chosen. Further, any functionality required from the control system when the emergency stop button is activated shall be clearly specified.³¹

The behaviour of all systems impacting the structural loading upon activation of the emergency stop button shall be clearly specified.

²⁸ Fault exclusions are described in standards such as ISO 13849-2. For mechanical components, fault exclusions are relevant for "safe-life" components.

²⁹ See IEC 61508-6 or IEC 62061 for suitable methods for demonstrating failure rates, e.g. fault trees, Markov models, etc. Also, ISO 13849-1 provides simplified methods for assessing the failure rates, including generic values for components.

³⁰ Measures to avoid systematic failures and software failures are covered within 6.4, 6.10 and 6.11 of IEC 62061:2005, IEC 62061:2005/AMD1:2012 and IEC 62061:2005/AMD2:2015, or 4.6, Annex G and Annex J of ISO 13849-1:2015.

³¹ This requirement is particularly important when stop category 1 (controlled stop) is chosen.

EXAMPLE 1 Disconnection of electrical systems may impact the loading of the drive train.

When the emergency stop function behaviour depends on operating conditions, these dependencies shall be clearly defined.

EXAMPLE 2 Application of the mechanical disc brake in case of emergency button activation may be conditioned on the rotational speed and/or wind speed, etc.

Effects of activation of the emergency stop button shall be evaluated under DLC 5.1 for all relevant operating scenarios (see 7.4).

8.7 Manual, automatic, and remote restart

Mechanisms for restarting the turbine following a stop shall be clearly defined and meet the following requirements.

Turbine restart behaviour and restart procedures³² following a control function failure shall be defined based on a failure mode analysis (for example via a fault tree analysis).

If failures in functions that define if a restart can occur could influence turbine loads then these faults should be considered to be control system fault events as defined in 8.4.1.

The behaviour following a control function failure may be defined by automatic or manual procedures, performed locally or remotely. In the case of remote restart, this shall include any remote inspection needed (for example, via the use of remote cameras and/or SCADA data), and suitable criteria that need to be met before it is deemed safe to allow remote restart.

Automatic restart shall not be allowed unless automatic diagnostics and criteria necessary to ensure that the turbine will remain safe (i.e. within an acceptable risk of turbine damage) after restart have been defined.

EXAMPLE Such diagnostics may consist of automatic substantiation that the structural design limits for rotor speed and tower top acceleration have not been exceeded.

The risks and consequences of an unintended remote restart (for example, due to a communications system error) shall be considered.

A turbine with automatic or remote restart capability shall be provided with a means to locally disable and lock out the automatic restart function and the remote restart function.

The turbine shall not incorrectly restart as a result of external factors such as loss (and reinstatement) of grid power or external loads or due to maintenance actions.

The number and frequency of remote or automatic restarts that are permissible shall be clearly defined based on the shutdown assumptions contained in the design loads assessment. The restart function shall ensure that these limits are not exceeded.

The design loads assessment shall consider the consequences of repeated restarts up to the limits defined above.

The functionality to control the number and frequency of remote or automatic restarts that are permissible shall not be incorrectly affected by external factors such as loss (and reinstatement) of grid power or external loads or due to maintenance actions.

³² A restart procedure needs to consider the reasons why the turbine shut down to in order to justify that it is safe to restart the turbine. For example, a restart might not be considered safe without an inspection taking place if the turbine has been shut down due to excessive mechanical shock.

8.8 Braking system

~~The braking system shall be able~~ It shall be possible to bring the rotor to idling mode or complete ~~stop~~ standstill from any operation condition, including loss of power.

Means shall be provided for bringing the rotor to a complete ~~stop from a hazardous idling state~~ standstill in any wind speed less than the wind speed limit defined for maintenance and repair, see 7.4.9, unless this is explicitly discounted based on the results of a risk assessment.

It is recommended that at least one braking system operate on an aerodynamic principle, as such acting directly on the rotor. If this recommendation is not met, at least one braking system shall act on the shaft directly connected to the rotor ~~shaft~~ or on the rotor of the wind turbine.

~~Brakes shall be designed to function even if their external power supply fails. A brake shall be able to keep the rotor in the full stop position for the defined wind conditions for at least one hour after the brake is applied. During longer periods of grid loss, it shall be possible to apply the brake by either an auxiliary power supply or by manual operation.~~

If a braking system is designed to bring the rotor to standstill upon emergency stop activation, it shall be able to keep the rotor in standstill for the defined wind conditions for at least one hour after it is applied.

9 Mechanical systems

9.1 General

A mechanical system for the purposes of this document is any system which does not consist solely of static structural components, or electrical components, but uses or transmits relative motion through the combination of shafts, links, bearings, slides, gears and other devices. Within a wind turbine, these systems may include elements of the drive train such as gearboxes, shafts and couplings, and auxiliary items such as brakes, blade pitch controls, yaw drives. Auxiliary items may be driven by electrical, hydraulic or pneumatic means.

All mechanical systems in the drive train and in the control ~~and protection~~ system shall be designed according to IEC or ISO standards wherever available. Otherwise, recognized standards shall be used. Partial safety factors shall be consistent with component class 2 in 7.6.1.3, unless the systems falls into component class 3.

Particular care shall be taken to ensure that cooling and filtration systems can maintain the relevant operating conditions throughout the operating temperature range when the specified maintenance procedures are followed.

The remaining life of any component subject to wear in the brake system shall be monitored automatically and subject to regular inspection. The turbine shall be parked when there is insufficient material for further emergency stops. All brake devices shall be designed and maintained to keep the response time within acceptable levels.

Load calculation shall be based on simulations including both the mean braking level and a minimum braking level that allows for minimum friction and application pressure predicted for the design. If the brake is able to slip at the minimum braking level, when the brake is applied, it shall be designed to avoid overheating and brake performance impairment and to avoid risk of fire.

For cold climate requirements, see 14.7.

9.2 Errors of fitting

Errors likely to be made when fitting or refitting certain parts that could be a source of risk shall be made impossible by the design of such parts or, failing this, by information given on the parts themselves and/or housings. The same information shall be given on the moving parts and/or their housings where the direction of movement ~~must~~ shall be known to avoid a risk. Any further information that may be necessary shall be given in the operator's instruction and maintenance manuals.

Where a faulty connection can be a source of risk, incorrect connections shall be made impossible by the design or, failing this, precautions shall be taken to avoid faulty connection by information given on the pipes, hoses and/or connector blocks.

9.3 Hydraulic or pneumatic systems

Where auxiliary items are powered by hydraulic or pneumatic energy, the systems ~~must~~ shall be so designed, constructed and equipped as to avoid all potential hazards associated with these types of energy. Means of isolating or discharging accumulated energy ~~must~~ shall be included in such systems. All pipes and/or hoses carrying hydraulic oil or compressed air and their attachments shall be designed to withstand or be protected from foreseen internal and external stresses. Precautions shall be taken to minimize risk of injury arising as a consequence of rupture.

9.4 Main gearbox

~~The main gearbox is to be considered as a class 2 component.~~

~~Gears shall be designed using appropriate calculation methods as described in ISO 6336-1 to ISO 6336-3. The material strength values shall be derived according to ISO 6336-5 and they shall at least correspond to the MQ quality. All relevant manufacturing tolerances and displacements shall be combined for the calculation of the face load distribution factor according to ISO 6336-1.~~

~~The safety factor S_H for pitting shall be calculated according to ISO 6336-2 using either method A or B. The direct Miner's rule shall be applied for the fatigue calculation. The calculated safety factor S_H shall be 1,2. This safety factor S_H includes the partial safety factor for consequence, material and load.~~

~~The safety factor S_F for tooth bending shall be calculated according ISO 6336-3 method A or B. The direct Miner's rule shall be used. The calculated safety factor S_F shall be at least 1,45. This safety factor S_F includes the partial safety factor for consequence, material and load.~~

~~For scuffing, fatigue loads have no significance, but even few high transient loads are able to initiate this failure especially with insufficient initial surface finish and at high lubricant temperature. The safety against scuffing shall be calculated using a relevant method, for example as described in ISO/TR 13989-1. The calculated safety factor S_S shall be at least 1,3.~~

~~Particular care shall be taken to ensure that the cooling and filtration systems can maintain the relevant lubrication state throughout the operating temperature range following the specified maintenance procedures.~~

The main gearbox shall be designed according to IEC 61400-4.

9.5 Yaw system

The yaw system may consist of means to maintain a fixed yaw orientation (e.g. hydraulic brakes), means to change that orientation (e.g. electric motors, gearboxes and pinions) and means to guide the rotation (e.g. a bearing).

Any motors shall comply with relevant parts of Clause 10. ~~For yaw gear systems with multiple yaw drives ensuring sufficient redundancy, the gears may be considered to be in component class 1. The safety factors S_H and S_F may then be reduced to 1,1 and 1,25. Otherwise component class 2 shall be used.~~

Non-redundant parts of the gear system such as the final yaw gear shall be considered as component class 2. When multiple yaw drives ensure sufficient redundancy in the yaw gear system, and easy replacement is possible, the reduction gearbox and the final drive pinion may be considered to be in component class 1.

The safety against pitting shall be determined in accordance with ISO 6336-2. The application of the upper limit curve (1) for life factor Z_{NT} , which allows limited pitting, is permissible. Sufficient tooth bending strength shall be proven in accordance with ISO 6336-3. The reverse bending loads on gear teeth shall be considered in accordance with ISO 6336-3:2006, Annex B. Minimum values for S_F and S_H are specified in Table 4. These values shall be achieved by using characteristic loads F_k . Hence, S_F and S_H include the partial safety factor for consequences, γ_n , materials, γ_M and loads, γ_f .

Table 4 – Minimum safety factor $S_{H,min}$ and $S_{F,min}$ for the yaw gear system

	Component class 1	Component class 2
Surface durability (pitting)	$S_{H,min} = 1,0$	$S_{H,min} = 1,1$
Tooth bending fatigue strength	$S_{F,min} \geq 1,1$	$S_{F,min} = 1,25$
Static bending strength	$S_{F,min} \geq 1,0$	$S_{F,min} = 1,2$

However, lower safety factors, S_F and S_H may be applicable in cases where efficient monitoring is implemented. If safety factors below 1,0 are applied, then the maintenance manual shall reflect anticipated replacement intervals.

9.6 Pitch system

The pitch system may consist of means to adjust blade pitch angle (e.g. hydraulic actuators, electric motors, gearboxes, brakes and pinions) and means to guide the rotation (e.g. a bearing).

Any motors shall comply with relevant parts of Clause 10. For pitch systems with individual pitch drives/actuators ensuring sufficient redundancy, these may be considered to be in component class 2.

For component class 2, gearboxes and gears shall comply with relevant parts of 9.5.

9.7 Protection function mechanical brakes

Where mechanical brakes are used for a protection function (see 7.4.3.3), they are generally friction devices applied by hydraulic or mechanical spring pressure. The remaining life of any wearing components, for example friction pads, shall be monitored by the control ~~and protection~~ system, which shall place the turbine in parked mode when insufficient material is available for a further emergency stop or braking.

Load calculation shall be based on simulations including an appropriate range of the braking level. If the brake is able to slip in the standstill state at the minimum braking level, whenever the brake is to maintain the wind turbine in a stationary state, the period of slip in a turbulent wind ~~must~~ shall be sufficiently short to avoid overheating and brake performance impairment and to avoid a risk of fire.

9.8 Rolling element bearings

~~The basis of rating analysis of rolling bearings shall be ISO 76 and ISO 281. For shaft bearings, for example main shaft, gearbox, the bearing lives (90 % survival probability) shall be at least 20 years. The calculation method shall consider the operating conditions. Any adjustment factors (i.e. a-factors) according to ISO 281 shall be applied with care.~~

~~Particular care shall be taken to ensure that cooling and filtration systems can maintain the relevant operating conditions throughout the operating temperature range with the specified maintenance procedures.~~

~~For bearings, design loads shall reflect the loads determined in the various load cases in 7.4 and appropriate safety factors in 7.6. The bearing design shall consider the expected amount of rotation during its lifetime and whether the rotations are continuous as in main shaft bearings or oscillating as in pitch and yaw bearings. Furthermore, consideration shall be given to the potential effect of insufficient lubrication due to small movement.~~

~~For slow bearings, the ratio of static rating to design load shall be at least 1,0 according to ISO 76. The load distribution due to flexibility of the connected parts shall be carefully considered.~~

9.8.1 General

The basis of rating analysis of rolling bearings shall be ISO 76, ISO 281 and ISO/TS 16281. The calculation shall consider the actual operating and lubrication conditions as well as the bearing environment. Any life adjustment factor according to ISO 281 and ISO/TS 16281 shall be applied with care.

The design loads shall reflect the loads determined in the various load cases in 7.4 and appropriate safety factors in 7.6. The bearing design shall consider the expected amount of rotation during its lifetime and whether the rotations are continuous or discontinuous.

9.8.2 Main shaft bearings

The modified reference rating life L_{10mr} (90 % survival probability) of main shaft bearings shall meet or exceed the specified design life of the wind turbine.

9.8.3 Generator bearings

The modified reference rating life L_{10mr} (90 % survival probability) of generator bearings shall meet or exceed the specified design life of the wind turbine.

Generator bearings that can be replaced in the wind turbine without special tools may be specified for a shorter design life.

9.8.4 Pitch and yaw bearings

For pitch and yaw bearings, the ratio of static rating to design load shall be at least 1,0 according to ISO 76. The load distribution due to flexibility of the connected parts shall be carefully considered.

Bearings used in the pitch and yaw systems are exposed to a discontinuous, oscillatory motion. Therefore, consideration shall be given to the potential effect of insufficient lubrication due to small movement.

10 Electrical system

10.1 General

The electrical system of a wind turbine installation comprises all electrical equipment installed in each individual wind turbine up to and including the wind turbine terminals; referred to below as the "wind turbine electrical system".

Clause 10 includes electrical components specific to wind turbine designs that have features and functions not typically addressed in other system or component standards. Clause 10 also addresses common wind turbine components but it is not intended to be all inclusive. Specific components are dictated by the turbine design and these components and assemblies shall be evaluated for the electrical, mechanical and environmental installation locations and application as defined in 10.2.

The power collection system is not covered by this document.

10.2 General requirements for the electrical system

The design of the electrical system shall ensure minimal hazards to people and livestock as well as minimal potential damage to the wind turbine and external electrical system during operation and maintenance under all normal and extreme ~~external~~ electrical and environmental conditions (as defined in 6.4.2 and 6.4.3) for the specific area where the equipment operates, including additional effects related to the overall turbine and its environmental ratings. Electrical components and subassemblies shall be rated for their electrical conditions and operating environment.

~~The electrical system, including all electrical equipment and components, shall comply with the relevant IEC standards. Specifically, the design of a wind turbine electrical system shall comply with the requirements of IEC 60204-1. For wind turbines that contain circuits at nominal voltages greater than 1000 V a.c. or 1500 V d.c. the design of a wind turbine electrical system shall comply with the requirements of IEC 60204-11. Fixed installations, not machine installations, shall comply with the requirements of IEC 60364. The manufacturer shall state the design standard(s) used. The design of the electrical system shall take into account the fluctuating nature of power generation from wind turbines.~~

Electrical equipment should be designed to provide protection from potential arc flashes using recognized national or international standards and risk assessment methodologies.

For cold climate requirements, see 14.8.

Unless otherwise specified in this document, the design of a wind turbine electrical system shall comply with the requirements of IEC 60204-1. For equipment that have input and or output circuits at nominal voltages greater than 1 000 V AC or 1 500V DC, the applicable requirements of IEC 60204-11 shall be applied. The manufacturer shall state the design standard(s) used. The design of the electrical system shall take into account the fluctuating nature of power generation from wind turbines.

10.3 Internal environmental conditions

The environmental conditions internal to the turbine are likely to be different from the external environmental conditions.

Environmental conditions shall be determined for the locations in which all major components and subassemblies within the wind turbine are located and shall be conducted in accordance with IEC 60721 (all parts). The locations for consideration normally include, but are not limited to, the hub, tower sections, nacelle, tower base, tower basement.

The internal environmental conditions are dependent upon the specific environmental control systems and foreseeable environmental pollution included in a specific turbine design. Heating, cooling and active ventilation shall be considered.

The manufacturer shall specify the following service conditions for operation, storage and transportation for each of the turbine subassemblies and major components. Where applicable, the classifications from IEC 60721 (all parts) shall be used:

- coolant temperature (min./max.);
- ambient temperature (min./max.);
- humidity (min./max.);
- pollution degree;
- vibration;
- OVC (overvoltage category);
- altitude for thermal consideration, if rated for operation above 1 000 m;
- altitude for insulation coordination considerations, if rated for operation above 2 000 m.

These environmental condition determinations are the basis for the insulation coordination defined in 10.3.

IEC 60664-1 and IEC 60664-3 for equipment having a rated voltage up to 1 000 V AC and IEC 60071-1 and IEC 60071-2 for equipment having a rated voltage above 1 000 V AC shall be used for evaluating the insulation coordination requirements for the specific wind turbine equipment unless otherwise specified by specific component requirements within this document. This insulation coordination evaluation shall address the overvoltage category, pollution degree, and environmental conditions for the electrical equipment within the turbine.

Minimum environmental conditions within the turbine are to be considered pollution degree 3. Specific areas where conductive pollution such as slip ring brush dust and brake dust are present shall be considered pollution degree 4.

The pollution degree may be reduced within certain areas of the equipment by the use of encapsulation, conformal coating, etc. Reduction of pollution degree within the overall equipment may also be achieved by the use of enclosures providing protection in accordance with IEC 60529. Steps may be taken to control and reduce the pollution degree at the creepage location by design features or the consideration of the operating characteristics of the component or equipment.

Pollution degree 2 can be achieved by reducing the possibilities of debris accumulation (filtered ventilation) and condensation or high humidity at the creepage locations. Continuous application of heat, through the use of heaters or continuous energizing of the equipment when it is in use, can be used to control condensation. Continuous energizing is considered to exist when the equipment is operated without interruption every day and 24 hours per day or when the equipment is operated with interruptions of duration which do not permit cooling to the point that condensation occurs.

Pollution degree 1 can be achieved by potting, moulding the equipment or circuit or by enclosing it in an IP 67 enclosure.

Overvoltage category IV shall be applied to determine clearance spacings in general locations within a wind turbine. Surge protectors that are relied upon to protect control and protection circuits and other circuits relied upon for the safe operation of the turbine shall include monitoring circuits or other automatic means to indicate a surge protective device has failed. Use of surge suppression protection may be used to locally reduce the overvoltage category to below IV for specific equipment or circuits.

Direct or nearby lightning strikes can induce high overvoltage conditions in the external electrical systems and wind turbine electrical systems including equipment circuits throughout the hub, nacelle and tower. Surge protective devices, if used, shall be installed in close proximity to the equipment being protected.

10.4 Protective devices

A wind turbine electrical system shall, in addition to the requirements of IEC 60364 (all parts), include suitable devices that ensure protection against malfunctioning ~~of~~ either within the wind turbine, equipment, subassemblies and components or as consequence of the external electrical system malfunction that may lead to an unsafe condition or state. These protective device functions include: short circuit, overcurrent, ground fault, over temperature and arc fault.

10.5 Disconnection ~~devices~~ from supply sources

~~It shall be possible to disconnect a wind turbine electrical system from all electrical sources of energy as required for maintenance or testing.~~

~~Semiconductor devices shall not be used alone as disconnect devices.~~

Lockable disconnect device or devices shall be provided to disconnect the equipment from each electrical source of supply that has a hazardous live voltage or exceeds the values for hazardous energy or from which a hazardous live voltage or energy is derived. The levels of hazardous voltage and energy are defined in IEC 60204-1 and IEC 60204-11.

The emergency stop is not intended to provide a routine disconnect function for this purpose.

Semiconductor switching devices without additional air gap disconnect contacts are not suitable to meet the requirements of 10.4.

Where lighting or other electrical systems are necessary for safety during maintenance, auxiliary circuits shall be provided with their own disconnect devices, such that these circuits may remain energized while all other circuits are de-energized.

Circuits and equipment rated more than 1 000 V AC or 1 500 V DC shall comply with Clause 5 of IEC 60204-11:2000.

10.6 Earth system

~~The design of~~ A wind turbine shall ~~include~~ be provided with a local earth electrode system to meet the requirements of IEC 60364 (all parts) (for the correct operation of the electrical installation) and ~~IEC 61024-1~~ IEC 62305-3 (for lightning protection).³³ The range of soil conditions for which the earth electrode system is adequate shall be stated in the design documentation, together with recommendations should other soil conditions be encountered.

The choice and installation of the equipment of the earthing arrangement (earth electrodes, earthing conductors, main earthing terminals and bars) shall be made in accordance with IEC 60364-5-54.

Provisions shall be made in any electrical system operating above 1 000 V AC or 1 500 V DC for earthing during maintenance in accordance with IEC 60204-11.

³³ Additional considerations are included in IEC 61400-24:2010, Clause 9.

10.7 Lightning protection

The lightning protection system of a wind turbine shall be designed in accordance with ~~IEC 61024-1~~ IEC 61400-24. ~~It is not necessary for protective measures to extend to all parts of the wind turbine, provided safety is not compromised.~~

A risk-based approach shall be applied during the lightning protection system design with respect to the risk of damage and personnel safety.

The design shall consider the protection of the following areas:

- rotor blades;
- hub/spinner;
- nacelle;
- tower.

Additional system components such as external transformers and switchgear outside the scope of this document may also need to be connected and or included in the lightning protection system.

The protection of electrical systems within the turbine shall follow a lightning protection approach as set out in IEC 62305-4, with the design incorporating a combination of bonding, shielding and surge protection devices.

~~Guidance is given~~ Design requirements of the lightning protection system are provided in IEC 61400-24.

10.8 Electrical cables

Electrical cables shall be rated for the electrical, flammability, mechanical and environmental applications where they are used and shall be installed in a manner for which they are rated. Where there is a probability of rodents or other animals damaging cables, armoured cables or conduits shall be used. ~~Underground cables shall be buried at a suitable depth to avoid damage by service vehicles or farm equipment. Underground cables shall, if not protected by a conduit or duct, be marked by cable covers or suitable marking tape.~~

- Cables shall be protected or rated to mitigate the possible risk of fire in the event of the fault.
- Control cables shall be segregated and or protected from power cables unless insulation failures are specifically addressed in the fault analysis.
- Cable clamps, supports and strain reliefs shall be suitable for the cable type so as to prevent damage to the cable insulation.
- Cables shall be protected or suitably located to prevent damage from abrasion and wear.

10.9 Self-excitation

Any electrical system that can alone self-excite a wind turbine shall be disconnected and remain safely disconnected in the event of loss of network power.

If a capacitor bank is connected in parallel with an induction generator (i.e. for power factor correction), a suitable switch is required to disconnect the capacitor bank whenever there is a loss of network power, to avoid self-excitation of the generator. Alternatively, if capacitors are fitted, it shall be sufficient to show that the capacitors cannot cause self-excitation.

10.10 Protection against lightning electromagnetic impulse

The overvoltage protection shall be designed in accordance with the requirements of ~~IEC 61312-1~~ IEC 62305-4.

The limits of the protection shall be so designed that any lightning electromagnetic impulse transferred to the electrical equipment will not exceed the limits governed by the equipment insulation levels.

10.11 Power quality

~~The power quality characteristics of the wind turbine shall be assessed in accordance with IEC 61400-21.~~

The procedures in IEC 61400-21 ~~may~~ can be used to demonstrate compliance with the requirements of the operator of the public distribution or transmission network.

10.12 Electromagnetic compatibility

~~Emissions of conducted disturbances are covered in 10.9.~~

~~Emissions of radiated disturbances shall meet the requirements of IEC 61000-6-4.~~

~~Immunity to conducted disturbances is covered in 10.6.~~

~~Immunity to radiated disturbances shall meet the requirements of IEC 61000-6-1 or IEC 61000-6-2. The turbine manufacturer shall state which of these two standards applies to the wind turbine design.~~

For immunity to radiated and conducted disturbances, all electrical components installed in the wind turbine shall meet the requirements of the relevant product standards and shall not be less than the greater of requirements of IEC 61000-6-2 or the requirements defined during the functional safety evaluation of the control system in Clause 8.

10.13 Power electronic converter systems and equipment

The converter shall be evaluated for the environment in which it is installed as defined by Table 18 of IEC 62477-1:2012. The interior of a turbine is not considered to be a conditioned space. If the converter is installed within a conditioned space, it shall be evaluated for that environment. The pollution degree shall be chosen with respect to ingress of moisture from humidity and condensation due to extended durations of de-energization. The environmental service conditions defined in IEC 62477-1 may be modified to accommodate the specific end application within the turbine.

IEC 61800-4 shall be applied for converters operating above 1 000 V AC or 1 500 V DC.

Converter controls and protection shall additionally comply with the applicable requirements in Clause 8.

10.14 Twist/drip loop

Wiring that is subject to movement, flexing, or twisting during operation of the wind turbine shall be investigated for suitability in the application conditions of use and rated life.

If operation of the wind turbine may result in twisting of flexible cables, such as the connecting cables between rotating parts (nacelle) and parts of the fixed structure (tower or foundation), the operational conditions of use shall not cause damage to the conductors or

their insulation. The evaluation shall address service life, electrical and environmental operating conditions of the subassembly.

Controls that prevent damage to conductors or their insulation including rotational limits shall be considered part of the control system.

Where multiple cables are grouped or tied together, the assembly loading shall be distributed such that the individual cables are not subjected to loads that exceed their individual ratings.

The cable support assemblies shall be designed for the mechanical loading and torsional forces of operation.

Cable size and temperature rating shall be evaluated based upon the operating temperature of the assembly including representative size and number of cables fully twisted, carrying maximum normal current and including electrical terminations similar in distance in the end application.

10.15 Slip rings

Slip rings shall comply with 10.2 and the applicable portions of IEC 60204-1 and shall be rated for the electrical and environmental conditions to which they are subjected within the turbine. The slip rings shall be rated for normal operating and abnormal (overload) conditions to which they may be subjected. The normal rating of a slip ring is based upon the circuit electrical loads. The overload rating shall be based upon source circuit fault current capacity and may account for overcurrent protection if provided.

Slip rings used in safety critical power and control circuits shall be provided with means to address failure and wear.

10.16 Vertical power transmission conductors and components

Vertical power transmission systems that are run up the tower, such as bus bar-based systems and cable-based systems, shall comply with the respective component standards. These are IEC 61439-1 and IEC 61439-6 for bus bar-based systems and IEC 60364-5-52 for cable-based systems.

The conductors and components shall comply with their applicable standard with regards to: operating temperature range, environmental conditions, electrical isolation, electrical impulse withstand and short circuit withstand capabilities as necessary for the electrical and environmental conditions within the turbine.

Vertical power transmission equipment shall be constructed with sufficient mechanical strength to withstand the foreseeable mechanical forces (deflection, movement and loading) for its use as determined from the results of the design load cases for the specific component within the specific turbine. Sections of vertical power transmission conductors and components shall be suitably attached to the tower or to components of the tower intended to support the assembly.

The evaluation of these vertical power transmission systems shall account for the following conditions:

- a) static loading on system components;
- b) expected deflection and forces on the transmissions assemblies and support structure resulting from bending of the tower under anticipated extreme conditions;
- c) expected force direction and magnitude of displacement of the assembly;
- d) component fatigue, loosening of fasteners;
- e) degradation, wear, deformation and creep of polymeric electrical insulating materials;

- f) loss of electrical conductivity or electrical isolation;
- g) operation for the intended turbine life span or specified maintenance period for the assembly.

The assembly may be evaluated by testing, analysis or a combination of the two.

Scaled testing may be used to represent the complete system.

The mechanical and structural suitability of the power transmission assembly and supporting members may be addressed via analysis per the design load case evaluation. The design load cases shall specifically include and address the forces on the assembly, subassemblies and components including insulating and conducting materials.

Consideration of short circuit conditions for vertical power transmission systems should include electrical, thermal and mechanical effects on components as well as installed systems.

If the analysis method does not include effects of abrasion/wear and material creep on the polymeric electrical insulation, testing may be necessary.

10.17 Motor drives and converters

Motor drives and converters shall comply with the applicable portions of IEC 61800-5-1.

Pitch and yaw motor drive and converter controls shall additionally comply with the applicable requirements in Clause 8.

10.18 Electrical machines

Electrical machines shall comply with relevant parts of IEC 60034 and shall have a duty rating suitable for the intended application³⁴.

The turbine generator shall be rated for continuous operation (duty S1 according to IEC 60034-1).

The combination of an electrical machine powered by a frequency converter drive shall have coordinated electrical and isolation ratings.

10.19 Power transformers

Power transformers included within or as part of a turbine system shall comply with IEC 60076 (all parts).

Low voltage transformers within the wind turbine shall either be fully enclosed, including all terminations, or they shall be located in dedicated areas behind barriers or panels as required in recognized national or international standards and codes. High voltage (HV) transformers within the wind turbine shall comply with the requirements for restricted accessibility and lock out as defined in 10.21.

10.20 Low voltage switchgear and controlgear

Low voltage switchgear and controlgear operating up to 1 000 V AC or 1 500 V DC shall comply with IEC 61439-1 and other parts of the IEC 61439 series and shall be rated for the electrical and environmental conditions to which it is subjected within the turbine.

³⁴ Consideration should be given to interconnection cable length, the drive voltage waveform, the use of insulated bearings and shaft earthing arrangements.

All enclosures for switchgear and controlgear shall be provided with cautionary markings required by IEC 61439-1 and other applicable parts of the IEC 61439 series.

10.21 High voltage switchgear

High voltage (HV) switchgear operating above 1 000 V AC or 1 500 V DC shall comply with IEC 62271 (all parts) and shall be rated for the electrical and environmental conditions to which it is subjected within the turbine.

HV switchgear shall be located in areas of the turbine only accessible by authorized personnel. Cautionary markings shall be posted on the turbine access, hatch or door to wear appropriate personnel protection equipment for the hazards inside the area beyond the access, hatch or door.

HV switchgear installed in areas accessible to normal maintenance personnel shall be metal enclosed and specified for internal arc containment classification (IAC). The IAC shall be classification A as defined in IEC 62271-200 for all equipment sides where personnel may reasonably have access.

HV switchgear shall be tested, rated and marked for the IAC fault current with a duration of not less than 1 s.

HV switchgear shall be installed in accordance with the manufacturer's ratings and instructions. Pressure relief vents shall output without obstruction and without risk to personnel or equipment.

Switchgear configured for automatic operation shall be switchable to lock out and disable the automatic operation.

As required by 10.4, HV switchgear and associated controls shall be provided with a means to be locked in a safe state.

SF6 switchgear shall be installed in areas with sufficient ventilation so as to avoid hazard to personnel in the event of a leak.

10.22 Hubs

Equipment within the hub shall be provided with enclosures rated for the electrical and environmental application in accordance with IEC 60529 to protect electrical components from damage. Electrical cabinets and enclosures shall be provided with doors or covers that are securely fastened.

Wiring associated with the control systems shall be mechanically protected from damage due to hub rotation, service personnel interaction and unintended impacts within the hub.

11 Assessment of a wind turbine for site-specific conditions

11.1 General

Wind turbines are subject to environmental and electrical conditions including the influence of nearby turbines, which may affect their loading, durability and operation. In addition to these conditions, account has to be taken of the seismic, topographic and soil conditions at the wind turbine site. It shall be shown that the site-specific conditions do not compromise the structural integrity. The demonstration requires an assessment of the site complexity, see 11.2, and an assessment of the wind conditions at the site, see 11.3. For assessment of structural integrity, two approaches may be used:

- a) a demonstration that all these conditions are not more severe than those assumed for the design of the wind turbine, see 11.9;
- b) a demonstration of the structural integrity for conditions, each equal to or more severe than those at the site, see 11.10.

If any conditions are more severe than those assumed in the design, the structural and electrical compatibility shall be demonstrated using the second approach.

The partial safety factors for loads in 7.6.2.2 assume that the site assessment of the normal and extreme wind conditions has been carried out according to the minimum requirements in Clause 11.

11.2 Assessment of the topographical complexity of the site and its effect on turbulence

~~The complexity of the site is characterised by the variations of the terrain topography from a plane. A site that fails to conform to all the restrictions of Table 4 is characterised as complex. The fitted plane slope, used in Table 4, denotes the slope of a plane that best fits the topographic variations within a specific distance from the wind turbine and passes through the wind turbine tower base. Accordingly, the terrain variation from the fitted plane denotes the distance, along a vertical line, between any surface point and the fitted plane. z_{hub} is the hub height of the wind turbine.~~

Table 4 — Terrain complexity indicators

Distance range from wind turbine	Max slope of fitted plane	Maximum terrain variation from a disc with radius $1,3 z_{hub}$ fitted to the terrain
$< 5 z_{hub}$		$< 0,3 z_{hub}$
$< 10 z_{hub}$	$< 10^\circ$	$< 0,6 z_{hub}$
$< 20 z_{hub}$		$< 1,2 z_{hub}$

~~The resolution of surface grids used for terrain complexity assessment must not exceed z_{hub} .~~

11.2.1 Assessment of the topographical complexity

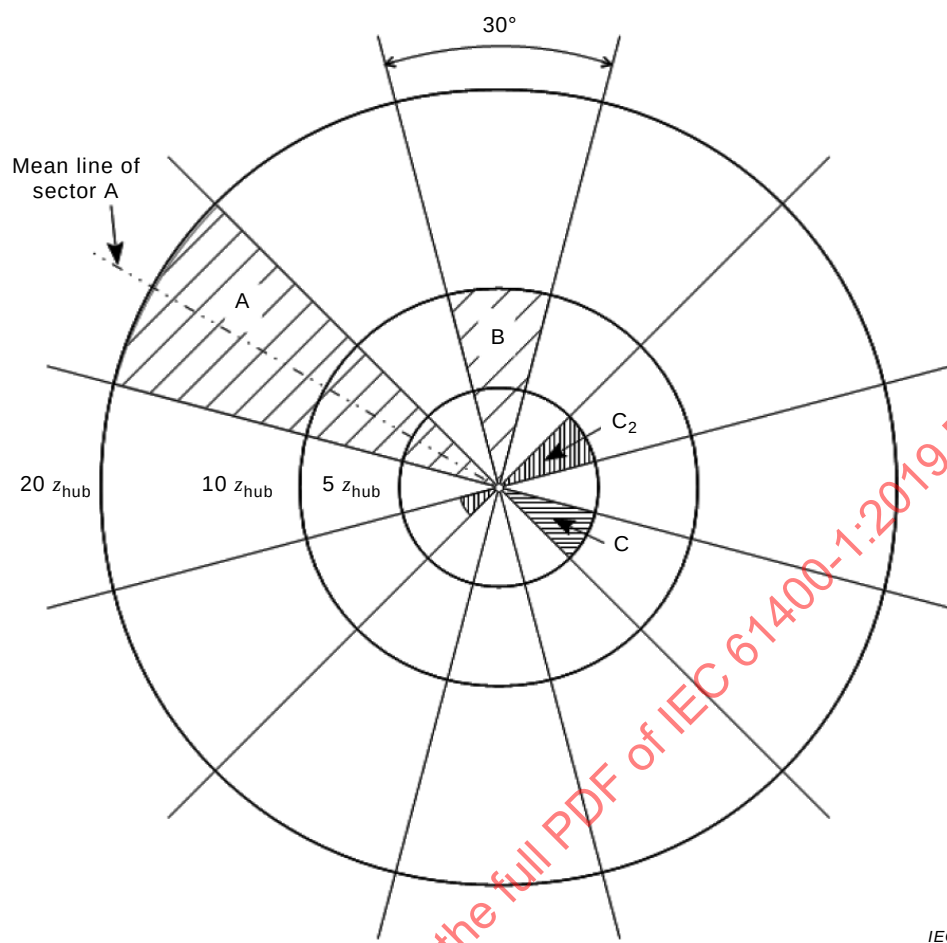
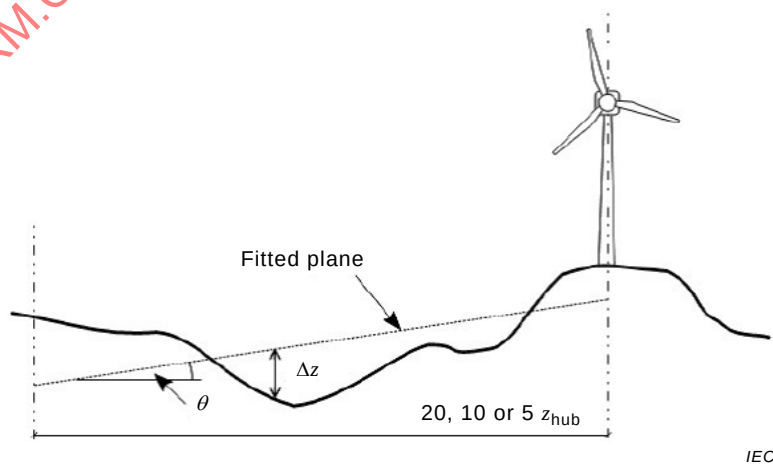
A site shall be assessed for the topographical complexity of the terrain, since it may cause distortion, and hence deviation, of the turbulence structure from the design conditions.

The complexity of the site is characterized by the slope of the terrain and variations of the terrain topography from a plane, and it may be assessed according to the following procedure.

To obtain the slope of the terrain, planes are defined that fit the terrain within specific distances and sector amplitudes for all wind direction sectors around the wind turbine, see Figures 10 and 11. The fitted planes do not need to pass through the tower base. The slope denotes the angle between a horizontal line and the different mean lines of sectors projected vertically on the fitted planes. Accordingly, the terrain variation from the fitted plane denotes the distance, along a vertical line, between the fitted plane and the terrain at the surface points.

The resolution of surface grid and its original source map used for terrain complexity assessment should not exceed 50 m.

The circle sectors shall be 30° . For the circle sectors with radius $5 z_{hub}$ the area used to fit the plane may be extended $2 z_{hub}$ downwind of the wind turbine position, see Figure 10.

**Key**A radius 20 z_{hub}B radius 10 z_{hub}C radius 5 z_{hub}C₂ radius 5 z_{hub} extended 2 z_{hub} behind the wind turbine position**Figure 10 – Examples of 30° sectors for fitting the terrain data****Figure 11 – Terrain variation (Δz) and terrain slope (θ)**

Using thus defined slope and terrain variation, terrain slope indices (*TSI*) and terrain variation indices (*TVI*) for each circle area are given by the following equations:

$$\begin{aligned}
 TSI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot |\theta(i)| \\
 TVI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot \frac{D_{\text{TV}}(i)}{R} \\
 TSI_{360} &= k_1 \cdot \theta_{360} \\
 TVI_{360} &= \frac{D_{\text{TV}360}}{k_2 \cdot R}
 \end{aligned} \tag{34}$$

where

TSI_{30}, TSI_{360} are the terrain slope indices calculated from 30° sectors and 360° circle area, respectively;

TVI_{30}, TVI_{360} are the terrain variation indices calculated from 30° sectors and 360° circle area, respectively;

i is the wind sector index (1, 2, ..., 12);

$f_{\text{Energy}}(i)$ is the percentage of the wind energy coming through i th 30° sector,
 $\sum f_{\text{Energy}}(i) = 1$;

$\theta(i)$ is the slope of fitted plane for i th 30° sector;

θ_{360} is the slope of the fitted 360° circle plane;

$D_{\text{TV}}(i)$ is the standard deviation of terrain variation in i th 30° sector;

$D_{\text{TV}360}$ is the standard deviation of terrain variation of the 360° circle area;

R is the radius of the circle area;

k_1 is the empirical adjustment factor for TSI_{360} , $k_1 = 5/3$;

k_2 is the empirical adjustment factor for TVI_{360} , $k_2 = 3$.

TSI_{30} is the mean absolute value of the slopes of the twelve sector-wise fitted planes weighted by energy inflow. Similarly, TVI_{30} is the mean value of the twelve sector-wise standard deviations of terrain variation normalized by the circle radius, weighted by the energy inflow.

TSI_{360} is the slope of the fitted 360° circle plane adjusted by an empirical factor k_1 .

TVI_{360} is the standard deviation of terrain variation in 360° circle area, normalized by the circle radius and adjusted by an empirical factor k_2 .

Terrain is assessed for terrain complexity by means of two indices TSI and TVI for each of the three circle areas ($5z_{\text{hub}}$, $10z_{\text{hub}}$, and $20z_{\text{hub}}$). For both indices, three complexity categories low (L), medium (M) and high (H) are defined, see Table 5. If the TSI_{30} and TVI_{30} values as well as the TSI_{360} and TVI_{360} values for all three circle areas are below the threshold value for category L, the site is assessed as not complex. If not, the site is assessed as complex and assigned one of the three complexity categories, L, M or H, depending on the highest category TSI or TVI for any of the circle areas.

Table 5 – Threshold values of the terrain complexity categories L, M and H

Radius of circle area	Sector amplitude of fitted plane	Threshold values (lower limit)					
		Terrain slope index (TSI)			Terrain variation index (TVI)		
		L	M	H	L	M	H
$5z_{hub}$	360°	10°	15°	20°	2 %	4 %	6 %
$5z_{hub}$	30°						
$10z_{hub}$							
$20z_{hub}$							

11.2.2 Assessment of turbulence structure at the site

The turbulence structure, i.e. the ratios of the three components of turbulence, of a site shall be determined primarily from measurements at the site. When there are no site data, it may be estimated by an appropriate flow model.

Alternatively, it may be estimated from the complexity of the site. Values shown in Table 6 may be assigned depending on the complexity category defined according to the procedure described in 11.2.1.

Table 6 – Values of lateral and vertical turbulence standard deviations relative to the longitudinal component depending on terrain complexity category L, M and H

	Category		
	L	M	H
σ_2/σ_1	0,85	0,93	1,00
σ_3/σ_1	0,60	0,65	0,70

The turbulence structure correction parameter C_{CT} , which may be used in the assessment of the structural integrity by reference to wind data in 11.9, may be defined by the following equation³⁵:

$$C_{CT} = \sqrt{1 + (\hat{\sigma}_2 / \hat{\sigma}_1)^2 + (\hat{\sigma}_3 / \hat{\sigma}_1)^2} / \sqrt{1 + (\sigma_2 / \sigma_1)^2 + (\sigma_3 / \sigma_1)^2}$$

in which σ_1 , σ_2 and σ_3 are values of the three components of turbulence, at hub height and at wind turbine location, averaged over a wind speed range between $0,6 V_r$ and $1,6 V_r$. The design values for the Kaimal and Mann models can be obtained from Annex C.

When there are no measured site data, the values in Table 7 may be used for C_{CT} depending on the complexity category of the site.

³⁵ If C_{CT} is less than 1, $C_{CT} = 1,0$ shall be used.

Table 7 – Values of turbulence structure correction parameter depending on terrain complexity category L, M and H

	Category		
	L	M	H
C_{CT}	1,05	1,10	1,15

Interpolation between the values in Table 6 and Table 7 is allowed.

11.3 Wind conditions required for assessment

11.3.1 General

The site wind parameters shall be either measured and extrapolated, or calculated using appropriate methods (e.g. monitoring measurements made at the site, long-term records from local meteorological stations, simulation models or local codes and standards). Simulation models shall be validated against representative data.

11.3.2 Wind condition parameters

~~Values at the wind turbine site of the following parameters shall be estimated:~~

The following parameters shall be derived for the position of the wind turbine at hub height:

- extreme 10 min average wind speed³⁶, V_{50} , at hub height with a ~~recurrence~~ return period of 50 years;
- wind speed probability density function $p(V_{hub})$ ~~in the range of V_{in} to V_{out} ;~~
- ~~ambient turbulence standard deviation $\hat{\sigma}$ (estimated as the mean value of the standard deviation of the longitudinal component³⁷) and the standard deviation $\hat{\sigma}_{\sigma}$ of $\hat{\sigma}$ at V_{hub} between V_{in} and V_{out} and V_{hub} equal to V_{ref} ;~~
- wind speed standard deviation $\hat{\sigma}$ from the ambient turbulence (estimated as the mean value of the standard deviation of the longitudinal component) and the standard deviation $\hat{\sigma}_{\sigma}$ of $\hat{\sigma}$ at all wind speeds required in 11.9 or 11.10;
- extreme ambient wind speed standard deviation³⁸, $\hat{\sigma}_{1ETM}$, with a return period of 50 years;

³⁶ The load partial safety factors for DLC 6.1 and DLC 6.2 are derived by assuming that the coefficient of variation of the annual maximum wind speed, COV, is smaller than 15 %. If COV is larger than 15 %, they can be increased linearly by a factor η from 1,0 at COV = 15 % to 1,15 at COV = 30 %. If $\eta > 1,0$ an adjusted value of the extreme 10 min average wind speed of $\tilde{V}_{50} = \sqrt{\eta} V_{50}$ can be used in the assessment of the structural integrity, see 11.9 and 11.10. COV of the annual maximum wind speed can approximately be obtained assuming a Gumbel distribution and assuming that for example 50 year and 100 year return values of the wind speed, V_{50} and V_{100} , are available. The parameters α and β are obtained from:

$$\alpha = \frac{V_{100} - V_{50}}{p_{100} - p_{50}}, \quad \beta = V_{50} - \alpha p_{50} \quad \text{with} \quad p_{100} = -\ln\left(-\ln\left(1 - \frac{1}{100}\right)\right) \quad \text{and} \quad p_{50} = -\ln\left(-\ln\left(1 - \frac{1}{50}\right)\right)$$

COV is determined from

$$COV = \frac{\sigma}{\mu} = \frac{\pi}{\sqrt{6}} \frac{1}{\frac{\beta}{\alpha} + 0,5772}$$

³⁷ ~~The longitudinal component of turbulence may be approximated by the horizontal component.~~

³⁸ The extreme ambient wind speed standard deviation $\hat{\sigma}_{1ETM}$ may be derived using an appropriate extrapolation method, for example, the IFORM method, or estimated by:

- flow inclination;
- wind shear³⁹;
- air density.

Where there is no site data for the air density, it shall be assumed that the air density is consistent with ISO 2533:1975, suitably corrected for annual average temperature.

The ~~interval~~ bin width of any wind speed ~~bin~~ used in the above shall be 2 m/s or less, and the wind direction sectors shall be 30° or less. All ~~parameters~~ measurements, except air density, shall be available as function of wind direction, given as a 10 min average.

~~The site wind parameters⁴⁰ shall be either~~

- ~~measured in the range of $0,2 V_{ref}$ and $0,4 V_{ref}$ and extrapolated, or~~
- ~~calculated from monitoring measurements made at the site, long term records from local meteorological stations or from local codes or standards.~~

~~If measurements are used, the site conditions shall be correlated with long term data from available local meteorological stations unless they can otherwise be shown to be conservative. The monitoring period shall be sufficient to obtain a minimum of six months of reliable data. Where seasonal variations contribute significantly to the wind conditions, the monitoring period shall be long enough to conservatively include these effects.~~

~~The value of the standard deviation of the longitudinal component shall be determined using appropriate statistical techniques applied to measured and preferably de-trended data. Where topographical or other local effects may influence the turbulence intensity, these effects shall be represented in the data. The characteristics of the anemometer, sampling rate and averaging time used to obtain measured data shall be considered when evaluating the turbulence intensity.~~

Attention should be given to wakes from significant structures and orographic obstacles within a distance from the wind turbine of 20 times the characteristic length of the structure or the orographic obstacle. The influence can be neglected if the bottom edge of the rotor is at least four times higher than the height of the structure or the orographic obstacle.

In regions prone to hurricanes, cyclones and typhoons, the extreme wind speed shall be evaluated by appropriate methods, for example as given in Annex J.

For cold climate, additional parameters should be derived for the position of the wind turbine. Icing condition may be assessed according to Annex L.

11.3.3 Measurement setup

The requirement for and use of measurements for wind turbine site suitability assessment and wind resource assessments differ in many respects, and therefore a balance needs to be

$$\hat{\sigma}_{1ETM} = \hat{\sigma} + k_p \hat{\sigma}_{\sigma}; \quad k_p = 0,01 \left(\frac{V_{ave}}{(m/s)} - 21 \right) \left(\frac{V_{hub}}{(m/s)} - 5 \right) + 5$$

³⁹ ~~High shear values for extended periods of time~~ Shear values with high variability have been reported for certain areas in connection with highly stratified flow, complex terrain or severe roughness changes. ~~The external conditions in Clause 6 are not intended to cover such cases.~~ In this case using the average wind shear may not be sufficient.

⁴⁰ ~~Attention should be given to wakes from significant structures within a distance from the wind turbine of 20 times the characteristic length of the structure.~~

found between the amount and the quality of measurements.⁴¹ Furthermore, for the purposes of a wind turbine site suitability measurement campaign, additional criteria should be taken into consideration.

- The measurement system should be installed in locations broadly representative of the majority of site areas (e.g. forest, ridge lines, plains, valleys, slopes and obstacles).
- The exact number and location of measuring systems recommended is very site-specific and depends upon the terrain, extent and ground cover of the proposed wind farm as well as the expected complexity of the flow regime and the on-site validation of the flow model to be used in the analysis.
- The wind condition measurement heights as well as the number of sensors should be chosen to be representative. Measurements should be performed at a range of heights within the proposed turbine rotor's swept area. Consideration should be given to surrounding terrain and vegetation.
- The vertical separation distance between the sensors should enable a robust analysis of the vertical wind shear, for example a separation of at least one third of the rotor diameter.
- A temperature as well as pressure sensor should be installed.
- 10 minutes averaging time, based on at least 1 Hz (mean, standard deviation and maximum wind speed, mean of wind direction and mean temperature) should be used.
- If measurements are performed in a cold climate zone, then additional heated sensors should be used and their performance relative to unheated sensors considered.
- In complex terrain, all wind components should be measured, for example with a 3D-ultrasonic anemometer.

11.3.4 Data evaluation

The recommendations with respect to data coverage and period are the following.

- The measurement period can deviate depending on the quality of data and the reliability of the correlation to a reference long term source. Where seasonal variations contribute significantly to the wind conditions, the monitoring period should be long enough to include these effects (the minimum to capture seasonal effects would be 12 months).
- The data coverage in each month should be sufficiently high to adequately represent the monthly variation in wind conditions.

During data evaluation, a quality check and filtering should be performed and documented. A measure-correlate-predict (MCP) procedure may be performed to extend the data.

The average value of the wind speed standard deviation $\hat{\sigma}$, i.e. the standard deviation of the longitudinal turbulence component, and its standard deviation $\hat{\sigma}_{\sigma}$ shall be determined using appropriate statistical techniques applied to measured and preferably linearly de-trended data.

A long-term assessment is normally required for the estimation of the extreme wind speed, long-term mean wind speed as well as air density, but only if the available long term source is appropriate and sufficiently reliable.

Alternative methods can be used. These methods should aim to improve the representativeness of the measurements for the site.

The above mentioned methods and procedures shall be documented.

⁴¹ IEC 61400-12-1 and IEA Recommendation 11 illustrate best-practice guidelines for measurement equipment installation and setup.

11.4 Assessment of wake effects from neighbouring wind turbines

Wake effects from neighbouring wind turbines during power production shall be considered. The assessment of the suitability of the wind turbine at a site in a wind farm shall take into account the deterministic and turbulent flow characteristics associated with single or multiple wakes from upwind machines, including the effects of the spacing between the machines, for all ambient wind speeds and wind directions relevant to power production.

The increase in loading generally assumed to result from wake effects may be accounted for by the use of an ~~effective~~ added turbulence ~~intensity~~ approach or by using more detailed wake models. In either case, the wake model shall include adequate representation of the effect on loading of ambient turbulence and discrete and turbulent wake effects.

For fatigue calculations, the effective turbulence intensity I_{eff} may be derived according to Annex E.

~~For ultimate loads, I_{eff} may be assumed to be the maximum of wake turbulence intensities from neighbouring wind turbines as defined in Annex D.~~

$$I_{\text{eff}} = \frac{1}{V_{\text{hub}}} \max \{ \hat{\sigma}_T \} \quad (33)$$

~~It should be noted that for wind turbine spacing less than 3 diameters the validity of such models is uncertain and caution shall be exercised.~~

The added turbulence for fatigue and ultimate loads may be assumed to be the same.

The DWM model described in Annex E is generally applicable to both fatigue and extreme load cases.

11.5 Assessment of other environmental conditions

The following environmental conditions shall be assessed for comparison with the assumptions made in the design of a wind turbine:

- normal and extreme temperature ranges;
- icing, hail and snow;
- humidity;
- lightning;
- solar radiation;
- chemically active substances;
- salinity.

11.6 Assessment of earthquake conditions

There are no earthquake resistance requirements for standard class turbines because such events are only design driving in a few regions of the world. No earthquake assessment analysis is required for sites already excluded by the applicable local seismic code due to their weak seismic action. For locations where the seismic load cases described below are critical, the engineering integrity shall be demonstrated for the wind turbine site conditions. The assessment may be based on Annex D. The evaluation of load shall take into account the combination of seismic loading with other significant, frequently occurring operational loads.

The seismic loading shall depend on ground acceleration and response spectrum requirements as defined in local codes. If a local code is not available or does not give the ground acceleration and response spectrum, an appropriate evaluation of these parameters shall be carried out.

The ground acceleration shall be evaluated for a 475-year ~~recurrence~~ return period.

The earthquake loading shall be superposed with operational loading that shall be ~~equal to the higher~~ largest of

- ~~a) loads during normal power production by averaging over the lifetime;~~
- ~~b) loads during emergency shutdown for a wind speed selected so that the loads prior to the shutdown are equal to those obtained with a);~~
- a) mean loads during normal power production determined at V_r ,
- b) loads during emergency stop at V_r , and
- c) loads during idling or parked condition at no wind and V_{out} .

The partial safety factor for load for all load components shall be 1,0. The material safety factor for steel can be set to 1,0.

The seismic load evaluation may be carried out through ~~frequency domain~~ response spectrum methods, in which case the operational load is added ~~directly to~~ using the SRSS (square-root-sum-of-squares) or equivalent load combination arising from the seismic loading.

The seismic load evaluation may be carried out through time-domain methods, in which case sufficient simulations shall be undertaken to ensure that the operational load is representative of the time averaged values referred to above.

The number of tower natural vibration modes used in either of the above evaluations shall be selected in accordance with a recognized seismic code. In the absence of such a code, consecutive modes with a total modal mass of 85 % of the total mass shall be used.

The evaluation of the resistance of the structure may assume elastic response only, or ductile energy dissipation. However, it is important that the latter is assessed correctly for the specific type of structure in use, in particular for lattice structures and bolted joints.

~~A conservative approach to the calculation and the combination of loads on the tower is provided in Annex C.~~ The acceleration response spectrum at the engineering bedrock and seismic response evaluation method are described in Annex D. ~~This procedure~~ The response spectrum method shall not be used if it is possible that seismic action will cause significant loading of structures other than the tower.

11.7 Assessment of electrical network conditions

The external electrical conditions at the wind turbine terminals at a proposed site shall be assessed to ensure compatibility with the electrical design conditions. The external electrical conditions shall include the following⁴²:

- normal voltage and range including requirements for remaining connected or disconnecting through specified voltage range and duration;
- normal frequency, range and rate of change, including requirements for remaining connected or disconnecting through specified frequency range and duration;
- voltage imbalance specified as a percentage negative phase-sequence voltage for symmetric and unsymmetrical faults;
- method of neutral grounding;
- method of ground fault detection/protection;

⁴² The turbine designer may need to take account of grid compatibility conditions. The list represents a set of minimum requirements. Local and national grid compatibility requirements need to be anticipated at the design stage.

- annual number of network outages;
- auto-reclosing cycles;
- required reactive compensation schedule;
- fault currents and duration;
- phase-phase and phase-ground short-circuit impedance at the wind turbine terminals;
- background harmonic voltage distortion of the network;
- presence of power line carrier signalling if any and frequency of same;
- fault profiles for ride-through requirements;
- power factor control requirements;
- ramp rate requirements; and
- other grid compatibility requirements.

11.8 Assessment of soil conditions

The soil properties at a proposed site shall be assessed by a professionally qualified geotechnical engineer, with reference to available local building codes.

11.9 Assessment of structural integrity by reference to wind data

11.9.1 General

It is possible to complete the assessment of structural integrity by comparison of the wind parameter values for the site to those used in design. ~~A wind turbine is suitable for a site when the following conditions are all satisfied:~~

- ~~the site estimate of extreme 10 min average wind speed at hub height with a recurrence period of 50 years shall be less than V_{ref} ⁴³;~~
- ~~the site value of the probability density function of V_{hub} shall be less than the design probability density function (see 6.3.1.1) at all values of V_{hub} between the wind speed $0,2 V_{ref}$ and $0,4 V_{ref}$;~~
- ~~the representative value of the turbulence standard deviation, σ_1 , (see equation (11)) shall be greater or equal to the site value of the estimated 90 % quantile of the turbulence standard deviation at all values of V_{hub} between the wind speed $0,2 V_{ref}$ and $0,4 V_{ref}$, and i.e.~~

$$\sigma_1 \geq \hat{\sigma} + 1,28 \hat{\sigma}_\sigma \quad (34)$$

~~When the terrain is complex, the estimate of the standard deviation of the longitudinal component of turbulence shall be increased in order to account for the distortion of the turbulent flow⁴⁴. The site flow inclination, taken as the maximum of all directions, shall be less than that specified in 6.3. Where there are no site data or calculations for the flow inclination and the terrain is complex, it shall be assumed that the flow is always parallel to the fitted plane, see 11.2, within a distance of $5 z_{hub}$ from the wind turbine.~~

⁴³ Alternatively, the wind turbine site central estimate of extreme 3 s average wind speed at hub height with a recurrence period of 50 years should be less than V_{e50} .

⁴⁴ The effect of complex terrain may be included by an additional multiplication with a turbulence structure correction parameter C_{CT} defined as

$$C_{CT} = \frac{\sqrt{1 + (\hat{\sigma}_2 / \hat{\sigma}_1)^2 + (\hat{\sigma}_3 / \hat{\sigma}_1)^2}}{1,375}$$

where ratios of the estimated standard deviations, $\hat{\sigma}_i$, correspond to hub height values. Where there are no site data for the components of turbulence and the terrain is complex, results of modelling or $C_{CT} = 1,15$ may be used.

~~The site average vertical wind shear exponent α , for direction shall be less than that specified in 6.3.1.2 and larger than zero. Where there are no site data for the wind shear, it shall be calculated taking topography and roughness into account.~~

~~The average site air density shall be less than that specified in 6.4.1 for wind speeds greater than or equal to V_f .~~

~~An adequate assessment of wake effects can be performed by verifying that the turbulence standard deviation σ_z from the normal turbulence model is greater or equal to the estimated 90 % quantile of the turbulence standard deviation (including both ambient and wake turbulence) between the wind speed $0,2 V_{ref}$ and $0,4 V_{ref}$ (or when the turbine properties are known, between $0,6 V_f$ and V_{out}), i.e.:~~

$$\sigma_z \geq I_{eff} \cdot V_{hub} + 1,28 \hat{\sigma}_\sigma \quad (35)$$

~~where I_{eff} for fatigue loads and extreme load calculations follows from 11.4.~~

The assessment can be performed separately for the fatigue load suitability and the ultimate load suitability.

11.9.2 Assessment of the fatigue load suitability by reference to wind data

A wind turbine is suitable for a site with respect to fatigue loading when the following conditions are all satisfied.

- a) The site value of the wind speed probability density function at hub height $p(V_{hub})$ shall be less than or equal to the design probability density function at all values of V_{hub} between the wind speeds V_{ave} and $2V_{ave}$. If the turbine has been designed with the wind speed distribution in 6.3.2.1 and the shape parameter k of the site-specific Weibull wind speed distribution is greater than or equal to 1,4 then, k shall fulfil the following equation, which depends on the site-specific mean wind speed at hub height normalized by the design mean wind speed, see Figure 12:

$$6,5 \times \frac{V_{ave,site}}{V_{ave,design}} - 4,5 \leq k \leq -6,0 \times \frac{V_{ave,site}}{V_{ave,design}} + 8,0 \quad (35)$$



Figure 12 – Possible combinations of normalized mean wind speed and Weibull shape parameter k (shaded area)

- b) An adequate assessment of the ambient turbulence intensity and wake effects can be performed by verifying that the wind speed standard deviation σ_1 from the normal turbulence model (NTM) used in design is greater than or equal to the effective wind speed standard deviation $\hat{\sigma}_{\text{eff}}$ (see Annex E) between the wind speeds V_{ave} and $2V_{\text{ave}}$, i.e.

$$\sigma_1 > \hat{\sigma}_{\text{eff}} (= I_{\text{eff}} V_{\text{hub}}) \quad (36)$$

Guidance for calculating I_{eff} can be found in Annex E. In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation, i.e. $\hat{\sigma}_c$, shall be increased in order to account for the distortion of the turbulent flow. This can be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

- c) The site flow inclination, taken as the wind energy weighted mean from all directions, shall be between -8° and $+8^\circ$. Where there are no site data or calculations for the flow inclination, it shall be assumed that the flow inclination is equal to the slope, θ , for the 30° sector within a distance of $5z_{\text{hub}}$ or the $5z_{\text{hub}}$ area extended by $2z_{\text{hub}}$ downwind of the wind turbine position from the wind turbine, see 11.2.
- d) The energy weighted average over all wind directions and wind speeds during power production of the vertical site wind shear exponent α shall be in the range of 0,05 to 0,25. Where there are no site data for the wind shear, it shall be calculated taking topography and roughness of the surrounding terrain into account.
- e) The average site air density shall be less than the one specified in 6.4.2 for wind speeds greater than or equal to V_r . As an alternative, for an air density greater than the one specified in 6.4, it shall be demonstrated that the following condition applies:

$$\rho_{\text{design}} \times V_{\text{ave,design}}^2 \geq \rho_{\text{site}} \times V_{\text{ave,site}}^2 \quad (37)$$

11.9.3 Assessment of the ultimate load suitability by reference to wind data

A wind turbine is suitable for a site with respect to ultimate loading when the following conditions are all satisfied.

- a) The design value of the wind speed standard deviation, σ_1 , (see Equation (10)) shall be greater than or equal to the site value of the estimated 90 % quantile⁴⁵ of the wind speed standard deviation at all values of V_{hub} between the wind speeds $0,6 V_r$ and $1,6 V_r$, i.e.

$$\sigma_1 \geq \hat{\sigma} + 1,28 \hat{\sigma}_{\sigma} \quad (38)$$

In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation shall be increased in order to account for the distortion of the turbulent flow. This may be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

- b) The site estimate of the extreme 10-min average wind speed V_{50} at hub height with a return period of 50 years shall be less than or equal to V_{ref} . Alternatively, the wind turbine site central estimate of extreme 3 s average wind speed at hub height with a return period of 50 years shall be less than V_{e50} . For Class S turbines, both the extreme 3 s average wind speed and the extreme 10 min average wind speed shall be assessed. V_{50} shall be modified according to Footnote 24 when the coefficient of variation of the annual maximum wind speed is larger than 15 %. If the average site air density is different from the one specified in 6.4.2, it shall be demonstrated that the following condition applies:

$$\rho_{design} \times V_{ref}^2 \geq \rho_{site} \times V_{50,hub}^2 \quad (39)$$

- c) It shall be demonstrated that the site-specific extreme ambient wind speed standard deviation does not exceed the ETM model in 6.3.3.4.
- d) In case of wake situations, it shall be demonstrated that the maximum centre-wake wind speed standard deviation in the most severe direction does not exceed the ETM model in 6.3.3.4. Alternatively, it can be demonstrated that the ambient site-specific extreme turbulence does not exceed the ETM model used for DLC 1.6 in Annex B and that the minimum site-specific inter-turbine distance does not fall below S_{min} from DLC 1.6. For determination of the site-specific turbulence, the site-specific conditions, the frequency of the wake situations and the wind farm layout shall be accounted for.

11.10 Assessment of structural integrity by load calculations with reference to site-specific conditions

The demonstration shall comprise a comparison of loads and deflections calculated for the specific wind turbine site conditions with those calculated during design, taking account of the reserve margins and the influence of the environment on structural resistance. The calculations shall account for variations of wind conditions with mean wind direction and speed as well as for wake effects, vertical wind shear, mean wind flow angle, etc.

For the fatigue loading, a comparison of damage equivalent moments and damage equivalent load of the load duration distribution of the driving torque is sufficient for verification of components. For ultimate loading a comparison of contemporaneous loads is not required.

Turbulence structure shall be based on site-specific values. Where there are no site data for the components of turbulence and the terrain is complex, ~~it shall be assumed that the longitudinal, lateral and upward turbulence component standard deviations are equal~~ values for the ratios of the components assigned for each complexity category in 11.2 may be used. As an alternative, the longitudinal turbulence intensity may be increased by the C_{CT} factor.

In the case of wake effects, it shall be verified that structural integrity is not compromised ~~for DLC 1.1 and 1.2 in which σ_1 in the normal turbulence model is replaced by the actual wake turbulence. This may be estimated by~~

⁴⁵ The right hand side of Equation (38) represents an approximation of the 90 % quantile.

$$\sigma_{\text{wake}} = I_{\text{eff}} V_{\text{hub}} + 1,28 \hat{\sigma}_g \quad (36)$$

where I_{eff} for fatigue load and extreme load calculations follows from 11.4.

This may be performed using a wake model, for example see Annex E, with the turbulence model adjusted to the site-specific parameters.

Since for fatigue load calculations, I_{eff} as defined in Annex E depends on the Wöhler curve exponent m of the material of the considered component, the loads on structural components with other material properties shall either be recalculated or assessed with the appropriate value of m .

~~For extreme load calculations, it is permitted to take into account the frequency of the wake situations and modify the load extrapolation in DLC 1.1 accordingly.~~

Fatigue load calculations shall be performed, if one of the criteria in 11.9.2 fails.

Ultimate limit state analyses shall be performed if one of the criteria in 11.9.3 fails. As a minimum, the following ultimate design load cases shall be assessed: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. If the design load cases for the standard classes are adequate, no further evaluations need to be performed.

Annex B provides definitions of the aforementioned ultimate and fatigue load cases for site-specific conditions. If relevant, other load cases in design situations 1), 6), and 7) in Table B.1 should be considered. Design situations 2), 3), 4), 5), and 8) in Table B.1 only need to be considered when the control system behaviour and transport, assembly, maintenance and repair procedures are site-dependent.

12 Assembly, installation and erection

12.1 General

The manufacturer of a wind turbine shall provide an installation manual clearly describing installation requirements for the wind turbine structure and equipment. The installation of a wind turbine shall be performed by personnel trained or instructed in these activities.

The site of a wind turbine facility shall be prepared, maintained, operated and managed so that work can be performed in a safe and efficient manner. This should include procedures to prevent unauthorized access where appropriate. The operator should identify and eliminate existing and potential hazards.

Checklists of planned activities shall be prepared, and logs of completed work and results of that work should be kept.

When appropriate, installation personnel shall use approved eye, foot, hearing, and head protection. All personnel climbing towers, or working above ground or water level, should be trained in such work and shall use approved safety ~~belts~~ harnesses, safety climbing aids or other safety devices. When appropriate, a buoyancy aid should be used around water.

All equipment shall be kept in good repair and be suitable for the task for which it is intended. Cranes, hoists and lifting equipment, including all slings, hooks and other apparatus, shall be adequate for safe lifting.

Particular consideration should be given to installation of the wind turbine under unusual conditions, such as hail, lightning, high winds, earthquake, icing, ~~etc.~~

In the case of a tower standing without a nacelle, appropriate means shall be taken to avoid critical wind speeds for vortex-generated transverse vibrations **unless the appropriate fatigue design load case has been analysed, or the resulting loads shall be included in the fatigue analysis**. The critical wind speeds and precaution measures shall be included in the installation manual.

12.2 Planning

The assembly, erection and installation of wind turbine and associated equipment shall be planned in order that the work is carried out safely and in accordance with local and national regulations. In addition to procedures for quality assurance, the planning shall include, where appropriate, consideration of the following:

- rules for safe execution of excavation work;
- detailed drawings and specifications of the work and inspection plan;
- rules for the proper handling of embedded items, such as foundations, bolts, anchors and reinforcement steel;
- rules for concrete composition, delivery, sampling, pouring, finishing and placement of conduits;
- safety rules for blasting;
- procedures for installation of towers and other anchors.

12.3 Installation conditions

During the installation of a wind turbine, the site shall be maintained in such a state that it does not present safety risks.

12.4 Site access

Access to a site shall be safe and the following shall be taken into account:

- barriers and routes of travel;
- traffic;
- road surface;
- road width;
- clearance;
- access weight bearing capacity;
- movement of equipment at the site.

12.5 Environmental conditions

During installation, environmental limits specified by the manufacturer shall be observed. Items such as the following should be considered:

- wind speed;
- snow and ice;
- ambient temperature;
- blowing sand;
- lightning;
- visibility;
- rain.

12.6 Documentation

The manufacturer of a wind turbine shall provide drawings, specifications and instructions for assembly procedures, installation and erection of the wind turbine. The manufacturer shall provide details of all loads, weights, lifting points and special tools and procedures necessary for the handling and installation of the wind turbine.

12.7 Receiving, handling and storage

Handling and transport of wind turbine generator equipment during installation shall be performed with equipment confirmed to be suitable to the task and in accordance with the manufacturer's recommended practice.

Wind turbines are often sited on hilly terrain. Therefore, heavy equipment shall be set down in such a manner that it cannot shift. A suitably-sized, level lay-down area is preferred for all handling and assembly operations. Where this cannot be provided, all heavy equipment shall be securely blocked in a stable position.

Where there is risk of movement caused by the wind with risk of consequent damage, blades, nacelles, other aerodynamic parts and light crates shall be secured with ropes and stakes, or ground anchors.

12.8 Foundation/anchor systems

Where specified by the manufacturer for safe installation or assembly, special tools, jigs and fixtures and other apparatus shall be used.

12.9 Assembly of wind turbine

A wind turbine shall be assembled according to the manufacturer's instructions. Inspection shall be carried out to confirm proper lubrication and pre-service conditioning of all components.

12.10 Erection of wind turbine

A wind turbine shall be erected by personnel trained and instructed in proper and safe erection practices.

No part of a wind turbine electrical system shall be energized during erection unless it is necessary for the erection process. In this case, the energization of such equipment shall be carried out in accordance with a written procedure to be provided by the wind turbine supplier.

All elements where motion (rotation or translation) may result in a potential hazard shall be secured from unintentional motion throughout the erection process.

12.11 Fasteners and attachments

Threaded fasteners and other attachment devices shall be installed according to the wind turbine manufacturer's recommended torque and/or other instructions. Fasteners identified as critical shall be checked and procedures for confirming installation torque and other requirements shall be obtained and used.

In particular, inspection shall be carried out to confirm the following:

- proper assembly and connection of guys, cables, turn buckles, gin poles and other apparatus and devices;
- proper attachment of lifting devices required for safe erection.

12.12 Cranes, hoists and lifting equipment

Cranes, hoists and lifting equipment, including all hoisting slings, hooks and other apparatus required for safe erection, shall be adequate for safe lifting and final placement of the loads. Manufacturer's instructions and documentation with respect to erection and handling should provide information on expected loads and safe lifting points for components and/or assemblies. All hoisting equipment, slings and hooks shall be tested and certified for safe load.

13 Commissioning, operation and maintenance

13.1 General

The commissioning, operation, inspection, and maintenance procedures shall be specified in the wind turbine manual with due consideration of the safety of personnel.

The design shall incorporate provisions for safe access for inspection and maintenance of all components.

The requirements of Clause 10 also cover electrical measurement equipment temporarily installed in the wind turbine for the purpose of measurements.

When appropriate, operation and maintenance personnel shall use approved eye, foot, hearing and head protection. All personnel climbing towers, or working above ground or water level, shall be trained in such work and shall use approved safety belt, safety climbing aids or other safety devices. When appropriate, a buoyancy aid should be used around water.

13.2 Design requirements for safe operation, inspection and maintenance

The normal operation of a wind turbine by the operating personnel shall be possible at ground level. A tagged, local, manual override on the automatic/remote control system shall be provided.

External events detected as faults but not critical for the future safety of a wind turbine, such as loss and reinstatement of the electrical load, may allow automatic return to normal operation after completion of the shutdown cycle.

Guards designed to protect personnel from accidental contact with moving components shall be fixed, unless frequent access is foreseen where they may be movable.

Guards shall

- a) be of robust construction,
- b) not be easy to by-pass, and
- c) where possible, enable essential maintenance work to be carried out without their dismantling.

Provisions shall be made in the design for use of diagnostic fault-finding equipment.

In order to ensure the safety of inspection and maintenance personnel, the design shall incorporate

- safe access paths and working places for inspection and routine maintenance,
- adequate means to protect personnel from accidental contact with rotating components or moving parts,
- provision for securing lifelines and safety ~~belts~~ harnesses or other approved protection devices when climbing or working above ground level,

- provisions for blocking rotation of the rotor and yawing mechanism or other mechanical motion, such as blade pitching, during servicing according to wind conditions and design situations specified in DLC 8.1, as well as provisions for safe unblocking,
- warning signs for live conductors,
- suitable devices for the discharge of accumulated electricity,
- suitable fire protection for personnel, and
- an alternative escape route from the nacelle.

Maintenance procedures shall require safety provisions for personnel entering any enclosed working space, such as hub or blade interior, that ensure any dangerous situation will be known by standby personnel to immediately initiate rescue procedures if necessary.

13.3 Instructions concerning commissioning

13.3.1 General

The manufacturer shall provide instructions for commissioning.

13.3.2 Energization

The manufacturer's instructions shall include a procedure for initial energization of the wind turbine electrical system.

13.3.3 Commissioning tests

The manufacturer's instructions shall include the procedures for wind turbine testing after installation, to confirm proper, safe and functional operation of all devices, controls and apparatus. These shall include, but not be limited to,

- safe start-up,
- safe shutdown,
- safe emergency ~~shutdown~~ stop,
- safe shutdown from overspeed or representative simulation thereof, and
- ~~function~~ test of protection ~~system~~ functions, see Clause 8.

13.3.4 Records

The manufacturer's instructions shall include the instruction that proper records shall be kept describing testing, commissioning, control parameters and results.

13.3.5 Post commissioning activities

At the completion of installation, and following operation for the manufacturer recommended running-in period, the specific actions that may be required by the manufacturer shall be completed.

These can include, but are not limited to, preloading of fasteners, changing of lubrication fluids, checking other components for proper setting and operation and proper adjustment of control parameters.

The wind turbine site should be refurbished to remove hazards and prevent erosion.

13.4 Operator's instruction manual

13.4.1 General

An operator's instruction manual shall be supplied by the wind turbine manufacturer and augmented with information on special local conditions at the time of commissioning as appropriate. The manual shall include, but not be limited to

- any requirements that the operation shall be performed by personnel suitably trained or instructed in this activity,
- safe operating limits and system descriptions,
- start-up and shutdown procedures,
- an alarms action list,
- emergency procedures plan, and
- stated requirements that
 - when appropriate, approved eye, feet, hearing and head protection shall be used,
 - when appropriate, all personnel climbing towers, or working above ground or water level, shall be trained in such work and shall use approved safety ~~belt~~ harness, safety climbing aids or other safety devices,
 - when appropriate, a buoyancy aid should be used around water, and
 - the manual shall be available to the operation and maintenance personnel in a language that can be read and understood by the operator.

13.4.2 Instructions for operations and maintenance records

The manual shall state that operations and maintenance records shall be kept and should include the following:

- wind turbine identification;
- energy produced;
- operating hours;
- shutdown hours;
- date and time of fault reported;
- date and time of service or repair;
- nature of fault or service;
- action taken;
- parts replaced.

13.4.3 Instructions for unscheduled automatic shutdown

The manual shall require that following any unscheduled automatic shutdown caused by a fault or malfunction, unless specified otherwise in the operations manual or instructions, the operator shall investigate the cause before a wind turbine is restarted. All unscheduled automatic shutdowns should be recorded.

13.4.4 Instructions for diminished reliability

The manual shall require that action shall be taken to eliminate the root cause of any indication or warning of abnormality or diminished reliability.

13.4.5 Work procedures plan

The manual shall require that the wind turbine shall be operated according to safe working procedures, taking account of the following:

- electrical systems operation;
- co-ordination of operation and maintenance;
- utility clearance procedures;
- tower climbing procedures;
- equipment handling procedures;
- activity during bad weather;
- communications procedures and emergency plans.

13.4.6 Emergency procedures plan

Probable emergency situations shall be identified in the operations manual and the required actions of the operating personnel prescribed.

The manual shall require that where there is a fire or apparent risk of structural damage to the wind turbine or its components, no one should approach the wind turbine unless the risk is specifically evaluated.

In preparing the emergency procedures plan, it shall be taken into account that the risk for structural damage may be increased by situations such as the following:

- overspeeding;
- icing conditions;
- lightning storms;
- earthquakes;
- broken or loose guy-wires;
- brake failure;
- rotor imbalance;
- loose fasteners;
- lubrication defects;
- sandstorms;
- fire, flooding;
- other component failures.

13.5 Maintenance manual

Each wind turbine model shall have a maintenance manual, which at a minimum consists of the maintenance requirements and emergency procedures specified by the wind turbine manufacturer. The manual shall also provide for unscheduled maintenance.

The maintenance manual shall identify parts subject to wear and indicate criteria for replacement.

Subjects which should also be covered in the manual include the following:

- any requirement that inspection and maintenance shall be carried out by personnel suitably trained or instructed in this activity, at the intervals specified in and in compliance with the instructions in the wind turbine maintenance manual;
- description of the subsystems of the wind turbine and their operation;
- lubrication schedule prescribing frequency of lubrication and types of lubricants or any other special fluids;
- recommissioning procedure;

- maintenance inspection periods and procedures;
- procedures for functional check of protection subsystems;
- complete wiring and interconnection diagram;
- guy cable inspection and re-tensioning schedules and bolt inspection and preloading schedules, including tension and torque loadings;
- diagnostic procedures and trouble-shooting guide;
- recommended spare parts list;
- set of field assembly and installation drawings;
- tooling list.

14 Cold climate

14.1 General

Cold climate (CC) weather conditions are defined as icing climate (IC) and/or low temperature climate (LTC). LTC is for temperatures below the normal environmental conditions (6.4.2). IC is defined as meteorological icing leading to rime and/or glaze ice accretion on the wind turbine. For ice type definitions, see ISO 12494. For simplicity, cold climate conditions will be treated here as IC and LTC conditions unless stated otherwise.

The impact of cold climate on the structural integrity or safety systems of the wind turbine shall be assessed.

14.2 Low temperature and icing climate

As a minimum, the following effects on a wind turbine from a LTC shall be considered:

- a) component materials;
- b) air density;
- c) start-up procedures;
- d) viscosity of oils and lubricants.

As a minimum, the following effects from an IC shall be considered:

- reduced turbine performance due to iced blades;
- inhomogeneous ice distribution on wind turbine blades;
- ice shedding from blades;
- icing effects on wind measurements;
- increased sound levels;
- prolonged standstills.

14.3 External conditions for cold climate

14.3.1 General

The external conditions for cold climate deviate from normal climate external conditions (6.4.2) in terms of ambient temperature, air density, and icing.

14.3.2 Wind turbine class for cold climate

The external conditions to be considered for design are dependent on the intended site or site type for a wind turbine installation. As a consequence of LTC effects in cold climate conditions, minimum ambient temperature conditions shall be assumed which are intended to

represent many different sites and do not give a precise representation of any specific site. Wind turbine class for cold climate is defined in terms of ambient temperature as follows:

$\theta_{\min, \text{operation}} = -30 \text{ }^{\circ}\text{C}$	Minimum allowable ambient temperature for wind turbine operation (instantaneous value)
$\theta_{1\text{year}, \min} = -40 \text{ }^{\circ}\text{C}$	Minimum ambient temperature to be expected in hourly average (return period 1 year) = minimum dimensioning temperature
$\theta_{\text{mean}} = -5 \text{ }^{\circ}\text{C}$	Yearly mean ambient temperature

Other environmental conditions are according to normal environmental conditions (6.4.2).

14.4 Structural design

For LTC, the air density of $1,225 \text{ kg/m}^3$ shall be used for structural design in order to allow the use of wind turbines designed according to standard wind turbine classes.

The effect of the actual air density at the site⁴⁶, as influenced by temperature and altitude, shall be considered during the site suitability analysis.

14.5 Design situations and load cases

14.5.1 General

Cold climate conditions result in specific design situations for a wind turbine. In IC, the effect of ice accretion on blade aerodynamic coefficients and on the blade mass distribution needs to be considered. In LTC, low ambient temperatures (14.3.2) resulting in higher air densities than in normal climate conditions (6.4.2), selection of suitable materials (14.5.3) and the resulting consequences shall be taken into account in turbine design.

Ice accretion on rotor blades often occurs for temperatures higher than minimum ambient temperatures (14.3.2).

In cold climate conditions, altered turbine performance resulting to a shift in turbine operational point shall be assessed. As a minimum, the following shall be considered:

- unfavourable turbine controller behaviour, for example, due to incorrect generator torque and pitch setpoints caused by different aerodynamic performances of the blades;
- increase in start-stop cycles;
- change in stall behaviour of turbine blades;
- eigenfrequency changes due to additional blade ice mass.

Higher loading may be a consequence of aforementioned effects. Higher loading during icing may also be a consequence of imbalances resulting from altered rotor aerodynamics and additional ice mass. Further guidance can be found in Annex L.

14.5.2 Load calculations

For cold climate conditions, the turbine controller behaviour and loads are primarily affected by IC effects resulting from ice accretion on the rotor blades and LTC effects resulting from increased air density. Further guidance can be found in Annex L.

⁴⁶ An air density of $1,3 \text{ kg/m}^3$ may be more representative for sea-level sites.

14.5.3 Selection of suitable materials

For LTC effects in cold climate, all load calculation shall be matched to the modified temperature range to take material properties into account. One air density according to 14.4 may be used for all cold climate temperature ranges.

Ultimate strength verifications for components⁴⁷ that are exposed to the ambient temperature shall be considered for $\theta_{\min, \text{operation}}$ except for loads derived from DLC 7.1, 8.1 and 8.2 to be considered with $\theta_{1\text{year}, \min}$. Alternatively, the minimum temperature for DLC 8.1 may also be defined by the manufacturer. Fatigue strength verifications shall be considered for θ_{mean} .

14.6 Control systems

In addition to normal climate requirements for control systems stated in Clause 8, the components of the control system shall be designed under consideration of a shift in turbine operational point due to icing of the turbine, the specified ambient temperatures during operation and standstill as defined in 14.3.2. Cold climate conditions are especially to be considered in the following situations:

- when ensuring safety of the turbine controller behaviour during cold climate conditions;
- when a start procedure shall be implemented to set the wind turbine safely back on-line after an event leading to the turbine being cooled off to minimum ambient operation temperature $\theta_{\min, \text{operation}}$ or below (due to grid failure, maintenance, or other);
- when the effect on wind turbine dynamics of different air density values shall be taken into account;
- in case of safety critical energy storages, for example in the hub;
- in case of ice/low temperature effects on sensors and data processing.

If operation of the iced turbine is not considered in the load assumptions, measures have to be taken to prevent operation of the iced turbine. These measures need to be redundant; a single failure shall not lead to unintended operation of an iced turbine.

14.7 Mechanical systems

In addition to normal climate requirements for mechanical systems stated in Clause 9, the mechanical systems of the wind turbine shall be designed under consideration of the ambient temperatures during operation and standstill as defined in 14.3.2.

It shall be assured that the oil temperature in the gearbox has reached a temperature to avoid damage before power can be transmitted. For a cold start procedure, see 14.6.

14.8 Electrical systems

In addition to normal climate requirements for electrical systems stated in Clause 10, the electrical installation of the wind turbine shall be designed under consideration of the ambient temperatures during operation and standstill as defined in 14.3.2.

Cold climate conditions are especially to be considered in the following areas:

- materials in the electrical components;
- grid return at minimum standstill ambient temperature $\theta_{1\text{year}, \min}$, as defined in 14.3.2;
- start procedure as defined in 14.6.

⁴⁷ Minimum temperature and corresponding load cases for components that are not exposed to the ambient conditions shall be defined by the manufacturer.

Annex A (normative)

Design parameters for external conditions

A.1 Design parameters for describing wind turbine class S

A.1.1 General

For wind turbines designed to site-specific or special conditions, i.e. class S turbines, the following information shall be given in the design documentation for all conditions that differ from conditions for the wind turbine classes as defined in 6.2. Remaining conditions may be stated by reference to the appropriate wind turbine class.

A.1.2 Machine parameters

Rated power	[kW]
Hub height operating wind speed range $V_{in} - V_{out}$	[m/s]
Design life time	[years]

A.1.3 Wind conditions

General:

~~Average inclined flow~~	~~[deg]~~
Air density	[kg/m ³]
Hub height extreme wind speeds V_{e1} and V_{e50}	[m/s]
Turbulence model and parameters	
Turbulence intensity mean and standard deviation as a function of mean wind speed	~~used for the NTM and ETM~~
Extreme gust model and parameters for 1- and 50-year return periods	
Extreme direction change model and parameters for 1- and 50-year ~~recurrence~~ return periods	
Extreme coherent gust model and parameters	
Extreme coherent gust with direction change model and parameters	
Extreme wind shear model and parameters	

Aggregated or sector-wise (30° or less):

Annual average wind speed	[m/s]
Flow inclination	[°]
Wind speed distribution (Weibull, Rayleigh, measured, other)	
Wind profile model and parameters	
Sector turbulence intensity mean and standard deviation as a function of mean wind speed	
Wake effect model and parameters (effective turbulence intensity or dynamic wake meandering)	

A.1.4 Electrical network conditions

~~Maximum duration of electrical power network outages~~	~~[days]~~
~~Number of electrical network outages~~	~~[1/year]~~
~~Behaviour during symmetric and unsymmetrical external faults (description)~~	

Normal supply voltage and range [V]
 Normal supply frequency and range [Hz]
 Voltage imbalance [V]

Method of neutral grounding

Method of ground fault detection/protection

Annual number and maximum duration of network outages

Auto-reclosing cycles ~~(description)~~

Required reactive compensation schedule

Fault currents and duration

Phase-phase and phase-ground short-circuit impedance at the wind turbine terminals

Background harmonic voltage distortion of the network

Presence of power line carrier signalling if any and frequency of same

Fault profiles for ride-through requirements

Power factor control requirements

Ramp rate requirements

Other grid compatibility requirements

A.1.5 Other environmental conditions (where taken into account)

~~Design conditions in case of offshore wind turbine (water depth, wave conditions, etc.)~~

~~Earthquake model and parameters~~

Normal and extreme temperature ranges [°C]

Relative humidity of the air [%]

Solar radiation [W/m²]

Rain, hail and snow ~~and icing~~

Icing model and parameters

Chemically active substances

Mechanically active particles

Lightning, including description of lightning protection system

Salinity [g/m³]

Foundation:

Foundation stiffness and damping

Earthquake model and parameters:

A.2 Additional design parameters for describing cold climate wind turbine class S (CC-S)

See Table A.1.

Table A.1 – Design parameters for describing cold climate wind turbine class S (CC-S)

External conditions		
Symbol	Unit	Description
$\theta_{\min, \text{operation}}$	[K]	Minimum allowable ambient temperature for wind turbine operation
$\theta_{1\text{year}, \min}$	[K]	Minimum ambient temperature to be expected in hourly average
$\rho(\theta_{\min, \text{operation}})$	[kg/m ³]	Air density for cold climate design load cases associated with the minimum allowable ambient temperature for wind turbine operation $\theta_{\min, \text{operation}}$
$\rho(\theta_{1\text{year}, \min})$	[kg/m ³]	Air density for cold climate design load cases associated with the minimum ambient temperature to be expected in hourly average $\theta_{1\text{year}, \min}$

The air densities used for load calculation and in the determination of the power curve should be calculated by applying the ideal gas law⁴⁸.

The following equation applies:

$$\rho(\theta) = \frac{p}{R_0 \times \theta} \quad (\text{A.1})$$

with

$p = 101\,325 \text{ N/m}^2$ (at sea level);

$R_0 = 287 \text{ J/(kg} \cdot \text{K)}$;

$\theta = \theta_{1\text{year}, \min} + 35 \text{ K}$ to calculate $\rho(\theta_{1\text{year}, \min})$;

$\theta = \theta_{\min, \text{operation}} + 25 \text{ K}$ to calculate $\rho(\theta_{\min, \text{operation}})$.

Corrections for different altitudes can be applied.

The air density of $1,225 \text{ kg/m}^3$ can be used for structural design in order to allow the use of wind turbines designed according to standard wind turbine classes

The effect of the actual air density at the site, as influenced by temperature and altitude, shall be considered during the site suitability analysis

⁴⁸ The temperature value $\theta_{1\text{year}, \min}$ can be set to $\theta_{1\text{year}, \min} + 35 \text{ K}$ and $\theta_{\min, \text{operation}}$ can be set to $\theta_{\min, \text{operation}} + 25 \text{ K}$ for determining the air density accordingly. This increase by $+35 \text{ K}$ and $+25 \text{ K}$, respectively, is equivalent to definitions of the normal climate conditions in 6.4.2 and 6.4.3.2. The standard air density for normal climate conditions is $1,225 \text{ kg/m}^3$ referring to $+15 \text{ }^\circ\text{C}$. The ambient temperature range for normal climate is $-10 \text{ }^\circ\text{C}$ to $+40 \text{ }^\circ\text{C}$, being $+15 \text{ }^\circ\text{C} \pm 25 \text{ K}$. The extreme temperature range for normal climate is $-20 \text{ }^\circ\text{C}$ to $+50 \text{ }^\circ\text{C}$, being $+15 \text{ }^\circ\text{C} \pm 35 \text{ K}$.

Annex B

(informative)

Design load cases for special class S wind turbine design or site suitability assessment

B.1 General

The design load cases for special class S wind turbine design or site suitability assessment are determined from the combination of operational modes or design situations with the applicable class S external conditions with design parameters as specified in Annex A.

In design situation power production, the analysis for NTM_S and ETM_S may be performed for each sector with wind conditions determined for each sector or for all sectors using aggregated wind conditions. For other design situations, the analysis is performed for all sectors using aggregated wind conditions. The aggregation of wind conditions shall be carried out such that proper fatigue and extreme loads are maintained, or the design parameters shall be chosen conservatively. Consideration should be given to the potential variation in wind shear, density and other parameters that can affect fatigue loading on the wind turbine.

Wake effects, earthquake loading and icing shall be considered in load cases as specified for other conditions, if appropriate.

When a wind speed range is indicated in Table B.1, wind speeds leading to the most adverse condition for wind turbine design shall be considered. The range of wind speeds may be represented by a set of discrete values, in which case the resolution shall be sufficient to assure accuracy of the calculation.⁴⁹ In the definition of the design load cases, reference is made to the wind conditions described in Clause 6.

As stated in 11.10, for site suitability assessment, the following ultimate design load cases shall be assessed as minimum: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. If the design load cases for the standard classes are adequate, no further evaluations need to be performed. If relevant, other load cases in design situations 1), 6), and 7) in Table B.1 should be considered. Design situations 2), 3), 4), 5), and 8) in Table B.1 only need to be considered when the control system behaviour and transport, assembly, maintenance and repair procedures are site-dependent.

B.2 Power production (DLC 1.1 to 1.9)

In this design situation, a wind turbine is running and connected to the electric load. The assumed wind turbine configuration shall take into account rotor imbalance. The maximum mass and aerodynamic imbalances (e.g. blade pitch and twist deviations) specified for rotor manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating situations, such as yaw misalignment and control system tracking errors, shall be taken into account in the analyses of operational loads.

Design load cases (DLC) 1.1 and 1.2 embody the requirements for loads resulting from site-specific atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime (NTM). For DLC 1.2, wake effects are additionally considered – see Annex E for guidance. DLC 1.3 embodies the requirements for ultimate loading resulting from

⁴⁹ In general, a resolution of 2 m/s is considered sufficient.

extreme site-specific turbulence conditions. DLC 1.4 and 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine.

The statistical analysis of DLC 1.1 simulation data shall include at least the calculation of extreme values of the blade root in-plane moment and out-of-plane moment and tip deflection. If the extreme design values of the blade root moments derived from DLC 1.1 are exceeded by the extreme design values derived for DLC 1.3, the further analysis of DLC 1.1 may be omitted.

If the extreme design values of the blade root moments derived from DLC 1.1 are not exceeded by the extreme design values derived for DLC 1.3, the factor c in Equation (20) for the extreme turbulence model used in DLC 1.3 may be increased until the extreme design values of the blade root moments computed in DLC 1.3 are equal to or exceed the relevant extremes. The characteristic values of the loads relevant for other turbine components may be determined from this analysis based on DLC 1.3 with the increased extreme turbulence. As an alternative to this analysis, the appropriate characteristic values of all load components relevant for each specific turbine component determined from the simulation may be directly extrapolated.

Table B.1 – Design load cases

Design situation	DLC	Wind condition ⁵⁰	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	$NTM_s \quad V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	$NTM_s \quad V_{in} < V_{hub} < V_{out}$	Wake effects	F	*
	1.3	$ETM_s \quad V_{in} < V_{hub} < V_{out}$		U	N
	1.4	$ECD_s \quad V_{hub} = V_r - 2 \text{ m/s},$ $V_r, V_r + 2 \text{ m/s}$		U	N
	1.5	$EWS_s \quad V_{in} < V_{hub} < V_{out}$		U	N
	1.6	$ETM_s \quad V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	Wake effects	U	N
	1.7	$NTM_s \quad V_{in} < V_{hub} < V_{out}$	Ice formation Wake effects	U	N
	1.8	$NTM_s \quad V_{hub} = V_r$	Earthquake plus grid loss	U	N
2) Power production plus occurrence of fault	2.1	$NTM_s \quad V_{in} < V_{hub} < V_{out}$	Normal control system fault or loss of electrical network or primary layer control function fault (see 7.4.3)	U	N
	2.2	$NTM_s \quad V_{in} < V_{hub} < V_{out}$	Abnormal control system fault or secondary layer protection function related fault (see 7.4.3)	U	A
	2.3	$EOG_s \quad V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	$NTM_s \quad V_{in} < V_{hub} < V_{out}$	Control system fault, electrical fault or loss of electrical network	F	*

⁵⁰ For Class S design, the wind conditions (gust amplitudes, turbulence intensity, etc.) are defined by the designer, as stated in Annex A.

Design situation	DLC	Wind condition ⁵⁰	Other conditions	Type of analysis	Partial safety factors
	2.5	NWP $V_{in} < V_{hub} < V_{out}$	Low voltage ride through	U	N
3) Start-up	3.1	NWP _s $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
	3.3	EDC _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
4) Normal shutdown	4.1	NWP _s $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
5) Emergency stop	5.1	NTM _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM _s 50-year return period		U	N
	6.2	EWM _s 50-year return period	Loss of electrical network connection	U	A
	6.3	EWM _s 1-year return period	Extreme yaw misalignment	U	N
	6.4	NTM _s $V_{hub} < 0,7 V_{ref}$		F	*
	6.4	NTM _s $V_{hub} < 0,7 V_{ref}$	Ice formation	U	N
	6.6	NTM _s $V_{hub} < 0,7 V_{ref}$	Extreme temperature range	U	N
	6.7	NTM _s $V_{hub} < 0,7 V_{ref}$	Earthquake plus grid loss	U	N
7) Parked and fault conditions	7.1	EWM _s 1-year return period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM _s V_{maint} to be stated by the manufacturer		U	N
	8.2	EWM _s 1-year return period		U	A

The following abbreviations are used:

DLC	Design load case
ECD_s	Site-specific extreme coherent gust with direction change. When site-specific values are not available, it may be assumed to be identical to the ECD defined in 6.3.3.6.
EDC_s	Site-specific extreme direction change. When site-specific values are not available, Equations (21) and (22) in 6.3.3.5 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1 .
EOG_s	Site-specific extreme operating gust. When site-specific values are not available, Equations (18) and (19) in 6.3.3.3 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1 .
EWM_s	Site-specific extreme wind speed. When site-specific values are not available, Equations (13) through (17) in 6.3.3.2 may be used, with site-specific extreme wind speed with 50 years return period in place of V_{ref} .
EWS_s	Site-specific extreme wind shear. When site-specific values are not available, Equations (27) and (28) in 6.3.3.7 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1 and site-specific wind shear exponent in place of $\alpha = 0,2$.
NTM_s	Site-specific representative ambient turbulence intensity, as a function of hub height wind speed, $\hat{\sigma}_c/V_{hub}$ (see 6.3.2.3).
ETM_s	Site-specific extreme ambient turbulence intensity as a function of hub height wind speed $\hat{\sigma}_{1,ETM}/V_{hub}$ (see 6.3.2.3 and footnote 25).
NWP_s	Site-specific wind profile model. When site-specific wind speed profile is not available, Equation (9) in 6.3.2.2 may be used with the site-specific wind shear exponent at hub height in place of $\alpha = 0,2$.
$V_r \pm 2 \text{ m/s}$	Sensitivity to all wind speeds in the range shall be analysed.
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
*	Partial safety for fatigue (see 7.6.3)

In DLC 1.6, the assessment of loads resulting from the ambient site-specific ETM_s model in combination with an inter-turbine wake condition shall be assessed. The inter-turbine spacing S shall cover the worst loading conditions between a minimum spacing S_{min} (to be defined by the manufacturer) and $S = 20D$, where D is the turbine rotor diameter.

Annex E provides guidance on the use of appropriate wake models for DLC 1.6. If an added wake turbulence model is used, the maximum centre-line wake turbulence intensity shall be applied. The use of a meandering wake model (e.g. DWM) shall consider at least five mean wake offset angles $\theta_{wake} = 0^\circ; \pm \theta_{hub-tip}; \pm \theta_{hub-tip} \times 1,5$, where $\theta_{hub-tip} = \sin^{-1}\left(\frac{D}{2S}\right)$.

The number of transient events for DLC 2.4, DLC 3.1 and DLC 4.2 may be site-dependent, and that should be considered in the analysis of site-specific loads. If there is no information available, the number of events suggested in 7.4.3, 7.4.4 and 7.4.5 (footnotes 7, 9 and 10) may be used.

Annex C (informative)

Turbulence models

C.1 General

Two turbulence models are given here for design load calculations. The turbulent velocity fluctuations are assumed to be a stationary, random vector field whose components have zero-mean Gaussian statistics. The first model is recommended.

- 1) Mann uniform shear model.
- 2) Kaimal spectral and exponential coherence model.

Parameters for the models have been selected to satisfy the general turbulence requirements given in 6.3.

C.2 Mann [3] uniform shear turbulence model

The description of this model differs somewhat from the previous models in that a three-dimensional velocity spectral tensor is defined. The model assumes that the isotropic von Karman [2] energy spectrum is rapidly distorted by a uniform, mean velocity shear. The resulting spectral tensor components are given by

$$\Phi_{11}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^4} \left(k_0^2 - k_1^2 - 2k_1(k_3 + \beta(k)k_1)\zeta_1 + (k_1^2 + k_2^2)\zeta_1^2 \right) \quad (C.1)$$

$$\Phi_{22}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^4} \left(k_0^2 - k_2^2 - 2k_2(k_3 + \beta(k)k_1)\zeta_2 + (k_1^2 + k_2^2)\zeta_2^2 \right) \quad (C.2)$$

$$\Phi_{33}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k^4} \left(k_1^2 + k_2^2 \right) \quad (C.3)$$

$$\Phi_{12}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^4} \left(-k_1k_2 - k_1(k_3 + \beta(k)k_1)\zeta_2 - k_2(k_3 + \beta(k)k_1)\zeta_1 + (k_1^2 + k_2^2)\zeta_1\zeta_2 \right) \quad (C.4)$$

$$\Phi_{13}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^2 k^2} \left(-k_1(k_3 + \beta(k)k_1) + (k_1^2 + k_2^2)\zeta_1 \right) \quad (C.5)$$

$$\Phi_{23}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^2 k^2} \left(-k_2(k_3 + \beta(k)k_1) + (k_1^2 + k_2^2)\zeta_2 \right) \quad (C.6)$$

where

$$\Phi_{ij}(k_1, k_2, k_3) = \Phi_{ji}^*(k_1, k_2, k_3) = \frac{1}{8\pi^3} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} R_{ij}(\delta_1, \delta_2, \delta_3) e^{-ik_1\delta_1} e^{-ik_2\delta_2} e^{-ik_3\delta_3} d\delta_1 d\delta_2 d\delta_3 ;$$

$$R_{ij}(\delta_1, \delta_2, \delta_3) = \frac{1}{\sigma_{\text{iso}}^2} E \left\langle u_i(x_1, x_2, x_3) u_j(x_1 + \ell \delta_1, x_2 + \ell \delta_2, x_3 + \ell \delta_3) \right\rangle$$

= a non-dimensional correlation tensor;

u_1, u_2, u_3 = the longitudinal, lateral, and upward velocity components, respectively;

$\delta_1, \delta_2, \delta_3$ = the non-dimensional spatial separation vector components;

k_1, k_2, k_3 = the non-dimensional spatial wave numbers for the three component directions;

$k = \sqrt{k_1^2 + k_2^2 + k_3^2}$ = the magnitude of the non-dimensional wave number vector;

$k_0 = \sqrt{k^2 + 2\beta(k)k_1k_3 + (\beta(k)k_1)^2}$ = the magnitude before shear distortion;

$$\zeta_1 = C_1 - \frac{k_2}{k_1} C_2, \quad \zeta_2 = \frac{k_2}{k_1} C_1 + C_2;$$

$$C_1 = \frac{\beta(k)k_1^2(k_1^2 + k_2^2 - k_3(k_3 + \beta(k)k_1))}{k^2(k_1^2 + k_2^2)};$$

$$C_2 = \frac{k_2 k_0^2}{(k_1^2 + k_2^2)^{3/2}} \arctan \left(\frac{\beta(k)k_1 \sqrt{k_1^2 + k_2^2}}{k_0^2 - (k_3 + \beta(k)k_1)k_1 \beta(k)} \right);$$

$$E(k) = \frac{1.453 k^4}{(1 + k^2)^{17/6}} = \text{the non-dimensional, von Karman isotropic energy spectrum};$$

$$\beta(k) = \frac{\gamma}{k^{2/3} \sqrt{{}_2F_1\left(\frac{1}{3}, \frac{17}{6}, \frac{4}{3}, -k^{-2}\right)}}$$

= a non-dimensional distortion time inversely proportional to $\sqrt{k^2 \int_k^\infty E(p) dp}$;

${}_2F_1$ = Hypergeometric function;

$\sigma_{\text{iso}}^2, \ell$ = the unsheared, isotropic variance and scale parameters respectively;

γ = a non-dimensional shear distortion parameter.

While this model is more complex than the von Karman isotropic model, it contains only one additional parameter, namely the shear distortion parameter, γ . When this parameter is zero, the isotropic model is recovered. As this parameter is increased, the longitudinal and lateral velocity component variances increase while the upward velocity component variance decreases. The resulting turbulent eddy structure is stretched in the longitudinal direction and tilted relative to the 1-2 plane.

Assuming that the random velocity field generated by the model is convected past the turbine at the hub-height wind speed, the velocity component spectra observed at a point may be computed by integrating the spectral tensor components. In particular, the non-dimensional, one-sided spectra are given by

$$\frac{f S_i(f)}{\sigma_i^2} = \frac{\sigma_{\text{iso}}^2}{\sigma_i^2} \left(\frac{4\pi \ell f}{V_{\text{hub}}} \right) \psi_{ii} \left(\frac{2\pi \ell f}{V_{\text{hub}}} \right) \quad (\text{C.7})$$

where

$$\Psi_{ij}(k_1) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Phi_{ij}(k_1, k_2, k_3) dk_2 dk_3$$

= the one-dimensional, wave number autospectrum for $i = j$, or cross-spectrum for $i \neq j$, and

$$\sigma_i^2 = \sigma_{\text{iso}}^2 \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \Phi_{ii}(k_1, k_2, k_3) dk_1 dk_2 dk_3 = \text{the component variance.}$$

Similarly, for spatial separations normal to the longitudinal direction the coherence is given by

$$\text{Coh}_{ij}(f, \ell \delta_2, \ell \delta_3) = \frac{\left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Phi_{ij}\left(\frac{2\pi \ell f}{V_{\text{hub}}}, k_2, k_3\right) e^{-i k_2 \delta_2} e^{-i k_3 \delta_3} dk_2 dk_3 \right|}{\sqrt{\Psi_{ii}\left(\frac{2\pi \ell f}{V_{\text{hub}}}\right) \Psi_{jj}\left(\frac{2\pi \ell f}{V_{\text{hub}}}\right)}} \quad (\text{C.8})$$

Unfortunately, the resulting integrals do not have known analytical forms and ~~must~~ shall be carried out numerically for a specific value of the parameter, γ . Mann [4] carried out such integrations and compared the results to the Kaimal spectral model. A least squares fit to the Kaimal model gave the shear parameter

$$\gamma = 3,9 \quad (\text{C.9})$$

with the resulting variance relations

$$\left. \begin{aligned} \sigma_1^2 &= 3,25 \sigma_{\text{iso}}^2 \\ \sigma_2^2 &= 1,65 \sigma_{\text{iso}}^2 \\ \sigma_3^2 &= 0,85 \sigma_{\text{iso}}^2 \end{aligned} \right\} \Rightarrow \begin{cases} \frac{\sigma_2}{\sigma_1} \approx 0,7 \\ \frac{\sigma_3}{\sigma_1} \approx 0,5 \end{cases} \quad (\text{C.10})$$

Note the resulting lateral variance is slightly less than given in Table C.1. The scale parameter may be found by equating the asymptotic, inertial-sub-range longitudinal spectra. Thus,

$$S_1(f) \rightarrow 0,475 \sigma_{\text{iso}}^2 \left(\frac{2\pi \ell}{V_{\text{hub}}} \right)^{-2/3} f^{-5/3} = 0,05 \sigma_1^2 \left(\frac{A_1}{V_{\text{hub}}} \right)^{-2/3} f^{-5/3} \Rightarrow \ell \approx 0,8 A_1 \quad (\text{C.11})$$

In summary, the three parameters required in the Mann model are given by

$$\begin{aligned} \gamma &= 3,9 \\ \sigma_{\text{iso}} &= 0,55 \sigma_1 \\ l &= 0,8 A_1 \end{aligned} \quad (\text{C.12})$$

where σ_1 and A_1 are specified in 6.3.

For three dimensional turbulent velocity simulations, the velocity components are determined from a decomposition of the spectral tensor and an approximation by the discrete Fourier transform. Thus, the three-dimensional spatial domain is divided into equally spaced discrete points and the velocity vector at each point is given by

$$\begin{bmatrix} u_1(x, y, z) \\ u_2(x, y, z) \\ u_3(x, y, z) \end{bmatrix} = \sum_{k_1, k_2, k_3} e^{i \frac{xk_1 + yk_2 + zk_3}{\ell}} \begin{bmatrix} C(k_1, k_2, k_3) \begin{bmatrix} n_1(k_1, k_2, k_3) \\ n_2(k_1, k_2, k_3) \\ n_3(k_1, k_2, k_3) \end{bmatrix} \end{bmatrix} \quad (\text{C.13})$$

where

$$\begin{bmatrix} C(k_1, k_2, k_3) \end{bmatrix} \approx \sigma_{\text{iso}} \sqrt{\frac{2\pi^2 \ell^3 E(k_0)}{N_1 N_2 N_3 \Delta^3 k_0^4}} \begin{bmatrix} k_2 \zeta_1 & k_3 - k_1 \zeta_1 + \beta k_1 & -k_2 \\ k_2 \zeta_2 - k_3 - \beta k_1 & -k_1 \zeta_2 & k_1 \\ \frac{k_0^2 k_2}{k^2} & -\frac{k_0^2 k_1}{k^2} & 0 \end{bmatrix}$$

u_1, u_2, u_3 = complex vector components whose real and imaginary parts are independent realizations of the turbulent velocity field;

n_1, n_2, n_3 = complex Gaussian random values that are independent for each different wave number and have real and imaginary parts with unit variance;

x, y, z = coordinates of the spatial grid points;

N_1, N_2, N_3 = the number of spatial grid points in the three directions;

Δ = the spatial grid resolution.

In this expression, the notation $\sum_{k_1, k_2, k_3}$ means the summation over all dimensionless wave numbers in the grid and may be accomplished using FFT techniques. In cases when the spatial domain is smaller than 8ℓ in any dimension, an adjustment is recommended for the spectral tensor factorization, $[C(k_1, k_2, k_3)]$. This procedure is detailed in Mann [4].

The Mann model parameters derived herein to represent the Mann sheared turbulence model are based on conforming to the external conditions defined in Clause 6 and whereby the resulting wind spectra are equivalent to the Kaimal spectra.

For site-specific analysis, the shear distortion (anisotropy) parameter γ , dissipation factor, $\alpha \epsilon^{2/3}$ and the length scale, l , may be determined based on high frequency site-specific measurements of the wind spectra $F_u(kl)$, $F_v(kl)$, $F_w(kl)$ and $F_{uw}(kl)$ at one fixed point. The Mann model turbulent wind field needs to be then generated based on the three model parameters derived from the measured spectra.

C.3 Kaimal [1]⁵¹ spectrum and exponential coherence model

The component power spectral densities are given in non-dimensional form by Equation (C.14):

⁵¹ Note that the turbulence component variance ratios in Table C.1 and the equation form for the upward velocity component differ somewhat from the original Kaimal spectral model. The longitudinal scale has been chosen to approximate the original Kaimal spectrum and, for the lateral and upward scales, to satisfy the spectral requirements in 6.3 for the asymptotic inertial subrange and the variance ratios given in Table C.1.

$$\frac{f S_k(f)}{\sigma_k^2} = \frac{4 f L_k / V_{\text{hub}}}{(1 + 6 f L_k / V_{\text{hub}})^{5/3}} \quad (\text{C.14})$$

where

f is the frequency, in hertz;

k is the index referring to the velocity component direction (i.e. 1 = longitudinal, 2 = lateral, and 3 = upward);

S_k is the single-sided velocity component spectrum;

σ_k is the velocity component standard deviation;

L_k is the velocity component integral scale parameter;

and with

$$\sigma_k^2 = \int_0^{\infty} S_k(f) df \quad (\text{C.15})$$

The turbulence spectral parameters are given in Table C.1.

Table C.1 – Turbulence spectral parameters for the Kaimal model

	Velocity component index, k		
	1	2	3
Standard deviation, σ_k	σ_1	$0,8 \sigma_1$	$0,5 \sigma_1$
Integral scale, L_k	$8,1 A_1$	$2,7 A_1$	$0,66 A_1$
σ_1 and A_1 are the standard deviation and scale parameters, respectively, of the turbulence as specified in 6.3.			

The following exponential coherence model may be used in conjunction with the Kaimal autospectrum to account for the spatial correlation structure of the longitudinal velocity component:

$$\text{Coh}(r, f) = \exp \left[-12 \left((f r / V_{\text{hub}})^2 + (0,12 r / L_c)^2 \right)^{0,5} \right] \quad (\text{C.16})$$

where

$\text{Coh}(r, f)$ is the coherence function defined by the complex magnitude of the cross-spectral density of the longitudinal wind velocity components at two spatially separated points divided by the autospectrum function;

r is the magnitude of the projection of the separation vector between the two points on to a plane normal to the average wind direction;

f is the frequency, in hertz;

$L_c = 8,1 A_1$ is the coherence scale parameter.

C.4 Reference documents

- [1] J.C. Kaimal, J.C. Wyngaard, Y. Izumi, and O.R. Cote, Spectral characteristics of surface-layer turbulence, *Q.J.R. Meteorol. Soc.*, v. 98, 1972, p. 563-598
- [2] T. von Karman, Progress in the statistical theory of turbulence, *Proc. Nat. Acad. Sci.*, v. 34, 1948, p. 530-539
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- [4] J. Mann, Wind field simulation, *Prob. Engng. Mech.*, v. 13, no. 4, 1998, p. 269-282

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Annex D (informative)

Assessment of earthquake loading

~~A simplified, conservative method for the calculation of seismic load is presented here for use when the need for a complex analysis cannot be readily established.~~

~~The principal simplifications are the ignoring of vibration modes higher than the first tower bending mode, and the assumption that the whole structure is subject to the same acceleration. Ignoring the second mode is a significant non-conservative simplification and is compensated for here by incorporating tower mass with the tower head mass and applying a conservative aerodynamic load.~~

~~The method for deriving the ground acceleration must still be consistent with 11.6. In the absence of detailed site data, conservative assumptions shall be made. ISO 3010 has been used as the basis of the terminology here.~~

~~The procedure includes the following steps:~~

- ~~• Evaluate or estimate the site and soil conditions required by the relevant local standard.~~
- ~~• Use the normalised design response spectrum and the seismic hazard zoning factor to establish the acceleration at the first tower bending eigen-frequency assuming a damping of 1 % of critical damping.~~
- ~~• Calculate the load for a system subject to the above acceleration in which the total rotor, nacelle and 50 % of the tower mass is concentrated at the tower head.~~
- ~~• Add the result to the characteristic loads calculated for an emergency stop at rated wind speed.~~
- ~~• Compare the result against the design loads or the design resistance for the wind turbine.~~

~~If the tower can sustain the resulting combined loading, no further investigation is needed. Otherwise, a thorough investigation shall be carried out according to 11.6.~~

D.1 General

There are two approaches to evaluate the seismic loading on wind turbine. One approach is the dynamic simulation in time domain and the other approach is the response spectrum method (RSM). In time domain approach, the ground acceleration at the surface is estimated from the response spectrum at the engineering bedrock, or the time history of the ground motion specified in the local building codes. The site-specific parameters of the response spectrum may be based on local building codes [1-7]. Special care is required when response spectrum method is used for wind turbine support structures due to its low damping ratio [8]. In Annex D, the design response spectrum is first presented in Clause D.2 followed by the description of the structure model in Clause D.3, seismic load evaluation methods in Clause D.4 and additional load in Clause D.5. An example of time domain simulation is described in [9-10].

D.2 Design response spectrum

The acceleration response spectrum shall be selected at the engineering bedrock for a 475-year return period. In general, the response spectrum is given by local codes.

The acceleration response spectrum may be defined according to Equation (D.1):

$$S_{a0}(T) = \begin{cases} a_0 \left[1 + (\beta_0 - 1) \frac{T}{T_B} \right] & (0 \leq T < T_B) \\ a_0 \beta_0 & (T_B \leq T < T_C) \\ a_0 \beta_0 \left(\frac{T_C}{T} \right)^{K_1} & (T_C \leq T < T_D) \\ a_0 \beta_0 \left(\frac{T_C}{T_D} \right)^{K_1} \left(\frac{T_D}{T} \right)^{K_2} & (T_D \leq T) \end{cases} \quad (D.1)$$

where a_0 is the peak ground acceleration at the engineering bedrock for a 475-year return period; β_0 is the acceleration response magnification ratio for the region where acceleration response becomes constant and may be taken as 2 to 3; T is the fundamental natural period of the structure; T_B , T_C , K_1 and K_2 are dependent on tectonic, geological and soil condition. T_B may be taken as 1/5 to 1/2 of T_C . T_C can be taken as 0,3 s to 0,5 s for stiff and hard soil conditions, 0,5 s to 0,8 s for intermediate soil conditions and 0,8 s to 1,2 s for loose and soft soil conditions. K_1 and K_2 are the exponents that can vary between 1/3 and 2. These parameters can be determined by local design codes as shown in references [2], [3], [4].

The design response spectrum can be written as in Equation (D.2) [2].

$$S_a(T, \zeta) = \begin{cases} a_0 G_s \left[1 + (F_\zeta \beta_0 - 1) \frac{T}{T_B} \right] & (0 \leq T < T_B) \\ a_0 G_s F_\zeta \beta_0 & (T_B \leq T < T_C) \\ a_0 G_s F_\zeta \beta_0 \left(\frac{T_C}{T} \right)^{K_1} & (T_C \leq T < T_D) \\ a_0 G_s F_\zeta \beta_0 \left(\frac{T_C}{T_D} \right)^{K_1} \left(\frac{T_D}{T} \right)^{K_2} & (T_D \leq T) \end{cases} \quad (D.2)$$

where G_s is the soil amplification factor and F_ζ is the damping correction factor of the structure. These parameters are described in Clause D.2.

Soil amplification factor G_s explains the difference of seismic wave amplification during its propagation through the soil where a structure is built. Local design codes usually define typical soil types and their amplification factor. Those valued in local design code may be used for the seismic load evaluation of the wind turbine.

The following damping correction factor may be used for the seismic response analysis of wind turbine [8]:

$$\begin{cases} F_\zeta(\zeta, T, \gamma) = \left(\frac{7}{2 + 100\zeta} \right)^{(-0,07T + 0,7r + 0,5)} & (\zeta \leq 5\%) \\ F_\zeta(\zeta, T, \gamma) = \left(\frac{2}{-3 + 100\zeta} \right)^{\left(0,15 \log_{10} \frac{T}{15\gamma} + 0,3 \right)} & (\zeta > 5\%) \end{cases} \quad (D.3)$$

where γ is a value to consider uncertainty in seismic loading, and a value between 0,5 and 0,85 can be used considering local requirement.

D.3 Structure model

For the estimation of seismic load on wind turbine, simplified N degree of freedom model (Figure D.1) can be used in which the mass and the inertia moment of rotor, gear box and generator are lumped at the top of tower (node N), and tower mass is distributed along the tower. The bottom of the tower can be fixed to the ground for the load estimation of tower. More complicated model may be needed for the load estimation of the foundation, which is out of scope of Annex D.

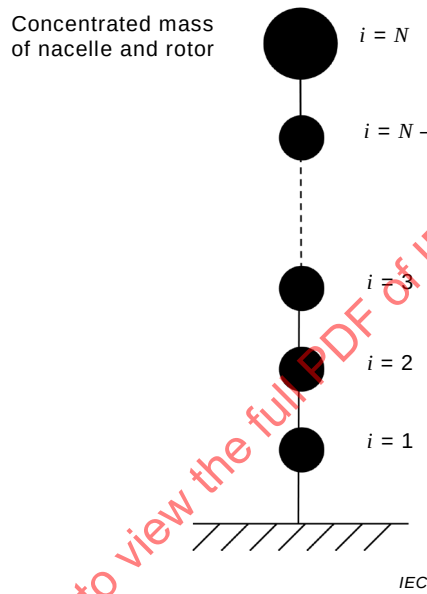


Figure D.1 – Structure model for response spectrum method

D.4 Seismic load evaluation

Using the response spectrum, maximum acceleration (A_{ij}), force (F_{ij}) and displacement (D_{ij}) corresponding to j^{th} mode at i^{th} node can be calculated as follows.

$$A_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta_j) \quad (\text{D.4})$$

$$F_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta_j) m_i \quad (\text{D.5})$$

$$D_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta_j) \left(\frac{T_j}{2\pi} \right)^2 \quad (\text{D.6})$$

where X_{ij} is the j^{th} mode shape obtained from eigenvalue analysis, $S_a(T_j, \zeta_j)$ is the amplitude of response spectrum for natural period T_j and damping ratio ζ_j of j^{th} mode, and γ_j is the modal participation factor for j^{th} mode.

$$\gamma_j = \frac{\sum_{i=1}^N X_{ij}}{\sum_{i=1}^N X_{ij}^2} \quad (\text{D.7})$$

where N is the number of nodes in the model.

The total acceleration (A_i^{total}), displacement (D_i^{total}), shear force (Q_i^{total}) and bending moment (M_i^{total}) considering all the relevant modes at i^{th} node can be calculated by using complete quadratic combination (CQC) method [Equations (D.8) to (D.11)].

$$A_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} A_{ij} A_{il}} \quad (\text{D.8})$$

$$D_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} D_{ij} D_{il}} \quad (\text{D.9})$$

$$Q_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} \left(\sum_{k=i}^N F_{kj} \right) \left(\sum_{k=i}^N F_{kl} \right)} \quad (\text{D.10})$$

$$M_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} \left[\sum_{k=i}^N F_{kj} (z_N - z_k) \right] \left[\sum_{k=i}^N F_{kl} (z_N - z_k) \right]} \quad (\text{D.11})$$

where

$$\rho_{jl} = \frac{8\sqrt{\zeta_j \zeta_l} (\zeta_j + X_{jl} \zeta_l) X_{jl}^{3/2}}{(1 - X_{jl}^2)^2 + 4\zeta_j \zeta_l X_{jl} (1 + X_{jl}^2) + 4(\zeta_j^2 + \zeta_l^2) X_{jl}^2} \quad (\text{D.12})$$

where ζ_j and ζ_l are the damping ratios for j^{th} and l^{th} modes, respectively, and X is the ratio of the j^{th} mode natural frequency to the l^{th} mode natural frequency.

D.5 Additional load

The torsional moment of the tower (M^t) can be calculated by using Equation (D.13) [8].

Additional bending moment caused by geometrical non-linearity, such as $p - \Delta$ effect, can be calculated by using maximum displacement, see [8].

$$M^t = 1,1M_n A_n L_e \quad (\text{D.13})$$

where M_n is the mass of the nacelle and rotor, A_n is the maximum acceleration at the nacelle and L_e is the distance between rotor centre and centre of gravity of the nacelle and rotor.

D.6 Reference documents

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Annex E (informative)

Wake and wind farm turbulence

E.1 ~~Wake effects~~ Added wake turbulence method

Wake effects from neighbouring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity I_{eff} , [1]. The effective turbulence intensity – conditioned on hub height mean wind speed V_{hub} – may be defined as

$$I_{\text{eff}}(V_{\text{hub}}) = \left\{ \int_0^{2\pi} p(\theta|V_{\text{hub}}) I^m(\theta|V_{\text{hub}}) d\theta \right\}^{\frac{1}{m}} \quad (\text{E.1})$$

where

p is the probability density function of wind direction;

I is the turbulence intensity of the combined ~~of~~ ambient and wake flows from wind direction θ , and

m is the Wöhler ~~(SN-curve) exponent for the considered material~~ curve exponent corresponding to the material of the considered structural component.

The approach is applicable for regular as well as irregular wind farm layouts.

In the following, a uniform distribution $p(\theta|V_{\text{hub}})$ and a regular rectangular wind farm layout are assumed. It is ~~also~~ acceptable to adjust the formulas for ~~other layouts~~ and other than uniform distribution.⁵² No reduction in mean wind speed inside the wind farm shall be assumed.

If $\min\{d_i\} \geq 10D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_c}{V_{\text{hub}}} \quad (\text{E.2})$$

If $\min\{d_i\} < 10D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_{\text{eff}}}{V_{\text{hub}}} = \frac{1}{V_{\text{hub}}} \left[(1 - N p_w) \hat{\sigma}_c^m + p_w \sum_{i=1}^N \hat{\sigma}_T^m(d_i) \right]^{\frac{1}{m}}; p_w = 0,06 \quad (\text{E.3})$$

where

D is turbine diameter;

$\hat{\sigma}_c = \hat{\sigma} + 1,28\hat{\sigma}_\sigma$ is the ~~representative ambient-estimated~~ turbulence standard deviation;

⁵² In the case of non-uniform distribution or non-grid wind farm layout, the formula should be modified accordingly, maintaining the concept implied in the more general Formula (E.1). It should be taken into consideration for each neighbour affecting wind turbine, the sector disturbed and their associated probability of occurrence conditioned on hub height mean wind speed.

$\hat{\sigma}$	is the ~~maximum centre-wake, hub-height~~ estimated ambient turbulence standard deviation;
$\hat{\sigma}_{\sigma}$	is the estimated standard deviation of the ambient turbulence standard deviation;
$\hat{\sigma}_T = \sqrt{\frac{V_{hub}^2}{\left(1,5 + \frac{0,8d_i}{\sqrt{C_T}}\right)^2} + \hat{\sigma}_c^2}$	is the representative value of the maximum centre-wake, hub height turbulence standard deviation ($\hat{\sigma}_c$ shall not account for farm generated ambient turbulence);
C_T	is the characteristic value of the wind turbine thrust coefficient for the corresponding hub height wind velocity. If the thrust coefficient for the neighbouring wind turbines are not known, a generic value $C_T = 7 c / V_{hub}$, can be used;
d_i	is the distance, normalized by rotor diameter, to neighbouring wind turbine no. i ;
c	is a constant equal to 1 m/s;
I_{eff}	is the effective turbulence intensity;
N	is the number of neighbouring wind turbines, see Table E.1.
~~m~~	~~is the Wöhler curve exponent corresponding to the material of the considered structural component.~~

Wake effects from wind turbines "hidden" behind other machines need not be considered, for example in a row only wakes from the two units closest to the machine in question are to be taken into account. Dependent on wind farm configuration, the number of nearest wind turbines to be included in the calculation of I_{eff} is as given in Table E.1.

Table E.1 – Number (N) of neighbouring wind turbines

Wind farm configuration	N
2 wind turbines	1
1 row	2
2 rows	5
Inside a wind farm with more than 2 rows	8

The wind farm configuration is illustrated in Figure E.1 for the case "Inside a wind farm with more than 2 rows" and a regular layout.

Inside large wind farms, wind turbines tend to generate their own "wind farm ambient" turbulence. Thus, when

- the number of wind turbines from the considered unit to the "edge" of the wind farm is more than 5, or
- the spacing in the rows perpendicular to the predominant wind direction is less than $3D$,

then the following representative wind farm ambient turbulence shall be assumed instead of $\hat{\sigma}_c$ except in the expression for $\hat{\sigma}_T$:

$$\hat{\sigma}'_c = \frac{1}{2} \left(\sqrt{\hat{\sigma}_w^2 + \hat{\sigma}^2} + \hat{\sigma} \right) + 1,28 \hat{\sigma}_{\sigma} \quad (E.4)$$

where

$$\hat{\sigma}_w = \frac{0,36V_{hub}}{1 + 0,2\sqrt{d_r d_f / C_T}} \quad (E.5)$$

C_T is the thrust coefficient, in which d_r and d_f are separations in rotor diameters in rows and separation between rows, respectively.

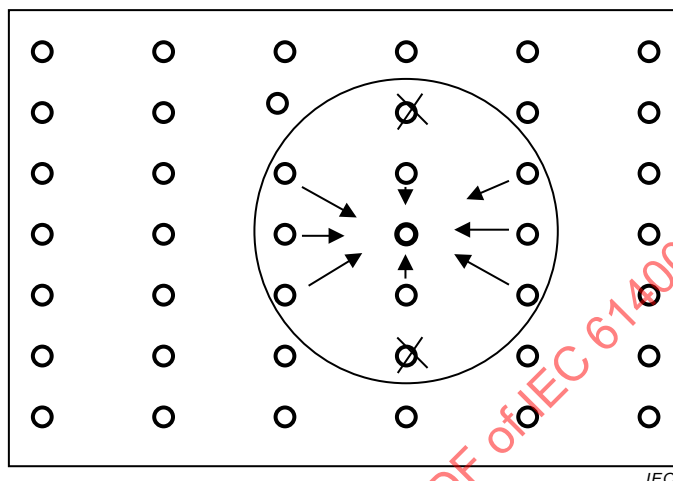


Figure E.1 – Configuration – Inside a wind farm with more than 2 rows

E.2 Dynamic wake meandering model

E.2.1 General

Wake effects from neighboring wind turbines may be taken into account for fatigue and ULS calculations by application of the Dynamic Wake Meandering (DWM) model [2], [3] and [4]. It describes the changes in the mean flow field over the wind farm as well as the changes in the turbulence intensity and turbulence structure compared to ambient conditions.

The DWM model is composed of three parts, see Figure E.2:

- 1) a model of the wake deficit formulated in the meandering frame of reference;
- 2) a stochastic model of the downstream wake meandering process;
- 3) a model of the self-induced wake turbulence described in the meandering frame of reference.

A summary description of recommended sub-models, their synthesis and their extension to the multiple wake case are given in the following.

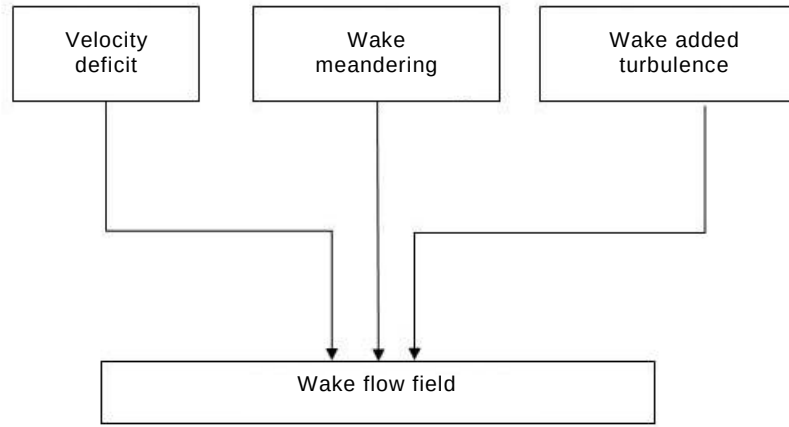


Figure E.2 – The three fundamental parts of the DWM model

E.2.2 Wake deficit

The mean wake deficit expands and attenuates with downstream distance from the wake generating rotor. The recommended modelling of the wake deficit is based on the thin shear layer approximation of the Navier-Stokes equations in their rotational symmetric form with the pressure term disregarded. Taking an eddy viscosity approach for the Reynolds stresses, the system of equations to be solved is:

$$\frac{1}{r} \frac{\partial}{\partial r} (rV(r,x)) + \frac{\partial U(r,x)}{\partial x} = 0 \quad (\text{E.6})$$

$$U \frac{\partial U(r,x)}{\partial x} + V(r,x) \frac{\partial U(r,x)}{\partial r} = \frac{\nu_T}{r} \frac{\partial}{\partial r} \left(r \frac{\partial U(r,x)}{\partial r} \right) \quad (\text{E.7})$$

where U and V denote the mean wake velocities in the axial and radial directions, respectively. The eddy viscosity, ν_T , includes contributions from both the ambient turbulence and the wake self-generated wake turbulence:

$$\frac{2\nu_T}{DV_{\text{hub}}} = 0,023 F_1(\tilde{x}) \left(\frac{\sigma}{V_{\text{hub}}} \right)^{0,3} + 0,016 F_2(\tilde{x}) \frac{R_w(\tilde{x})}{D} \left(1 - \frac{U_{\text{min}}(\tilde{x})}{V_{\text{hub}}} \right) \quad (\text{E.8})$$

where normalized spatial variables are introduced as

$$\tilde{r} = \frac{2r}{D} ; \tilde{x} = \frac{2x}{D} \quad (\text{E.9})$$

and F_1 and F_2 are filter functions depending on the axial coordinate, R_w is the wake radius, and U_{min} is the minimum wake velocity. The empirical filter functions, accounting for the near field pressure influence (i.e. F_2) and the lack of equilibrium between the mean shear flow field and the turbulence field in the near and intermediate wake regime (i.e. F_1), are given by

$$F_1(\tilde{x}) = \begin{cases} \left(\frac{\tilde{x}}{8}\right)^{3/2} - \frac{\sin\left(2\pi \tilde{x}^{3/2} / 8^{3/2}\right)}{2\pi} & ; 0 \leq \tilde{x} < 8 \\ 1 & ; \tilde{x} \geq 8 \end{cases} \quad (\text{E.10})$$

$$F_2(\tilde{x}) = \begin{cases} 0,0625 & ; 0 \leq \tilde{x} < 4 \\ 0,025 \tilde{x} - 0,0375 & ; 4 \leq \tilde{x} < 12 \\ 0,00105 (\tilde{x} - 12)^3 + 0,025 \tilde{x} - 0,0375 & ; 12 \leq \tilde{x} < 20 \\ 1 & ; 20 \leq \tilde{x} \end{cases} \quad (\text{E.11})$$

The pressure influence is implicitly taken into account by the introduction of F_2 and further by including the part of the wake expansion dictated by the pressure recovery in the boundary conditions associated with the system of differential Equations (E.6) and (E.7). Thus, the initial wake radius is approximated by

$$R_w(0) = D \left(1 - 0,45 a_m^2\right) \sqrt{\frac{1+m}{8}} \quad (\text{E.12})$$

where a_m denotes the mean induction over the rotor, and

$$m = \frac{1}{\sqrt{1-C_T}} \quad (\text{E.13})$$

with C_T being the rotor thrust coefficient. The initial wake deficit to be developed downstream using Equations (E.6) and (E.7) is thus obtained from a blade element momentum far-field induction prediction combined with the radial scaling given by Equation (E.12).

E.2.3 Meandering

The wake meandering part is based on the fundamental presumption that the transport of wakes in the atmospheric boundary layer can be modelled by considering the wakes to act as passive tracers driven by the large-scale turbulence structures. Modelling of the meandering process consequently includes considerations of a suitable description of the "carrier" stochastic transport media (i.e. the large scale turbulence field) as well as of a suitable definition of the cut-off frequency defining large-scale turbulence structures in this context.

The stochastic modelling of wake meandering is established by considering a cascade of wake deficit releases "emitted" at consecutive time instants in agreement with the passive tracer analogy. The propagation of each "emitted" wake deficit is subsequently modelled, and the collective description of these constitutes the wake meandering model in space and time.

Adopting Taylor's hypothesis, the downstream advection of each wake deficit "release" is dictated by a suitable advection velocity often taken as the ambient mean wind speed. As for the dynamics in the lateral and vertical directions, each considered wake cascade-element is successively displaced according to the large scale lateral and vertical turbulence velocities at the instantaneous wake deficit position. In mathematical terms, the wake deficit dynamics in the lateral direction, y , and in the vertical direction, z , are thus described by the following differential equation system:

$$\frac{dy}{dt} = v_c(y, z, t) \quad (\text{E.14})$$

$$\frac{dz}{dt} = w_c(y, z, t) \quad (\text{E.15})$$

where v_c and w_c are the spatially dependent large scale turbulent velocities at time t .

The recommended spatial averaging, defining the large scale part of the turbulence, may be expressed in terms of a cut off frequency using Taylor's frozen hypothesis:

$$f_c = \frac{U_u}{4R} \quad (\text{E.16})$$

Note that with this formulation the large scale part of the turbulence is assumed unaffected by the presence of the wind farm.

E.2.4 Wake induced turbulence

Wake induced turbulence includes contributions from conventional mechanically generated turbulence, caused by the wake shear, as well as from the blade shed and trailed vortices mainly in terms of tip and root vortices gradually breaking down downstream of the wake generating rotor. Thus, this turbulence contribution is considered independent of the ambient turbulence.

With a length scale comparable with the characteristic size of the wake deficit, the basic DWM split in scales implies that the wake induced turbulence meanders with the wake deficit. The induced small scale turbulence is consequently formulated in the meandering frame of reference. Although violating the second order statistics (i.e. the cross correlation), the in-homogeneity of the induced turbulence is approximated by simple scaling of a homogeneous and isotropic turbulence field with a length scale equal to one rotor diameter and a turbulence standard deviation equal to 1 m/s. Rotational symmetry of the induced wake turbulence intensity is assumed, resulting in a scaling coefficient that for a given downstream distance only depends on the radial coordinate. The empirical scaling factor, k_{wt} , depends on the deficit depth, $(V_{hub} - U_{min})$, at the considered downstream distance, as well as on the wake deficit radial gradient $\partial U / \partial r$:

$$k_{wt}(\tilde{x}, \tilde{r}) = 0,6 \left| 1 - \frac{U(\tilde{x}, \tilde{r})}{V_{hub}} \right| + \frac{0,35}{V_{hub}} \left| \frac{\partial U(\tilde{x}, \tilde{r})}{\partial \tilde{r}} \right| \quad (\text{E.17})$$

E.2.5 Wake superposition

Wake superposition is important when dealing with wind farm flow fields. This is a complicated process that calls for simplification. Wakes (including associated small scale wake induced turbulence) from the turbines in question are treated individually, and their correlated meandering is then subsequently modelled. Referring to ambient wind speed conditions, two different approaches are applied for the wind regimes corresponding to below and above rated power, respectively.

- **Below rated wind speed:** For a turbine with the rotor centre located at the spatial position, x , within the wind farm, the temporally varying flow field at the rotor polar coordinate (r, θ) is determined by the dominating wake among contributions from all upstream turbines at any time:

$$U_t(r, \theta, t | x) = \min_i (U_{t,i}(r, \theta, t | x)) \quad (\text{E.18})$$

where $(r, \theta, t | x)$ denotes a temporal coordinate combined with a spatial coordinate in a polar frame of reference centred at the spatial position x , and where each individual wake flow

field is given by $U_{t,i} = (U_i + u_i)e_1 + v_ie_2 + w_ie_3$, with e_j , $j = 1, 2, 3$, being unit normal vectors in the longitudinal, transversal and vertical flow directions. The parameter i includes all upstream turbines relative to the spatial position x for a given mean wind direction. Note that with the recipe formulated in Equation (E.18), the induced small scale turbulence, associated with the wakes contributing to U_t , is aggregated in a non-consistent manner. However, since the induced turbulence contributions are small scale this does not compromise the present application.

- *Above rated wind speed*: Using the nomenclature introduced above, Equation (E.18) is replaced by a summation of the deficit contributions of all upstream turbines:

$$U_t(r, \theta, t|x) = \sum_i U_{t,i}(r, \theta, t|x) \quad (\text{E.19})$$

E.2.6 Model synthesis

For each rotor in a wind farm, the inflow wind field is composed of the ambient, undisturbed wind field with relevant (see Equation (E.18)) wake deficits and wake induced small scale turbulence linearly superimposed. The undisturbed wind field is the site-specific mean wind speed consisting of a deterministic part (i.e. the mean wind shear) and the conventional turbulent part with ambient turbulence characteristics. The resulting inflow wake effects to be superimposed consist of stochastically moving wake deficits, $(V_{\text{hub}} - U)$, and associated wake induced turbulence contributions, respectively, and added according to the recipe formulated in Equation (E.18). Note that the wake deficit meandering is by far the dominating wake effect.

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Annex F (informative)

Prediction of wind distribution for wind turbine sites by measure-correlate-predict (MCP) methods

F.1 General

The assessment of the suitability of a wind turbine for a specific site requires the evaluation of the design-critical wind speed parameters at a site. Frequently, there is insufficient data even at a single point within a wind farm to carry out the evaluation. However, the extended data record can be synthesized by extrapolation based on a long-term record for another location. The MCP methods are a means to create that extended record. The following explanation is taken from [2]. Further information can be found in [3], [4] and [5].

F.2 Measure-correlate-predict (MCP)

The MCP method takes a number of forms in which the averaging period and directional nature of the data vary. One version is described here, based upon the concurrent hourly data from the wind turbine site and a nearby reference meteorological station (Met. Station). These data are cross-plotted and used to derive sector-wise linear regression equations; the sectors being consistent with those used by the Met. Station, typically 30° sectors. The data sets used for deriving the regression equations should be as long as possible, at least conservatively covering the conservative part of any seasonal variations.

F.3 Application to annual mean wind speed and distribution

The above regression equations are applied to the long-term Met. Station record sector by sector, for a period sufficiently long to eliminate short-term variations, probably at least seven years. The result is an hourly mean record for the site, which may be processed into a probability distribution for site assessment.

F.4 Application to extreme wind speed

The classical method for the prediction of the extreme wind speed is a Gumbel analysis modified to improve accuracy (e.g. Best Leiblein Unbiased Estimators (BLUE) method described in [1]). The minimum recommended length of data set is ten years.

It is also possible to apply the method of independent storms (MIS), a derivative of the Gumbel method, which utilizes more than one data point per year from a data set, also described by Cook [1]. This method can be used for data sets that are as short as ~~seven~~ four years. MIS selects individual storms' peak wind speeds by application of thresholds and time filters to ensure that all values are from independent events.

The sector-specific regression coefficients are applied to a table of the maximum hourly wind speed at the Met. Station, by year for basic Gumbel and by storm event for MIS, and by sector. A similar table is therefore built up for the wind turbine site. The maximum value in each year for the candidate site is extracted for use in a Gumbel analysis.

The use of the coefficients is appropriate here since they have been formed from hourly mean data and are being applied to hourly mean data. In this method, there is no assumption that the maximum value at the candidate site occurs in the same sector as the maximum at the reference site. By using the sector-specific regression coefficients, the maximum at the candidate site can be more accurately determined, taking account of the inter-site relationships.

The selection of the relevant ~~recurrence~~ return period in the extreme value analysis should account for the number of events per annum.

The gust factors should be estimated from the site-measured data, or by theoretical methods.

Users of these methods for estimation of extreme wind speed should note that the resulting accuracy depends significantly on data quality and actual local conditions compared to the reference station. As a result, correlations from a regression analysis may be poor. In cases where existing local codes are recognized as applicable by authorities having jurisdiction, the extreme values obtained using such codes should be considered as minimum values for design in preference to MCP.

F.5 Reference documents

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Annex G (informative)

Statistical extrapolation of loads for ultimate strength analysis

F.1 Statistical extrapolation of loads

Failure of a structure occurs when the stress at a critical location exceeds the resistance capacity of the material. Assuming that local stresses are related to the loading so that the stress progressively increases with increased loading, the strength of a structural component can be defined in terms of an ultimate load that causes failure. Given the service loading, one can assess the suitability of the structure by comparing the extreme values of the loading with the ultimate load resistance, applying suitable factors of safety.

For wind turbines, loading depends on the turbulent wind inflow for a variety of wind conditions. Thus, it is necessary to analyse the extreme values of the loading on a statistical basis in order to determine a suitable characteristic load.

$$\text{Prob}(F_{\text{ext}} \geq F \mid V, T) = 1 - \left(F_{\text{max}}(F \mid V) \right)^{E(n \mid V, T)} \quad (\text{F.1})$$

where $F_{\text{max}}(F \mid V)$ is the short-term probability distribution function of the local maxima for the load process, and $E(n \mid V, T)$ is the expected number of local maxima in the observation time period. As indicated, these statistical quantities are conditioned on the mean wind speed, V , and, where indicated, also depend on the observation time period, T .

Considering all the operating wind conditions, the long-term exceedance probability is then given by integrating overall operating wind speeds,

$$\text{Prob}(F_{\text{ext}} \geq F \mid T) \equiv P_e(F, T) = \int_{V_{\text{in}}}^{V_{\text{out}}} \text{Prob}(F_{\text{ext}} \geq F \mid V, T) p(V) dV, \quad (\text{F.2})$$

where $p(V)$ is the probability density function for the hub height wind speed and is prescribed for the standard wind turbine classes in 6.3.1.1. The acceptable probability of exceedance is the reciprocal of the number of time intervals of length T in the recurrence period T_r associated with the characteristic load. The resulting characteristic load, F_k , is then given by solving the equation

$$P_e(F_k, T) = \frac{T}{T_r} \quad (\text{F.3})$$

The function $\text{Prob}(F_{\text{ext}} \geq F \mid V, T)$ is determined from response simulations, from which extremes are taken in the following way:

- the extracted extremes must be selected so that they may be assumed to be independent;
- the number of extremes must be sufficient to determine the type of distribution (Gumbel, Weibull, or other) and provide reliable estimation of the behaviour of the tail;
- the wind speeds, where the highest loads due to turbulence are expected, must be included in the simulations.

The characteristic load may be estimated by the following procedure:

- a) from the simulation data for a given wind speed, V_j , extract independent extreme values of the load. One method of doing this is to select the largest value between successive upcrossings of the mean plus 1,4 times the standard deviation of the load process;
- b) fit a distribution to the selected extreme value data. Guidance for one method for fitting the distribution can be found in Moriarty, et al. (2002). The distribution type selected should be checked to see if the fit to the data is acceptable and whether there is sufficient data for reliable estimation of the behaviour of the tail compared to the data. A minimum of 300 min of time series data distributed over the range of significant wind conditions is recommended;
- c) estimate the expected number of maxima for a typical 10 min observation period, T , from the equation

$$n_j = n_s \frac{T}{T_s} \quad (\text{F.4})$$

- where T_s is the total time period of all the simulation data for the given wind speed, V_j , and n_s is the total number of maxima extracted from the same simulation data;

- d) compute the long term exceedance probability as a function of load level from the following equation (assuming the required Rayleigh wind speed distribution for the standard turbine classes given in 6.3.1.1):

$$P_e(F) = \sum_j \left(1 - (F_{\max}(F|V_j))^{n_j} \right) e^{-\pi \left(\frac{V_j - \Delta V_j/2}{2V_{\text{ave}}} \right)^2} - e^{-\pi \left(\frac{V_j + \Delta V_j/2}{2V_{\text{ave}}} \right)^2} \quad (\text{F.5})$$

where V_j is the wind speed bin centre and ΔV_j is the bin width;

- e) solve for the characteristic load either graphically or by using a numerical root finding technique:

$$P_e(F_k) = 3,8 \times 10^{-7} \quad (\text{F.6})$$

- for the 50 year recurrence period and the reference period of 10 min.

In using this procedure, care must be taken that an adequate number and resolution of wind speed bins is selected to approximate the integration in equation (F.2). Attention should be given to wind speeds around V_r and V_{out} . The accuracy of the discretization may be estimated by neglecting every other bin value and determining the resulting difference in the characteristic load.

Figure F.1 illustrates how the 1-year and 50-year extremes are determined from the computed long-term exceedance probability. The blade bending load has been normalized by the mean blade bending load at rated wind speed. Also shown on the plot is the largest computed blade bending load for all the simulations at the different mean wind speeds between cut-in and cut-out.

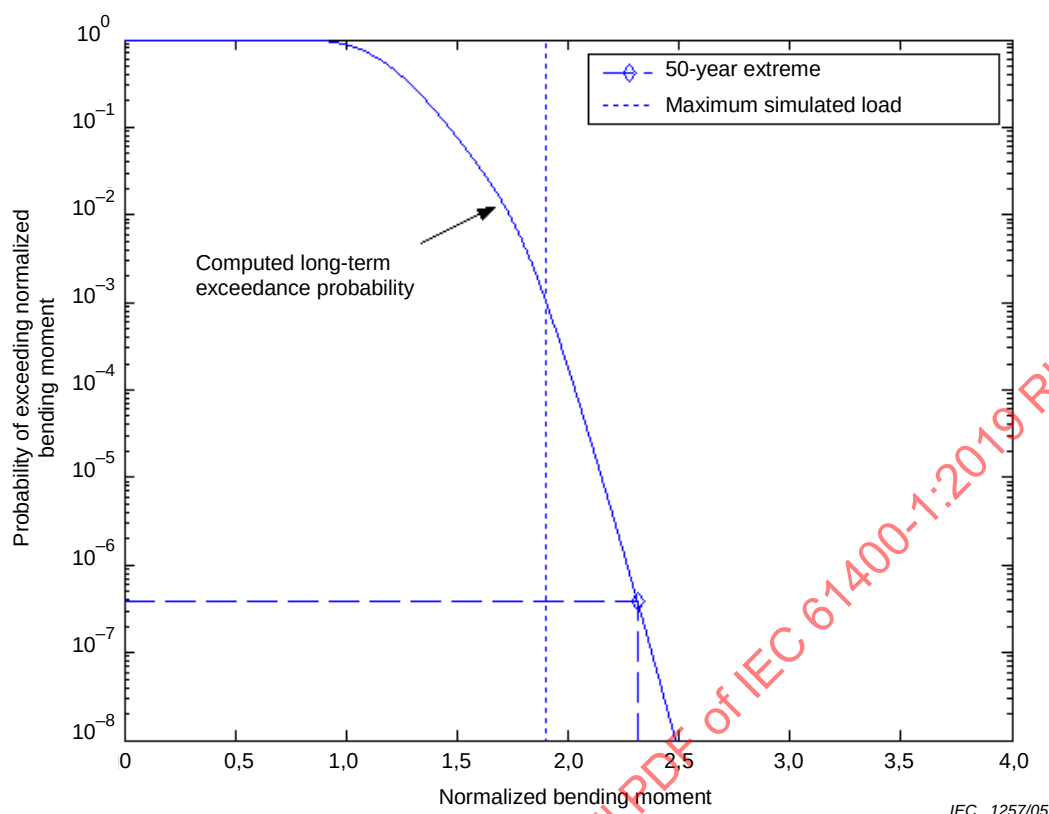


Figure F.1 — Exceedance probability for largest out-of-plane blade bending load in 10 min (normalized by mean bending load at rated wind speed)

F.2 — Reference documents

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G.1 General

Failure of a structure occurs when the stress at a critical location exceeds the resistance capacity of the component material. Assuming that local stresses are related to the loading so that the stress progressively increases with increased loading, the strength of a structural component can be defined in terms of an ultimate load that causes failure. Given the service loading, the adequacy of the structure can be assessed by comparing the extreme values of the loading with the ultimate load resistance, applying suitable factors of safety.

For wind turbines, loading depends on the turbulent wind inflow for a variety of wind conditions. Thus, it is necessary to analyse the extreme values of the loading on a statistical basis in order to determine a suitable characteristic load.

For a given wind condition, it is reasonable to model the short-term load response as a stationary random process. Given that loads can be represented as such processes, methods

are described in the following for the extraction of data for extrapolation and load extrapolation. Convergence criteria also are proposed and an alternative for estimating the long-term loads using the inverse first-order reliability method (IFORM) is given.

The methods have been tested for a 3-bladed horizontal-axis upwind turbine. Special attention may be necessary for other wind turbine concepts and/or control schemes including load feedback. More information and guidance can be found in [1].

G.2 Data extraction for extrapolation

Data used in extrapolation methods are extracted from time series of turbine simulation over the operating range of the turbine in specified wind conditions. Data may be extracted by choosing the global individual response extremes from each simulation or some subset created by breaking the simulation into blocks of equal time or ensuring a minimum time separation between extremes.

Establishing independence among the individual load response extremes is important for some methods of extrapolation. When extracting, the designer should consider the effect of independence between peaks on the extrapolation and minimize dependence when possible. If the method chosen for extrapolation is sensitive to independence assumption (e.g. the method involves transforming probability functions between time bases), the designer should attempt to statistically test for independence.

A simple approach to ensure independence is to assume that the global extreme in each ten-minute simulation or local extremes from intervals no shorter than three response cycles are independent and thus require a minimum time separation between individual response extremes of three response cycles (defined by three mean crossings over the block size). If a systematic statistical approach is desired, the designer may test for independence using standard estimation techniques (e.g. [5], [6]) and then minimize dependence in a controlled manner.

Peak over threshold methods may also be employed, but the designer should be careful that truncation errors and correlation introduced by the threshold do not influence the shape of the empirical distribution dramatically.

G.3 Load extrapolation methods

G.3.1 General

The 50-year return period load of a wind turbine may be defined as the extreme loading that has an annual probability of exceedance of $\frac{1}{50 \text{ years}} = 0,02$ per year.

The suggested approaches of extrapolation of extreme events for determination of the 50-year load can be divided into the following procedures.

1) Parametric fitting and aggregation afterwards

- Subdivide the operational range of the turbine into discrete wind speeds and perform time domain simulations at the normal turbulence (NTM) level.
- Estimate an extreme value (parametric) distribution [2] for every wind speed realization.
- Aggregate all distributions according to the long-term distribution function of the mean wind speed.
- Predict the 50-year value of the aggregated distribution function.

For global extreme from ten-minute simulations, the probability of the 50-year load is approximately $3,8 \times 10^{-7}$.

2) Data aggregation first and fitting afterwards

- Subdivide the operational range of the turbine into discrete wind speeds and performance of time domain simulations at normal turbulence (NTM) level.
- Aggregate all relevant extremes from all time series according to the long-term distribution function of the mean wind speed within the operational range of the turbine.
- Estimate one (aggregated) distribution function for all extremes.
- Predict the 50-year value from the resulting distribution function.

Two different cases are regarded for aggregation of simulated short-term distributions of extremes for a specific observation period T into an empirical distribution of the long-term extremes for the same period: extrapolation from global extremes, and from local extremes.

G.3.2 Global extremes

The short-term distribution of global extremes in the observation period, T , is denoted

$$F_{\text{short-term}}(s|V;T) \quad (\text{G.1})$$

where s stands for load response and V is the mean wind speed for the observation period. Using the long-term distribution of the mean wind speeds, the long-term distribution of extreme values is obtained:

$$F_{\text{long-term}}(s;T) = e^{\int_{V_{\text{in}}}^{V_{\text{out}}} \ln(F_{\text{short-term}}(s|V;T)) f(V) dV} \quad (\text{G.2})$$

This equation is derived assuming that the exceedances of the value s form a composite Poisson point process with independent increments. The extreme load response, s_r , of the desired return period, T_r , is obtained from Equation (G.3):

$$F_{\text{long-term}}(s;T) = \left(1 - \frac{1\text{yr}}{T_r}\right)^{\frac{T}{1\text{yr}}} \approx 1 - \frac{T}{T_r} \quad (\text{G.3})$$

for sufficiently small values of $\frac{T}{T_r}$.

The practical implementation of these formulas would typically be to use discrete wind speed values. Then one has

$$F_{\text{long-term}}(s;T) \approx \prod_{k=1}^M (F_{\text{short-term}}(s|V_k;T))^{p_k},$$

$$p_k = f(V_k) \Delta V_k, \quad V_{\text{in}} \leq V_1 < \dots < V_M \leq V_{\text{out}} \quad (\text{G.4})$$

For small short-term exceedance probabilities, this may be conservatively approximated as

$$\begin{aligned}
 F_{\text{long-term}}(s; T) &\approx 1 - \sum_{k=1}^M (1 - F_{\text{short-term}}(s|V_k; T)) p_k \\
 &= \sum_{k=1}^M F_{\text{short-term}}(s|V_k; T) p_k
 \end{aligned} \tag{G.5}$$

The latter equivalence results because the exceedance probability outside the operating range is assumed to be zero.

The distribution $F_{\text{short-term}}$ may be obtained by fitting to the empirical distribution

$$\hat{F}_{\text{short-term}}(s_{ki}|V_k) = \frac{r_i}{n_k + 1}, i = 1, \dots, n_k \tag{G.6}$$

where s_{ki} denotes the i th extreme value sample from wind speed k and r_i is s_{ki} 's rank among the n_k extremes arising from wind speed k . For the following developments, it is worth noting that an equivalent expression for the empirical distribution by use of a summation is

$$\hat{F}_{\text{short-term}}(s_{ki}|V_k) = \sum_{j=1}^{n_k} \frac{1}{n_k + 1} I(s_{kj} - s_{ki}), i = 1, \dots, n_k \tag{G.7}$$

where an indicator function $I(x)$ has the expression

$$I(x) = \begin{cases} 1 & \text{for } x \leq 0 \\ 0 & \text{for } x > 0 \end{cases} \tag{G.8}$$

The task of the indicator function is to pick out all values less than or equal to s_{ki} in order that they can contribute to the empirical probability of having values less than or equal to s_{ki} . Note that the specific definition of the indicator function ensures that the event that identical extreme values should be realized is accounted for.

G.3.3 Local extremes

Now the short-term distribution of global extremes in the observation period, T , is obtained from $n(V)$ independent local extreme values in the period (assuming the extremes are positive, otherwise a change of sign may be made):

$$F_{\text{short-term}}(s|V; T) = F_{\text{local}}(s|V; T)^{n(V)} \tag{G.9}$$

The long-term distribution, defined in Equation (G.9), and the extreme load response, s_r , of the desired return period, T_r , are established as described in G.3.2. Strictly, n should be a random number for which a distribution (dependent on V) should be assumed. However, n has for wind turbine applications limited variation compared to its mean value. Consequently, replacing n by its mean value (conditional on V), as implicitly done above, is sufficiently accurate. The approximation may be accepted if, when applying the formulas proposed in the following, one uses an s -value representative of the wind speeds that contribute most to the specific load response under consideration. Based on the approximation, one has the following expression:

$$F_{\text{long-term}}(s; T) = e^{\int_{V_{\text{in}}}^{V_{\text{out}}} n(V) \ln(F_{\text{local}}(s|V; T)) f(V) dV} \quad (\text{G.10})$$

G.3.4 Long-term empirical distributions

There are advantages to aggregating data from all wind speeds and then fitting a distribution to the combined data. One method for accomplishing this is to compute a number of simulations, where the number of simulations per bin is determined by the Weibull (or appropriate) distribution of wind speed.

$$N_{\text{sims}}(V_k) \approx N_{\text{total}} p_k, \quad p_k = f(V_k) \Delta V_k, \quad V_{\text{in}} \leq V_1 < \dots < V_M \leq V_{\text{out}} \quad (\text{G.11})$$

Once simulations are completed and maxima are extracted, all maxima from all wind speeds are combined into a single distribution and ranked such that

$$\hat{F}_{\text{long-term}}(s_i) = \frac{r_i}{n_k + 1}, \quad i = 1, \dots, n_{\text{total}} \quad (\text{G.12})$$

where s_i denotes the i th extreme value sample over all wind speeds and r_i is s_i 's rank among the n_{total} extremes arising from the combined distribution.

One potential disadvantage of this method is that loads that are dominated by high wind speeds may have very few simulations from which to extract large extreme values in the tail of the empirical distribution. To address this issue, additional long-term distributions can be calculated using additional simulations for the low probability wind speed bins. The total simulation time per bin should follow the original wind speed distribution. But, a number of new long-term empirical distributions can be formed using randomly bootstrapped data from all bins, in which a large number of simulations are available. Once a number of long-term distributions are formed, they can be averaged to form a single aggregate long-term distribution that can be used for extrapolation to lower probability levels.

G.4 Convergence criteria

G.4.1 General

In the context of turbine extreme loads, the importance of different wind speeds varies depending on the load that is being extrapolated. Some loads are dominated by wind speeds near rated while others are dominated near cut-out or other wind speeds. It is important that the designer examine the dominant wind speeds closely to ensure that a sufficient number of simulations are carried out to ensure stability of the method. A minimum of 15 simulations is necessary for each wind speed from $(V_r - 2 \text{ m/s})$ to cut-out and six simulations are necessary for each wind speed with V below $(V_r - 2 \text{ m/s})$.

In addition to a minimum number of simulations for the wind speeds $(V_r - 2 \text{ m/s})$ to cut-out, an additional convergence criterion shall also be applied according to 7.6.2. The recommended number of simulations is determined by calculating a confidence interval for the resulting empirical distribution. The number of simulations deemed sufficient is that for which the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile. This interval may be estimated using bootstrapping methods [3], the binomial estimation method [4], or it may be inherently estimated as a part of the extrapolation method employed.

If the extremes are obtained using any other method (e.g. block maxima) that results in m extremes per 10-minute simulation, on average, then the 84 % fractile above needs to be replaced by p^* where

$$p^* = (0,84)^{1/m} \quad (\text{G.13})$$

The convergence criterion⁵³ should be applied individually to each short-term load distribution whether the long-term distribution is to be established using aggregation of wind speed data before fitting or whether fitting parametric distributions to data from each wind speed is carried out before aggregation.

In the procedure that involves aggregation before fitting, empirical long-term distributions for the loads following aggregation of all wind speed bins can be established by making use of similar convergence criteria as proposed above for short-term distributions. The appropriate fractile at which to impose the convergence criterion should be higher than the fractile corresponding to any apparent "knee" (often observed) in the empirical long-term distribution to ensure that convergence is checked closer to the tail of this empirical distribution.

G.4.2 Load fractile estimate

The desired load fractile, $\hat{L}_p$, corresponding to a non-exceedance probability, P , is estimated as follows.

Rank order all the loads data such that $S_1 \leq S_2 \leq \dots \leq S_m$ if we have m such values from simulations. Note that m will be equal to the number of simulations if global maxima are used.

For any specified p , make sure it is possible to find some integer i (where $2 \leq i \leq m$), such that

$$\frac{i-1}{m+1} \leq p \leq \frac{i}{m+1} \quad (\text{G.14})$$

A sufficient number of extremes, m , should be available (for which a sufficient number of simulations will have to be run) so that the above inequality results and a value of i found.

The load fractile estimate is then computed by (linear) interpolation as follows:

$$\hat{S}_p = S_{i-1} + [p(m+1) - (i-1)](S_i - S_{i-1}); \text{ where } 2 \leq i \leq m \quad (\text{G.15})$$

G.4.3 Confidence bounds

Confidence bounds are estimated such that the 90 % confidence interval on the 84 % fractile, $\hat{S}_{0,84}$, is as follows:

$$\frac{\hat{S}_{0,84;0,05} - \hat{S}_{0,84;0,95}}{\hat{S}_{0,84}} < 0,15 \quad (\text{G.16})$$

The interval, $\langle \hat{S}_{0,84;0,05}, \hat{S}_{0,84;0,95} \rangle$, represents the desired 90 % confidence interval.

⁵³ The criterion should only be evaluated where the 84 % fractile is much larger than 0. For example, blade flap moments away from tower for outboard sections might be problematic at certain wind speeds; i.e. criterion should be handled with a certain engineering judgement.

G.4.4 Confidence intervals based on bootstrapping

Using the bootstrap procedure to form confidence intervals [3, 7] begins with taking the initial set of data on p global maxima ($m_1, m_2, m_3, m_4, m_5 \dots m_p$) and randomly resampling these data with replacement to form a new set ($m_1^*, m_2^*, m_3^*, m_4^*, m_5^* \dots m_p^*$) or a bootstrap resampling of the same size as the original sample. Note that bootstrap resamplings will be composed of repeated values from the original sample since, for each resampling, data are sampled randomly with replacement. The process is repeated so as to form a large number, N_b , of bootstrap resamplings. From each of these sets of p data, individual estimates of the 84 % fractile can be obtained. From these N_b estimates, constituting the set, ($l_1, l_2, l_3, l_4, l_5, \dots, l_{N_b}$), confidence intervals can be found in the usual manner by ordering the data. These can then be used for the numerator of Equation (G.16). The estimate of the 84 % fractile that is obtained from the original data represents the denominator of Equation (G.16).

A minimum number of 25 bootstrap resamplings may be sufficient to determine a reasonable estimate of confidence bounds. However, a larger number closer to 5 000 will lead to more reliable estimates.

G.4.5 Confidence intervals based on the binomial distribution

Confidence intervals based on the binomial distribution [7] are computationally less intensive than those computed using the bootstrap procedure. This saving is simplified by tabulating parameters for calculating a binomial confidence interval that will result for most common situations. For the load fractile equal to 0,84 and 90 % confidence interval, Table G.1 provides values of k^* and l^* as well as two other values, A and B , needed for interpolating the estimate confidence bounds in Equation (G.17), below. The number of simulations is of the order of 15 to 35 for each wind speed bin.

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Table G.1 – Parameters needed to establish binomial-based confidence intervals

For 90 % confidence interval on the 84th percentile load	No. of sims.	k^*	l^*	A	B
	15	9	14	0,50	0,32
	16	10	15	0,27	0,19
	17	11	16	0,10	0,03
	18	11	16	0,87	0,96
	19	12	17	0,58	0,90
	20	13	18	0,35	0,83
	21	14	19	0,16	0,76
	22	14	20	1,00	0,69
	23	15	21	0,69	0,60
	24	16	22	0,45	0,50
	25	17	23	0,25	0,39
	26	18	24	0,08	0,26
	27	18	25	0,85	0,12
	28	19	25	0,58	0,98
	29	20	26	0,36	0,91
	30	21	27	0,18	0,83
	31	22	28	0,02	0,75
	32	22	29	0,75	0,66
	33	23	30	0,51	0,56
	34	24	31	0,31	0,44
	35	25	32	0,13	0,32

The parameters in Table G.1 are used with a design equation that is tailored to give the 90 % confidence interval for the 84th percentile ten-minute maximum. The design equation can be written as follows:

$$(x_l - x_k) = (x_{l^*} - x_{k^*}) + B \left(x_{(l+1)^*} - x_{l^*} \right) - A \left(x_{(k+1)^*} - x_{k^*} \right) \quad (\text{G.17})$$

where l^* , k^* , A , and B are as given in Table G.1 as a function of the number of simulations run and x_{l^*} , $x_{(l+1)^*}$, x_{k^*} , and $x_{(k+1)^*}$ are obtained from the rank-ordered simulated extremes. This estimate can then be inserted into Equation (G.16) to determine if the convergence criteria are met, where

$$\hat{S}_{0,84;0,05} - \hat{S}_{0,84;0,95} \approx x_l - x_k \quad (\text{G.18})$$

G.5 Inverse first-order reliability method (IFORM)

An alternative to typical loads extrapolation methods is the use of IFORM to estimate long-term loads. In this method, turbulence and wind turbine response simulations are carried out for NTM conditions. A minimum of 15 simulations should be carried out for wind speeds ($V_r - 2$ m/s) to cut-out. The wind speed(s) that yields the highest load is (are) then identified.

Extrapolation of the short-term load distributions to a probability level consistent with the definition of a 50-year return period yields the 50-year load for use with DLC 1.1.

The convergence criteria for IFORM should be the same as for the other extrapolation methods, except that the designer need only estimate confidence intervals for the load distributions from identified important wind speeds (often only one).

The theory for the use of the inverse FORM (IFORM) technique (which relies on transformation of physical random variables to standard normal random variables [8]) is well-documented, see for example [9], and can be applied to estimate long-term wind turbine loading under NTM conditions.

In order to implement IFORM for wind turbine extreme loads, use the following steps.

- a) Carry out 15 simulations for the wind speed bins ($V_r - 2$ m/s) to cut-out.
- b) Identify which bins yield the largest load maxima.
- c) Refine the search by performing another 15 simulations for the bins identified in step b). Again, identify the design dominating wind speed(s), v^* , which produce the largest loads. Ensure that the number of simulations at the important wind speed(s) is sufficient such that the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile.
- d) Perform short-term analysis only for the bin(s) identified in step c). The desired fractile of the load distribution for this bin is derived and depends on the target probability level.
 - Using Rayleigh CDF, compute $U_1 = \Phi^{-1}[P_R(v^*)]$.
 - For probability of exceedance in 10 min once in 50 years, $p_T = 3,8 \times 10^{-7}$. This corresponds to $\beta = 4,95$.
 - Solve $U_2 = [\beta^2 - U_1^2]^{1/2}$.
 - Derive the load fractile $P_S = \Phi(U_2)$, see Table G.2.
 - The long term load is the P_S fractile of the short-term distribution for the wind speed bin, v^* . To reach the appropriate fractile, extrapolation may be required.

Table G.2 – Short-term load exceedance probabilities as a function of hub-height wind speed for different wind turbine classes for use with the IFORM procedure

v^* [m/s]	$1-P_{S, \text{class I}}$	$1-P_{S, \text{class II}}$	$1-P_{S, \text{class III}}$
5	5,91E-07	4,95E-07	4,42E-07
6	4,86E-07	4,24E-07	3,94E-07
7	4,26E-07	3,90E-07	3,80E-07
8	3,94E-07	3,80E-07	3,91E-07
9	3,81E-07	3,90E-07	4,24E-07
10	3,83E-07	4,17E-07	4,84E-07
11	3,97E-07	4,64E-07	5,78E-07
12	4,24E-07	5,35E-07	7,20E-07
13	4,66E-07	6,38E-07	9,33E-07
14	5,26E-07	7,85E-07	1,26E-06
15	6,08E-07	9,97E-07	1,75E-06
16	7,20E-07	1,30E-06	2,54E-06
17	8,71E-07	1,75E-06	3,82E-06
18	1,08E-06	2,43E-06	5,93E-06
19	1,36E-06	3,46E-06	9,54E-06
20	1,75E-06	5,06E-06	1,59E-05
21	2,31E-06	7,60E-06	2,74E-05
22	3,10E-06	1,17E-05	4,89E-05
23	4,25E-06	1,86E-05	9,02E-05
24	5,93E-06	3,03E-05	1,73E-04
25	8,45E-06	5,06E-05	3,42E-04

G.6 Reference documents

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Annex H (informative)

Fatigue analysis using Miner's rule with load extrapolation

H.1 Fatigue analysis

Fatigue failure results from an accumulation of damage due to fluctuating loads. For this kind of macroscopic view of fatigue, there is general agreement that an increment of damage results from each hysteresis cycle displayed in the local stress-strain diagram. Thus, each local maximum of the load time history is paired with the local minimum that completes a full cycle (rain-flow cycle counting, see [1] or [2]). Each of these cycles is characterized by the paired extreme values (or equivalently by the range and midpoint values, i.e. the difference between and the mean of the two paired cycle extremes). If the damage accumulates linearly and independently for each cycle [5, 3] then the total damage, D , will be given by⁵⁴

$$D = \sum_i \frac{1}{N(S_i)} \quad (\text{H.1})$$

where S_i is the load range for the i th cycle, and $N(\)$ is the number of cycles to failure for a constant amplitude loading with the range given by the argument (i.e. the S-N curve). In this expression, it has been further assumed that the local stress at the failure location is linearly related to the loading. Typically, for fatigue analysis, the S-N curve selected for design is associated with a given survival probability (often 95 %) and level of confidence (often 95 %) in determining the curve from materials data. Thus, the desired minimum level of reliability may be expected when the damage sums to unity.

For the life of a wind turbine, there will be many cycles of varying sizes resulting from a broad range of wind conditions. Therefore, for design purposes, a load spectrum ~~must~~ should be estimated. The largest cycles for this spectrum will be estimated from a smooth fit to the data obtained from simulations or testing of a duration that is significantly shorter than the turbine lifetime. For each wind condition, it may be assumed that the load is modelled by a stationary random process. Thus, the expected damage for a given wind speed, V , and a specific time period, T , will be given by

$$E\langle D|V, T \rangle = \int_0^{\infty} \frac{n_{ST}(S|V, T)}{N(S)} dS \quad (\text{H.2})$$

where $n_{ST}(S|V, T)$ is the short term load spectrum defined as a density function for the number of cycles. In this case, the expected number of cycles in any load range interval

(S_A, S_B) during the time period T is given by $\int_{S_A}^{S_B} n_{ST}(S|V, T) dS$. The expected damage from

normal operating loads for the whole turbine life is then given by extending the time interval to the full lifetime and integrating over the range of operating wind speeds, so that

⁵⁴ For ease of presentation, the effect of variation in the midpoint load level for each cycle is neglected. This restriction is eliminated later when the issue of varying midpoint levels is addressed through the use of an equivalent cyclic range.

$$E\langle D \rangle = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} E\langle D|V, T \rangle p(V) dV = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} \int_0^{\infty} \frac{n_{\text{ST}}(S|V, T)}{N(S)} p(V) dS dV \quad (\text{H.3})$$

where $p(V)$ is the probability density function for the hub-height wind speed prescribed for the standard wind turbine classes in 6.3.2.1.

Now, defining the long-term load spectrum

$$n_{\text{LT}}(S) = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} n_{\text{ST}}(S|V, T) p(V) dV \quad (\text{H.4})$$

then gives

$$E\langle D \rangle = \int_0^{\infty} \frac{n_{\text{LT}}(S)}{N(S)} dS \quad (\text{H.5})$$

In many cases, it is convenient, for practical purposes, to divide the ranges of load and wind speed values into discrete bins. In this case, the expected damage can be approximated by

$$E\langle D \rangle \approx \sum_{j,k} \frac{n_{jk}}{N(S_k)} \quad (\text{H.6})$$

where n_{jk} is the expected number of lifetime load cycles in the j^{th} wind speed and the k^{th} load bins, and S_k is the centre value for the k^{th} load bin. Thus, from the above definition,

$$n_{jk} = \frac{\text{Lifetime}}{T} \int_{V_j - \Delta V_j/2}^{V_j + \Delta V_j/2} \int_{S_k - \Delta S_k/2}^{S_k + \Delta S_k/2} n_{\text{ST}}(S|V, T) p(V) dS dV \quad (\text{H.7})$$

where ΔV_j is the width of the j^{th} wind speed bin and ΔS_k is the width of the k^{th} load bin.

Utilizing these results, and considering the requirement from 7.6.3 that the safety factors be applied to the load, the limit state relation for fatigue analysis becomes

$$\int_0^{\infty} \frac{n_{\text{LT}}(S)}{N(\gamma S)} dS \leq 1 \quad (\text{H.8})$$

where $\gamma = \gamma_f \gamma_m \gamma_n$ is the product of all three general partial safety factors for load, materials, and consequences of failure, respectively. In discrete terms, this equation results in

$$\sum_{j,k} \frac{n_{jk}}{N(\gamma S_k)} \leq 1 \quad (\text{H.9})$$

In cases where significant damage occurs in more than one load case from Table 2, the damage fractions for all the load cases, computed using the left side of Equation (H.9), ~~must~~ **should** sum to be less than or equal to one.

The formulation up to this point has ignored the effect of the variability in the midpoint levels for each load cycle. One simple way of dealing with this variability is to define damage equivalent load cycles with a fixed midpoint value. In this case, the damage done by the equivalent cycles is exactly the same as that done by the cycles with varying midpoints. Thus, failure will occur (on average) for the same number of constant amplitude cycles for the equivalent cyclic range, S_{eq} , as for cycles at any given cyclic range and midpoint value. Thus, defining a family of S-N curves for varying midpoint values, $N(S, M)$, the equivalent damage equation

$$N(S_{eq}, M_0) = N(S, M) \quad (H.10)$$

is solved for S_{eq} given values for S, M and the selected constant midpoint level M_0 . In mathematical terms, this can be stated as

$$S_{eq} = N^{-1}(N(S, M), M_0) \quad (H.11)$$

where the inverse refers to solution for the first argument in the function, N , given the second argument. Typically, M_0 is chosen to give R values (the ratio of maximum load to minimum load) for the equivalent load cycles that are in the middle of the range of values observed directly in the load data. Often, an acceptable value is the mean load considering all operating wind speeds. Fortunately, in most cases where the S-N curves are defined analytically (e.g. power law or exponential forms), the equivalent cyclic load range is easily computed. Care ~~must~~ **should** be taken, however, as the range becomes large. Depending on the midpoint value, the maximum or minimum load value for the given cycle can get close to the static strength, in which case the simple, high-cycle S-N curve may not be applicable. Also, for larger range values, the local stress or strain may transition from a compression-compression or tension-tension dominated case to a tension-compression case, which could have a different analytical S-N curve representation. It is important to utilize the proper S-N relation in determining the equivalent cyclic range. For a given load time history, the rain flow cycles are first identified. Then a set of equivalent constant-midpoint cycles is computed considering the proper S-N relation for each cycle. The distribution of these equivalent cycles is then estimated giving a new short-term equivalent load spectrum. This new spectrum is then used to define the number of cycles used for the damage fraction for each load and wind speed bin. The main advantage of using this method is that the estimation of the equivalent spectrum is statistically more robust than tracking the midpoint levels as an independent variable. This advantage results because many more load cycles are counted from typical time series load data for each load and wind speed bin than when midpoint bins are also tracked separately.

An additional practical issue that arises in determining the short-term load spectrum is the large number of small cycles determined by the rain-flow method. These small cycles can often occur at nearby points in time and may therefore be correlated. The small cycles can also distort the shape of analytical approximations to the tail of the distribution. It is therefore recommended to only consider cycles above a threshold when approximating the tail of the short-term distribution. A threshold value of at least the 95th percentile typically works well in practice. Lower threshold values may be appropriate if the small cycles have been eliminated or if the increased number of data points used for the fitting process is expected to yield significant additional statistical reliability.

For practical wind turbine design applications, it is necessary to estimate the short-term equivalent load spectrum from dynamic simulation data and then compute the lifetime damage. One method of accomplishing this task is given by the following procedure.

- a) Select the reference midpoint level as the mean load level considering all wind speeds.

From the simulation data for a given wind speed, extract the sequence of local maxima and minima. The sequences of local maxima and minima from multiple time series for the same wind conditions may be concatenated into a single series.

- b) Use the rain flow method to identify the midpoint and range for each simulated load cycle.
- c) Determine the equivalent range for each load cycle in relation to the selected reference midpoint level.
- d) Determine an analytical fit for the short-term probability distribution of equivalent load cycles, $F_{ST}(S|V,T)$ for the data above the selected threshold. Guidance for one method for fitting the distribution may be found in [4]. The distribution type selected should be checked to see if the fit to the data is acceptable and whether there is sufficient data for reliable estimation of the behaviour of the tail compared to the data.
- e) Determine the expected number of lifetime cycles in each bin using the data when the load bin is below the threshold and the fitted load distribution when the load bin is above the threshold. This results in

$$n_{jk} \approx \left(\frac{\text{Lifetime}}{T} \right) P_j \left\{ \begin{array}{ll} m_{jk} & \text{if } S_k \text{ is below the } j^{\text{th}} \text{ threshold} \\ M_j \left(F \left(S_k + \frac{\Delta S_k}{2} | V_j, T \right) - F \left(S_k - \frac{\Delta S_k}{2} | V_j, T \right) \right) & \text{if } S_k \text{ is above the } j^{\text{th}} \text{ threshold} \end{array} \right\} \quad (\text{H.12})$$

where m_{jk} is the number of simulation fatigue cycles counted in the data for the j^{th} wind speed bin and k^{th} load bin below the threshold, M_j is the number of fatigue cycles counted in the simulation above the threshold, and

$$P_j = e^{-\pi \left(\frac{V_j - \frac{\Delta V_j}{2}}{2V_{\text{ave}}} \right)^2} - e^{-\pi \left(\frac{V_j + \frac{\Delta V_j}{2}}{2V_{\text{ave}}} \right)^2}$$

is the fraction of time the wind speed is in bin j for the assumed Rayleigh wind speed distribution.

- 1) Sum the damage using the left hand side of Equation (G.9).
- 2) Sum the total lifetime damage from all fatigue load cases.

In using this procedure, care ~~must~~ **should** be taken that

- the resolution of the wind speed and load range bins is sufficient for the desired numerical precision, and
- sufficiently large values of load range are used to adequately represent the tail of the long-term load distribution.

The first issue may be addressed by approximating the error as half the difference between results computed by two different bin resolutions skipping data from every other wind speed or load range. An alternative would be to compute the damage summation using the endpoints for the bin values instead of the central values to bound the result. The second issue may be addressed by progressively increasing the highest load range bin value until a negligible increase in the lifetime damage is observed. Note because the ratio $\frac{\text{Lifetime}}{T}$ is a large

number, the largest required load bin may be significantly larger than the largest cycle observed in the simulation data. This results because the total simulated load time history is much smaller than the turbine lifetime, and statistical extrapolation is required to accurately estimate damage from the tail of the long-term load distribution.

H.2 Reference documents

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Annex I (informative)

Contemporaneous loads

I.1 General

Detailed structural analyses of wind turbine components commonly use a finite element or other suitable model for determination of the local stress or strain resulting from the loading applied to the component. Such analyses often define a suitable interface plane where the applied loads are acting (e.g. the yaw bearing interface, defining the tower top loading). In this case, there are six load components defining the boundary conditions for loading, three forces, F_x , F_y , and F_z , and three moments, M_x , M_y , and M_z . For convenience here, the x, y axes are taken to be in the loading plane and the z axis normal to the plane. To describe the extreme loading situations, a load matrix is often defined as shown in Table I.1.

Table I.1 – Extreme loading matrix

	F_x	F_y	F_z	M_x	M_y	M_z	F_R	θ_F	M_R	θ_M
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Max.										

In this table, each column represents a load component value delineated by the heading at the top. Each row represents contemporaneous values (i.e. all values occurring at the same time) and the shaded cell shows the specific component that has either a maximum or minimum value as indicated on the left. These maximum and minimum values are intended to cover the full range of values for that particular load component. The detailed structural model is then exercised using each of the rows to determine resulting local stress or strain values, which are compared to an appropriate failure criterion. When the structural stiffness and strength in response to loading in the plane is similar for the different loading directions, the most extreme loading can result when both x and y components are large in magnitude but not at their very largest values. Thus, the in-plane vector resultant values are also displayed in the additional columns on the right and the rows at the bottom. These in-plane resultants are defined as

$$F_R = \sqrt{F_x^2 + F_y^2} \quad \text{and} \quad M_R = \sqrt{M_x^2 + M_y^2} \quad (\text{I.1})$$

The angular directions of these resultants are also defined as

$$\theta_F = \arctan(F_x / F_y) \text{ and } \theta_M = \arctan(M_x / M_y) \quad (1.2)$$

The values in the table are determined by post-processing analysis of the time series for the six load components determined as the outputs from the complete wind turbine dynamic simulation code. In this analysis, the time series are searched for the maximum and minimum values for each component as well as the maxima for the resultants. The contemporaneous values associated with each of these corresponding time points are then inserted in the rows of the table. Each of the load cases defined in Clause 7 are analysed in this way and the most extreme loading in each row from the different load cases is then used to define an overall loads envelope for that part of the wind turbine.

In Clauses I.2 and I.3, two approaches are given. Note that caution should be exercised in order to obtain conservative contemporaneous loads.

I.2 Scaling

- For each cross section and load component, one bin of the considered load case delivers the largest among candidate characteristic loads.
- A time series from this bin being close with its maximum within $\pm 5\%$ to this characteristic load is selected.
- The maximum of this time series is scaled to the characteristic load. The obtained scaling factor is then also applied to all contemporaneous load components to this selected maximum of this time series.
- For each load component, one load case series is obtained to be used for extreme design load analysis.
- For minimum values, a corresponding procedure is applied considering appropriate scaling of magnitude.

I.3 Averaging

- For a load case consisting of more than one realization, the candidate characteristic maximum load is calculated as the mean of the maximum of all realizations.
- Contemporaneous loads are calculated as the mean of the absolute contemporaneous values of each realization. Signs on the contemporaneous loads are applied in accordance with the signs of the contemporaneous loads of the realization with the highest load.
- The candidate characteristic minimum load is calculated as the mean of the minimum of each realization. Contemporaneous loads are calculated in the same manner as in the positive case.
- The ultimate maximum and minimum characteristic loads are determined as the maximum and minimum, respectively, of the candidate characteristic loads described above with the corresponding contemporaneous values.

Annex J (informative)

Prediction of the extreme wind speed of tropical cyclones by using Monte Carlo simulation method

J.1 General

In the areas where the strong wind is dominated by extratropical cyclones, the extreme wind speed can be estimated by using the Gumbel method for extended data obtained from a nearby reference meteorological station with the measure-correlate-predict (MCP) approach as described in Annex F. On the other hand, tropical and subtropical regions, where both tropical and extratropical cyclones are dominant, are known as mixed climates and the examination of each significant wind-producing meteorological phenomenon is required as mentioned by [2]. It was noticed that the MCP method without consideration for different type of storms underestimates the extreme wind speed in mixed climate regions.

Annex J describes a Monte Carlo simulation (MCS) method for the prediction of tropical cyclone induced extreme wind speeds. Refer to [1] for the detail of the MCS method.

J.2 Prediction of tropical cyclone induced extreme wind speeds

J.2.1 General

Monte Carlo simulation of tropical cyclones has been proposed (e.g. [3]) in order to obtain reliable statistical wind speed induced by tropical cyclones. The prediction of strong wind induced by tropical cyclones should be performed as follows.

J.2.2 Evaluation of tropical cyclone parameters

The number of tropical cyclones per year at specific site λ can be defined as the number of the tropical cyclones whose passes are included within the simulation circle (usually, the radius of which is 500 km) per year and obtained from the track records of past tropical cyclones. For each tropical cyclone, four tropical cyclone parameters, namely, the central pressure p_c , the translation speed C , the translation angle q measured counterclockwise positive from east and the minimum distance $d_{\min}$ when the cyclone approached the site of the interest most closely, are obtained from the historical track record of the tropical cyclones. The other tropical cyclone parameter is the radius of maximum wind speed R_m , which can be identified by the pressure field model proposed by [4].

$$\frac{p(r) - p_c}{p_\infty - p_c} = \exp\left(-\frac{R_m}{r}\right)^B \quad (\text{J.1})$$

where $p(r)$ is the sea surface pressure at the distance r from the centre of the tropical cyclone. R_m can be identified by the least square method using the measured sea surface pressure at the meteorological stations, and periphery pressure p_∞ can be assumed to be 1 013 hPa or identified simultaneously. The central pressure difference is defined as Δ or $i_\infty - p_c$. In the case of $B = 1,0$, this relationship becomes the formulae proposed by [5].

These six parameters are approximated by analytical functions: Δh , R_m and C can be approximated by mixed probability density functions based on lognormal and Weibull distribution (e.g. [6]), q by normal or bi-normal distribution (e.g. [7]), $d_{\min}$ by a polynomial function and λ by Poisson's distribution. The correlations between these parameters except for λ should also be calculated.

J.2.3 Generation of synthetic tropical cyclones

Synthetic tropical cyclones are generated for long period to satisfy the modelled probability distribution functions and the correlations. The change in the pressure field of the tropical cyclones can be neglected since the wind speed and direction are estimated only when the tropical cyclone is located inside the simulation circle with the radius of 500 km.

A modified orthogonal decomposition (MOD) method should be used to satisfy the statistical distribution functions of the tropical cyclone parameters and the correlations between them at the same time, as proposed by [6]. The detailed procedure of the MOD method is described below.

Five parameters describing a tropical cyclone are normalized and written in vector form as follows.

$$\mathbf{x}^T = \{\ln(\Delta p), \ln(R_m), \ln(C), \theta, d_{\min}\} \quad (\text{J.2})$$

The covariance matrix of $\mathbf{x}$ is defined as $\mathbf{S}$. The eigenvalues $\lambda^{(k)}$ and the eigenvectors $\Phi^{(k)}$ are calculated by solving the following equation.

$$[\mathbf{S} - \lambda^{(k)}\mathbf{E}]\Phi^{(k)} = 0 \quad (\text{J.3})$$

The independent parameters $\mathbf{z}_i$ with five components are then generated following the approximated distributions to the intended ones for specified years and the number of the generated vectors following the estimated annual occurrence rate. The correlated parameters $\mathbf{x}_i$ can be obtained by the following equation.

$$\mathbf{x}_i = [\Phi^{(1)} \quad \Phi^{(2)} \quad \dots \quad \Phi^{(5)}]^{-1} \mathbf{z}_i \quad (\text{J.4})$$

These vectors $\mathbf{x}_i$ should be considered as the set of parameters for tropical cyclones. Note that although the correlations between each component of $\mathbf{x}_i$ satisfy the intended correlations, the probability distributions of them do not follow the intended ones.

Finally, $\mathbf{x}_i$ should be rearranged in an ascending order and modified so that its probability distribution follows the intended probability distributions. This operation hardly affects the correlations because it does not change the set of parameters.

J.2.4 Prediction of wind speeds in the tropical cyclone boundary

A tropical cyclone induced wind at the site of interest $\vec{\mathbf{x}}$ is affected by local topography. Wind speed $u_T(\vec{\mathbf{x}})$ and direction $\theta_T(\vec{\mathbf{x}})$ at the hub height can be written as

$$u_T(\vec{\mathbf{x}}) = S_t E_p u_g(\vec{\mathbf{x}}) \quad (\text{J.5})$$

$$\theta_T(\vec{\mathbf{x}}) = \theta_g(\vec{\mathbf{x}}) - \gamma_p + D_t \quad (\text{J.6})$$

where $u_g(\vec{\mathbf{x}})$ and $\theta_g(\vec{\mathbf{x}})$ are the gradient wind speed and direction (clockwise positive from south), E_p and γ_p are the wind profile factor and the inflow angle measured counterclockwise positive from the gradient wind velocity vector, S_t and D_t are the speed up ratio and the

difference in wind direction due to local topography as functions of the wind direction $(\theta_g(\vec{x}) - \gamma_p)$ over flat terrain.

The gradient wind speed and direction at the site $\vec{x}(r, \phi)$ can be calculated from the pressure field of the tropical cyclone assuming the balance among pressure gradient force, centrifugal force and Coriolis force.

$$u_g(\vec{x}) = \frac{-C \sin(\phi - \theta) - fr}{2} + \sqrt{\left(\frac{-C \sin(\phi - \theta) - fr}{2} \right)^2 + \frac{r}{\rho} \frac{\partial p(r)}{\partial r}} \quad (J.7)$$

$$\theta_g(\vec{x}) = \pi - \phi \quad (J.8)$$

where r is the distance from the centre of the tropical cyclone, ϕ is the angle measured counterclockwise positive from east, f is the Coriolis parameter, u_g and θ_g are the functions of time due to the motion of tropical cyclones.

The wind profile factor E_p and the inflow angle γ_p are used to calculate the wind speed at the hub height above the ground, which can be estimated by semi-theoretical formulae (e.g. [6]) or computational fluid dynamics (CFD). The speed up ratio S_t and the difference in wind direction D_t show the effect of local topography on the wind speed and direction. These factors are defined as functions of the wind direction over flat terrain and can be calculated by CFD (e.g. [8]).

Ten-minute average wind speed can be predicted by adding random values to the wind speed estimated by the wind field models. These random values are assumed to follow the lognormal distribution with the mean value of zero and the standard deviation of σ_a , which can be modelled as

$$\sigma_a = \gamma \times u_T(\vec{x}) \quad (J.9)$$

Here, 0,1 was used for γ as proposed by [9].

J.3 Prediction of extreme wind speed in mixed climate regions

J.3.1 General

The relation between the return period R and the probability distribution of annual maximum wind speed $F(u)$ can be written as follows:

$$F(u) = 1 - 1/R \quad (J.10)$$

In mixed climate regions, the probability distributions should be evaluated separately for extratropical cyclones and tropical cyclones, and then combined probability distribution should be predicted.

J.3.2 Extreme wind distributions of extratropical cyclones by the MCP method

The extreme wind distribution (i.e. the probability distribution of annual maximum wind speed) of extratropical cyclones can be estimated by the MCP method from limited length of measurement data for N years at nearby reference meteorological station as follows.

- a) First, the time series of the wind speed at the site for N years can be obtained from wind records at nearby reference station by using the MCP method or CFD method.
- b) Next, the maximum wind speed $u_{E,i}$ caused by extratropical cyclones in each calendar year at the site is extracted and ranked in ascending order from $u_{E,1}$ to $u_{E,N}$, for which a probability distribution of annual maximum wind speed induced by extratropical cyclones defined as Equation (J.11) is assigned.

$$F_E(u_{E,i}) = \frac{i}{N+1} \quad (\text{J.11})$$

- c) Then, $u_{E,i}$ is plotted against a reduced variate $y_{E,i}$, expressed as

$$y_{E,i} = -\ln(-\ln(F_E(u_{E,i}))) \quad (\text{J.12})$$

A best fitting function can be obtained by the least square method, and the extreme wind speed with specified return period can be predicted from this function.

J.3.3 Extreme wind distributions of tropical cyclones by the MCS method

The extreme wind distribution of tropical cyclones can be estimated from the M years of Monte Carlo simulation described in Clause J.2. The procedure is as follows:

- a) From M years of Monte Carlo simulation of tropical cyclones, annual maximum wind speed can be extracted and ranked in the ascending order from $u_{T,1}$ to $u_{T,M}$. A probability distribution $F_T(u_T)$ is assigned, and reduced variate $y_{T,i}$ is calculated similarly.
- b) Then, $u_{T,i}$ is plotted against the reduced variate $y_{T,i}$. In case of the MCS method, extrapolation of $F_T(u_T)$ by the best fitting is not necessary since sufficient data are obtained.

J.3.4 Determination of extreme wind speed in a mixed climate region

The combined probability distribution of annual maximum wind speed can be obtained considering both extratropical and tropical cyclones. Assuming that wind speeds induced by extratropical cyclones and tropical cyclones are independent events, the combined probability distribution can be estimated by

$$F_C(u_C) = F_E(u_E)F_T(u_T) \quad (\text{J.13})$$

where $F_C(u_C)$ denotes the combined probability distribution. It should be made sure that the predicted extreme wind speeds have comparable values with the measurement.

J.4 Reference documents

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Annex K (informative)

Calibration of structural material safety factors and structural design assisted by testing

K.1 Overview and field of application

Annex K provides guidance on selection of partial safety factors for materials in Clauses K.2 to K.6 and on statistical analysis of tests for material parameters and resistances in Clauses K.7 to K.12.

K.2 Target reliability level

For calibration of partial safety factors, a measure of reliability should be identified with the survival probability $P_S = (1 - P_F)$, where P_F is the probability of failure⁵⁵ for the considered failure mode within an appropriate reference period. If the calculated failure probability is larger than a pre-set target value P_0 , the structure should be considered to be unsafe.

An alternative measure of reliability is conventionally defined by the reliability index β which is related to P_F by

$$P_F = \Phi(-\beta) \quad (\text{K.1})$$

where $\Phi()$ is the cumulative distribution function of the standardized normal distribution.

A target value for the nominal failure probability for structural design for extreme and fatigue failure modes for a reference period of one year is

$$P_F^t = 5 \times 10^{-4} \quad (\text{K.2})$$

The corresponding target value for the reliability index is $\beta^t = 3,3$. Application of this target value assumes that the risk to human lives is negligible in case of failure of a structural element, see [5]. The target reliability level is assumed to correspond to component class 2.

K.3 Safety formats

The resistance model is assumed to be obtained by the following general model:

$$R = b \delta R(X, a) \quad (\text{K.3})$$

where

$R(X, a)$ is the resistance model as defined in a relevant structural and materials standard;
 X is the strength (and stiffness) material parameter(s). Each of the strength parameters is modelled as a lognormal stochastic variable with coefficient of variation V_X ;

⁵⁵ The probability of failure and its corresponding reliability index are notional values that do not necessarily represent the actual failure rates but are used as operational values for code calibration purposes and comparison of reliability levels of structures.

- a is the geometrical parameter(s);
- δ is the model uncertainty related to resistance model (can be determined using the method in Clause K.12). δ is modelled as a lognormal stochastic variable with mean value 1 and coefficient of variation V_δ ;
- b is the bias in resistance model. b can be determined using the method in Clause K.12.

The design value of the resistance, R_d can be determined by different models⁵⁶.

- a) Model 1 where design values are determined for the material strength parameters:

$$R_d = \frac{R(X_d, a_d)}{\gamma_\Delta} \quad (\text{K.4})$$

where

- a_d is the design value for geometrical data;
- X_d is the design values for strength parameters;
- γ_Δ is the partial safety factor related to the model uncertainty for the resistance model including bias in resistance model.

If more than one strength parameter is used in the resistance model, then design values are applied for each strength parameter in Equation (K.4).

The design value of a strength parameter(s) X_d is determined by

$$X_d = \eta \frac{X_k}{\gamma_m} \quad (\text{K.5})$$

where

- η is the conversion factor taking into account load duration effects, moisture, temperature, scale effects;
- X_k is the characteristic value of strength parameter generally defined by the 5 % quantile;
- γ_m is the partial safety factor for strength parameter depending on the coefficient of variation V_X .

If the resistance model is linear in the strength parameters, then $R_d = R(X_d, a_d)$ and X_d for each of the strength parameters is obtained using a partial safety factor $\gamma_M = \gamma_m \gamma_\Delta$.

The partial safety factor γ_Δ depends on the uncertainty of the resistance model, including bias:

$$\gamma_\Delta = \frac{\gamma_\delta}{b} \quad (\text{K.6})$$

where

- γ_δ is the partial safety factor depending on the model uncertainty with coefficient of variation V_δ without taking into account bias in the resistance model.

- b) Model 2 where a characteristic resistance is obtained using characteristic values of the material strength parameters, and the design value of the resistance is obtained from:

$$R_d = \frac{R(\eta X_k, a_k)}{\gamma_M} \quad (\text{K.7})$$

⁵⁶ The following three models correspond to the basic resistance models in the Eurocodes [2].

where

γ_M is the partial safety factor for the resistance related to the uncertainty of the resistance including uncertainty in material parameters, uncertainty in resistance model and bias.

The total uncertainty of the resistance depends on the model uncertainty δ , the bias of the resistance model and the uncertainty related to the strength parameters X through the resistance function $R(X,a)$. The material partial safety factors are correspondingly obtained from

$$\gamma_M = \frac{\gamma_\delta \gamma_{Rm}}{b} \quad (K.8)$$

where

γ_{Rm} is the partial safety factor depending on the resistance uncertainty with coefficient of variation V_{Rm} from the strength parameters through the resistance function $R(X,a)$;

γ_δ is the partial safety factor depending on the model uncertainty with coefficient of variation V_δ .

c) Model 3 where a characteristic resistance is estimated based on tests:

$$R_d = \frac{R_k}{\gamma_M} \quad (K.9)$$

where

R_k is the characteristic resistance estimated based on tests, see Clause K.12. R_k is generally defined by the 5 % quantile;

γ_M is the partial safety factor for the resistance related to uncertainty of the resistance obtained based on tests, V_R .

The material partial safety factors should be calibrated such that failure probabilities for the relevant failure modes are close to the target reliability level in Equation (K.2) – see Clause K.4 – where relevant statistical uncertainty and uncertainty related to transformation from laboratory to real structure should be included.

K.4 Reliability-based calibration

The partial safety factors for loads and resistances are determined such that the failure probability obtained using the limit state function

$$g = R - S \quad (K.10)$$

is less than the target failure probability P_F^t . In Equation (K.10), the resistance is modelled by Equation (K.3) and S is the load effect. The corresponding design equation is

$$R_d - \gamma_f S_k \geq 0 \quad (K.11)$$

where R_d is the design value of the resistance and S_k is the characteristic value of the load effect defined usually as the 98 % quantile in the distribution function for the annual maximum load effect corresponding to a 50 year return period. Other reference periods might also be used in some cases. γ_f is the load partial safety factor.

Table K.1 – Partial safety factor for model uncertainty, γ_δ ⁵⁷

Coefficient of variation for model uncertainty for resistance model in model 1, V_δ	≤ 5 %	10 %	15 %	20 %
γ_δ	1,20	1,25	1,35	1,45

If the load partial safety factors for ULS in 7.6 are used, then the partial safety factors are calibrated for a failure mode such that the reliability level becomes equal to the target reliability level R_F^t specified by Equation (K.2), see [5]. The recommended partial safety factors for Models 1 and 2 are $\gamma_m = 1,0$, $\gamma_{Rm} = 1,0$ and γ_δ as shown in Table K.1^{58 59}. For Model 3, the recommended partial safety factor is $\gamma_M = 1,2$, corresponding to the value of γ_δ for $V_\delta \leq 5\%$ in Table K.1.

K.5 Calibration using the design value format

Alternatively, to the reliability-based method in Clause K.4 for calibration of partial safety factors, the design value format can be applied, see ISO 2394.

K.6 Partial safety factors for fatigue for welded details in steel structures

The SN-approach is assumed to be used together with the Miner's rule for linear fatigue accumulation⁶⁰.

For linear SN-curves, the number of cycles, N , to failure with constant stress range, $\Delta\sigma$, is written

$$N(\Delta\sigma) = \left(\frac{\Delta\sigma}{\Delta\sigma_C} \right)^{-m} 2 \times 10^6 = K \Delta\sigma^{-m} \quad (\text{K.12})$$

where

$\Delta\sigma_C$ is the characteristic fatigue strength defined as the 5 % quantile;

m is the slope of SN-curve (Wöhler exponent);

K is the SN-curve parameter.

For variable amplitude fatigue loading, the design value of the Miner's sum should fulfil

⁵⁷ The partial safety factors in Table K.1 are calibrated without taking into account the bias b and with the characteristic value for the model uncertainty equal to 1.

⁵⁸ The reason that $\gamma_m = 1,0$ and $\gamma_{Rm} = 1,0$ is that the partial safety factor for resistance becomes independent of the uncertainty of the strength parameters because the 5 % quantile used to define the characteristic values covers the influence of this uncertainty. The characteristic value of the model uncertainty is defined as the mean value and therefore γ_δ depends on V_δ . V_δ should be determined from tests, see Clause K.12 (design assisted by testing) or from the literature.

⁵⁹ The partial safety factor for a steel component with a yielding failure criteria becomes $\gamma_M = 1,1$ using coefficients of variation for yield strength equal to 5 % and for resistance model equal to 5 %, and bias equal to 1,1 (yield strength is less than 90 % of the tensile or compression strength).

The parametric formulas based on membrane theory in [6] for shell buckling applicable to tubular steel towers with $D/t < 300$ include a bias (design buckling curve is 85 % of the mean value of experimental values) and a model uncertainty with a coefficient of variation equal to 13 % implying that γ_M for buckling becomes 1,1.

⁶⁰ Fatigue failure of welded details is considered in Clause K.6. The same principles could be used for fatigue failure of other fatigue critical details made by other materials such as composites and cast steel where the mean value of the fatigue load can be important.

$$\sum_i \frac{n_i}{2 \times 10^6} \left(\frac{\gamma_n \gamma_{Ff} \Delta \sigma_i}{\Delta \sigma_C / \gamma_{Mf}} \right)^m \leq 1 \quad (\text{K.13})$$

where

- γ_n is the consequence of failure factor, see 7.6.1.3;
- γ_{Ff} is the partial factor for fatigue load depending on uncertainties related to fatigue stresses;
- γ_{Mf} is the partial factor for fatigue strength depending on uncertainties related to the SN-curve and the Miner's rule;
- n_i is the number of cycles with fatigue stress range $\Delta \sigma_i$.

For non-linear SN-curves, the design value of the Miner's sum should fulfil

$$\sum_i \frac{n_i}{N(\gamma_n \gamma_{Mf} \gamma_{Ff} \Delta \sigma_i)} \leq 1 \quad (\text{K.14})$$

The partial safety factors γ_{Mf} and γ_{Ff} in Tables K.2 and K.3 are calibrated such that failure probabilities for the relevant failure modes are close to the target reliability level in Clause K.2 for a welded structural detail in component class 2. The partial safety factor γ_{Ff} depends on the coefficient of variation, V_{Ff} , for the fatigue stresses.

The fatigue strength parameter, $\log K$, can be assumed normal distributed with coefficient depending on the actual SN-curve, but typically 0,2 for welded details. The Miner sum can be assumed lognormal distributed with coefficient of variation equal to 0,3. The uncertainty for the fatigue stress ranges can be assumed lognormal distributed with a coefficient of variation representing the uncertainty for the assessment of the fatigue load and the uncertainty for the calculation of stress ranges given the fatigue loading, see [5]. Normally, the coefficient of variation V_{Ff} can be taken as 0,15 to 0,20, see [5].

The required reliability can be achieved as follows.

a) Damage tolerant method:

- selecting details, materials and stress levels so that in the event of the formation of cracks a low rate of crack propagation and a long critical crack length would result;
- provision of multiple load path;
- provision of crack-arresting details;
- provision of readily inspectable details during regular inspections.

b) Safe-life method:

- selecting details and stress levels resulting in a fatigue life sufficient to achieve the target value β^t at the end of the design service life. No inspections are required.

**Table K.2 – Recommended values for partial safety factor
for fatigue strength, γ_{Mf}**

Assessment method	γ_{Mf}
Damage tolerant	1,10
Safe-life	1,25

**Table K.3 – Recommended partial safety factor
for fatigue stresses, γ_{Ff}**

Coefficient of variation, V_{Ff} , for fatigue stress ranges	15 % to 20 %	20 % to 25 %	25 % to 30 %
γ_{Ff}	1,00	1,10	1,20

K.7 Types of tests for materials⁶¹

A distinction needs to be made between the following types of tests:

- tests to establish directly the ultimate resistance or serviceability properties of structures or structural members for given loading conditions;
- tests to obtain specific material properties using specified testing procedures; for instance, coupon tests for material properties for blades;
- tests to reduce uncertainties in parameters used in resistance models; for instance by subcomponent and full-scale tests.

K.8 Planning of tests

K.8.1 General

Prior to the carrying out of tests, a test plan should be agreed with the testing organization. This plan should contain the objectives of the test and all specifications necessary for the selection or production of the test specimens, the execution of the tests and the test evaluation. The test plan should cover the following:

- objectives and scope;
- prediction of test results;
- specification of test specimens and sampling;
- loading specifications;
- testing arrangement;
- measurements;
- evaluation and reporting of the tests.

K.8.2 Objectives and scope

The objective of the tests should be clearly stated, for example the required properties, the influence of certain design parameters varied during the test and the range of validity. Limitations of the test and required conversions (e.g. scaling effects) should be specified.

K.8.3 Prediction of test results

All properties and circumstances that can influence the prediction of test results should be taken into account, including

- geometrical parameters and their variability,
- geometrical imperfections,
- material properties,

⁶¹ Clauses K.8 to K.11 are based on ISO 2394:2015 [3] and EN 1990:2002 [2].

- parameters influenced by fabrication and execution procedures, and
- scale effects of environmental conditions taking into account, and if relevant, any sequencing.

The expected modes of failure and/or calculation models, together with the corresponding variables should be described. If there is a significant doubt about which failure modes might be critical, then the test plan should be developed on the basis of accompanying pilot tests.⁶²

K.8.4 Specification of test specimen and sampling

Test specimens should be specified, or obtained by sampling, in such a way as to represent the conditions of the real structure.

Factors to be taken into account include

- dimensions and tolerances,
- material and fabrication of prototypes,
- number of test specimens,
- sampling procedures, and
- restraints.

The objective of the sampling procedure should be to obtain a statistically representative sample. Attention should be drawn to any difference between the test specimens and the product population that could influence the test results.

K.8.5 Loading specifications

The loading and environmental conditions to be specified for the test should include

- loading points,
- loading history,
- restraints,
- temperatures,
- relative humidity,
- loading by deformation or force control, etc.

Load sequencing should be selected to represent the anticipated use of the structural member, under both normal and severe conditions of use. Interactions between the structural response and the apparatus used to apply the load should be taken into account where relevant.

Where structural behaviour depends upon the effects of one or more actions that will not be varied systematically, then those effects should be specified by their representative values.

K.8.6 Testing arrangement

The test equipment should be relevant for the type of tests and the expected range of measurements. Special attention should be given to measures to obtain sufficient strength and stiffness of the loading and supporting rigs, and clearance for deflections, etc.

⁶² Attention needs to be given to the fact that a structural member can possess a number of fundamentally different failure modes.

K.8.7 Measurements

Prior to the testing, all relevant properties to be measured for each individual test specimen should be listed. Additionally, a list should be made

- a) of measurement-locations, and
- b) of procedures for recording results, including if relevant,
 - 1) time histories of displacements,
 - 2) velocities,
 - 3) accelerations,
 - 4) strains,
 - 5) forces and pressures,
 - 6) required frequency,
 - 7) accuracy of measurements, and
 - 8) appropriate measuring devices.

K.8.8 Evaluation and reporting the test

For specific guidance, see Clause K.9. Any standards on which the tests are based should be reported.

K.9 General principles for statistical evaluations

When evaluating test results, the behaviour of test specimens and failure modes should be compared with theoretical predictions. When significant deviations from a prediction occur, an explanation should be sought: this might involve additional testing, perhaps under different conditions, or modification of the theoretical model.

The evaluation of test results should be based on statistical methods, with the use of available (statistical) information about the type of distribution to be used and its associated parameters. The methods given in Annex K may be used only when the following conditions are satisfied:

- a) the statistical data (including prior information) are taken from identified populations which are sufficiently homogeneous; and
- b) a sufficient number of observations is available.

At the level of interpretation of test results, three main categories can be distinguished.

- Where one test only (or very few tests) is (are) performed, no classical statistical interpretation is possible. Only the use of extensive prior information, associated with hypotheses about the relative degrees of importance of this information and of the test results, make it possible to present an interpretation as statistical (Bayesian procedures, see ISO 12491 [4]).
- If a larger series of tests is performed to evaluate a parameter, a classical statistical interpretation might be possible. This interpretation will still need to use some prior information about the parameter; however, this will normally be less than above.
- When a series of tests is carried out in order to calibrate a model (as a function) and one or more associated parameters, a classical statistical interpretation is possible.

The result of a test evaluation should be considered valid only for the specifications and load characteristics considered in the tests. If the results are to be extrapolated to cover other design parameters and loading, additional information from previous tests or from theoretical bases should be used.

K.10 Derivation of characteristic values

The derivation of a characteristic value from tests should take into account

- a) the scatter of test data,
- b) statistical uncertainty associated with the number of tests, and
- c) prior statistical knowledge.

If the response of the structure or structural member or the resistance of the material depends on influences not sufficiently covered by the tests such as

- time and duration effects,
- scale and size effects,
- different environmental, loading and boundary conditions, and
- resistance effects,

then the calculation model should take such influences into account as appropriate.

K.11 Statistical determination of characteristic value for a single property

Clause K.11 gives expressions for deriving characteristic values from (a) test types and (b) a single property (for example, a strength) ⁶³.

NOTE The expressions presented here, which use Bayesian procedures with "vague" prior distributions, lead to almost the same results as classical statistics with confidence levels equal to 75 %.

The table and expressions below are based on the following assumptions:

- a) all variables follow either a normal or a lognormal distribution;
- b) there is no prior knowledge about the value of the mean;
- c) for the case " V_X unknown", there is no prior knowledge about the coefficient of variation;
- d) for the case " V_X known", there is full knowledge of the coefficient of variation.

In practice, it is often preferable to use the case " V_X known" together with a conservative upper estimate of V_X , rather than to apply the rules given for the case " V_X unknown". Moreover, V_X , when unknown, should be assumed to be not smaller than 0,10.

The characteristic value of a property X should be found by using

$$X_k = m_X (1 - k_n V_X) \quad (\text{K.15})$$

where m_X is the sample mean and the value of k_n can be found from Table K.4.

When using Table K.4, one of two cases should be considered as follows.

- The row " V_X known" should be used if the coefficient of variation, V_X , or a realistic upper bound of it, is known from prior knowledge⁶⁴.
- The row " V_X unknown" should be used if the coefficient of variation V_X is not known from prior knowledge and so needs to be estimated from the sample as:

⁶³ Adopting a lognormal distribution for certain variables has the advantage that no negative values can occur as for example for geometrical and resistance variables.

⁶⁴ Prior knowledge can come from the evaluation of previous tests in comparable situations. What is "comparable" needs to be determined by engineering judgement.

$$m_x = \frac{1}{n} \sum x_i \quad (\text{K.16})$$

$$s_x^2 = \frac{1}{n-1} \sum (x_i - m_x)^2 \quad (\text{K.17})$$

$$V_x = \frac{s_x}{m_x} \quad (\text{K.18})$$

Table K.4 – Values of k_n for the 5 % characteristic value

N	1	2	3	4	5	6	8	10	20	30	∞
V_x known	2,31	2,01	1,89	1,83	1,80	1,77	1,74	1,72	1,68	1,67	1,64
V_x unknown	-	-	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

Table K.4 is based on the normal distribution. With a lognormal distribution expression, Equation (K.15) becomes:

$$X_k = \exp(m_y - k_n s_y)$$

where

$$m_y = \frac{1}{n} \sum \ln(x_i)$$

If V_x is known from prior knowledge, $s_y = \sqrt{\ln(V_x^2 + 1)} \cong V_x$

If V_x is unknown from prior knowledge, $s_y = \sqrt{\frac{1}{n-1} \sum (\ln x_i - m_y)^2}$

K.12 Statistical determination of characteristic value for resistance models

K.12.1 General

Clause K.12 is mainly intended to define procedures (methods) for calibrating resistance models and for deriving design values from test type c), see Clause K.7. Use will be made of available prior information (knowledge or assumptions).

Based on the observation of actual behaviour in tests and on theoretical considerations, a "design model" should be developed, leading to the derivation of a resistance function. The validity of this model should then be checked by means of a statistical interpretation of all available test data. If necessary, the design model is adjusted until sufficient correlation is achieved between the theoretical values and the test data.

Deviation in the predictions obtained by using the design model should also be determined from the tests. This deviation will need to be combined with the deviations of the other variables in the resistance function in order to obtain an overall indication of deviation. These other variables include:

- deviation in material strength and stiffness;
- deviation in geometrical properties.

The characteristic resistance should be determined by taking account of the deviations of all the variables.

The method is presented as a number of discrete steps, and some assumptions regarding the test population are made and explained; these assumptions are to be considered to be no more than recommendations covering some of the most common cases.

For the standard evaluation procedure, the following assumptions are made:

- a) the resistance function is a function of a number of independent variables X ;
- b) a sufficient number of test results is available;
- c) all relevant geometrical and material properties are measured;
- d) there is no correlation (statistical dependence) between the variables in the resistance function;
- e) all variables follow either a normal or a lognormal distribution⁶⁵.

The standard procedure comprises seven steps, see K.12.2 to K.12.8.

K.12.2 Step 1: Develop a design model

Develop a design model for the theoretical resistance r_t of the member or structural detail considered, represented by the resistance function:

$$r_t = g_r(\underline{X}) \quad (\text{K.19})$$

The resistance function should cover all relevant basic variables $\underline{X}$ that affect the resistance at the relevant limit state.

All basic parameters should be measured for each test specimen and should be available for use in the evaluation.

K.12.3 Step 2: Compare experimental and theoretical values

Substitute the actual measured properties into the resistance function so as to obtain theoretical values r_{ti} to form the basis of a comparison with the experimental values r_{ei} from the tests.

The points representing pairs of corresponding values (r_{ti} , r_{ei}) should be plotted on a diagram, as indicated in Figure K.1.

⁶⁵ Adopting a lognormal distribution for a variable has the advantage that no negative values can occur.

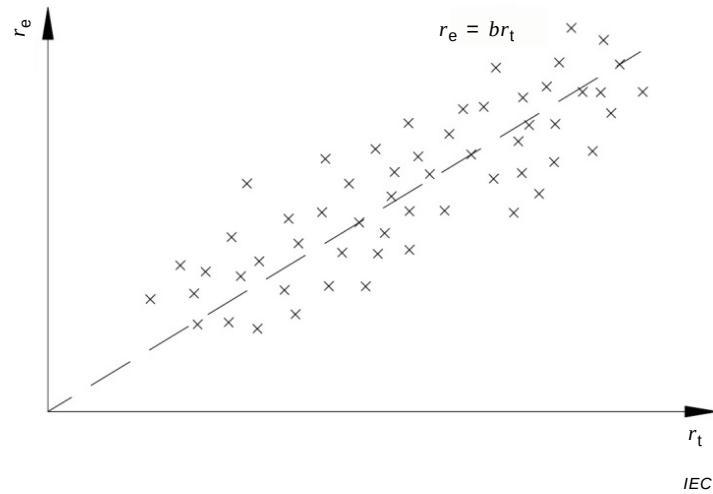


Figure K.1 – r_e - r_t diagram

If the resistance function is exact and complete, then all of the points will lie on the line with $b = 1$. In practice, the points will show some scatter, but the causes of any systematic deviation from that line should be investigated to check whether this indicates errors in the test procedures or in the resistance function.

K.12.4 Step 3: Estimate the mean value correction factor (bias) b

Represent the probabilistic model of the resistance r in the format

$$r = b r_t \delta \quad (\text{K.20})$$

where

b is the least squares best-fit to the slope, given by

$$b = \frac{\sum r_{ei} r_{ti}}{\sum r_{ti}^2} \quad (\text{K.21})$$

The mean value of the theoretical resistance function, calculated using the mean values $\underline{X}_m$ of the basic variables, can be obtained from

$$r_m = b r_t \left(\underline{X}_m \right) \delta = b g_{r_t} \left(\underline{X}_m \right) \delta \quad (\text{K.22})$$

K.12.5 Step 4: Estimate the coefficient of variation of the errors

The error term δ_i for each experimental value r_{ei} should be determined from the expression

$$\delta_i = \frac{r_{ei}}{b r_{ti}} \quad (\text{K.23})$$

From the values of δ_i an estimated value for V_δ should be determined by defining

$$A_i = \ln(\delta_i) \quad (\text{K.24})$$

The estimated value $\bar{A}$ for $E(A)$ should be obtained from

$$\bar{A} = \frac{1}{n} \sum A_i \quad (\text{K.25})$$

The estimated value s_A^2 for σ_A^2 should be obtained from

$$s_A^2 = \frac{1}{n-1} \sum (A_i - \bar{A})^2 \quad (\text{K.26})$$

The expression

$$V_\delta = \sqrt{\exp(s_A^2) - 1} \quad (\text{K.27})$$

may be used as the coefficient of variation V_δ of the δ_i error terms.

K.12.6 Step 5: Analyse compatibility

The compatibility of the test population with the assumptions made in the resistance function should be analysed.

If the scatter of the (r_{ti}, r_{ei}) values is too high to give economical design resistance functions, this scatter may be reduced in one of the following ways:

- by correcting the design model to take into account parameters which had previously been ignored;
- by modifying b and V_δ by dividing the total test population into appropriate subsets for which the influence of such additional parameters may be considered to be constant.

To determine which parameters have most influence on the scatter, the test results may be split into subsets with respect to these parameters.⁶⁶

When determining the fractile factors k_n (see step 7), the k_n value for the subsets may be determined on the basis of the total number of the tests in the original series.

K.12.7 Step 6: Determine the coefficients of variation V_{Xi} of the basic variables

If it can be shown that the test population is fully representative of the variation in reality, then the coefficients of variation V_{Xi} of the basic variables in the resistance function may be determined from the test data. However, since this is not generally the case, the coefficients of variation V_{Xi} will normally need to be determined on the basis of some prior knowledge.

K.12.8 Step 7: Determine the characteristic value r_k of the resistance

If the resistance function is of the form

⁶⁶ The purpose is to improve the resistance function per subset by analysing each subset using the standard procedure. The disadvantage of splitting the test results into subsets is that the number of test results in each subset can become very small.

$$r = b \, r_t \, \delta = b \, g_{r_t} \left(\underline{X_1, \dots, X_j} \right) \delta \quad (\text{K.28})$$

the mean value may be obtained from

$$E(r) = b \, g_{r_t} \left(E(X_1), \dots, E(X_j) \right) \delta = b \, g_{r_t} \left(\underline{X_m} \right) \delta \quad (\text{K.29})$$

and the coefficient of variation V_r may be approximated by

$$V_r^2 \cong V_\delta^2 + V_{r_t}^2 \quad (\text{K.30})$$

where V_δ is obtained from Equation (K.30)⁶⁷ and the coefficient of variation V_{r_t} may be obtained from

$$V_{r_t}^2 = \frac{1}{g_{r_t}(\underline{X_m})^2} \sum_{i=1}^j \left(\frac{\partial g_{r_t}(\underline{X})}{\partial X_i} \sigma_i \right)^2 \quad (\text{K.31})$$

where

σ_i is the standard deviation of X_i .

If the number of tests is limited (say $n < 100$), allowance should be made in the distribution of Δ for statistical uncertainties. The distribution should be considered as a central t-distribution with the parameters $\bar{\Delta}$, V_Δ and n .

The characteristic (5 % fractile) resistance r_k should be obtained from

$$r_k = b \, g_{r_t}(\underline{X_m}) \exp \left(-k_\infty \alpha_{\ln r_t} \sigma_{\ln r_t} - k_n \alpha_{\ln \delta} \sigma_{\ln \delta} - 0,5 \sigma_{\ln r}^2 \right) \quad (\text{K.32})$$

with

$$\sigma_{\ln r} = \sqrt{\ln(V_r^2 + 1)}$$

$$\sigma_{\ln r_t} = \sqrt{\ln(V_{r_t}^2 + 1)}$$

$$\sigma_{\ln \delta} = \sqrt{\ln(V_\delta^2 + 1)}$$

$$\alpha_{\ln r_t} = \frac{\sigma_{\ln r_t}}{\sigma_{\ln r}}$$

⁶⁷ The value of V_δ is estimated from the test sample under consideration.

$$\alpha_{\ln \delta} = \frac{\sigma_{\ln \delta}}{\sigma_{\ln r}}$$

where

k_n is the characteristic fractile factor from Table 5 with V_X unknown;

k_∞ is the value of k_n for $n \rightarrow \infty$ [$k_\infty = 1,64$];

$\alpha_{\ln r_t}$ is the weighting factor for $\sigma_{\ln r_t}$;

$\alpha_{\ln \delta}$ is the weighting factor for $\sigma_{\ln \delta}$.

K.13 Reference documents

- [1] JCSS:2002, Joint Committee on Structural Safety (JCSS). Probabilistic Model Code. <http://www.jcss.ethz.ch/>
- [2] EN 1990:2002, *Eurocode – Basis of structural design*
- [3] ISO 2394:2015, *General principles on reliability for structures*
- [4] ISO 12491:1997, *Statistical methods for quality control of building materials and components*
- [5] Safety Factors – IEC 61400-1 ed. 4 – background document DTU Wind Energy-E-Report-0066(EN) (ISBN: 978-87-93278-08-0) November 2014 John Dalsgaard Sørensen, Henrik Stensgaard Toft
- [6] EN 1993-1-6:2007, *Eurocode 3 – Design of steel structures – Part 1-6: Strength and Stability of Shell Structures*

Annex L (informative)

Cold climate: assessment and effects of icing climate

L.1 Assessment of icing climate conditions

L.1.1 General

In icing climate conditions, meteorological icing is defined as the accretion of ice or snow on structures which are exposed to the atmosphere. In general, two different types of atmospheric icing that impact wind turbines can be distinguished: in-cloud icing (rime ice or glaze ice) and precipitation icing (freezing rain or drizzle, wet snow, see [1]). Typically in-cloud icing is more common and in many cases the frequency of in-cloud icing increases with increasing altitude. This is due to a higher probability of a structure being inside clouds and due to lower temperature.

Icing climate conditions can be assessed using various methods and measurement sensors. In order to assess icing climate effects for a wind turbine, the severity and duration of expected long-term rotor icing needs to be assessed. Clause L.1 describes some methods that can be used to assess expected rotor icing effects.

It is recommended to assess icing near blade tip or hub height (if necessary, extrapolate assessed icing to representative rotor icing height as presented in Equation (L.1)), use multiple ice detection methods in parallel for increased availability and reliability and use long-term site-specific data (preferably 10 years or more) to assess icing whenever possible as observed icing frequency may have a high inter-annual variation.

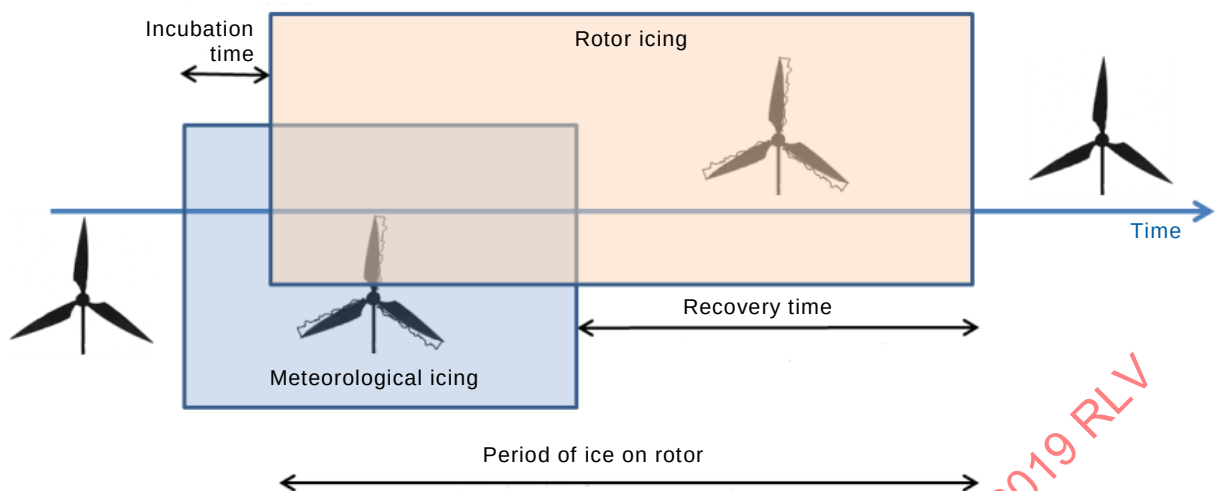
Additional information for guidance can be found in [3], [4], [5] and [6].

L.1.2 Icing climate

In general, an icing event can be described with the following expressions applicable to wind turbines exposed to meteorological icing (see Figure L.1).

- Meteorological icing: Period during which the meteorological conditions for ice accretion are favourable (active ice formation).
- Rotor icing⁶⁸: Period during which a wind turbine rotor is disturbed by ice.
- Incubation time: Delay between the start of meteorological icing and the start of rotor icing (dependent on the surface, the temperature of the structure and the wind turbine operating point).
- Recovery time: Delay between the end of meteorological icing and the end of rotor icing (period during which the ice remains but is not actively formed).

⁶⁸ The term "rotor icing" is used in this document instead of typical literature term "instrumental icing" because "rotor icing" specifies the phenomenon more accurately in case ice is affecting a rotating turbine rotor. For the rotating turbine rotor, high flow velocity and blade vibrations result to typically shorter incubation and recovery times than for stationary instruments.



IEC

Figure L.1 – Definition of meteorological icing and rotor icing

L.1.3 Rotor icing

Rotor icing is defined as the period during which the wind turbine rotor is disturbed by ice. Ice is accreted continuously on a wind turbine rotor until the meteorological conditions for icing are not present anymore (end of the meteorological icing). Ice will remain at the wind turbine for a certain time – the recovery time – until ice erodes, sublimates, melts or sheds away from the rotor (end of the rotor icing).

In general, the frequency of meteorological in-cloud icing conditions increases significantly with altitude, thus a representative height above ground level for a wind turbine rotor is required to take these effects in to account. This representative height, rotor icing height (h_{ri}), is defined as:

$$h_{ri} = z_{hub} + \frac{1}{3}D \quad (L.1)$$

where

z_{hub} is hub height of the wind turbine [m];

D is the rotor diameter [m].

Figure L.2 illustrates the definition of rotor icing height. For cloud heights below the rotor icing height, it may be assumed that the complete rotor above is in cloud.

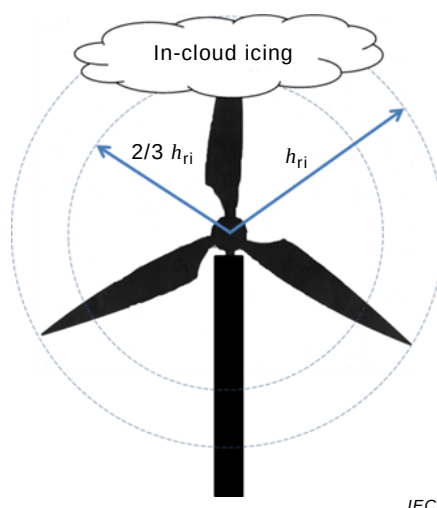


Figure L.2 – Representative ice affected rotor area as defined by rotor icing height

L.1.4 Measurement methods

Icing climate conditions may be assessed with following methods:

- use of dedicated ice detectors that measure severity and/or duration of meteorological and/or instrumental icing conditions;
- use pair of heated/unheated cup anemometers, which can be used to approximate the duration of instrumental icing;
- synoptic or camera system on stationary, for example met mast, or rotating component such as blades;
- measurements or observations via cloud base height and/or visibility and temperature;
- other validated method to assess meteorological icing.

Measurement equipment and/or the wind turbine may also be affected by a phenomenon called secondary icing. Secondary icing is formed through the process of ice accretion, melting and refreezing. Secondary icing may affect, for example, instrument availability and reliability.

Finally assessment of icing climate (IC) effects for wind turbines in terms of expected long-term rotor icing is needed. Typical severity and duration of IC effects on rotor blades presented in Clauses L.2 and L.3 may be used if no further data is available.

L.1.5 Profile coefficients modification for ice

Ice accretion on rotor blades deteriorates the airfoil aerodynamic performance characteristics versus clean airfoil performance. To account for the changes in airfoil performance, the following procedure for modifying the static airfoil characteristics may be used. It should be noted that the below mentioned range is arbitrary and should be chosen and evaluated according to the specific polar. Especially the merging into the background polar should be handled with care.

Airfoil penalty factors are to be multiplied with clean airfoil lift (C_L) and drag (C_D) coefficients for angles of attack from -2° to $\alpha = \alpha_{C_{lmax}}$. Coefficients outside this range may be extrapolated e.g. by Viterna [2] or similar method. The lift and drag penalties are a function of airfoil angle of attack as follows:

$$C_{L,pen}(\alpha) = -0,0014 \alpha^2 - 0,0017 \alpha + 0,9509 \quad (L.2)$$

$$C_{D,pen}(\alpha) = 0,0191 \alpha + 3,1151;$$

$$C_{L,iced} = C_{L,pen} \times C_{L,clean}$$

$$C_{D,iced} = C_{D,pen} \times C_{D,clean}$$

where

$C_{L,pen}$ is the clean airfoil lift coefficient penalty factor [-];

$C_{D,pen}$ is the clean airfoil drag coefficient penalty factor [-];

α is the angle of attack [°].

There is no modification applied for moment coefficient (C_m). It should be noted that the angle of attack range from -2° is arbitrary and should be adjusted according to angle of attack definition. This value could be adjusted to approximately the mid-point between $\alpha_{C_{lmax}}$ and $\alpha_{C_{lmin}}$.

Figure L.3 illustrates the penalty factors for iced airfoils. In the figure equations, x refers to the angle of attack, α , and y to the penalty factor.

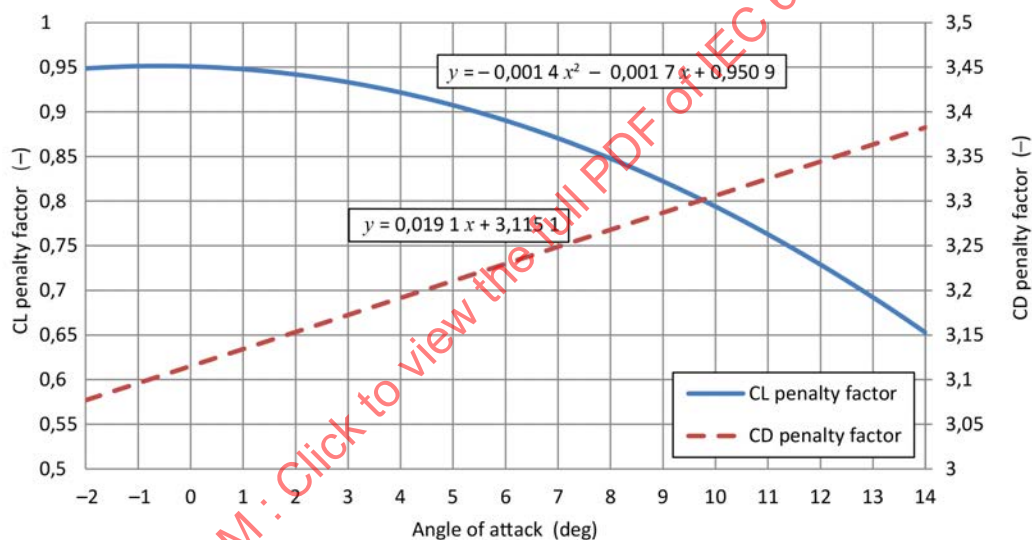


Figure L.3 – Iced airfoil lift and drag penalty factors

L.2 Ice mass effects on wind turbine blades

The duration ice remains on a rotor varies significantly geographically and from one year to another. It is recommended to assess the icing climate effects for a wind turbine with site measurements, see more guidance in Clause L.1. If no other information is available, 750 h of annual expected long-term rotor icing may be assumed.

The ice mass distribution (mass / unit length) for a wind turbine blade shall be assumed at the leading edge. It increases linearly from zero in the rotor axis to the maximum value at the rotor tip. The ice load distribution is calculated as follows:

$$M(r) = A \times C_{85\%} \times r \quad (L.4)$$

where

M is the mass distribution on the leading edge of the rotor blade [kg/m];

A is 0,125 [kg/m³];
 $C_{85\%}$ is the chord length at 85 % rotor radius [m];
 r is the radial position from rotor axis [m].

L.3 Cold climate design situations and load case

L.3.1 General

Additional load cases according to cold climate conditions are listed in Table L.1.

Table L.1 – Cold climate design load cases

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1. Power production	1.6	NTM $V_{in} < V_{hub} < V_{out}$	Ice formation	F / U	N
6. Parked (standstill or idling)	6.5	NTM $V_{hub} < 0,7 V_{ref}$	Ice formation	F / U	N
7. Parked and fault conditions	7.1	EWM 1-year return period	Ice formation	U	A

The duration ice remains on a rotor varies significantly geographically and from one year to another. It is recommended to assess the icing climate effects for a wind turbine with site measurements, see more guidance in Clause L.1. If no other information is available, 750 h of annual expected long-term rotor icing may be assumed.

L.3.2 Power production (DLC 1.1 to 1.6)

If icing of the blades can be expected and not actively prevented, safety of the turbine controller behaviour and turbine performance (Clause L.2) due to iced blades needs to be evaluated.

L.3.3 Parked (standstill or idling) (DLC 6.1 to 6.5)

For DLC 6.5 iced turbine idling, safety of the turbine controller behaviour needs to be evaluated.

L.3.4 Parked and fault conditions (DLC 7.1)

If no autonomous energy supply exists for the wind turbine, a cooling of the wind turbine down to $\theta_{1year,min}$ is to be assumed in case of grid failure. It shall be observed that low oil sump temperatures lead to significantly increased power train losses and damping, which obstruct free idling of the rotor. Iced turbine idling safety regarding turbine controller behaviour needs to be evaluated.

L.4 Cold climate load calculations

All load calculations are mainly for investigations regarding the behaviour and safety of turbine controller. Simulations with aerodynamic penalties according to Clause L.2 and ice induced rotor masses according to Clause L.3 may be implemented in the absence of other information. For ultimate load analysis, ice mass formation on all rotor blades except one and aerodynamic penalties on all rotor blades should be investigated. For fatigue analysis, ice mass on all rotor blades except one rotor blade where 50 % of the ice mass should be considered, in addition to aerodynamic penalties on all rotor blades, should be investigated.

Increased air density according to 14.4 shall be used.⁶⁹ The approach is summarized in Table L.2.

For fatigue load analysis, ice mass distribution according to Equation (L.4) may be used. For ultimate load analysis, Formula (L.4) is to be increased by a factor of two.

Table L.2 – Blade ice mass and airfoil penalty factors used in different analysis types

Analysis Type	Blade No. 1	Blade No. 2	Blade No. <i>N</i>	Airfoil penalty factor, applied for all blades
Ultimate	Equation (L.4)	Equation (L.4)	-	Equations (L.2) and (L.3)
Fatigue	Equation (L.4)	Equation (L.4)	Equation (L.4) – 50 %	Equations (L.2) and (L.3)

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⁶⁹ Special care should be taken to investigate different lateral (perpendicular to main wind direction) stiffness and damping coefficients especially for foundations. Variations in these properties might significantly influence the effects of rotor mass imbalances.

Annex M (informative)

Medium wind turbines

M.1 Overview

There is a significant market for the deployment of turbines in a size category smaller than typical utility size and larger than the category dealt with in IEC 61400-2. This category is referred to as "medium wind turbines". Depending on the application, it may be appropriate to use design requirements that differ from those in the main text.

Annex M provides information on design requirements that may be appropriate to medium wind turbines as defined in 3.29. All requirements described in this document shall be met with the following optional additions and clarifications for medium wind turbine systems.

M.2 External conditions

M.2.1 General

External conditions as defined in Clause 6 apply to medium wind turbine systems with the following clarifications.

Medium wind turbines may be installed in more complex terrain and/or near industrial areas. Therefore, it may be more appropriate to use a turbulence intensity class A+ or A for wind turbines in these environments.

M.2.2 Wind shear

On some medium wind turbine sites, higher shear exponents can arise in combination with high turbulence levels at such sites. Therefore, for a medium wind turbine, it may be appropriate to use a shear exponent, α , larger than 0,2. A shear exponent of $\alpha = 0,3$ provides a more conservative value of the wind profile for such sites.

A generic class wind turbine may also be designated with an "M" sub-class. If a value of $\alpha > 0,2$ is needed, the value shall be stated in the design documentation and the load analysis shall be executed with this value.

M.3 Assembly, installation and erection

Assembly, installation and erection of medium wind turbine systems shall meet the requirements described in Clause 12 with the following optional additional paragraphs.

12.6 Documentation

Additional paragraphs:

Information on the how to install, assemble and erect the turbine shall be specified in the documentation provided to the installer. This could include, but is not be limited to:

- details on the correct sequencing and assembly of the turbine installation;
- any general or specific training or competence standards recommended or mandated to enable contractors to undertake the installation safely and in accordance with local rules;
- technical and health and safety information regarding foundation installation, in case the turbine manufacturer is responsible for the foundation – if not, turbine loads and turbine-

foundation interface details, as well as any other turbine requirement to be taken into account for the correct foundation design and construction;

- technical and health and safety information regarding tower, blade and nacelle installation;
- technical and health and safety information regarding any other structure or system being installed (e.g. gearbox);
- technical and health and safety information regarding the installation of anchors or any equivalent systems;
- advice on site management, site access and the receiving handling and storage of the turbine and associate equipment to enable the protection of workers and others including the turbine and its components during the installation of the turbine;
- any specified loads or environmental conditions (e.g. wind speeds), including specified limits that need to be observed or not exceeded with specific reference to the installation of the tower and blades;
- technical and health and safety information necessary to enable the safe use of any specified equipment (e.g. cranes and lifting equipment) as part of the installation of the turbine;
- any additional or alternative requirements to safely decommission the turbine; and
- all necessary information to record and communicate the final as installed information to customers or end users.

Unless specific installation equipment is supplied by the manufacturer, the final selection of any equipment used or systems of work applied shall be the responsibility of the installer.

Any specific regulatory requirements or obligations relevant to the turbine and any duties mandated to fulfil national regulations in the jurisdiction supplied may be specified in the documentation provided.

Any specific standards or codes relevant to the turbine and any duties mandated to fulfil national standards and codes in the jurisdiction supplied may be specified in the documentation provided.

M.4 Commissioning, operation and maintenance

Commissioning, operation and maintenance of medium wind turbine systems shall meet the requirements described in Clause 13 with the following optional paragraphs.

13.1 General

Additional paragraphs:

Information and instruction on the how to operate and maintain the turbine shall be specified in the documentation provided to the operator. This shall include, but not be limited to:

- drawings, diagrams, descriptions and explanations necessary for the operation, maintenance, repair and testing of the wind turbine;
- instructions for training of operators and maintenance personnel, which shall indicate important aspects to be covered – as a minimum, description of access and egress to the wind turbine, climbing instructions, use of the lift, instructions about safe access to electrical installations and emergency escape procedures, maximum maintenance wind speed and the maximum number of persons allowed inside the nacelle or working on it;
- information about the maximum number of people allowed in different parts of the wind turbine at the same time;
- information about the protective measures to be taken by the operator including, where appropriate, the personal protective equipment (PPE) to be provided;

- requirements for maintenance, inspection and testing of safety critical components and systems;
- details of control and operating modes of the turbine control system;
- specification of rescue equipment;
- list of potential danger zones and specification of hazards associated with each potential danger zone;
- specification of fire extinguishers and their location;
- description of essential special tools to be used during maintenance and repair; and
- recommended service intervals for the turbine and the key components and systems;
- limits of stability during operation, maintenance, repair and breakdown. This includes description of the environmental limits to enter the turbine for maintenance work.

13.2 Design requirements for safe operation, inspection and maintenance

Additional paragraphs:

The protective measures that have been incorporated into the turbine shall be documented. This could include, but not be limited to:

- a description of significant hazards that may exist;
- specification of the limits of the wind turbine, including
 - the intended use of the wind turbine including different operating modes and intervention procedures for the operators,
 - the space limits defining working areas and access to them, operator-machine interfaces and machine-power supply interfaces,
 - any time limits specifying the design life of components critical to safety;
- details of the safety requirements and protective measures including the control systems that the turbine design has taken into account; and
- details of any residual risks that need to be brought to the attention of the buyer or operator of the turbine.

M.5 Documentation

All necessary manuals, diagrams, specifications, instructions, drawings or safety instructions sufficient to enable the safe and correct supply, assembly, installation, operation and maintenance of the wind turbine structure and equipment shall be provided as appropriate. The final scope and content of all information provided shall take into account:

- a) risk assessments performed by the manufacturer;
- b) the size and configuration of the turbine;
- c) the applicable class and load characteristics of the turbine as supplied; and
- d) site and environmental conditions for which the turbine is appropriate.

Documentation provided to the buyer shall be written in the English language and one or more official languages of the country in which the turbine is to be installed if English is not one of them. It shall include:

- the name of the manufacturer and its local representative, if a separate organization;
- the designation of the wind turbine, including name, model and class;
- any specified declarations of conformity; and
- a clear statement regarding the limitations regarding the operations that can be carried out by the buyer/user and those which should be entrusted to specialized/authorized

companies/technicians and the evidences these companies/technicians shall show to be allowed to carry out these operations.

All the documentation shall be arranged in a logical order and it shall be updated when new information becomes available. The content of the documentation shall also cover reasonably foreseeable misuse.

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~~IEC 60038, IEC standard voltages~~

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IEC 60245 (all parts), *Rubber insulated cables – Rated voltages up to and including 450/750 V*

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⁷⁰ Under preparation. Stage at the time of publication: IEC CDV 61400-3-1:2017.

⁷¹ Under preparation. Stage at the time of publication: IEC CDV 61400-6:2017.

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INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind energy generation systems –
Part 1: Design requirements**

**Systèmes de génération d'énergie éolienne –
Partie 1: Exigences de conception**

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 1: Design requirements

FOREWORD

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International Standard IEC 61400-1 has been prepared by IEC technical committee 88: Wind energy generation systems.

This fourth edition cancels and replaces the third edition published in 2005 and Amendment 1:2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) general update and clarification of references and requirements;
- b) extension of wind turbine classes to allow for tropical cyclones and high turbulence;
- c) Weibull distribution of turbulence standard deviation for normal turbulence model (NTM);
- d) updated design load cases (DLCs), in particular DLC 2.1 and 2.2;
- e) revision of partial safety factor specifications;
- f) major revision of Clauses 8, 10 and 11;

- g) introduction of cold climate requirements, Clause 14;
- h) new Annex B on design load cases for site-specific or special class S wind turbine design or site suitability assessment;
- i) new Annex J on prediction of the extreme wind speed of tropical cyclones by using Monte Carlo simulation method;
- j) new Annex K on calibration of structural material safety factors and structural design assisted by testing;
- k) new Annex L on assessment and effects of icing climate;
- l) new Annex M on medium wind turbines.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
88/696/FDIS	88/701/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of the IEC 61400 series, published under the general title *Wind energy generation systems*, can be found on the IEC website.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "<http://webstore.iec.ch>" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

The contents of the corrigendum of September 2019 have been included in this copy.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

This part of IEC 61400 outlines minimum design requirements for wind turbines and is not intended for use as a complete design specification or instruction manual.

Any of the requirements of this document may be altered if it can be suitably demonstrated that the safety of the system is not compromised. This provision, however, does not apply to the classification and the associated definitions of external conditions in Clause 6. Compliance with this document does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

This document is not intended to give requirements for wind turbines installed offshore, in particular for the support structure. For offshore installations, reference is made to the IEC 61400-3 series.

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WIND ENERGY GENERATION SYSTEMS –

Part 1: Design requirements

1 Scope

This part of IEC 61400 specifies essential design requirements to ensure the structural integrity of wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.

This document is concerned with all subsystems of wind turbines such as control and protection functions, internal electrical systems, mechanical systems and support structures.

This document applies to wind turbines of all sizes. For small wind turbines, IEC 61400-2 can be applied. IEC 61400-3-1 provides additional requirements to offshore wind turbine installations.

This document is intended to be used together with the appropriate IEC and ISO standards mentioned in Clause 2.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60034 (all parts), *Rotating electrical machines*

IEC 60038, *IEC standard voltages*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2, *Insulation co-ordination – Part 2: Application guidelines*

IEC 60076 (all parts), *Power transformers*

IEC 60204-1, *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*

IEC 60204-11:2000, *Safety of machinery – Electrical equipment of machines – Part 11: Requirements for HV equipment for voltages above 1 000 V AC or 1 500 V DC and not exceeding 36 kV*

IEC 60364 (all parts), *Low voltage electrical installations*

IEC 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 60664-1, *Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*

IEC 60664-3, *Insulation coordination for equipment within low-voltage systems – Part 3: Use of coating, potting or moulding for protection against pollution*

IEC 60721 (all parts), *Classification of environmental conditions*

IEC 61000-6-2, *Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity standard for industrial environments*

IEC 61400-3, *Wind turbines – Part 3: Design requirements for offshore wind turbines*

IEC 61400-4, *Wind Turbines – Part 4: Design requirements for wind turbine gearboxes*

IEC 61400-24, *Wind turbines – Part 24: Lightning protection*

IEC 61439 (all parts), *Low-voltage switchgear and controlgear assemblies*

IEC 61800-4, *Adjustable speed electrical power drive systems – Part 4: General requirements – Rating specifications for AC power drive systems above 1 000 V AC and not exceeding 35 kV*

IEC 61800-5-1, *Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy*

IEC 62271 (all parts), *High-voltage switchgear and controlgear*

IEC 62305-3, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

IEC 62477-1:2012, *Safety requirements for power electronic converter systems and equipment – Part 1: General*

ISO 76, *Rolling bearings – Static load ratings*

ISO 281, *Rolling bearings – Dynamic load ratings and rating life*

ISO 2394, *General principles on reliability for structures*

ISO 2533, *Standard Atmosphere*

ISO 4354, *Wind actions on structures*

ISO 6336-2, *Calculation of load capacity of spur and helical gears – Part 2: Calculation of surface durability (pitting)*

ISO 6336-3:2006, *Calculation of load capacity of spur and helical gears – Part 3: Calculation of tooth bending strength*

ISO 12494:2001, *Atmospheric icing on structures*

ISO 13850, *Safety of machinery – Emergency stop function – Principles for design*

ISO/TS 16281, *Rolling bearings – Methods for calculating the modified reference rating life for universally loaded bearings*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1

annual average

mean value of a set of measured data of sufficient size and duration to serve as an estimate of the expected value of the quantity

Note 1 to entry: The averaging time interval should be a whole number of years (e.g. 10) to average out non-stationary effects such as seasonality.

3.2

annual average wind speed

V_{ave}

wind speed averaged according to the definition of annual average

3.3

auto-reclosing cycle

event with a time period, varying from approximately 0,01 s to a few seconds, during which a breaker released after a grid fault is automatically reclosed and the line is reconnected to the network

3.4

blocking

<wind turbines> use of a mechanical pin or other device (other than the ordinary mechanical brake) that cannot be released accidentally to prevent movement, for instance of the rotor shaft or yaw mechanism

3.5

brake

<wind turbines> device capable of reducing the rotor speed or stopping rotation

Note 1 to entry: The brake may operate on, for example, aerodynamic, mechanical or electrical principles.

3.6

characteristic value

value having a prescribed probability of not being attained (i.e. an exceedance probability of less than or equal to a prescribed amount)

3.7

complex terrain

surrounding terrain that features significant variations in topography and terrain obstacles that may cause flow distortion

3.8

control functions

<wind turbines> functions of the control system that, based on information about the condition of the wind turbine and/or its environment, adjust the turbine in order to maintain it within its operating limits

3.9 control system

<wind turbines> system implementing the turbine control functions, including sensors, logic elements, actuators, communication networks, and power supplies

Note 1 to entry: The intent of the control system is to control operation of the turbine by active and passive means and keep the operating parameters within the limits assumed in the structural design. The control system is likely to include control loops for normal operation as well as alarms and shutdown mechanisms to ensure that limits are not exceeded.

3.10 cut-in wind speed

V_{in}
lowest 10 min average wind speed at hub height at which the wind turbine starts to produce power in the case of steady wind without turbulence

3.11 cut-out wind speed

V_{out}
highest 10 min average wind speed at hub height at which the wind turbine is designed to produce power in the case of steady wind without turbulence

3.12 design limits

maximum or minimum values used in a design

3.13 dormant failure

failure of a component or system which remains undetected during normal operation

3.14 downwind

in the direction of the main wind vector

3.15 electrical power network

particular installations, substations, lines or cables for the transmission and distribution of electricity

Note 1 to entry: The boundaries of the different parts of this network are defined by appropriate criteria, such as geographical situation, ownership, voltage.

3.16 emergency stop

<wind turbines> rapid shutdown of the wind turbine triggered by manual intervention

3.17 environmental conditions

characteristics of the environment (wind, altitude, temperature, humidity, etc.) which may affect the wind turbine behaviour

3.18 external conditions

<wind turbines> factors affecting operation of a wind turbine, including the environmental conditions (temperature, snow, ice, etc.) and the electrical network conditions

3.19 extreme wind speed

value of the highest wind speed, averaged over t in seconds, with an annual probability of exceedance of $1/N$ ("return period": N years)

Note 1 to entry: In this document, return periods of $N = 50$ years and $N = 1$ year and averaging time intervals of $t = 3$ s and $t = 10$ min are used. In popular language, the less precise term, survival wind speed, is often used. In this document, however, the turbine is designed using extreme wind speeds for design load cases.

3.20

fail-safe

design property of an item which prevents its failures from resulting in critical faults

3.21

gust

temporary change in the wind speed

Note 1 to entry: A gust may be characterized by its rise time, its magnitude and its duration.

3.22

horizontal axis wind turbine

wind turbine whose rotor axis is substantially horizontal

3.23

hub

<wind turbines> fixture for attaching the blades or blade assembly to the rotor shaft

3.24

hub height

z_{hub}

<wind turbines> height of the centre of the swept area (3.57) of the wind turbine rotor above the terrain surface

3.25

idling

<wind turbines> condition of a wind turbine that is rotating slowly and not producing power

3.26

inertial sub-range

frequency interval of the turbulence spectrum, where eddies – after attaining isotropy – undergo successive break-up with negligible energy dissipation

Note 1 to entry: At a typical 10 m/s wind speed, the inertial sub-range is roughly from 0,2 Hz to 1 kHz.

3.27

limit state

state of a structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirement

Note 1 to entry: The purpose of design calculations (i.e. the design requirement for the limit state) is to keep the probability of a limit state being reached below a certain value prescribed for the type of structure in question (see ISO 2394).

3.28

mean wind speed

statistical mean of the instantaneous value of the wind speed averaged over a given time period which can vary from a few seconds to many years

3.29

medium wind turbine

wind turbine with a rotor swept area or, in the case of a ducted or shrouded turbine, the larger of the duct or shroud entry and exit areas greater than 200 m² and less than or equal to 1 000 m²

3.30

nacelle

housing which contains the drive-train and other elements on top of a horizontal axis wind turbine tower

3.31

network connection point

<wind turbines> cable terminals of a single wind turbine or, for a wind power station, the connection point to the electrical bus of the site power collection system

3.32

network loss

loss of electrical network (grid) for a period exceeding any ride through provision in the turbine control system

3.33

normal shutdown

<wind turbines> shutdown in which all stages are under the control of the control system

3.34

operating limits

set of conditions defined by the wind turbine designer that governs the activation of the turbine control functions

3.35

parked wind turbine

turbine being either in a standstill or an idling condition, depending on the design of the wind turbine

3.36

performance level

PL

discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions

3.37

power collection system

<wind turbines> electric system that collects the power from one or more wind turbines

Note 1 to entry: It includes all electrical equipment connected between the wind turbine terminals and the network connection point.

3.38

power output

power delivered by a device in a specific form and for a specific purpose

Note 1 to entry: For a wind turbine, it is the electric power it delivers.

3.39

primary layer protection function

protection function (3.40) in a protection system with two or more independent layers which may be implemented as a part of the wind turbine control system and is separate from a secondary layer protection function (3.52) with a similar purpose

3.40

protection functions

<wind turbine> functions of the control system which ensure that a wind turbine remains within the design limits

3.41**rated power**

quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment

Note 1 to entry: For a wind turbine, it is the maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating and external conditions.

3.42**rated wind speed** V_r

minimum wind speed at hub height at which a wind turbine's rated power is achieved in the case of steady wind without turbulence

3.43**Rayleigh distribution** P_R

probability distribution function

Note 1 to entry: See 3.68.

3.44**reference wind speed** V_{ref}

basic parameter for wind speed used for defining wind turbine classes

Note 1 to entry: Other design related climatic parameters are derived from the reference wind speed and other basic wind turbine class parameters (see Clause 6).

Note 2 to entry: A turbine designed for a wind turbine class with a reference wind speed V_{ref} is designed to withstand climates for which the extreme 10 min average wind speed with a return period of 50 years at turbine hub height is lower than or equal to V_{ref} .

3.45**resistance partial safety factor** γ_M

factor which takes account of possible unfavourable deviations/uncertainties of the material strength parameters and of the resistance model including bias in the resistance model

3.46**rotationally sampled wind velocity**

wind velocity experienced at a fixed point of the rotating wind turbine rotor

Note 1 to entry: The turbulence spectrum of a rotationally sampled wind velocity is distinctly different from the normal turbulence spectrum. While rotating, the blade cuts through a wind flow that varies in space. Therefore, the resulting turbulence spectrum will contain sizeable amounts of variance at the frequency of rotation and harmonics of the same.

3.47**rotor speed**

<wind turbines> rotational speed of a wind turbine rotor about its axis

3.48**roughness length** z_0

extrapolated height at which the mean wind speed becomes zero if the vertical wind profile is assumed to have a logarithmic variation with height

3.49**safe-life**

design property for a critical system which is either very difficult to repair or may cause severe damage to life and property

Note 1 to entry: Such systems are designed to work for the full system lifetime without requirement of any repairs or inspections.

3.50

safety integrity level

SIL

discrete level (one out of a possible four), corresponding to a range of safety integrity values for the control functions, where 4 and 1 belong to the highest and lowest levels, respectively

Note 1 to entry: Target failure measures for the four safety integrity levels are defined in Tables 2 and 3 of IEC 61508-1:2010. These levels can be used for specifying safety integrity requirements of safety functions allocated to the systems. A SIL is not a property of a system, subsystem, element or component. As defined in IEC 61508-1, the phrase "SIL n safety-related system" (where n is 1, 2, 3, or 4) means that the system is potentially capable of supporting safety functions with a safety integrity level up to n .

3.51

scheduled maintenance

preventive maintenance carried out in accordance with an established schedule

3.52

secondary layer protection function

dedicated protection function which operates using a layer of monitoring and logic separate from a primary layer protection function (3.39) with a similar purpose

3.53

site data

environmental, seismic, soil and electrical network data for the wind turbine site

Note 1 to entry: Wind data shall be the statistics of 10 min samples unless otherwise stated.

3.54

standstill

condition of a wind turbine that is stopped

3.55

support structure

<wind turbines> part of a wind turbine comprising the tower and foundation

3.56

survival wind speed

maximum wind speed that a construction is designed to withstand

Note 1 to entry: This is a popular expression that is not used in this document. Design conditions instead refer to extreme wind speed (3.19).

3.57

swept area

projected area perpendicular to the wind direction that a rotor will describe during one complete rotation

3.58

turbulence intensity

I

ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified period of time

3.59

turbulence scale parameter

λ_1

wavelength where the non-dimensional, longitudinal power spectral density is equal to 0,05

Note 1 to entry: The wavelength is thus defined as $\lambda_1 = V_{\text{hub}}/f_0$, where $f_0 S_1(f_0)/\sigma_1^2 = 0,05$.

3.60

turbulence standard deviation

σ_1

standard deviation of the longitudinal component of the turbulent wind velocity at hub height

3.61

ultimate limit state

limit states which generally correspond to maximum load carrying capacity

3.62

unscheduled maintenance

maintenance carried out, not in accordance with an established time schedule, but after receipt of an indication regarding the state of an item

3.63

upwind

in the direction opposite to the main wind vector

3.64

vertical axis wind turbine

wind turbine whose rotor axis is vertical

3.65

Weibull distribution

P_w

probability distribution function

Note 1 to entry: See 3.68.

3.66

wind power station

wind farm

group or groups of wind turbines

3.67

wind profile

wind shear law

mathematical expression for assumed wind speed variation with height above ground

Note 1 to entry: Commonly used profiles are the logarithmic profile (Equation (1)) or the power law profile (Equation (2)).

$$V(z) = V(z_r) \cdot \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \quad (1)$$

$$V(z) = V(z_r) \cdot \left(\frac{z}{z_r} \right)^\alpha \quad (2)$$

where

- $V(z)$ is the wind speed at height z ;
- z is the height above ground;
- z_r is a reference height above ground used for fitting the profile;
- z_0 is the roughness length;
- α is the wind shear (or power law) exponent.

3.68

wind speed distribution

probability distribution function, used to describe the distribution of wind speeds over an extended period of time

Note 1 to entry: Often used distribution functions are the Rayleigh, $P_R(V_0)$, and the Weibull, $P_W(V_0)$, functions.

$$\begin{aligned} P_R(V_0) &= 1 - \exp\left[-\pi(V_0 / 2V_{ave})^2\right] \\ P_W(V_0) &= 1 - \exp\left[-(V_0 / C)^k\right] \end{aligned} \quad (3)$$

$$\text{with } V_{ave} = \begin{cases} C \Gamma(1 + \frac{1}{k}) \\ C \sqrt{\pi} / 2, \text{ if } k = 2 \end{cases} \quad (4)$$

where

- $P(V_0)$ is the cumulative probability function, i.e. the probability that $V < V_0$;
- V_0 is the wind speed (limit);
- V_{ave} is the average value of V ;
- C is the scale parameter of the Weibull function;
- k is the shape parameter of the Weibull function;
- Γ is the gamma function.

Both C and k can be evaluated from real data. The Rayleigh function is identical to the Weibull function if $k = 2$ is chosen and C and V_{ave} satisfy the condition stated in Equation (4) for $k = 2$.

The distribution functions express the cumulative probability that the wind speed is lower than V_0 . Thus $(P(V_1) - P(V_2))$, if evaluated between the specified limits V_1 and V_2 , will indicate the fraction of time that the wind speed is within these limits. Differentiating the distribution functions yields the corresponding probability density functions.

3.69

wind shear

variation of wind speed across a plane perpendicular to the wind direction

3.70

wind speed

V

speed of motion of a minute amount of air surrounding a specified point in space

Note 1 to entry: It is also the magnitude of the local wind velocity (vector) (see 3.73).

3.71

wind turbine generator system

<wind turbine> system which converts kinetic energy in the wind into electrical energy

3.72

wind turbine site

location of an individual wind turbine either alone or within a wind farm

3.73**wind velocity**

vector pointing in the direction of motion of a minute amount of air surrounding the point of consideration, the magnitude of the vector being equal to the speed of motion of this air "parcel" (i.e. the local wind speed)

Note 1 to entry: The vector at any point is thus the time derivative of the position vector of the air "parcel" moving through the point.

3.74**wind turbine electrical system**

electrical equipment internal to the wind turbine, up to and including the wind turbine terminals, including equipment for earthing, bonding and communications

Note 1 to entry: Conductors local to the wind turbine, which are intended to provide an earth termination network specifically for the wind turbine, are included.

3.75**wind turbine terminals**

point or points identified by the wind turbine supplier at which the wind turbine may be connected to the power collection system

Note 1 to entry: This includes connection for the purposes of transferring energy and communications.

3.76**yawing**

rotation of the rotor axis about a vertical axis

Note 1 to entry: For horizontal axis wind turbines only.

3.77**yaw misalignment**

horizontal deviation of the wind turbine rotor axis from the wind direction

4 Symbols and abbreviated terms**4.1 Symbols and units**

C	scale parameter of the Weibull distribution function	[m/s]
C_{CT}	turbulence structure correction parameter	
C_T	thrust coefficient	[-]
Coh	coherence function	[-]
D	rotor diameter	[m]
$D_{TV,i}$	standard deviation of terrain variation Δz in i th 30° sector	[m]
$D_{TV,360}$	standard deviation of terrain variation Δz of the 360° circle area	[m]
f	frequency	[s ⁻¹]
f_d	design value for material strength	[-]
f_k	characteristic value for material strength	[-]
F_d	design value for loads	[-]
F_k	characteristic value for loads	[-]
I_{ref}	reference value of the turbulence intensity corresponding to the 70 % quantile at 15 m/s	[-]
I_{eff}	effective turbulence intensity	[-]
k	shape parameter of the Weibull distribution function	[-]

k_1	empirical adjustment factor for TSI360, $k_1 = 5/3$	[-]
k_2	empirical adjustment factor for TVI360, $k_2 = 3$	[-]
K	modified Bessel function	[-]
L	isotropic turbulence integral scale parameter	[m]
L_e	coherence scale parameter	[m]
L_k	velocity component integral scale parameter	[m]
m	Wöhler curve exponent	[-]
n_i	counted number of fatigue cycles in load bin i	[-]
$N(.)$	number of cycles to failure as a function of the stress (or strain) indicated by the argument (i.e. the characteristic S-N curve)	[-]
N	return period for extreme situations	[years]
p	air pressure	[N/m ²]
$P(V_0)$	probability distribution, i.e. the probability that $V < V_0$	[-]
$P_R(V_0)$	Rayleigh probability distribution, i.e. the probability that $V < V_0$	[-]
P_s	survival probability	[-]
$P_W(V_0)$	Weibull probability distribution	[-]
r	magnitude of separation vector projection	[m]
R	radius of circle segment	[m]
R_0	gas constant	[J/(kg·K)]
S	load function	[-]
s_i	the stress (or strain) level associated with the counted number of cycles in bin i	[-]
$S_1(f)$	power spectral density function for the longitudinal wind velocity component	[m ² /s]
$S_{F,min}$	minimum value of safety factor for tooth breakage	[-]
$S_{H,min}$	minimum value of safety factor for pitting	[-]
$S_k(f)$	one-sided power spectral density function for wind velocity component k : $k = 1$ longitudinal component $k = 2$ lateral component $k = 3$ vertical component	[m ² /s]
T	gust characteristic time	[s]
t	time	[s]
V	wind speed	[m/s]
$V(z)$	wind speed at height z	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_{cg}	extreme coherent gust magnitude over the whole rotor swept area	[m/s]
V_{eN}	expected extreme wind speed (averaged over three seconds), with a recurrence time interval of N years. V_{e1} and V_{e50} for 1 year and 50 years, respectively	[m/s]
V_{gust}	largest gust magnitude with an expected return period of 50 years	[m/s]
V_{hub}	wind speed at hub height	[m/s]
V_{in}	cut-in wind speed	[m/s]

V_0	limit wind speed in wind speed distribution model	[m/s]
V_{50}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 50 years	[m/s]
V_{100}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 100 years	[m/s]
V_{out}	cut-out wind speed	[m/s]
V_r	rated wind speed	[m/s]
V_{ref}	reference wind speed	[m/s]
$V_{ref,T}$	reference wind speed for tropical-like conditions	[m/s]
$V(y,z,t)$	longitudinal wind velocity component to describe transient horizontal wind shear	[m/s]
$V(z,t)$	longitudinal wind velocity component to describe transient variation for extreme gust and shear conditions	[m/s]
x, y, z	co-ordinate system used for the wind field description; along wind (longitudinal), across wind (lateral) and height respectively	[m]
Z_{NT}	life factor for contact stress for reference test conditions	[-]
z_{hub}	hub height of the wind turbine	[m]
z_r	reference height above ground	[m]
z_0	roughness length for the logarithmic wind profile	[m]
α	wind shear power law exponent	[-]
β	parameter for extreme direction change model	[-]
δ	coefficient of variation	[-]
Γ	gamma function	[-]
γ_f	partial safety factor for loads	[-]
γ_M	partial safety factor for resistances	[-]
γ_n	partial safety factor for consequences of failure	[-]
$\theta(t)$	wind direction change transient	[deg]
θ_{cg}	angle of maximum deviation from the direction of the average wind speed under gust conditions	[deg]
θ_{eN}	extreme direction change with a return period of N years	[deg]
θ_i	slope of fitted plane for i th 30° sector	[deg]
θ_{360}	slope of the fitted 360° plane	[deg]
$\theta_{1year,min}$	minimum ambient temperature to be expected in hourly average	[K]
$\theta_{min,operation}$	minimum allowable ambient temperature for wind turbine operation	[K]
λ_1	turbulence scale parameter defined as the wavelength where the non-dimensional, longitudinal power spectral density, $fS_1(f)/\sigma_1^2$, is equal to 0,05	[m]
ρ	air density	[kg/m ³]
$\hat{\sigma}$	estimated wind speed standard deviation	[m/s]
$\hat{\sigma}_c$	representative ambient turbulence standard deviation	[m/s]
$\hat{\sigma}_{eff}$	effective estimated wind speed standard deviation	[m/s]
σ_{wake}	wind speed standard deviation in the wake	[m/s]

$\hat{\sigma}_T$	maximum centre-wake wind speed standard deviation	[m/s]
$\hat{\sigma}_\sigma$	standard deviation of estimated wind speed standard deviation $\hat{\sigma}$	[m/s]
$\hat{\sigma}_{1\text{ETM}}$	extreme ambient turbulence standard deviation	[m/s]
σ_1	hub-height longitudinal wind velocity standard deviation	[m/s]
σ_2	hub-height lateral wind velocity standard deviation	[m/s]
σ_3	hub-height upward wind velocity standard deviation	[m/s]
Φ	standardized normal probability function	[-]
$E[]$	expected value of parameter inside brackets	[-]
$\text{Var}[]$	variance of parameter inside brackets	[-]

4.2 Abbreviated terms

A	abnormal (for partial safety factors)
AC	alternating current
DC	direct current
CC	cold climate
COV	coefficient of variation
DLC	design load case
DWM	dynamic wake meandering
ECD	extreme coherent gust with direction change
EDC	extreme wind direction change
EOG	extreme operating gust
ETM	extreme turbulence model
EWM	extreme wind speed model
EWS	extreme wind shear
F	fatigue
FMEA	failure mode and effect analysis
HV	high voltage
IAC	internal arc classification
IC	icing climate
LTC	low temperature climate
LVRT	low voltage ride through
N	normal and extreme (for partial safety factors)
NWP	normal wind profile model
NTM	normal turbulence model
S	special IEC wind turbine class
T	transport and erection (for partial safety factors)
TSI	terrain slope index
TVI	terrain variation index
U	ultimate
ULS	ultimate limit state

5 Principal elements

5.1 General

The engineering and technical requirements to ensure the safety of the structural, mechanical, electrical and control systems of the wind turbine are given in the following clauses. This specification of requirements applies to the design, manufacture, installation and manuals for operation and maintenance of a wind turbine and the associated quality management process. In addition, safety procedures, which have been established in the various practices that are used in the installation, operation and maintenance of wind turbine, are taken into account.

5.2 Design methods

This document requires the use of an aeroelastic dynamics model to predict design loads. Such a model shall be used to determine the loads over a range of wind speeds, using the turbulence conditions and other wind conditions defined in Clause 6 and design situations defined in Clause 7. All relevant combinations of external conditions and design situations shall be analysed. A minimum set of such combinations has been defined as load cases in this document.

Data from full scale testing of a wind turbine shall be used to increase confidence in predicted design values and to verify structural dynamics models and design situations as specified in 7.2.

Verification of the adequacy of the design shall be made by calculation and/or by testing. If test results are used in this verification, the external conditions during the test shall be shown to reflect the characteristic values and design situations defined in this document. The selection of test conditions, including the test loads, shall take account of the relevant safety factors.

5.3 Safety classes

A wind turbine shall be designed according to one of the following two safety classes:

- a normal safety class which applies when a failure results in risk of personal injury or other social or economic consequence;
- a special safety class that applies when the safety requirements are determined by local regulations and/or the safety requirements are agreed between the manufacturer and the customer.

Partial safety factors, for normal safety class wind turbines, are specified in 7.6.

Partial safety factors for special safety class wind turbines shall be agreed between the manufacturer and the customer. A wind turbine designed according to a special safety class shall be classified as a class S wind turbine, as defined in 6.2.

5.4 Quality assurance

Quality assurance shall be an integral part of the design, procurement, manufacture, installation, operation and maintenance of the wind turbines and all their components.

It is recommended that the quality system comply with the requirements of ISO 9001.

5.5 Wind turbine markings

The following information, as a minimum, shall be prominently and legibly displayed on the indelibly marked turbine nameplate:

- wind turbine manufacturer and country;
- model and serial number;
- production year;
- rated power;
- reference wind speed, V_{ref} ;
- hub height operating wind speed range, $V_{in} - V_{out}$;
- operating ambient temperature range;
- IEC wind turbine class (see Table 1);
- rated voltage at the wind turbine terminals;
- frequency at the wind turbine terminals or frequency range in the case that the nominal variation is greater than 2 %.

6 External conditions

6.1 General

The external conditions described in Clause 6 shall be considered in the design of a wind turbine.

Wind turbines are subjected to environmental and electrical conditions that may affect their loading, durability and operation. To ensure the appropriate level of safety and reliability, environmental, electrical and soil parameters shall be taken into account in the design and shall be explicitly stated in the design documentation.

The environmental conditions are further divided into wind conditions and other environmental conditions. The electrical conditions refer to the electrical power network conditions. Soil properties are relevant to the design of wind turbine foundations.

The external conditions are subdivided into normal and extreme categories. The normal external conditions generally concern recurrent structural loading conditions, while the extreme external conditions represent rare external design conditions. The design load cases shall consist of potentially critical combinations of these external conditions with wind turbine operational modes and other design situations.

Wind conditions are the primary external conditions affecting structural integrity. Other environmental conditions also affect design features such as control system function, durability, corrosion.

The normal and extreme conditions, which are to be considered for design according to wind turbine classes, are prescribed in 6.2 to 6.4.

6.2 Wind turbine classes

The external conditions to be considered for design are dependent on the intended site or site type for a wind turbine installation. Wind turbine classes are defined in terms of wind speed, wind turbine class I, II and III, and turbulence parameters, turbulence category A+, A, B, and C. The intention of the classes is to cover most applications. The values of wind speed and turbulence parameters are intended to represent many different sites and do not give a precise representation of any specific site, see 11.3. The wind turbine classification offers a range of robustness clearly defined in terms of the wind speed and turbulence parameters. In order to allow the use of wind turbine classes for areas, which may experience very high extreme winds in an otherwise moderate wind climate, a T class reference wind speed is included. Such conditions may be found in areas subject to tropical cyclones. This reference wind speed may be used with the average wind speed in class I to III and turbulence

categories A+ to C¹. Table 1 specifies the basic parameters, which define the wind turbine classes.

Table 1 – Basic parameters for wind turbine classes

Wind turbine class		I	II	III	S
V_{ave} (m/s)		10	8,5	7,5	Values specified by the designer
V_{ref}	(m/s)	50	42,5	37,5	
	Tropical (m/s) $V_{ref,T}$	57	57	57	
A+ I_{ref} (-)		0,18			
A I_{ref} (-)		0,16			
B I_{ref} (-)		0,14			
C I_{ref} (-)		0,12			
The parameter values apply at hub height and					
V_{ave} is the annual average wind speed;					
V_{ref} is the reference wind speed average over 10 min;					
$V_{ref,T}$ is the reference wind speed average over 10 min applicable for areas subject to tropical cyclones;					
A+ designates the category for very high turbulence characteristics;					
A designates the category for higher turbulence characteristics;					
B designates the category for medium turbulence characteristics;					
C designates the category for lower turbulence characteristics; and					
I_{ref} is a reference value of the turbulence intensity (see 6.3.2.3).					

Class T assumes all wind model parameters to be the same and allows the combination of $V_{ref,T}$ with all turbulence categories. It does not cover all the areas prone to tropical cyclones. A site assessment based on Clause 11 is needed, as a minimum assessing that V_{50} is below V_{ref} of class T ($V_{ref,T}$).

An optional wind turbine class CC, which may be used for areas with cold climate, is defined in Clause 14. The optional wind turbine class specifies additional requirements and parameters to what is given in Clause 6.

A further wind turbine class, class S, is defined for use when special wind or other external conditions or a special safety class, see 5.3, are required by the designer and/or the customer. The design values for the wind turbine class S shall be chosen by the designer and specified in the design documentation. For such special designs, the values chosen for the design conditions shall reflect an environment at least as severe as is anticipated for the use of the wind turbine.

Wind turbines to be designed for site-specific or very extreme conditions may require wind turbine class S design.

In addition to the basic parameters showed in Table 1, several other important parameters are required to completely specify the external conditions to be used in wind turbine design. In the case of the wind turbine classes I_{A+} through III_C, later referred to as the standard wind turbine classes, the values of these additional parameters are specified in 6.3, 6.4 and 6.5.

The design lifetime for wind turbine classes I to III shall be at least 20 years.

¹ A turbine class using for example the annual average wind speed of class II and turbulence category B together with the T class reference wind speed is designated class IIB,T.

For the wind turbine class S the manufacturer shall, in the design documentation, describe the models used and values of design parameters. Where the models in Clause 6 are adopted, statement of the values of the parameters will be sufficient. The design documentation of wind turbine class S shall contain the information listed in Annex A. Guidance on turbine class S design load cases is given in Annex B.

The abbreviations added in parentheses in the subclause headings in 6.3.2.2 to 6.3.3.7 are used for describing the wind conditions for the design load cases defined in 7.4.

6.3 Wind conditions

6.3.1 General

A wind turbine shall be designed to safely withstand the wind conditions defined by the selected wind turbine class.

The design values of the wind conditions shall be clearly specified in the design documentation.

The wind regime for load and safety considerations is divided into the normal wind conditions, which will occur frequently during normal operation of a wind turbine, and the extreme wind conditions that are defined as having a 1-year or 50-year return period.

The wind conditions include a constant mean flow combined, in many cases, with either a varying deterministic gust profile or with turbulence. In all cases, the influence of an inclination of the mean flow with respect to a horizontal plane of 8° shall be considered. This flow inclination angle shall be assumed to be invariant with height.

The expression "turbulence" denotes random variations in the wind velocity from 10 min averages. The turbulence model, when used, shall include the effects of varying wind speed, shears and direction and allow rotational sampling through varying shears. The three vector components of the turbulent wind velocity are defined as

- longitudinal – along the direction of the mean wind velocity,
- lateral – horizontal and normal to the longitudinal direction, and
- upward – normal to both the longitudinal and lateral directions, i.e. tilted from the vertical by the mean flow inclination angle.

For the standard wind turbine classes, the random wind velocity field for the turbulence models shall satisfy the Kaimal model together with the coherence model described in Annex C. This model satisfies the following requirements.

- a) The turbulence standard deviation, σ_1 , with values given in the following subclauses, shall be assumed to be invariant with height. The components normal to the mean wind direction shall have the following minimum standard deviations²:

- lateral component: $\sigma_2 \geq 0,7 \sigma_1$;
- upward component: $\sigma_3 \geq 0,5 \sigma_1$;

- b) The longitudinal turbulence scale parameter, A_1 , at hub height z shall be given by

$$A_1 = \begin{cases} 0,7z & z \leq 60m \\ 42m & z \geq 60m \end{cases} \quad (5)$$

² The actual values can depend on the choice of turbulence model and the requirements in b).

The power spectral densities of the three orthogonal components, $S_1(f)$, $S_2(f)$, and $S_3(f)$ shall asymptotically approach the following forms as the frequency in the inertial sub-range increases:

$$S_1(f) = 0,05 \sigma_1^2 (A_1 / V_{\text{hub}})^{-2/3} f^{-5/3} \quad (6)$$

$$S_2(f) = S_3(f) = \frac{4}{3} S_1(f) \quad (7)$$

- c) A recognized model for the coherence, defined as the magnitude of the co-spectrum divided by the auto-spectrum for the longitudinal velocity components at spatially separated points in a plane normal to the longitudinal direction, shall be used.

As an alternative, the corresponding Mann model may be applied as described in Annex C.

Other turbulence models may be applied; however, for the standard wind turbine classes (I to III), the turbulence model shall satisfy the requirements a) to c) and also result in fatigue loads that are higher or equal to the fatigue loads generated using the models in Annex C. For Class S, a validated turbulence model may be applied.

6.3.2 Normal wind conditions

6.3.2.1 Wind speed distribution

The wind speed distribution is significant for wind turbine design because it determines the frequency of occurrence of individual load conditions for the normal design situations. The mean value of the wind speed for an averaging period of 10 min shall be assumed to follow a Rayleigh distribution at hub height given by

$$P_R(V_{\text{hub}}) = 1 - \exp\left[-\pi(V_{\text{hub}} / 2V_{\text{ave}})^2\right] \quad (8)$$

where, in the standard wind turbine classes, V_{ave} shall be chosen from Table 1.

6.3.2.2 Normal wind profile model (NWP)

The wind profile, $V(z)$, denotes the average wind speed as a function of height, z , above the ground. In the case of the standard wind turbine classes, the normal wind speed profile shall be given by the power law:

$$V(z) = V_{\text{hub}} (z / z_{\text{hub}})^\alpha \quad (9)$$

The power law exponent, α , shall be assumed to be 0,2.

The assumed wind profile is used to define the average vertical wind shear across the rotor swept area.

6.3.2.3 Normal turbulence model (NTM)

For the normal turbulence model, the representative value of the turbulence standard deviation, σ_1 , shall be given by the 90 % quantile for the given hub height wind speed. This value for the standard wind turbine classes shall be given by

$$\sigma_1 = I_{\text{ref}} (0,75V_{\text{hub}} + b); \quad b = 5,6 \text{ m/s} \quad (10)$$

Values for the turbulence standard deviation σ_1 and the turbulence intensity σ_1/V_{hub} are shown in Figure 1.

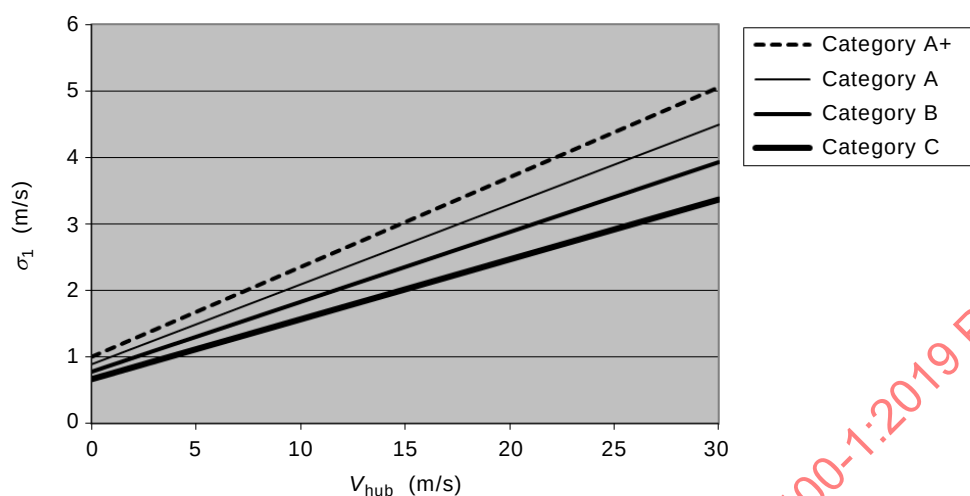


Figure 1a – Turbulence standard deviation

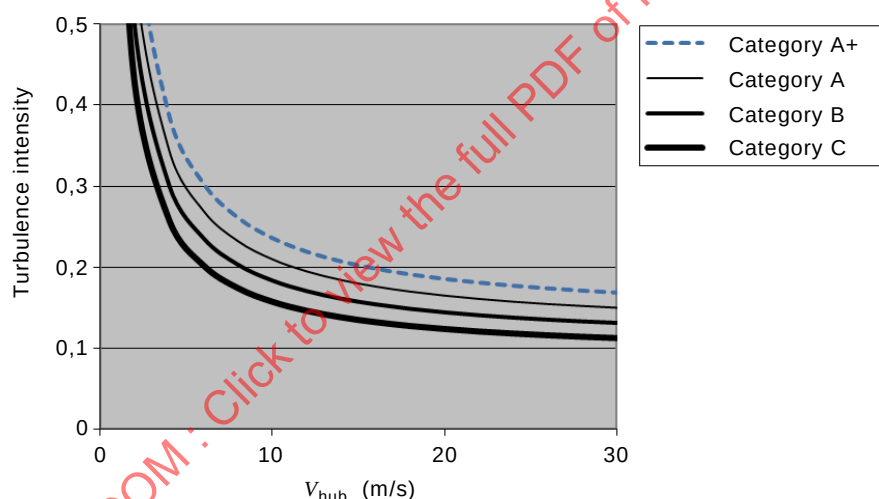


Figure 1b – Turbulence intensity

Figure 1 – Turbulence standard deviation and turbulence intensity for the normal turbulence model (NTM)

Values for I_{ref} are given in Table 1.

As an alternative to Equation (10), a Weibull distribution shall be assumed for σ_1 with Weibull scale and shape parameters:

$$P_W(\sigma_1 < \sigma_0) = 1 - \exp \left[- \left(\frac{\sigma_0}{C} \right)^k \right] \quad (11)$$

where

$$k = 0,27 V_{\text{hub}} (\text{s/m}) + 1,4$$

$$C = I_{\text{ref}} (0,75V_{\text{hub}} + 3,3 \text{ m/s}) \quad (12)$$

6.3.3 Extreme wind conditions

6.3.3.1 General

The extreme wind conditions include wind shear events, as well as peak wind speeds due to storms and rapid changes in wind speed and direction.

6.3.3.2 Extreme wind speed model (EWM)

The EWM shall be either a steady or a turbulent wind model. The wind models shall be based on the reference wind speed, V_{ref} , and a fixed turbulence standard deviation, σ_1 . If the wind turbine type is designed for a T class reference wind speed, V_{ref} shall be replaced by $V_{\text{ref,T}}$ in the extreme wind speed model while keeping other parameters.

For the steady extreme wind model, the extreme wind speed, V_{e50} , with a return period of 50 years, and the extreme wind speed, V_{e1} , with a return period of 1 year, shall be computed as a function of height, z , using the following equations:

$$V_{\text{e50}}(z) = 1,4 V_{\text{ref}} \left(\frac{z}{z_{\text{hub}}} \right)^{0,11} \quad (13)$$

and

$$V_{\text{e1}}(z) = 0,8 V_{\text{e50}}(z) \quad (14)$$

In the steady extreme wind model, allowance for short-term deviations from the mean wind direction shall be made by assuming constant yaw misalignment in the range of $\pm 15^\circ$.

For the turbulent extreme wind speed model, the 10 min average wind speeds as functions of z with return periods of 50 years and 1 year, respectively, shall be given by

$$V_{50}(z) = V_{\text{ref}} \left(\frac{z}{z_{\text{hub}}} \right)^{0,11} \quad (15)$$

$$V_1(z) = 0,8 V_{50}(z) \quad (16)$$

The longitudinal turbulence standard deviation³ shall be

$$\sigma_1 = 0,11 V_{\text{hub}} \quad (17)$$

6.3.3.3 Extreme operating gust (EOG)

The hub height gust magnitude V_{gust} ⁴ shall be given for the standard wind turbine classes by the following relationship:

³ The turbulence standard deviation for the turbulent extreme wind model is not related to the normal (NTM) or the extreme turbulence model (ETM). The steady extreme wind model is related to the turbulent extreme wind model by a peak factor of approximately 3,5.

⁴ The gust magnitude is calibrated, together with the probability of an operation event such as starts and stops, to give a return period of 50 years.

$$V_{\text{gust}} = \text{Min} \left\{ 1,35(V_{e1} - V_{\text{hub}}); 3,3 \left(\frac{\sigma_1}{1 + 0,1 \left(\frac{D}{A_1} \right)} \right) \right\} \quad (18)$$

where

σ_1 is given in Equation (10);

A_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The wind speed shall be defined by Equation (19):

$$V(z,t) = \begin{cases} V(z) - 0,37V_{\text{gust}} \sin(3\pi t / T) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V(z) & \text{otherwise} \end{cases} \quad (19)$$

where

$V(z)$ is defined in Equation (9);

$T = 10,5$ s.

An example of the extreme operating gust ($V_{\text{hub}} = 25$ m/s, Class I_A, $D = 42$ m) is shown in Figure 2.

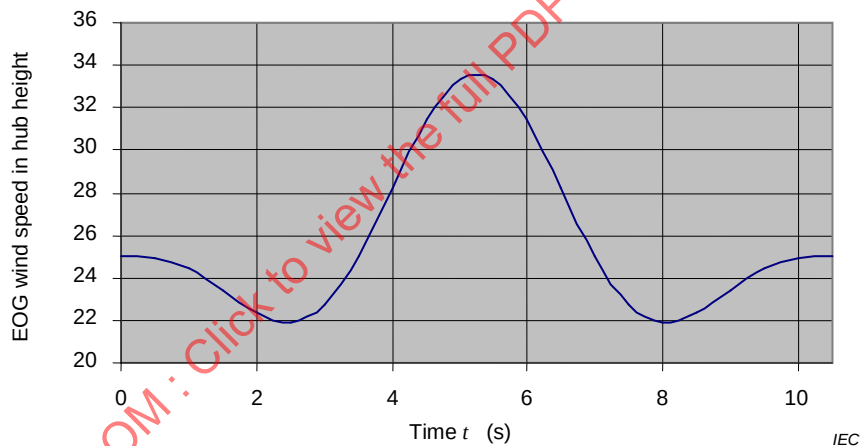


Figure 2 – Example of extreme operating gust

6.3.3.4 Extreme turbulence model (ETM)

The extreme turbulence model shall use the normal wind profile model in 6.3.2.2 and turbulence with longitudinal component standard deviation given by

$$\sigma_1 = c \cdot I_{\text{ref}} \left(0,072 \left(\frac{V_{\text{ave}}}{c} + 3 \right) \left(\frac{V_{\text{hub}}}{c} - 4 \right) + 10 \right); \quad c = 2 \text{ m/s.} \quad (20)$$

6.3.3.5 Extreme direction change (EDC)

The extreme direction change magnitude, θ_e , shall be calculated using the following relationship:

$$\theta_e = \pm 4 \arctan \left(\frac{\sigma_1}{V_{hub} \left(1 + 0,1 \left(\frac{D}{A_1} \right) \right)} \right) \quad (21)$$

where

- σ_1 is given by Equation (10) for the NTM;
- θ_e is limited to the interval $\pm 180^\circ$;
- A_1 is the turbulence scale parameter, according to Equation (5);
- D is the rotor diameter.

The extreme direction change transient, $\theta(t)$, shall be given by

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0,5\theta_e(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ \theta_e & \text{for } t > T \end{cases} \quad (22)$$

where $T = 6$ s is the duration of the extreme direction change. The sign shall be chosen so that the worst transient loading occurs. At the end of the direction change transient, the direction is assumed to remain unchanged. The wind speed shall follow the normal wind profile model in 6.3.2.2.

As an example, the magnitude of the extreme direction change with turbulence category A, $D = 42$ m, $z_{hub} = 30$ m is shown in Figure 3 for varying V_{hub} . The corresponding transient for $V_{hub} = 25$ m/s is shown in Figure 4.

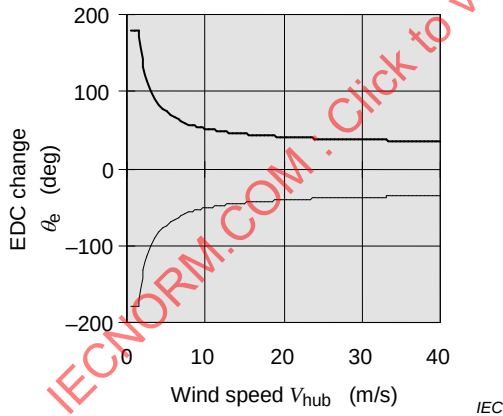


Figure 3 – Example of extreme direction change magnitude

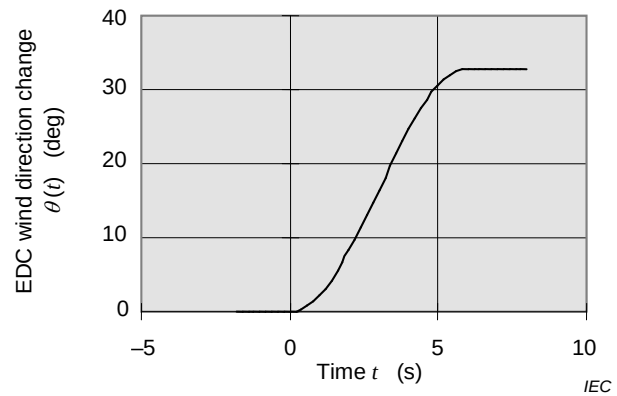


Figure 4 – Example of extreme direction change transient

6.3.3.6 Extreme coherent gust with direction change (ECD)

The extreme coherent gust with direction change shall have a magnitude of

$$V_{cg} = 15 \text{ m/s} \quad (23)$$

The wind speed shall be defined by

$$V(z,t) = \begin{cases} V(z) & \text{for } t \leq 0 \\ V(z) + 0,5V_{cg}(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ V(z) + V_{cg} & \text{for } t \geq T \end{cases} \quad (24)$$

where $T = 10$ s is the rise time and the wind speed $V(z)$ is given by the normal wind profile model in 6.3.2.2. The rise in wind speed during the extreme coherent gust is illustrated in Figure 5 for $V_{hub} = 25$ m/s.

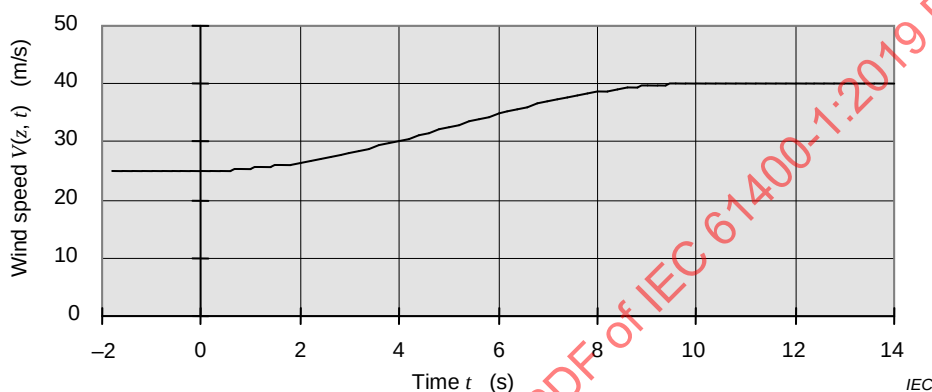


Figure 5 – Example of extreme coherent gust amplitude for ECD

The rise in wind speed shall be assumed to occur simultaneously with the direction change θ from 0° up to and including θ_{cg} , where the magnitude θ_{cg} is defined by

$$\theta_{cg}(V_{hub}) = \begin{cases} 180^\circ & \text{for } V_{hub} < 4 \text{ m/s} \\ \frac{720^\circ (V_{hub})}{V_{hub}} & \text{for } 4 \text{ m/s} < V_{hub} < V_{ref} \end{cases} \quad (25)$$

The simultaneous direction change is then given by

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0,5\theta_{cg}(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ \pm\theta_{cg} & \text{for } t > T \end{cases} \quad (26)$$

where $T = 10$ s is the rise time.

The direction change magnitude, θ_{cg} , and the direction change $\theta(t)$ are shown in Figures 6 and 7, as a function of V_{hub} and as a function of time for $V_{hub} = 25$ m/s, respectively.

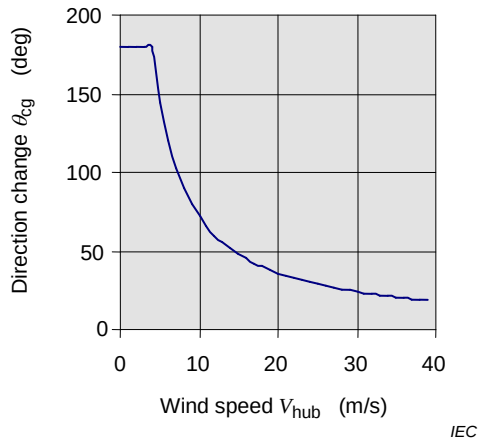


Figure 6 – Direction change for ECD

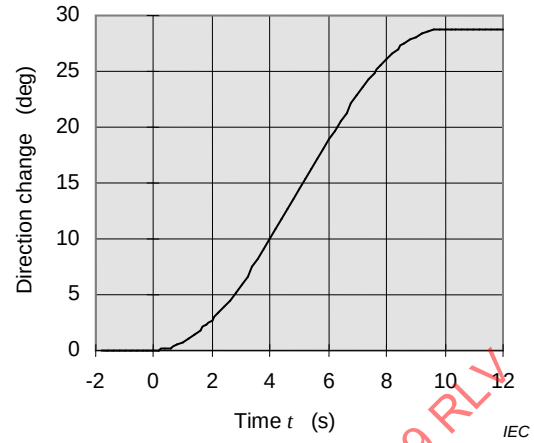


Figure 7 – Example of direction change transient

6.3.3.7 Extreme wind shear (EWS)

The extreme wind shear shall be accounted for using the following wind speed transients.

Transient (positive and negative) vertical shear:

$$V(z,t) = \begin{cases} V_{\text{hub}} \left(\frac{z}{z_{\text{hub}}} \right)^{\alpha} \pm \left(\frac{z - z_{\text{hub}}}{D} \right) \left(2,5[\text{m/s}] + 0,2\beta\sigma_1 \left(\frac{D}{A_1} \right)^{1/4} \right) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V_{\text{hub}} \left(\frac{z}{z_{\text{hub}}} \right)^{\alpha} & \text{otherwise} \end{cases} \quad (27)$$

Transient horizontal shear:

$$V(y,z,t) = \begin{cases} V_{\text{hub}} \left(\frac{z}{z_{\text{hub}}} \right)^{\alpha} \pm \left(\frac{y}{D} \right) \left(2,5[\text{m/s}] + 0,2\beta\sigma_1 \left(\frac{D}{A_1} \right)^{1/4} \right) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V_{\text{hub}} \left(\frac{z}{z_{\text{hub}}} \right)^{\alpha} & \text{otherwise} \end{cases} \quad (28)$$

where for both vertical and horizontal shear:

$\alpha = 0,2$; $\beta = 6,4$; $T = 12$ s;

σ_1 is given by Equation (10) for the NTM;

A_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The sign for the horizontal wind shear transient shall be chosen so that the worst transient loading occurs. The two extreme wind shears are not applied simultaneously.

As an example, the extreme vertical wind shear (turbulence category A, $z_{\text{hub}} = 30$ m, $V_{\text{hub}} = 25$ m/s, $D = 42$ m) is illustrated in Figure 8, which shows the wind profiles before onset

of the extreme event ($t = 0$ s) and at maximum shear ($t = 6$ s). Figure 9 shows the wind speeds at the top and the bottom of the rotor, to illustrate the time development of the shear (assumptions as in Figure 8).

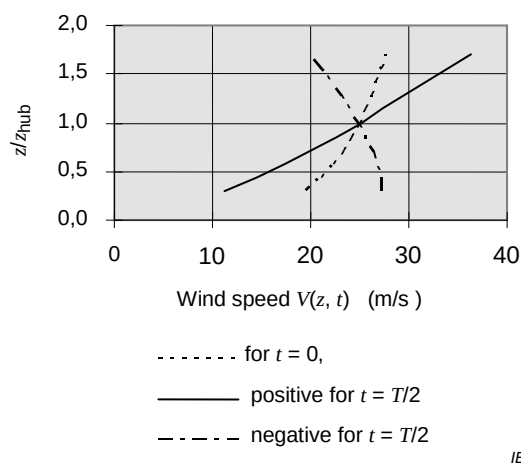


Figure 8 – Examples of extreme positive and negative vertical wind shear, wind profile before onset ($t = 0$, dashed line) and at maximum shear ($t = 6$ s, full line)

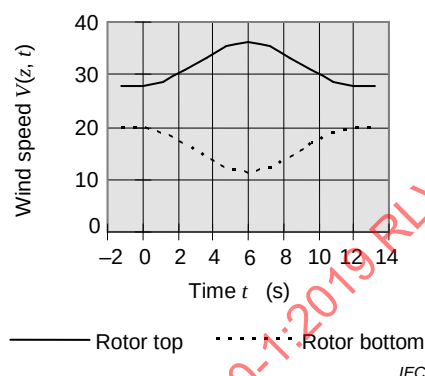


Figure 9 – Example of wind speeds at rotor top and bottom, respectively, which illustrate the transient positive wind shear

6.4 Other environmental conditions

6.4.1 General

Environmental (climatic) conditions other than wind can affect the integrity and safety of wind turbines, by thermal, photochemical, corrosive, mechanical, electrical or other physical action. Moreover, combinations of climatic conditions may increase their effects.

The following other environmental conditions, at least, shall be taken into account and the resulting action stated in the design documentation:

- temperature;
- humidity;
- air density;
- solar radiation;
- rain, hail, snow and ice;
- chemically active substances;
- mechanically active particles;
- salinity;
- lightning;
- earthquakes.

An offshore environment requires additional consideration, as per IEC 61400-3.

An optional cold climate class is defined in Clause 14.

The climatic conditions taken into account shall be defined in terms of either representative values or limits of the variable conditions. The probability of simultaneous occurrence of climatic conditions shall be taken into account when the design values are selected.

Variations in climatic conditions within the normal limits corresponding to a 1-year return period shall not interfere with the designed normal operation of a wind turbine.

Unless correlation exists, other extreme environmental conditions according to 6.4.3 shall be combined with normal wind conditions according to 6.3.2. A general description on how to combine design situations with external conditions is given in 7.4.

6.4.2 Normal other environmental conditions

The normal other environmental condition values that shall be taken into account are the following:

- ambient temperature range of -10 °C to $+40\text{ °C}$;
- relative humidity up to 95 %;
- atmospheric content equivalent to that of a non-polluted inland atmosphere (see IEC 60721-2-1);
- solar radiation intensity of $1\,000\text{ W/m}^2$;
- air density of $1,225\text{ kg/m}^3$.

When additional external conditions are specified by the designer, the parameters and their values shall be stated in the design documentation and shall conform to the requirements of IEC 60721-2-1.

6.4.3 Extreme other environmental conditions

6.4.3.1 General

The extreme other environmental conditions that shall be considered for wind turbine design are temperature, lightning, ice and earthquakes (see 11.6 for assessment of earthquake conditions).

6.4.3.2 Temperature

The extreme temperature range for the standard wind turbine classes shall be at least -20 °C to $+50\text{ °C}$.

6.4.3.3 Lightning

The provisions of lightning protection required in 10.7 may be considered as adequate for turbine designs for the standard wind turbine classes.

6.4.3.4 Ice

No minimum ice requirements are given for the standard wind turbine classes. For cold climate, ice requirements are given in Clause 14 and Annex L.

6.4.3.5 Earthquakes

No minimum earthquake requirements are given for the standard wind turbine classes. For consideration of earthquake conditions and effects, see 11.6 and Annex D.

6.5 Electrical power network conditions

The normal conditions at the wind turbine terminals to be considered are listed below.

Normal electrical power network conditions apply when the following parameters fall within the ranges stated below.

- Voltage – nominal value (according to IEC 60038) $\pm 10\%$.
- Frequency – nominal value $\pm 2\%$.
- Voltage imbalance – the ratio of the negative-sequence component of voltage not exceeding 2% .
- Auto-reclosing cycles – auto-reclosing cycle periods of 0,1 s to 5 s for the first reclosure and 10 s to 90 s for a second reclosure shall be considered.
- Outages – electrical network outages shall be assumed to occur 20 times per year. An outage of up to 6 h⁵ shall be considered a normal condition. An outage of up to 1 week shall be considered an extreme condition.

7 Structural design

7.1 General

The integrity of the load-carrying components of the wind turbine structure shall be verified and an acceptable safety level shall be ascertained. The ultimate and fatigue strength of structural members shall be verified by calculations, tests or both to demonstrate the structural integrity of a wind turbine with the appropriate safety level.

The structural analysis shall be based on ISO 2394.

Calculations shall be performed using appropriate methods. Descriptions of the calculation methods shall be provided in the design documentation. The descriptions shall include evidence of the validity of the calculation methods or references to suitable verification studies. The load level in any test for strength verification shall correspond to the safety factors appropriate for the characteristic loads according to 7.6.

Tower, rotor, and drive train resonances shall be identified for the frequency range up to and including 2 times the blade passing frequency excitation. Possible resonances shall be investigated at turbulence levels of 30 % of the NTM category C design turbulence for DLC 1.2, see 7.4.2. If high resonant loads are found at low turbulence, means shall be taken to avoid the resonances or they shall be included in the design loads.

7.2 Design methodology

It shall be verified that limit states are not exceeded for the wind turbine design. Model testing and prototype tests may also be used as a substitute for calculation to verify the structural design, as specified in ISO 2394.

The design calculations shall be based on validated methods and recognized codes.

The design methodology assumes that the aeroelastic simulation model used for the specific design calculations is subsequently validated by measurements. Such measurements shall be made on a wind turbine that is dynamically and structurally similar to, but may differ in detail (such as alternative tower designs) from the turbine designed. Requirements for load measurements can be found in IEC 61400-13.

7.3 Loads

7.3.1 General

Loads described in 7.3.2 through 7.3.5 shall be considered for the design calculations.

⁵ Six hours of operation is assumed to correspond to the duration of the severest part of a storm.

7.3.2 Gravitational and inertial loads

Gravitational and inertial loads are static and dynamic loads that result from gravity, vibration, rotation and seismic activity.

The allowable tolerances in tower verticality shall be stated in the design documentation and shall include initial and long term effects due to permanent soil subsidence. The effect of tower verticality on gravitational loads shall be taken into account separately during the structural analysis of tower and foundation.

7.3.3 Aerodynamic loads

Aerodynamic loads are static and dynamic loads that are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.

The airflow is dependent upon the average wind speed and turbulence across the rotor plane, the rotational speed of the rotor, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including aeroelastic effects.

It is not required in the aerodynamic load calculations to account for geometric tolerances in tower verticality of less than or equal to 3°.

7.3.4 Actuation loads

Actuation loads result from the operation and control of wind turbines. They are in several categories including torque control from a generator or inverter or both, yaw and pitch actuator loads and mechanical braking loads. In each case, it is important in the calculation of response and loading to consider the range of actuator forces available, including friction. In particular, for mechanical brakes, the range of friction, spring force or pressure as influenced by temperature, and ageing shall be taken into account in checking the response and the loading during any braking event.

7.3.5 Other loads

Other loads such as wake loads, impact loads, ice loads, tower loads resulting for example from vortex-induced vibrations might occur and shall be considered where appropriate. For other loads associated with cold climate, see Clause 14 and Annex L.

7.4 Design situations and load cases

7.4.1 General

Subclause 7.4 describes the design load cases for a wind turbine and specifies a minimum number to be considered.

For design purposes, the life of a wind turbine can be represented by a set of design situations covering the most significant conditions that the wind turbine may experience.

The load cases shall be determined from the combination of operational modes or other design situations, such as specific assembly, erection or maintenance conditions, with the external conditions. All relevant load cases with a reasonable probability of occurrence shall be considered, together with the behaviour of the control system. The design load cases used to verify the structural integrity of a wind turbine shall be calculated by combining the following:

- normal design situations and appropriate normal or extreme external conditions;
- fault design situations and appropriate external conditions;
- transportation, installation and maintenance design situations and appropriate external conditions.

If correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a design load case.

Within each design situation, several design load cases shall be considered. As a minimum, the design load cases in Table 2 shall be considered. In that table, the design load cases are specified for each design situation by the description of the wind, electrical and other external conditions.

If the wind turbine controller can, during design load cases with a deterministic wind model, cause the wind turbine to shut down prior to reaching maximum yaw angle and/or wind speed, then it shall be shown that the turbine can reliably shut down under turbulent conditions with the same deterministic wind condition change.

Other design load cases shall be considered, if relevant to the structural integrity of the specific wind turbine design.

For each design load case, the appropriate type of analysis is stated by "F" and "U" in Table 2. "F" refers to analysis of fatigue loads, to be used in the assessment of fatigue strength. "U" refers to the analysis of ultimate loads, with reference to material strength, blade tip deflection and structural stability.

The design load cases indicated with "U" are classified as normal (N) or abnormal (A). Normal design load cases are expected to occur frequently. The turbine is in a normal state or may have experienced minor faults or abnormalities. Abnormal design situations are less likely to occur. They usually correspond to design situations with severe faults that result in the activation of system protection functions. The type of design situation, N or A, determines the partial safety factor γ_f to be applied to the ultimate loads. These factors are given in Table 3.

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Table 2 – Design load cases (DLC)

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM $V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD $V_{hub} = V_r - 2 \text{ m/s}, V_r, V_r + 2 \text{ m/s}$		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Normal control system fault or loss of electrical network or primary layer control function fault (see 7.4.3)	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Abnormal control system fault or secondary layer protection function related fault (see 7.4.3)	U	A
	2.3	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	Control system fault, electrical fault or loss of electrical network	F	*
	2.5	NWP $V_{in} < V_{hub} < V_{out}$	Low voltage ride through	U	N
3) Start-up	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
	3.3	EDC $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
4) Normal shutdown	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
5) Emergency stop	5.1	NTM $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM 50-year return period		U	N
	6.2	EWM 50-year return period	Loss of electrical network connection	U	A
	6.3	EWM 1-year return period	Extreme yaw misalignment	U	N
	6.4	NTM $V_{hub} < 0,7 V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM 1-year return period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM V_{maint} to be stated by the manufacturer		U	N
	8.2	EWM 1-year return period		U	A

Key	
DLC	Design load case
ECD	Extreme coherent gust with direction change (see 6.3.3.6)
EDC	Extreme direction change (see 6.3.3.5)
EOG	Extreme operating gust (see 6.3.3.3)
EWM	Extreme wind speed model (see 6.3.3.2)
EWS	Extreme wind shear (see 6.3.3.7)
NTM	Normal turbulence model (see 6.3.2.3)
ETM	Extreme turbulence model (see 6.3.3.4)
NWP	Normal wind profile model (see 6.3.2.2)
$V_r \pm 2$ m/s	Sensitivity to all wind speeds in the range shall be analysed
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
*	Partial safety for fatigue (see 7.6.3)

When a wind speed range is indicated in Table 2, wind speeds leading to the most adverse condition for wind turbine design shall be considered. The range of wind speeds may be represented by a set of discrete values, in which case the resolution shall be sufficient to assure accuracy of the calculation⁶. In the definition of the design load cases, reference is made to the wind conditions described in Clause 6.

In the further specifications of design load cases (DLCs) in 7.4.2 to 7.4.9, some DLCs allow alternative formulations. Where alternatives are mentioned, the party designing to this document shall decide which alternative shall be used throughout the analysis of the DLC.

7.4.2 Power production (DLC 1.1 to 1.5)

In this design situation, a wind turbine is running and connected to the electric load. The assumed wind turbine configuration shall take into account rotor imbalance. The maximum mass and aerodynamic imbalances (e.g. blade pitch and twist deviations) specified for rotor manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating situations such as yaw misalignment and control system tracking errors shall be taken into account in the analyses of operational loads.

Design load cases (DLCs) 1.1 and 1.2 embody the requirements for loads resulting from atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime (NTM). DLC 1.3 embodies the requirements for ultimate loading resulting from extreme turbulence conditions. DLC 1.4 and 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine.

The statistical analysis of DLC 1.1 simulation data, see 7.6.2.2 and Annex G, shall include at least the calculation of extreme values of the blade root in-plane moment and out-of-plane moment and tip deflection. If the extreme design values of the blade root moments derived from DLC 1.1 are exceeded by the extreme design values derived for DLC 1.3, the further analysis of DLC 1.1 may be omitted.

If the extreme design values of the blade root moments derived from DLC 1.1 are not exceeded by the extreme design values derived for DLC 1.3, the factor c in Equation (20) for

⁶ In general, a resolution of 2 m/s is considered sufficient. However, in the wind speed range where the power curve rises quickly, 2 m/s steps may be too large to assure accuracy.

the extreme turbulence model used in DLC 1.3 may be increased until the extreme design values of the blade root moments computed in DLC 1.3 are equal to or exceed the relevant extremes. The characteristic values of the loads relevant for other turbine components may be determined from this analysis based on DLC 1.3 with the increased c value. As an alternative to this analysis, the appropriate characteristic values of all load components relevant for each specific turbine component may be directly determined or extrapolated from the simulation.

7.4.3 Power production plus occurrence of fault or loss of electrical network connection (DLC 2.1 to 2.5)

7.4.3.1 General

This design situation involves a transient event triggered by a fault or by the loss of electrical network connection while the turbine is producing power. Any fault in the control system, or internal fault in the electrical system, significant for wind turbine loading (such as generator short circuit) shall be considered. This design situation is considered to be relevant for fatigue analysis as well, see DLC 2.4.

A failure mode and effect analysis (FMEA) or equivalent fault analysis shall be carried out to determine fault events relevant for the wind turbine loading.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random.

Faults in the control system shall be considered in DLC 2.1 and DLC 2.2 as described in 7.4.3.2. For architectures where turbine safety is ensured by two independent sets of functions (via primary layer control functions and secondary layer protection functions, respectively), the method described in 7.4.3.3 may be used. See Clause 8 for guidance on identification of failure modes, assessment of failure mode return periods, fault exclusions, and measures to avoid common-cause failures.

7.4.3.2 Control system failure (DLC 2.1 and DLC 2.2) – Quantitative approach

For DLC 2.1, the following shall be considered as normal events:

- a) control system failure related events that have an expected failure mode return period that is equal to or less than 50 years;
- b) control system failure related events where the expected failure mode return period cannot be obtained;
- c) loss of electrical network connection.

For events with expected failure mode return periods between 10 and 50 years, the partial load factor applied is found as function of the failure mode return period as stated in Table 3.

For DLC 2.2, control system failure events or internal electrical and mechanical system faults with expected failure mode return period greater than 50 years shall be considered as abnormal.

Fault events with a return period in excess of 2000 years and fault events that are not relevant for wind turbine loading may be disregarded. The fault event return period is based on the statistical calculation of the probability of an event whereby a control or internal electrical system part is in or enters a failed state such that a structural failure could occur.

7.4.3.3 Control system failure (DLC 2.1 and DLC 2.2) – Two-layer approach

This approach can be used for control system architectures consisting of two or more independent layers. Within this approach,

- a) primary layer control and protection functions aim to keep the turbine operating parameters within their normal operating limits and their design limits, respectively, and
- b) secondary layer protection functions aim to keep the turbine operating parameters within their design limits. These shall be activated as a result of failure of the primary layer control functions or as a result of the effects of an internal or external failure or dangerous event.

For DLC 2.1, primary layer control function faults, activation of primary layer protection functions or loss of electrical network connection shall be considered as normal events. Control function faults which lead to exceedance of the limits and the activation of the secondary layer protection functions shall be included in DLC 2.2.

Primary layer control function faults considered in DLC 2.1 typically include faults relating to rotor speed, yaw angle, and blade pitch angles.

For DLC 2.2, rare events that have relevance for the wind turbine loading, including faults relating to activation of secondary layer protection functions, shall be considered as abnormal. Such faults may include erroneous activation of actuators, non-activation of braking systems, and blocking of the pitch system. This load case shall at least address the following: independent overspeed protection, generator overload/fault protection, uncontrolled blade pitch protection (blade pitch runaway), uncontrolled yaw protection and excessive vibration or shock protection.

7.4.3.4 Other power production plus occurrence of fault or loss of electrical network connection (DLC 2.3 to 2.5)

For DLC 2.3, the potentially significant wind event, the extreme operating gust (EOG), is combined with loss of one or more phases in a multiphase electrical network connection and considered as an abnormal event. In this case, the timing of these two events shall be chosen to achieve the worst loading.

As an alternative to the specification of DLC 2.3 above and in Table 2, DLC 2.3 may instead be considered as a normal event (i.e. a partial safety factor for load of 1,35) to be analysed using stochastic wind simulations ($NTM - V_{in} < V_{hub} < V_{out}$) combined with an internal or external electrical system fault (including loss of electrical network connection). In this case, 12 response simulations shall be carried out for each considered mean wind speed. For each response simulation, the extreme response after the electrical fault has occurred is sampled. The fault shall be introduced after the effect of initial conditions has become negligible. For each mean wind speed, a nominal extreme response is evaluated as the mean of the 12 sampled extreme responses plus three times the standard deviation of the 12 samples. The characteristic response value for DLC 2.3 is determined as the extreme value among the nominal extreme responses.

If a fault or loss of electrical network connection does not cause an immediate shutdown and the subsequent loading can lead to significant fatigue damage, the likely duration of this situation along with the resulting fatigue damage in normal turbulence conditions (NTM) shall be evaluated in DLC 2.4. The manufacturer shall estimate the expected frequency/duration for the events⁷.

⁷ If there is no relevant data/information available, the following frequency/duration can be applied for the below listed events:

- 10 shut-downs per year for overspeed event;
- 24 hours per year of operation for events with yaw error;
- 24 hours per year of operation for events with pitch error;
- 20 times per year with loss of electrical network connection.

For DLC 2.5, the event of low voltage ride through (LVRT)⁸ is considered as normal. The design low voltage ride through event shall be specified by voltage drop and duration.

7.4.4 Start-up (DLC 3.1 to 3.3)

This design situation includes all the events resulting in loads on a wind turbine during the transients from any standstill or idling situation to power production. The number of occurrences shall be estimated based on the control system behaviour.⁹

For DLC 3.2, at least four different timing events between the EOG and the start-up event shall be considered for each wind speed. The first timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 50 % of maximum power. The last timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 95 % of maximum power. At least two additional timings shall be chosen, evenly distributed within the interval from 50 % to 95 % of maximum power.

For each wind speed, the characteristic value of the load may be computed as the average value of the extreme computed transient value for the four defined distinct points of time.

As an alternative to the EOG gust, the DLC 3.2 may instead be analysed using at least 12 stochastic wind simulations for each mean wind speed with the ETM. For each mean wind speed, a nominal extreme response is evaluated as the mean of the simulated extremes.

7.4.5 Normal shutdown (DLC 4.1 to 4.2)

This design situation includes all the events resulting in loads on a wind turbine during normal transient situations from a power production situation to a standstill or idling condition. The number of occurrences shall be estimated based on the control system behaviour.¹⁰

For DLC 4.2, the timing of the gust and the shutdown event shall be chosen such that the EOG gust starts at different times relative to the shutdown, with minimum six events evenly distributed from 10 s before the beginning of the shutdown, till the power reaches 50 % of the initial power production level.

At least four evenly distributed rotor azimuth positions shall be applied for each distinct point of time. For each wind speed, the characteristic value of the load may be computed as the mean value of the extreme computed loads among all timings and azimuth positions considered.

If, due to the safety and control system, a shutdown event is automatically triggered during the EOG gust, that event shall also be considered in the analysis.

⁸ Low voltage ride through situations are normally defined by the electrical utilities as situations with grid disturbances or failures the wind turbine should be able to handle without shutting down. The reason for a demand for riding through these situations is that if the wind turbines (especially in wind farms) shut down it can result in a collapse of the grid.

⁹ If historical data on start-ups for similar wind turbines are unavailable, the following annual frequencies for DLC 3.1 can be assumed:

- 1000 start-up procedures at V_{in} ;
- 50 start-up procedures at V_r ;
- 50 start-up procedures at maximum start-up wind speed.

¹⁰ If historical data on shutdowns for similar wind turbines are unavailable, the following annual frequencies for DLC 4.1 can be assumed:

- 1000 shut-down procedures at V_{in} ;
- 50 shut-down procedures at V_r ;
- 50 shut-down procedures at V_{out} .

As an alternative to the EOG gust, the DLC 4.2 may instead be analysed using at least 12 stochastic wind simulations for each mean wind speed with the ETM. For each mean wind speed, a nominal extreme response is evaluated as the mean of simulated extremes.

7.4.6 Emergency stop (DLC 5.1)

Loads arising from activation of the emergency stop button shall be considered.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random.

7.4.7 Parked (standstill or idling) (DLC 6.1 to 6.4)

In this design situation, the rotor of a parked wind turbine is either in a standstill or idling condition. In DLC 6.1, 6.2 and 6.3, this situation shall be considered with the extreme wind speed model (EWM). For DLC 6.4, the normal turbulence model (NTM) shall be considered.

For design load cases, where the wind conditions are defined by EWM, either the steady extreme wind model or the turbulent extreme wind model may be used. If the turbulent extreme wind model is used, the response shall be estimated using either a full dynamic simulation or a quasi-steady analysis with appropriate corrections for gusts and dynamic response using the formulation in ISO 4354. If the steady extreme wind model is used, the effects of resonant response shall be estimated from the quasi-steady analysis above. If the ratio of resonant to background response (R/B) is less than 5 %, a static analysis using the steady extreme wind model may be used. If slippage in the wind turbine yaw system can occur at the characteristic load, the largest possible unfavourable slippage shall be added to the mean yaw misalignment. If the wind turbine has a yaw system where yaw movement is expected in the extreme wind situations (e.g. free yaw, passive yaw or semi-free yaw), the turbulent wind model shall be used and the yaw misalignment will be governed by the turbulent wind direction changes and the turbine yaw dynamic response. Also, if the wind turbine is subject to large yaw movements or change of equilibrium during a wind speed increase from normal operation to the extreme situation, this behaviour shall be included in the analysis.

In DLC 6.1, for a wind turbine with an active yaw system, a yaw misalignment of up to $\pm 15^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 8^\circ$ using the turbulent extreme wind model shall be imposed, provided restraint against slippage in the yaw system can be assured.

In DLC 6.2, a loss of the electrical power network at an early stage in a storm containing the extreme wind situation shall be assumed. Unless power back-up is provided for the control and yaw system with a capacity for yaw alignment for a period of at least 6 h, the effect of a wind direction change of up to $\pm 180^\circ$ shall be analysed.

The partial safety factors for loads for DLC 6.1 and DLC 6.2 in Table 3 are derived by assuming that the coefficient of variation of the annual maximum wind speed is smaller than 15 %; for other COV, see footnote 31 in 11.3.2.

In DLC 6.3, the extreme wind with a 1-year return period shall be combined with an extreme yaw misalignment. An extreme yaw misalignment of up to $\pm 30^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 20^\circ$ using the turbulent wind model shall be assumed.

If for the cases DLC 6.1 with steady extreme wind model, DLC 6.2 and DLC 6.3, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades.

In DLC 6.4, the expected number of hours of non-power production time at a fluctuating load appropriate for each wind speed where significant fatigue damage can occur to any components (e.g. from the weight of idling blades) shall be considered.

7.4.8 Parked plus fault conditions (DLC 7.1)

Deviations from the normal behaviour of a parked wind turbine, resulting from faults on the electrical network or in the wind turbine, shall require analysis. As a minimum, failures in the following systems shall be evaluated: brake system, pitch system, and yaw system. The fault condition shall be combined with EWM for a return period of one year. Those conditions shall be either turbulent or quasi-steady with correction for gusts and dynamic response.

In case of a fault in the yaw system, yaw misalignment of $\pm 180^\circ$ shall be considered. If for the cases DLC 7.1 with fault in the yaw system, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades. For any other fault, yaw misalignment shall be consistent with DLC 6.1.

If slippage in the yaw system can occur at the characteristic load found in DLC 7.1, the largest unfavourable slippage possible shall be considered.

7.4.9 Transport, assembly, maintenance and repair (DLC 8.1 and 8.2)

For DLC 8.1, the manufacturer shall state all the wind conditions and design situations assumed for transport, assembly on site, maintenance and repair of a wind turbine. The maximum stated wind conditions shall be considered in the design if they can produce significant loading on the turbine. The manufacturer shall allow sufficient margin between the stated conditions and the wind conditions considered in design to give an acceptable safety level. Sufficient margin may be obtained by adding 5 m/s to the stated wind condition.

In addition, DLC 8.2 shall include all transport, assembly, maintenance and repair turbine states which may persist for longer than one week. This shall, when relevant, include a partially completed tower, the tower standing without the nacelle and the turbine without one or more blades. In the case of a tower standing without a nacelle, appropriate means shall be taken to avoid critical wind speeds for vortex generated transverse vibrations, or the appropriate fatigue design load case shall be added¹¹. It shall be assumed that the electrical network is not connected in any of these states. Measures may be taken to reduce the loads during any of these states as long as these measures do not require the electrical network connection.

Blocking devices shall be able to sustain the loads arising from relevant situations in DLC 8.1. Non-redundant blocking devices shall be designed in component class 3. In particular, application of maximum design actuator forces shall be taken into account. It is recommended that standards for lifting appliances including safety factors/influence factors are additionally applied when relevant. Unless permanently installed, the lifting appliance itself is not covered by this document and should be designed and tested according to relevant standards for lifting appliances.

7.5 Load calculations

Loads as described in 7.3.2 through 7.3.5 shall be taken into account for each design load case. Where relevant, the following shall also be taken into account:

- wind field perturbations due to the wind turbine itself (wake induced velocities, tower shadow, etc.);
- the influence of three dimensional flow on the blade aerodynamic characteristics (e.g. three dimensional stall and aerodynamic tip loss);
- unsteady aerodynamic effects;
- structural dynamics and the coupling of vibration modes;

¹¹ Guidance for tower loads from vortex-induced vibrations can be found in IEC 61400-6 (under preparation; stage at the time of publication: IEC CDV 61400-6:2017).

- aeroelastic effects;
- the behaviour of the control system of the wind turbine.

Dynamic simulations utilizing a structural dynamics model are usually used to calculate wind turbine loads. Certain load cases have a turbulent wind input. The total period of load data, for these cases, shall be long enough to ensure statistical reliability of the estimate of the characteristic load. At least six 10-min stochastic realizations (or a continuous 60 min period) shall be required for each mean, hub-height wind speed used in the simulations. However, for DLC 2.1, 2.2 and 5.1, at least 12 simulations shall be carried out for each event at the given wind speed. Since the initial conditions used for the dynamic simulations typically have an effect on the load statistics during the beginning of the simulation period, the first 5 s of data (or longer if necessary) shall be eliminated from consideration in any analysis interval involving turbulent wind input.

It shall be ensured that during application of a cycle count on the load time series, the remaining residuals from each time series shall be taken into consideration by half-cycles for fatigue failure mode evaluation. Furthermore, the discretization of the load range shall ensure a sufficient resolution.

When turbulent winds are used for dynamic simulations, attention should be given to the grid resolution regarding the spatial¹² and time resolution.

In many cases, the local strains or stresses for critical locations in a given wind turbine component are governed by simultaneous multi-axial loading. In this case, time series of orthogonal loads that are output from simulations are sometimes used to specify design loads. When such orthogonal component time series are used to calculate fatigue and ultimate loads, they shall be combined to preserve both phase and magnitude. Thus, the direct method is based on the derivation of the significant stress as a time history. Extreme and fatigue prediction methods can then be applied to this single signal, avoiding load combination issues.

Ultimate load components may also be combined in a conservative manner assuming the extreme component values occur simultaneously. In case this option is pursued, both minimum and maximum extreme component values shall be applied in all possible combinations to avoid introducing non-conservatism.

Guidance for the derivation of extreme design loads from contemporaneous loads taken from a number of realizations is given in Annex I.

7.6 Ultimate limit state analysis

7.6.1 Method

7.6.1.1 General

Partial safety factors account for the uncertainties and variability in loads and resistances, the uncertainties in the analysis methods and the importance of structural components with respect to the consequences of failure.

For the ultimate limit state analysis of the wind turbine, the following four types of analysis shall be performed where relevant:

- analysis of ultimate strength (see 7.6.2);

¹² Concerning the spatial resolution, the maximum distance between adjacent points should be smaller than 25 % of λ_1 (Equation (5)) and no larger than 15 % of the rotor diameter. This distance is meant to be the diagonal distance between points in each grid cell defined by four points. In the case of a non-uniform grid, an average value over the rotor surface of the distance between grid points can be considered as the representative spatial resolution, but this distance typically decreases towards the blade tip.

- analysis of fatigue failure (see 7.6.3);
- stability analysis (e.g. buckling) (see 7.6.4);
- critical deflection analysis (mechanical interference between blade and tower, etc.) (see 7.6.5).

Each type of analysis requires a different formulation of the limit state function and deals with different sources of uncertainties through the use of safety factors.

7.6.1.2 Partial safety factors for loads and resistance

The uncertainties and variability in loads and resistances (including variability in materials) are taken into account by partial safety factors as defined in Equations (29) and (30) in order to assure safe design values.

$$F_d = \gamma_f F_k \quad (29)$$

where

- F_d is the design value for the aggregated internal load or load response to multiple simultaneous load components from various sources for the given design load case;
- γ_f is the partial safety factor for loads;
- F_k is the characteristic value for the load.

$$R_d = \frac{1}{\gamma_M} R_k \quad (30)$$

where

- R_d are the design values for resistances, see Annex K;
- γ_M are the partial safety factors¹³ accounting for uncertainties in the material parameters and resistance models, see Annex K;
- R_k are the characteristic values of resistances including load duration effects, scale effects, etc. accounted for by a conversion factor, see Annex K.

The partial safety factors for loads used in this document take account of

- a) possible unfavourable deviations/uncertainties of the load from the characteristic value, and
- b) uncertainties in the loading model.

The partial safety factors for resistances γ_M used in this document, as in ISO 2394, take account of

- possible unfavourable deviations/uncertainties of the strength of material from the characteristic value,
- possible inaccurate assessment of the resistance of sections or load-carrying capacity of parts of the structure,
- uncertainties in the geometrical parameters,
- uncertainties in the relation between the material properties in the structure and those measured by tests on control specimens, and
- uncertainties in conversion factors.

¹³ Alternatively, the partial safety factor for resistance γ_M can be included as a partial safety factor related to uncertainty in material parameters and a partial safety factor related to uncertainty in the resistance model, see Annex K.

These different uncertainties are sometimes accounted for by means of individual partial safety factors; but in this document, as in most others, the load related factors are combined into one factor, γ_f , and the material and resistance related factors into one factor, γ_M . Values of γ_f and γ_M are given in 7.6.2 to 7.6.5. However, these values may be replaced if it can be documented that assumptions leading to these values are conservative, in which case a calibration of load and resistance safety factors may be performed to meet the intended safety level in this document¹⁴.

7.6.1.3 Partial safety factor for consequence of failure and component classes

A consequence of failure factor, γ_n , is introduced to distinguish between:

- a) component class 1: used for "fail-safe" structural components whose failure does not result in the failure of a major part of a wind turbine, for example replaceable bearings with monitoring;
- b) component class 2: used for "safe-life" structural components whose failures may lead to the failure of a major part of a wind turbine;
- c) component class 3: used for "safe-life" mechanical components that link actuators and brakes to main structural components for the purpose of implementing non-redundant wind turbine protection functions. Regarding blocking devices, see 7.4.9.

Partial safety factors for consequences of failure:

- component class 1: $\gamma_n = 0,9$;
- component class 2: $\gamma_n = 1,0$;
- component class 3: $\gamma_n = 1,2$.

The consequences of failure factor shall be included in the test load when performing tests such as, for example, full scale blade testing.

Other values of γ_n apply for critical deflection analysis, see 7.6.5.

7.6.1.4 Application of recognized material codes

When determining the structural integrity of elements of a wind turbine, national or international design codes for the relevant material may be employed. Special care shall be taken when partial safety factors from national or international design codes are used together with partial safety factors from this document. It shall be ensured that the resulting safety level is not less than the intended safety level in this document.

Different codes subdivide the partial safety factors for resistance, γ_M , into several material factors accounting for separate types of uncertainty, for example inherent variability of material strength, extent of production control or production method. If the code gives partial safety factors or uses reduction factors on the characteristic values to account for other uncertainties, these shall also be taken into account.

Individual codes may choose different factorizations of partial safety factors on the load and the material parts of the design verification. The division of factors intended here is the one defined in ISO 2394. If the division of factors in the code of choice deviates from that of ISO 2394, the necessary adjustments in the code of choice shall be taken into account in verifications according to this document.

¹⁴ Annex K provides a guideline for calibration of material partial safety factors.

7.6.2 Ultimate strength analysis

7.6.2.1 General

The limit state function can be separated into load and resistance functions S and R so that the condition becomes

$$\gamma_n \cdot S(F_d) \leq R_d \quad (31)$$

The function S for ultimate strength analysis is usually defined as the highest value of the structural response, hence $S(F_d) = F_d$. The equation then becomes

$$\gamma_n \gamma_f F_k \leq \frac{1}{\gamma_M} R_k \quad (32)$$

Note that γ_n is a consequence of failure factor and shall not be treated as a safety factor on materials.

For each wind turbine component assessed and for each load case in Table 2 where ultimate strength analysis is appropriate, the limit state condition in Equation (32) shall be verified for the most critical limit state, identified on the basis of having the least margin.

7.6.2.2 Partial safety factors for loads

For DLC 1.1, a characteristic value of load shall be determined by a statistical analysis of the extreme loading that occurs for normal design situations and shall correspond to one of the following alternatives.

- The characteristic value is obtained as the largest (or smallest) among the average values of the 10 min extremes determined for each wind speed in the given range, multiplied by 1,35. This method can only be applied for the calculation of the blade root in-plane moment and out-of-plane moment and tip deflection.
- The characteristic value is obtained as the largest (or smallest) among the 99th percentile (or 1st percentile in the case of minima) values of the 10 min extremes determined for each wind speed in the given range, multiplied by 1,2.
- The characteristic value is obtained as the value corresponding to a 50 year return period, based on load extrapolation methods, considering the wind speed distribution given in 6.3.2.1 and the normal turbulence model in 6.3.2.3. Guidance about load extrapolation is given in Annex G.

The design load will be then obtained by multiplying the characteristic loads according to any of these alternatives by the partial safety factor for DLC 1.1 defined in Table 3.

For all three alternatives above, data used in the statistical analysis shall be extracted from time series of turbine simulations of at least 10 minutes in length over the operating range of the turbine for DLC 1.1. A minimum of 15 simulations is required for each wind speed from $(V_r - 2 \text{ m/s})$ to cut-out, and six simulations are required for each wind speed below $(V_r - 2 \text{ m/s})$. When extracting data, the designer shall consider the effect of independence between peaks on the statistical analysis and minimize dependence when possible. For guidance on dependency checks, see Annex G.

For load cases with specified deterministic wind field events, the characteristic value of the load shall be the worst case computed transient value. If more simulations are performed at a given wind speed, representing the rotor azimuth, the characteristic value for the load case is taken as the average value of the worst case computed transient values at each azimuth. Guidance for the derivation of the contemporaneous load can be found in Annex I. When turbulent inflow is used, the mean value among the worst case computed loads for different

10 min stochastic realizations shall be taken, except for DLC 2.1, 2.2 and 5.1, where the characteristic value of the load shall be the mean value of the largest half of the maximum loads.

Partial safety factors for loads shall be at least the values specified in Table 3.

The approach in 7.6.1.2, where the partial safety factor for loads is applied to the load response, assumes that a proper representation of the dynamic response is of prime concern. Where a proper representation of non-linear material behaviour or geometrical nonlinearities (such as, for example, for foundations) or both are of primary concern, the design load response S_d shall be obtained from a structural analysis for the combination of the design loads F_d , where the design load is obtained by multiplication of the characteristic loads F_k by the specified partial load factor γ_f for favourable and unfavourable loads:

$$F_d = \gamma_f F_k \quad (33)$$

The load responses in the tower at the interface (shear forces and bending moments) factored with γ_f from Table 3 shall be applied as boundary conditions.

Table 3 – Partial safety factors for loads γ_f

Unfavourable loads		Favourable loads ¹⁵
Type of design situation (see Table 2)		All design situations
Normal (N)	Abnormal (A)	
1,35 ^a	1,1	0,9
^a For design load case DLC 1.1, the partial load factor shall be $\gamma_f = 1,25$. If for normal design situations the characteristic value of the load response $F_{gravity}$ due to gravity can be calculated for the design situation in question, and gravity is an unfavourable load, the partial load factor for combined loading from gravity and other sources may have the value $\gamma_f = 1,1 + \varphi \zeta^2 \text{ and } \varphi = \begin{cases} 0,15 & \text{for DLC 1.1} \\ 0,25 & \text{otherwise} \end{cases}$ $\zeta = \begin{cases} 1 - \left \frac{F_{gravity}}{F_k} \right & ; F_{gravity} \leq F_k \\ 0 & ; F_{gravity} > F_k \end{cases}$ For design load case DLC 2.1, the partial load factor may be calculated from the following expression if the mean time between failures (MTBF), in years, for the considered failure mode has been evaluated (see 7.4.3.2): $\gamma_f = \begin{cases} 1,35 & \text{MTBF} \leq 10 \\ 1,71 - 0,155 \ln(\text{MTBF}) & 10 < \text{MTBF} \leq 50 \\ 1,10 & \text{MTBF} > 50 \end{cases}$ For design load case DLC 2.5, the partial load factor shall be 1,2.		

Use of the partial safety factors for loads for normal and abnormal design situations specified in Table 3 requires that the load calculation model is validated by load measurements. These measurements shall be made on a wind turbine that is similar to the wind turbine design under consideration with respect to aerodynamics, control and dynamic response.

¹⁵ Pretension and gravity loads that significantly relieve the total load response are considered favourable loads. In the case of both favourable and unfavourable loads, Equation (32) becomes

$$\gamma_n S(\gamma_{t,unfav} F_{k,unfav}, \gamma_{t,fav} F_{k,fav}) \leq R(f_d)$$

7.6.2.3 Partial safety factors for gravity foundations

For gravity foundations, the limit states considering overall stability (rigid body motion with no failure in soil) and bearing capacity of soil and foundation shall be regarded and calculated according to a recognized standard. In general, a partial safety factor of $\gamma_f = 1,1$ for unfavourable gravity loads and $\gamma_f = 0,9$ for favourable gravity loads shall be applied for foundation load, backfilling and buoyancy. If it can be demonstrated by respective quality management and surveillance that the foundation material densities specified in the design documentation are met on site, a partial safety factor for gravity foundation load $\gamma_f = 1,0$ can be used for the limit states regarding bearing capacity of soil and foundation. If buoyancy is calculated equal to a terrain water level, a partial safety factor for buoyancy $\gamma_f = 1,0$ can be applied.

Alternatively, the check of capacity of soil and foundation can be based on a partial safety factor $\gamma_f = 1,0$ for both favourable and unfavourable gravity loads, and the check of overall stability can be based on a partial safety factor of $\gamma_f = 1,1$ for unfavourable gravity loads and $\gamma_f = 0,9$ for favourable gravity loads, using in all cases conservative estimates of weights or densities defined as 5 %/95 % fractiles. The lower fractile is to be used when the load is favourable. Otherwise the upper fractile is to be used.

7.6.2.4 Partial safety factors for resistances where recognized design codes are not available

Partial safety factors for resistances shall be selected in relation to the adequacy of the available material properties test data. The safety level in this document corresponds to a partial safety factor for resistances, $\gamma_M = 1,2$ when applied to characteristic material properties of 95 % survival probability.¹⁶ This value assumes no bias (typically systematic conservatism in the resistance model) and small uncertainty related to the resistance model (coefficient of variation less than 5 %), see Annex K; and applies to components with ductile behaviour whose failure may lead to the failure of a major part of a wind turbine.

To derive the design values for resistances, it is necessary to account for scale effects, tolerances and degradation due to external actions, for example, ultraviolet radiation or humidity. These effects can be taken into account through additional factors on the partial safety factor for resistance or through a conversion factor used to obtain the characteristic value of the resistance, see Annex K.

In the following cases with ductile failure modes, the partial safety factor for resistance, γ_M , shall be not less than

- 1,1 for materials with a well-defined elastic limit (yield strength is 90 % or less of the ultimate strength), and
- 1,1 for bolt rupture in a connection with sufficient number of bolts to ensure a ductile failure mode.

For "safe-life" mechanical/structural components with non-ductile behaviour whose failures lead rapidly to the failure of a major part of a wind turbine, the partial safety factor for resistance, γ_M , shall be not less than

- 1,3 when materials with no well-defined elastic limit (yield strength is more than 90 % of the tensile or compression strength) are used, and

¹⁶ Alternatively, the characteristic strength parameters can be selected as the 95 % fractile using the Bayesian approach, see Annex K and ISO 2394. The characteristic strength parameters should be selected as the 95 % fractile (determined with 75 % confidence) or the certificate value for materials with established routines for testing of representative samples.

- 1,2 for global buckling of curved shells such as tubular towers and blades.¹⁷

7.6.2.5 Partial safety factors for materials where recognized design codes are available

The combined partial safety factors for loads, resistance and the consequences of failure, γ_f , γ_M , and γ_n , shall be not less than those specified in 7.6.1.3, 7.6.2.2 and 7.6.2.4.

7.6.3 Fatigue failure

7.6.3.1 General

Fatigue damage shall be estimated using an appropriate fatigue damage calculation. For example, in the case of Miner's rule, the limit state is reached when the accumulated damage exceeds 1. Thus, in this case, the accumulated damage over the design lifetime of a turbine shall be less than or equal to 1. Fatigue damage calculations shall consider the formulation, including effects of both cyclic range and mean strain (or stress) levels. All partial safety factors (load, material and consequences of failure) shall be applied to the cyclic strain (or stress) range for assessing the increment of damage associated with each fatigue cycle. An example formulation is given for Miner's rule in Annex H.

7.6.3.2 Partial safety factor for loads

The partial safety factor for loads, γ_f , shall be 1,0.

7.6.3.3 Partial safety factors for resistances where recognized codes are not available

The partial safety factor for resistances, γ_M , shall be at least 1,7 provided that the SN-curve is based on 50 % survival probability and coefficient of variation < 15 %. For components with large coefficient of variation for fatigue strength¹⁸, i.e. 15 % to 20 % (such as for many components made of composites, for example reinforced concrete or fibre composites), γ_M shall be increased accordingly and at least to 2,0.

The fatigue strengths shall be derived from a statistically significant number of tests and the derivation of characteristic values shall account for scale effects, tolerances, degradation due to external actions, such as ultraviolet radiation, and defects that would not normally be detected.

For welded and structural steel, traditionally the 97,7 % survival probability is used as basis for the SN-curves. In this case, γ_M may be taken as 1,25, corresponding to a safe-life assessment approach, see Annex K. In cases where it is possible to detect critical crack development through introduction of a periodic inspection programme, a lower value of γ_M may be used, corresponding to a damage tolerant assessment approach, see Annex K. In all cases, γ_M shall be larger than 1,0.

For fibre composites, the strength distribution shall be established from test data for the actual material. The 95 % survival probability shall be used as a basis for the SN-curve. In that case, γ_M may be taken as 1,35. The same approach may be used for other materials.

¹⁷ The parametric formulas based on membrane theory in Eurocode 3 Part 6 (EN 1993-1-6:2007) for shell buckling applicable to tubular steel towers with $D/t < 300$ include a bias that can be accounted for by reducing γ_M for buckling to 1,1.

¹⁸ Fatigue strength is defined here as stress ranges associated with given numbers of cycles.

7.6.3.4 Partial material factors where recognized design codes are available

The combined partial safety factors for loads, materials and consequences of failure shall not be less than those specified in 7.6.3.2 and 7.6.3.3, with due consideration of the quantiles specified in the code.

7.6.4 Stability

The load-carrying parts of "non fail-safe" components shall not buckle under the design load. For all other components, elastic buckling under the design load is acceptable. Buckling shall not occur in any component under the characteristic load.

A minimum value for the partial safety factor for loads, γ_f , shall be chosen in accordance with 7.6.2.2 to obtain the design value. The material partial safety factors shall be not less than those specified in 7.6.2.4.

7.6.5 Critical deflection analysis

7.6.5.1 General

It shall be verified that no deflections affecting structural integrity occur in the design conditions detailed in Table 2. The maximum elastic deflection in the unfavourable direction shall be determined for the load cases detailed in Table 2. A characteristic value for the resulting deflections is determined in a manner consistent with the other load components. The resulting characteristic deflection is then multiplied by the combined partial safety factor for loads, materials and consequences of failure.

7.6.5.2 Partial safety factor for loads

The values of γ_f shall be chosen from Table 3.

7.6.5.3 Partial safety factor for the elastic properties of materials

The value of γ_M shall be 1,1 except when the elastic properties of the component in question have been determined by testing and monitoring, in which case it may be reduced. Particular attention shall be paid to geometrical uncertainties and the accuracy of the deflection calculation method.

7.6.5.4 Partial safety factor for consequences of failure

The partial safety factor for consequences of failure, γ_n , shall be 1,0.

The elastic deflection shall then be added to the un-deflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference.

7.6.5.5 Blade (tip) deflection

One of the most important considerations is to verify that no mechanical interference between blade and tower will occur. The combined safety factor, $\gamma_f \gamma_n \gamma_m$, for blade-tower clearance shall be at least 1,15.

In general, blade deflections have to be calculated for the ultimate load cases. The deflections caused by the ultimate load cases can be calculated based on beam models, finite element models or the like. All relevant load cases from Table 2 have to be taken into account with the relevant partial load safety factors.

Moreover, for DLC 1.1 a statistical analysis of maximum tip deflection or minimum tower clearance is mandatory according to 7.4.2. Here, direct dynamic deflection or tower clearance

analysis can be used. The probability in the most unfavourable direction shall be the same for this characteristic value as for the characteristic blade loading. For a deflection analysis, the characteristic deflection is then to be multiplied by the combined partial factors for loads, materials and consequences of failure and be added to the undeflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference. In the case of direct dynamic tower clearance analysis, the minimum allowable clearance is determined by multiplying the nominal undeflected tower clearance by the ratio of the combined partial factors for loads, materials and consequences of failure minus one to the combined partial factor (i.e. $\frac{\gamma_f \gamma_n \gamma_m - 1}{\gamma_f \gamma_n \gamma_m}$).

7.6.6 Special partial safety factors

Lower partial safety factors for loads may be used where the magnitudes of loads have been established by measurement or by analysis confirmed by measurement to a higher than normal degree of confidence. The values of all partial safety factors used shall be stated in the design documentation.

8 Control system

8.1 General

Wind turbine operation shall be governed by a control system that meets the requirements of Clause 8.

The scope of Clause 8 is limited to ensuring that the control system provides an appropriate level of protection against structural failure of the turbine main components.¹⁹

For special cold climate requirements, see 14.6.

8.2 Control functions

The control functions of a wind turbine shall control the operation by active or passive means and keep the operating parameters within the envelope assumed in the structural design.

The control functions may govern or otherwise limit functions or parameters such as

- power,
- rotor speed,
- connection of the electrical load,
- start-up and shutdown procedures,
- cable twist,
- excessive vibrations,
- alignment to the wind, and
- blade pitch angle.

The ability of the control functions to control the turbine during failure-free operation of the control functions shall be demonstrated in the design load cases (but excluding the DLC 2.1 and 2.2 load cases).

¹⁹ Risk assessments may result in requirements for additional control system functionality needed for ensuring personnel safety. These functions should be designed and evaluated according to recognized methods and design principles, such as those specified in ISO 13849 or IEC 62061.

When a control function failure occurs, the wind turbine must maintain a safe mode of operation, which may include maintaining operation or bringing the wind turbine to a shutdown.

Turbine behaviour following a fault in the control functions shall be clearly defined, including any procedures for automatic or manual restart, see 8.7.

8.3 Protection functions

The control system shall make use of protection functions in order to prevent turbine structural overloading due to failure modes. These protection functions may be implemented as either control functions that apply inherently safe design measures²⁰, or as separate secondary layer protection functions.

Where a secondary layer protection function is used to bring the turbine to a safe mode of operation, it shall overrule the primary layer control function.

Functions protecting against structural overloading shall be implemented by means of multi-channel architectures²¹ with diagnostic coverage to yield sufficiently high mean time between failure.

The ability of protection functions to protect against structural overloading shall be demonstrated in design load cases DLC 2.1 and 2.2, cf. 7.4.3.

8.4 Control system failure analysis

8.4.1 General

Faults or errors in the systems implementing the control and protection functions may lead to a number of failure modes, where the failure mode is defined as the behaviour of the control system in case of a fault or error. Such failure modes may lead to events affecting the turbine structure.

EXAMPLE A sensor fault may lead to erroneous pitch action (the failure mode), which may lead to excessive rotor speed (the event).

Failure modes of the control system shall be identified according to the requirements in this clause and evaluated according to the requirements given in 7.4.3.

FMEA or equivalent fault analysis shall be carried out to determine fault events relevant for wind turbine loading. This may include fault-tree analysis or similar methods to identify any common cause failures.

The set of events addressed in the fault analysis shall include at least the following:

- a) excessive rotor speed;
- b) excessive vibrations;
- c) excessive power production;
- d) actuator faults, e.g. pitch and yaw actuation faults.

²⁰ ISO 12100:2010, 6.2.11 and 6.2.12 provides guidance on applying inherently safe design measures to control systems.

²¹ Multichannel architectures include but are not limited to the use of redundancy. A single functional channel with high diagnostic coverage provided by a separate test channel may suffice if the resulting mean time to dangerous failure is sufficiently high. The designated architecture for Category 2 systems as per ISO 13849-1 constitutes such architecture.

8.4.2 Independence and common-cause failures

It may be assumed that independent faults do not occur simultaneously. If independent faults are assumed, measures against common-cause failures shall be implemented, and there shall be sufficient diagnostic coverage to protect against dormant failures.²²

8.4.3 Fault exclusions

Control system failures subject to fault exclusions²³ as described in recognized standards can be omitted.

All mechanical components of the control system where fault exclusions are applied shall be considered in component class 3 with an appropriate consequences-of-failure partial safety factor (as defined in 7.6). All such critical components shall be analysed for ultimate strength, fatigue, buckling and critical deflection.

8.4.4 Failure mode return periods

If failure mode return periods are claimed in the load calculations (see 7.4.3.2) then these shall be demonstrated by recognized methods.²⁴

For mechanical components, failure mode return periods need only to be established if fault exclusions do not apply.

8.4.5 Systematic failures

For protection functions and for control functions where failure mode return periods higher than 10 years are claimed, measures for avoiding systematic failures²⁵ (including software failures) described by recognized standards shall be applied.

8.5 Manual operation

Manual or automatic intervention shall not compromise the control system's ability to keep the turbine within limits. Any device allowing manual intervention shall be clearly visible and identifiable, by appropriate marking where necessary.

Where selection of control mode can be exercised, for example for maintenance, the mode selection shall be governed by a selector, which can be locked in each position corresponding with a single mode.

Settings of the control system shall be protected against unauthorized interference.

8.6 Emergency stop button function

An emergency stop button function shall be implemented using recognized methods and design principles, such as those specified in ISO 13850, which gives guidance on emergency stop button availability, location, choice of stop functionality, and reset behaviour.

²² ISO 13849-1 may be used to judge whether the measures against common cause failures are sufficient.

²³ Fault exclusions are described in standards such as ISO 13849-2. For mechanical components, fault exclusions are relevant for "safe-life" components.

²⁴ See IEC 61508-6 or IEC 62061 for suitable methods for demonstrating failure rates, e.g. fault trees, Markov models, etc. Also, ISO 13849-1 provides simplified methods for assessing the failure rates, including generic values for components.

²⁵ Measures to avoid systematic failures and software failures are covered within 6.4, 6.10 and 6.11 of IEC 62061:2005, IEC 62061:2005/AMD1:2012 and IEC 62061:2005/AMD2:2015, or 4.6, Annex G and Annex J of ISO 13849-1:2015.

It shall be specified which stop category is chosen. Further, any functionality required from the control system when the emergency stop button is activated shall be clearly specified.²⁶

The behaviour of all systems impacting the structural loading upon activation of the emergency stop button shall be clearly specified.

EXAMPLE 1 Disconnection of electrical systems may impact the loading of the drive train.

When the emergency stop function behaviour depends on operating conditions, these dependencies shall be clearly defined.

EXAMPLE 2 Application of the mechanical disc brake in case of emergency button activation may be conditioned on the rotational speed and/or wind speed, etc.

Effects of activation of the emergency stop button shall be evaluated under DLC 5.1 for all relevant operating scenarios (see 7.4).

8.7 Manual, automatic, and remote restart

Mechanisms for restarting the turbine following a stop shall be clearly defined and meet the following requirements.

Turbine restart behaviour and restart procedures²⁷ following a control function failure shall be defined based on a failure mode analysis (for example via a fault tree analysis).

If failures in functions that define if a restart can occur could influence turbine loads then these faults should be considered to be control system fault events as defined in 8.4.1.

The behaviour following a control function failure may be defined by automatic or manual procedures, performed locally or remotely. In the case of remote restart, this shall include any remote inspection needed (for example, via the use of remote cameras and/or SCADA data), and suitable criteria that need to be met before it is deemed safe to allow remote restart.

Automatic restart shall not be allowed unless automatic diagnostics and criteria necessary to ensure that the turbine will remain safe (i.e. within an acceptable risk of turbine damage) after restart have been defined.

EXAMPLE Such diagnostics may consist of automatic substantiation that the structural design limits for rotor speed and tower top acceleration have not been exceeded.

The risks and consequences of an unintended remote restart (for example, due to a communications system error) shall be considered.

A turbine with automatic or remote restart capability shall be provided with a means to locally disable and lock out the automatic restart function and the remote restart function.

The turbine shall not incorrectly restart as a result of external factors such as loss (and reinstatement) of grid power or external loads or due to maintenance actions.

The number and frequency of remote or automatic restarts that are permissible shall be clearly defined based on the shutdown assumptions contained in the design loads assessment. The restart function shall ensure that these limits are not exceeded.

²⁶ This requirement is particularly important when stop category 1 (controlled stop) is chosen.

²⁷ A restart procedure needs to consider the reasons why the turbine shut down to in order to justify that it is safe to restart the turbine. For example, a restart might not be considered safe without an inspection taking place if the turbine has been shut down due to excessive mechanical shock.

The design loads assessment shall consider the consequences of repeated restarts up to the limits defined above.

The functionality to control the number and frequency of remote or automatic restarts that are permissible shall not be incorrectly affected by external factors such as loss (and reinstatement) of grid power or external loads or due to maintenance actions.

8.8 Braking system

It shall be possible to bring the rotor to idling mode or complete standstill from any operation condition, including loss of power.

Means shall be provided for bringing the rotor to a complete standstill in any wind speed less than the wind speed limit defined for maintenance and repair, see 7.4.9, unless this is explicitly discounted based on the results of a risk assessment.

It is recommended that at least one braking system operate on an aerodynamic principle, as such acting directly on the rotor. If this recommendation is not met, at least one braking system shall act on the shaft directly connected to the rotor or on the rotor of the wind turbine.

If a braking system is designed to bring the rotor to standstill upon emergency stop activation, it shall be able to keep the rotor in standstill for the defined wind conditions for at least one hour after it is applied.

9 Mechanical systems

9.1 General

A mechanical system for the purposes of this document is any system which does not consist solely of static structural components, or electrical components, but uses or transmits relative motion through the combination of shafts, links, bearings, slides, gears and other devices. Within a wind turbine, these systems may include elements of the drive train such as gearboxes, shafts and couplings, and auxiliary items such as brakes, blade pitch controls, yaw drives. Auxiliary items may be driven by electrical, hydraulic or pneumatic means.

All mechanical systems in the drive train and in the control system shall be designed according to IEC or ISO standards wherever available. Otherwise, recognized standards shall be used. Partial safety factors shall be consistent with component class 2 in 7.6.1.3, unless the systems falls into component class 3.

Particular care shall be taken to ensure that cooling and filtration systems can maintain the relevant operating conditions throughout the operating temperature range when the specified maintenance procedures are followed.

The remaining life of any component subject to wear in the brake system shall be monitored automatically and subject to regular inspection. The turbine shall be parked when there is insufficient material for further emergency stops. All brake devices shall be designed and maintained to keep the response time within acceptable levels.

Load calculation shall be based on simulations including both the mean braking level and a minimum braking level that allows for minimum friction and application pressure predicted for the design. If the brake is able to slip at the minimum braking level, when the brake is applied, it shall be designed to avoid overheating and brake performance impairment and to avoid risk of fire.

For cold climate requirements, see 14.7.

9.2 Errors of fitting

Errors likely to be made when fitting or refitting certain parts that could be a source of risk shall be made impossible by the design of such parts or, failing this, by information given on the parts themselves and/or housings. The same information shall be given on the moving parts and/or their housings where the direction of movement shall be known to avoid a risk. Any further information that may be necessary shall be given in the operator's instruction and maintenance manuals.

Where a faulty connection can be a source of risk, incorrect connections shall be made impossible by the design or, failing this, precautions shall be taken to avoid faulty connection by information given on the pipes, hoses and/or connector blocks.

9.3 Hydraulic or pneumatic systems

Where auxiliary items are powered by hydraulic or pneumatic energy, the systems shall be so designed, constructed and equipped as to avoid all potential hazards associated with these types of energy. Means of isolating or discharging accumulated energy shall be included in such systems. All pipes and/or hoses carrying hydraulic oil or compressed air and their attachments shall be designed to withstand or be protected from foreseen internal and external stresses. Precautions shall be taken to minimize risk of injury arising as a consequence of rupture.

9.4 Main gearbox

The main gearbox shall be designed according to IEC 61400-4.

9.5 Yaw system

The yaw system may consist of means to maintain a fixed yaw orientation (e.g. hydraulic brakes), means to change that orientation (e.g. electric motors, gearboxes and pinions) and means to guide the rotation (e.g. a bearing).

Any motors shall comply with relevant parts of Clause 10.

Non-redundant parts of the gear system such as the final yaw gear shall be considered as component class 2. When multiple yaw drives ensure sufficient redundancy in the yaw gear system, and easy replacement is possible, the reduction gearbox and the final drive pinion may be considered to be in component class 1.

The safety against pitting shall be determined in accordance with ISO 6336-2. The application of the upper limit curve (1) for life factor Z_{NT} , which allows limited pitting, is permissible. Sufficient tooth bending strength shall be proven in accordance with ISO 6336-3. The reverse bending loads on gear teeth shall be considered in accordance with ISO 6336-3:2006, Annex B. Minimum values for S_F and S_H are specified in Table 4. These values shall be achieved by using characteristic loads F_k . Hence, S_F and S_H include the partial safety factor for consequences, γ_n , materials, γ_M and loads, γ_f .

Table 4 – Minimum safety factor $S_{H,min}$ and $S_{F,min}$ for the yaw gear system

	Component class 1	Component class 2
Surface durability (pitting)	$S_{H,min} = 1,0$	$S_{H,min} = 1,1$
Tooth bending fatigue strength	$S_{F,min} \geq 1,1$	$S_{F,min} = 1,25$
Static bending strength	$S_{F,min} \geq 1,0$	$S_{F,min} = 1,2$

However, lower safety factors, S_F and S_H , may be applicable in cases where efficient monitoring is implemented. If safety factors below 1,0 are applied, then the maintenance manual shall reflect anticipated replacement intervals.

9.6 Pitch system

The pitch system may consist of means to adjust blade pitch angle (e.g. hydraulic actuators, electric motors, gearboxes, brakes and pinions) and means to guide the rotation (e.g. a bearing).

Any motors shall comply with relevant parts of Clause 10. For pitch systems with individual pitch drives/actuators ensuring sufficient redundancy, these may be considered to be in component class 2.

For component class 2, gearboxes and gears shall comply with relevant parts of 9.5.

9.7 Protection function mechanical brakes

Where mechanical brakes are used for a protection function (see 7.4.3.3), they are generally friction devices applied by hydraulic or mechanical spring pressure. The remaining life of any wearing components, for example friction pads, shall be monitored by the control system, which shall place the turbine in parked mode when insufficient material is available for a further emergency stop or braking.

Load calculation shall be based on simulations including an appropriate range of the braking level. If the brake is able to slip in the standstill state at the minimum braking level, whenever the brake is to maintain the wind turbine in a stationary state, the period of slip in a turbulent wind shall be sufficiently short to avoid overheating and brake performance impairment and to avoid a risk of fire.

9.8 Rolling element bearings

9.8.1 General

The basis of rating analysis of rolling bearings shall be ISO 76, ISO 281 and ISO/TS 16281. The calculation shall consider the actual operating and lubrication conditions as well as the bearing environment. Any life adjustment factor according to ISO 281 and ISO/TS 16281 shall be applied with care.

The design loads shall reflect the loads determined in the various load cases in 7.4 and appropriate safety factors in 7.6. The bearing design shall consider the expected amount of rotation during its lifetime and whether the rotations are continuous or discontinuous.

9.8.2 Main shaft bearings

The modified reference rating life L_{10mr} (90 % survival probability) of main shaft bearings shall meet or exceed the specified design life of the wind turbine.

9.8.3 Generator bearings

The modified reference rating life L_{10mr} (90 % survival probability) of generator bearings shall meet or exceed the specified design life of the wind turbine.

Generator bearings that can be replaced in the wind turbine without special tools may be specified for a shorter design life.

9.8.4 Pitch and yaw bearings

For pitch and yaw bearings, the ratio of static rating to design load shall be at least 1,0 according to ISO 76. The load distribution due to flexibility of the connected parts shall be carefully considered.

Bearings used in the pitch and yaw systems are exposed to a discontinuous, oscillatory motion. Therefore, consideration shall be given to the potential effect of insufficient lubrication due to small movement.

10 Electrical system

10.1 General

The electrical system of a wind turbine installation comprises all electrical equipment installed in each individual wind turbine up to and including the wind turbine terminals; referred to below as the "wind turbine electrical system".

Clause 10 includes electrical components specific to wind turbine designs that have features and functions not typically addressed in other system or component standards. Clause 10 also addresses common wind turbine components but it is not intended to be all inclusive. Specific components are dictated by the turbine design and these components and assemblies shall be evaluated for the electrical, mechanical and environmental installation locations and application as defined in 10.2.

The power collection system is not covered by this document.

10.2 General requirements for the electrical system

The design of the electrical system shall ensure minimal hazards to people and livestock as well as minimal potential damage to the wind turbine and external electrical system during operation and maintenance under all normal and extreme electrical and environmental conditions (as defined in 6.4.2 and 6.4.3) for the specific area where the equipment operates, including additional effects related to the overall turbine and its environmental ratings. Electrical components and subassemblies shall be rated for their electrical conditions and operating environment.

Electrical equipment should be designed to provide protection from potential arc flashes using recognized national or international standards and risk assessment methodologies.

For cold climate requirements, see 14.8.

Unless otherwise specified in this document, the design of a wind turbine electrical system shall comply with the requirements of IEC 60204-1. For equipment that have input and or output circuits at nominal voltages greater than 1 000 V AC or 1 500V DC, the applicable requirements of IEC 60204-11 shall be applied. The manufacturer shall state the design standard(s) used. The design of the electrical system shall take into account the fluctuating nature of power generation from wind turbines.

10.3 Internal environmental conditions

The environmental conditions internal to the turbine are likely to be different from the external environmental conditions.

Environmental conditions shall be determined for the locations in which all major components and subassemblies within the wind turbine are located and shall be conducted in accordance with IEC 60721 (all parts). The locations for consideration normally include, but are not limited to, the hub, tower sections, nacelle, tower base, tower basement.

The internal environmental conditions are dependent upon the specific environmental control systems and foreseeable environmental pollution included in a specific turbine design. Heating, cooling and active ventilation shall be considered.

The manufacturer shall specify the following service conditions for operation, storage and transportation for each of the turbine subassemblies and major components. Where applicable, the classifications from IEC 60721 (all parts) shall be used:

- coolant temperature (min./max.);
- ambient temperature (min./max.);
- humidity (min./max.);
- pollution degree;
- vibration;
- OVC (overvoltage category);
- altitude for thermal consideration, if rated for operation above 1 000 m;
- altitude for insulation coordination considerations, if rated for operation above 2 000 m.

These environmental condition determinations are the basis for the insulation coordination defined in 10.3.

IEC 60664-1 and IEC 60664-3 for equipment having a rated voltage up to 1000 V AC and IEC 60071-1 and IEC 60071-2 for equipment having a rated voltage above 1000 V AC shall be used for evaluating the insulation coordination requirements for the specific wind turbine equipment unless otherwise specified by specific component requirements within this document. This insulation coordination evaluation shall address the overvoltage category, pollution degree, and environmental conditions for the electrical equipment within the turbine.

Minimum environmental conditions within the turbine are to be considered pollution degree 3. Specific areas where conductive pollution such as slip ring brush dust and brake dust are present shall be considered pollution degree 4.

The pollution degree may be reduced within certain areas of the equipment by the use of encapsulation, conformal coating, etc. Reduction of pollution degree within the overall equipment may also be achieved by the use of enclosures providing protection in accordance with IEC 60529. Steps may be taken to control and reduce the pollution degree at the creepage location by design features or the consideration of the operating characteristics of the component or equipment.

Pollution degree 2 can be achieved by reducing the possibilities of debris accumulation (filtered ventilation) and condensation or high humidity at the creepage locations. Continuous application of heat, through the use of heaters or continuous energizing of the equipment when it is in use, can be used to control condensation. Continuous energizing is considered to exist when the equipment is operated without interruption every day and 24 hours per day or when the equipment is operated with interruptions of duration which do not permit cooling to the point that condensation occurs.

Pollution degree 1 can be achieved by potting, moulding the equipment or circuit or by enclosing it in an IP 67 enclosure.

Overvoltage category IV shall be applied to determine clearance spacings in general locations within a wind turbine. Surge protectors that are relied upon to protect control and protection circuits and other circuits relied upon for the safe operation of the turbine shall include monitoring circuits or other automatic means to indicate a surge protective device has failed. Use of surge suppression protection may be used to locally reduce the overvoltage category to below IV for specific equipment or circuits.

Direct or nearby lightning strikes can induce high overvoltage conditions in the external electrical systems and wind turbine electrical systems including equipment circuits throughout the hub, nacelle and tower. Surge protective devices, if used, shall be installed in close proximity to the equipment being protected.

10.4 Protective devices

A wind turbine electrical system shall, in addition to the requirements of IEC 60364 (all parts), include suitable devices that ensure protection against malfunctioning either within the wind turbine, equipment, subassemblies and components or as consequence of the external electrical system malfunction that may lead to an unsafe condition or state. These protective device functions include: short circuit, overcurrent, ground fault, over temperature and arc fault.

10.5 Disconnection from supply sources

Lockable disconnect device or devices shall be provided to disconnect the equipment from each electrical source of supply that has a hazardous live voltage or exceeds the values for hazardous energy or from which a hazardous live voltage or energy is derived. The levels of hazardous voltage and energy are defined in IEC 60204-1 and IEC 60204-11.

The emergency stop is not intended to provide a routine disconnect function for this purpose.

Semiconductor switching devices without additional air gap disconnect contacts are not suitable to meet the requirements of 10.4.

Where lighting or other electrical systems are necessary for safety during maintenance, auxiliary circuits shall be provided with their own disconnect devices, such that these circuits may remain energized while all other circuits are de-energized.

Circuits and equipment rated more than 1 000 V AC or 1 500 V DC shall comply with Clause 5 of IEC 60204-11:2000.

10.6 Earth system

A wind turbine shall be provided with a local earth electrode system to meet the requirements of IEC 60364 (all parts) (for the correct operation of the electrical installation) and IEC 62305-3 (for lightning protection).²⁸ The range of soil conditions for which the earth electrode system is adequate shall be stated in the design documentation, together with recommendations should other soil conditions be encountered.

The choice and installation of the equipment of the earthing arrangement (earth electrodes, earthing conductors, main earthing terminals and bars) shall be made in accordance with IEC 60364-5-54.

Provisions shall be made in any electrical system operating above 1 000 V AC or 1 500 V DC for earthing during maintenance in accordance with IEC 60204-11.

10.7 Lightning protection

The lightning protection system of a wind turbine shall be designed in accordance with IEC 61400-24. A risk-based approach shall be applied during the lightning protection system design with respect to the risk of damage and personnel safety.

The design shall consider the protection of the following areas:

²⁸ Additional considerations are included in IEC 61400-24:2010, Clause 9.

- rotor blades;
- hub/spinner;
- nacelle;
- tower.

Additional system components such as external transformers and switchgear outside the scope of this document may also need to be connected and or included in the lightning protection system.

The protection of electrical systems within the turbine shall follow a lightning protection approach as set out in IEC 62305-4, with the design incorporating a combination of bonding, shielding and surge protection devices.

Design requirements of the lightning protection system are provided in IEC 61400-24.

10.8 Electrical cables

Electrical cables shall be rated for the electrical, flammability, mechanical and environmental applications where they are used and shall be installed in a manner for which they are rated. Where there is a probability of rodents or other animals damaging cables, armoured cables or conduits shall be used.

- Cables shall be protected or rated to mitigate the possible risk of fire in the event of the fault.
- Control cables shall be segregated and or protected from power cables unless insulation failures are specifically addressed in the fault analysis.
- Cable clamps, supports and strain reliefs shall be suitable for the cable type so as to prevent damage to the cable insulation.
- Cables shall be protected or suitably located to prevent damage from abrasion and wear.

10.9 Self-excitation

Any electrical system that can alone self-excite a wind turbine shall be disconnected and remain safely disconnected in the event of loss of network power.

If a capacitor bank is connected in parallel with an induction generator (i.e. for power factor correction), a suitable switch is required to disconnect the capacitor bank whenever there is a loss of network power, to avoid self-excitation of the generator. Alternatively, if capacitors are fitted, it shall be sufficient to show that the capacitors cannot cause self-excitation.

10.10 Protection against lightning electromagnetic impulse

The overvoltage protection shall be designed in accordance with the requirements of IEC 62305-4.

The limits of the protection shall be so designed that any lightning electromagnetic impulse transferred to the electrical equipment will not exceed the limits governed by the equipment insulation levels.

10.11 Power quality

The procedures in IEC 61400-21 can be used to demonstrate compliance with the requirements of the operator of the public distribution or transmission network.

10.12 Electromagnetic compatibility

For immunity to radiated and conducted disturbances, all electrical components installed in the wind turbine shall meet the requirements of the relevant product standards and shall not be less than the greater of requirements of IEC 61000-6-2 or the requirements defined during the functional safety evaluation of the control system in Clause 8.

10.13 Power electronic converter systems and equipment

The converter shall be evaluated for the environment in which it is installed as defined by Table 18 of IEC 62477-1:2012. The interior of a turbine is not considered to be a conditioned space. If the converter is installed within a conditioned space, it shall be evaluated for that environment. The pollution degree shall be chosen with respect to ingress of moisture from humidity and condensation due to extended durations of de-energization. The environmental service conditions defined in IEC 62477-1 may be modified to accommodate the specific end application within the turbine.

IEC 61800-4 shall be applied for converters operating above 1 000 V AC or 1 500 V DC.

Converter controls and protection shall additionally comply with the applicable requirements in Clause 8.

10.14 Twist/drip loop

Wiring that is subject to movement, flexing, or twisting during operation of the wind turbine shall be investigated for suitability in the application conditions of use and rated life.

If operation of the wind turbine may result in twisting of flexible cables, such as the connecting cables between rotating parts (nacelle) and parts of the fixed structure (tower or foundation), the operational conditions of use shall not cause damage to the conductors or their insulation. The evaluation shall address service life, electrical and environmental operating conditions of the subassembly.

Controls that prevent damage to conductors or their insulation including rotational limits shall be considered part of the control system.

Where multiple cables are grouped or tied together, the assembly loading shall be distributed such that the individual cables are not subjected to loads that exceed their individual ratings.

The cable support assemblies shall be designed for the mechanical loading and torsional forces of operation.

Cable size and temperature rating shall be evaluated based upon the operating temperature of the assembly including representative size and number of cables fully twisted, carrying maximum normal current and including electrical terminations similar in distance in the end application.

10.15 Slip rings

Slip rings shall comply with 10.2 and the applicable portions of IEC 60204-1 and shall be rated for the electrical and environmental conditions to which they are subjected within the turbine. The slip rings shall be rated for normal operating and abnormal (overload) conditions to which they may be subjected. The normal rating of a slip ring is based upon the circuit electrical loads. The overload rating shall be based upon source circuit fault current capacity and may account for overcurrent protection if provided.

Slip rings used in safety critical power and control circuits shall be provided with means to address failure and wear.

10.16 Vertical power transmission conductors and components

Vertical power transmission systems that are run up the tower, such as bus bar-based systems and cable-based systems, shall comply with the respective component standards. These are IEC 61439-1 and IEC 61439-6 for bus bar-based systems and IEC 60364-5-52 for cable-based systems.

The conductors and components shall comply with their applicable standard with regards to: operating temperature range, environmental conditions, electrical isolation, electrical impulse withstand and short circuit withstand capabilities as necessary for the electrical and environmental conditions within the turbine.

Vertical power transmission equipment shall be constructed with sufficient mechanical strength to withstand the foreseeable mechanical forces (deflection, movement and loading) for its use as determined from the results of the design load cases for the specific component within the specific turbine. Sections of vertical power transmission conductors and components shall be suitably attached to the tower or to components of the tower intended to support the assembly.

The evaluation of these vertical power transmission systems shall account for the following conditions:

- a) static loading on system components;
- b) expected deflection and forces on the transmissions assemblies and support structure resulting from bending of the tower under anticipated extreme conditions;
- c) expected force direction and magnitude of displacement of the assembly;
- d) component fatigue, loosening of fasteners;
- e) degradation, wear, deformation and creep of polymeric electrical insulating materials;
- f) loss of electrical conductivity or electrical isolation;
- g) operation for the intended turbine life span or specified maintenance period for the assembly.

The assembly may be evaluated by testing, analysis or a combination of the two.

Scaled testing may be used to represent the complete system.

The mechanical and structural suitability of the power transmission assembly and supporting members may be addressed via analysis per the design load case evaluation. The design load cases shall specifically include and address the forces on the assembly, subassemblies and components including insulating and conducting materials.

Consideration of short circuit conditions for vertical power transmission systems should include electrical, thermal and mechanical effects on components as well as installed systems.

If the analysis method does not include effects of abrasion/wear and material creep on the polymeric electrical insulation, testing may be necessary.

10.17 Motor drives and converters

Motor drives and converters shall comply with the applicable portions of IEC 61800-5-1.

Pitch and yaw motor drive and converter controls shall additionally comply with the applicable requirements in Clause 8.

10.18 Electrical machines

Electrical machines shall comply with relevant parts of IEC 60034 and shall have a duty rating suitable for the intended application²⁹.

The turbine generator shall be rated for continuous operation (duty S1 according to IEC 60034-1).

The combination of an electrical machine powered by a frequency converter drive shall have coordinated electrical and isolation ratings.

10.19 Power transformers

Power transformers included within or as part of a turbine system shall comply with IEC 60076 (all parts).

Low voltage transformers within the wind turbine shall either be fully enclosed, including all terminations, or they shall be located in dedicated areas behind barriers or panels as required in recognized national or international standards and codes. High voltage (HV) transformers within the wind turbine shall comply with the requirements for restricted accessibility and lock out as defined in 10.21.

10.20 Low voltage switchgear and controlgear

Low voltage switchgear and controlgear operating up to 1 000 V AC or 1 500 V DC shall comply with IEC 61439-1 and other parts of the IEC 61439 series and shall be rated for the electrical and environmental conditions to which it is subjected within the turbine.

All enclosures for switchgear and controlgear shall be provided with cautionary markings required by IEC 61439-1 and other applicable parts of the IEC 61439 series.

10.21 High voltage switchgear

High voltage (HV) switchgear operating above 1 000 V AC or 1 500 V DC shall comply with IEC 62271 (all parts) and shall be rated for the electrical and environmental conditions to which it is subjected within the turbine.

HV switchgear shall be located in areas of the turbine only accessible by authorized personnel. Cautionary markings shall be posted on the turbine access, hatch or door to wear appropriate personnel protection equipment for the hazards inside the area beyond the access, hatch or door.

HV switchgear installed in areas accessible to normal maintenance personnel shall be metal enclosed and specified for internal arc containment classification (IAC). The IAC shall be classification A as defined in IEC 62271-200 for all equipment sides where personnel may reasonably have access.

HV switchgear shall be tested, rated and marked for the IAC fault current with a duration of not less than 1 s.

HV switchgear shall be installed in accordance with the manufacturer's ratings and instructions. Pressure relief vents shall output without obstruction and without risk to personnel or equipment.

²⁹ Consideration should be given to interconnection cable length, the drive voltage waveform, the use of insulated bearings and shaft earthing arrangements.

Switchgear configured for automatic operation shall be switchable to lock out and disable the automatic operation.

As required by 10.4, HV switchgear and associated controls shall be provided with a means to be locked in a safe state.

SF6 switchgear shall be installed in areas with sufficient ventilation so as to avoid hazard to personnel in the event of a leak.

10.22 Hubs

Equipment within the hub shall be provided with enclosures rated for the electrical and environmental application in accordance with IEC 60529 to protect electrical components from damage. Electrical cabinets and enclosures shall be provided with doors or covers that are securely fastened.

Wiring associated with the control systems shall be mechanically protected from damage due to hub rotation, service personnel interaction and unintended impacts within the hub.

11 Assessment of a wind turbine for site-specific conditions

11.1 General

Wind turbines are subject to environmental and electrical conditions including the influence of nearby turbines, which may affect their loading, durability and operation. In addition to these conditions, account has to be taken of the seismic, topographic and soil conditions at the wind turbine site. It shall be shown that the site-specific conditions do not compromise the structural integrity. The demonstration requires an assessment of the site complexity, see 11.2, and an assessment of the wind conditions at the site, see 11.3. For assessment of structural integrity, two approaches may be used:

- a) a demonstration that all these conditions are not more severe than those assumed for the design of the wind turbine, see 11.9;
- b) a demonstration of the structural integrity for conditions, each equal to or more severe than those at the site, see 11.10.

If any conditions are more severe than those assumed in the design, the structural and electrical compatibility shall be demonstrated using the second approach.

The partial safety factors for loads in 7.6.2.2 assume that the site assessment of the normal and extreme wind conditions has been carried out according to the minimum requirements in Clause 11.

11.2 Assessment of the topographical complexity of the site and its effect on turbulence

11.2.1 Assessment of the topographical complexity

A site shall be assessed for the topographical complexity of the terrain, since it may cause distortion, and hence deviation, of the turbulence structure from the design conditions.

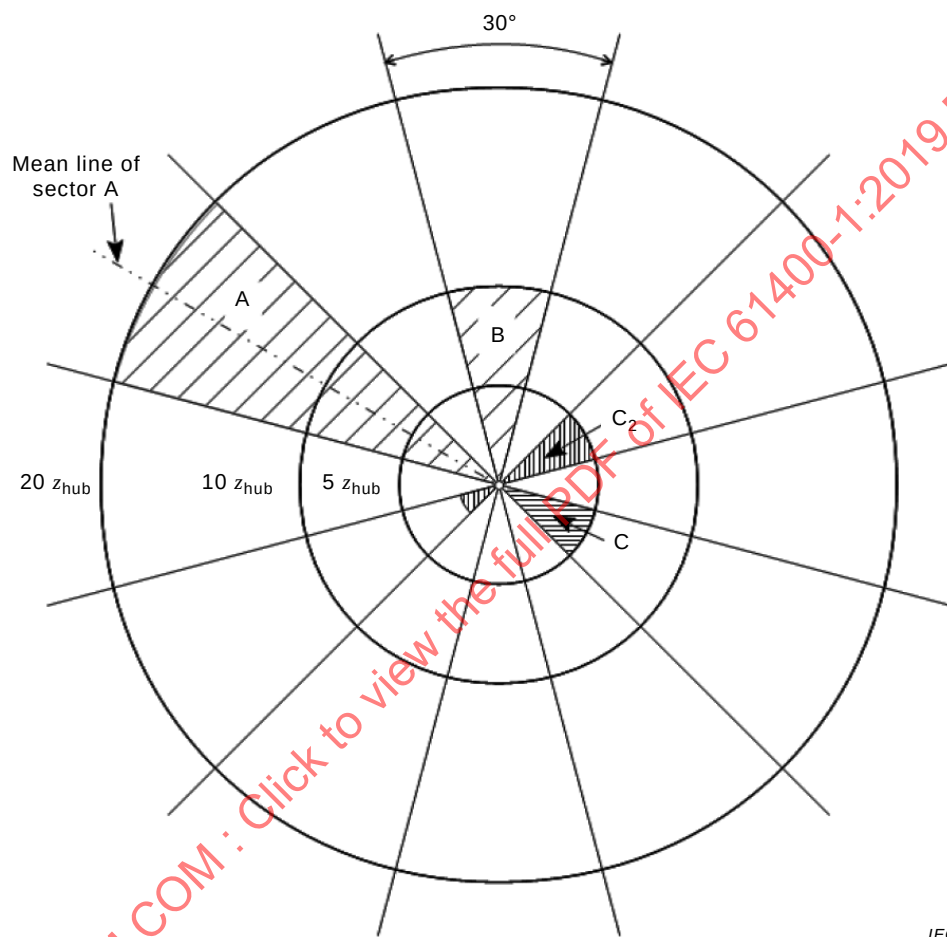
The complexity of the site is characterized by the slope of the terrain and variations of the terrain topography from a plane, and it may be assessed according to the following procedure.

To obtain the slope of the terrain, planes are defined that fit the terrain within specific distances and sector amplitudes for all wind direction sectors around the wind turbine, see Figures 10 and 11. The fitted planes do not need to pass through the tower base. The slope denotes the angle between a horizontal line and the different mean lines of sectors projected

vertically on the fitted planes. Accordingly, the terrain variation from the fitted plane denotes the distance, along a vertical line, between the fitted plane and the terrain at the surface points.

The resolution of surface grid and its original source map used for terrain complexity assessment should not exceed 50 m.

The circle sectors shall be 30°. For the circle sectors with radius $5z_{\text{hub}}$ the area used to fit the plane may be extended $2z_{\text{hub}}$ downwind of the wind turbine position, see Figure 10.



IEC

Key

A radius $20z_{\text{hub}}$

B radius $10z_{\text{hub}}$

C radius $5z_{\text{hub}}$

C_2 radius $5z_{\text{hub}}$ extended $2z_{\text{hub}}$ behind the wind turbine position

Figure 10 – Examples of 30° sectors for fitting the terrain data

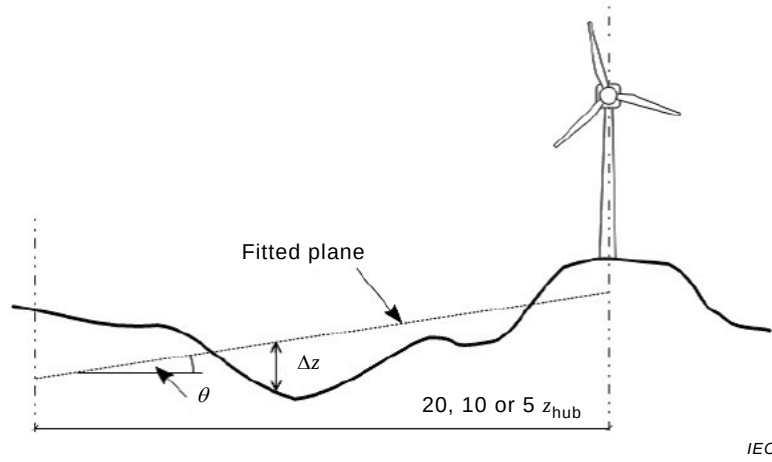


Figure 11 – Terrain variation (Δz) and terrain slope (θ)

Using thus defined slope and terrain variation, terrain slope indices (TSI) and terrain variation indices (TVI) for each circle area are given by the following equations:

$$\begin{aligned}
 TSI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot |\theta(i)| \\
 TVI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot \frac{D_{TV}(i)}{R} \\
 TSI_{360} &= k_1 \cdot \theta_{360} \\
 TVI_{360} &= \frac{D_{TV360}}{k_2 \cdot R}
 \end{aligned} \tag{34}$$

where

TSI_{30}, TSI_{360} are the terrain slope indices calculated from 30° sectors and 360° circle area, respectively;

TVI_{30}, TVI_{360} are the terrain variation indices calculated from 30° sectors and 360° circle area, respectively;

i is the wind sector index (1, 2, ..., 12);

$f_{\text{Energy}}(i)$ is the percentage of the wind energy coming through i th 30° sector,

$$\sum f_{\text{Energy}}(i) = 1;$$

$\theta(i)$ is the slope of fitted plane for i th 30° sector;

θ_{360} is the slope of the fitted 360° circle plane;

$D_{TV}(i)$ is the standard deviation of terrain variation in i th 30° sector;

D_{TV360} is the standard deviation of terrain variation of the 360° circle area;

R is the radius of the circle area;

k_1 is the empirical adjustment factor for TSI_{360} , $k_1 = 5/3$;

k_2 is the empirical adjustment factor for TVI_{360} , $k_2 = 3$.

TSI_{30} is the mean absolute value of the slopes of the twelve sector-wise fitted planes weighted by energy inflow. Similarly, TVI_{30} is the mean value of the twelve sector-wise standard deviations of terrain variation normalized by the circle radius, weighted by the energy inflow.

TSI_{360} is the slope of the fitted 360° circle plane adjusted by an empirical factor k_1 .

TVI_{360} is the standard deviation of terrain variation in 360° circle area, normalized by the circle radius and adjusted by an empirical factor k_2 .

Terrain is assessed for terrain complexity by means of two indices TSI and TVI for each of the three circle areas ($5z_{hub}$, $10z_{hub}$, and $20z_{hub}$). For both indices, three complexity categories low (L), medium (M) and high (H) are defined, see Table 5. If the TSI_{30} and TVI_{30} values as well as the TSI_{360} and TVI_{360} values for all three circle areas are below the threshold value for category L, the site is assessed as not complex. If not, the site is assessed as complex and assigned one of the three complexity categories, L, M or H, depending on the highest category TSI or TVI for any of the circle areas.

Table 5 – Threshold values of the terrain complexity categories L, M and H

Radius of circle area	Sector amplitude of fitted plane	Threshold values (lower limit)					
		Terrain slope index (TSI)			Terrain variation index (TVI)		
		L	M	H	L	M	H
5 z _{hub}	360°	10°	15°	20°	2 %	4 %	6 %
5 z _{hub}	30°						
10 z _{hub}							
20 z _{hub}							

11.2.2 Assessment of turbulence structure at the site

The turbulence structure, i.e. the ratios of the three components of turbulence, of a site shall be determined primarily from measurements at the site. When there are no site data, it may be estimated by an appropriate flow model.

Alternatively, it may be estimated from the complexity of the site. Values shown in Table 6 may be assigned depending on the complexity category defined according to the procedure described in 11.2.1.

Table 6 – Values of lateral and vertical turbulence standard deviations relative to the longitudinal component depending on terrain complexity category L, M and H

	Category		
	L	M	H
σ_2/σ_1	0,85	0,93	1,00
σ_3/σ_1	0,60	0,65	0,70

The turbulence structure correction parameter C_{CT} , which may be used in the assessment of the structural integrity by reference to wind data in 11.9, may be defined by the following equation³⁰:

$$C_{CT} = \sqrt{1 + (\hat{\sigma}_2 / \hat{\sigma}_1)^2 + (\hat{\sigma}_3 / \hat{\sigma}_1)^2} / \sqrt{1 + (\sigma_2 / \sigma_1)^2 + (\sigma_3 / \sigma_1)^2}$$

³⁰ If C_{CT} is less than 1, $C_{CT} = 1,0$ shall be used.

in which σ_1 , σ_2 and σ_3 are values of the three components of turbulence, at hub height and at wind turbine location, averaged over a wind speed range between $0,6 V_r$ and $1,6 V_r$. The design values for the Kaimal and Mann models can be obtained from Annex C.

When there are no measured site data, the values in Table 7 may be used for C_{CT} depending on the complexity category of the site.

Table 7 – Values of turbulence structure correction parameter depending on terrain complexity category L, M and H

	Category		
	L	M	H
C_{CT}	1,05	1,10	1,15

Interpolation between the values in Table 6 and Table 7 is allowed.

11.3 Wind conditions required for assessment

11.3.1 General

The site wind parameters shall be either measured and extrapolated, or calculated using appropriate methods (e.g. monitoring measurements made at the site, long-term records from local meteorological stations, simulation models or local codes and standards). Simulation models shall be validated against representative data.

11.3.2 Wind condition parameters

The following parameters shall be derived for the position of the wind turbine at hub height:

- extreme 10 min average wind speed³¹, V_{50} , at hub height with a return period of 50 years;
- wind speed probability density function, $p(V_{hub})$;
- wind speed standard deviation $\hat{\sigma}$ from the ambient turbulence (estimated as the mean value of the standard deviation of the longitudinal component) and the standard deviation $\hat{\sigma}_\sigma$ of $\hat{\sigma}$ at all wind speeds required in 11.9 or 11.10;
- extreme ambient wind speed standard deviation³², $\hat{\sigma}_{1ETM}$, with a return period of 50 years;

³¹ The load partial safety factors for DLC 6.1 and DLC 6.2 are derived by assuming that the coefficient of variation of the annual maximum wind speed, COV, is smaller than 15 %. If COV is larger than 15 %, they can be increased linearly by a factor η from 1,0 at COV = 15 % to 1,15 at COV = 30 %. If $\eta > 1,0$ an adjusted value of the extreme 10 min average wind speed of $\tilde{V}_{50} = \sqrt{\eta} V_{50}$ can be used in the assessment of the structural integrity, see 11.9 and 11.10. COV of the annual maximum wind speed can approximately be obtained assuming a Gumbel distribution and assuming that for example 50 year and 100 year return values of the wind speed, V_{50} and V_{100} , are available. The parameters α and β are obtained from:

$$\alpha = \frac{V_{100} - V_{50}}{p_{100} - p_{50}}, \quad \beta = V_{50} - \alpha p_{50} \quad \text{with} \quad p_{100} = -\ln\left(-\ln\left(1 - \frac{1}{100}\right)\right) \quad \text{and} \quad p_{50} = -\ln\left(-\ln\left(1 - \frac{1}{50}\right)\right)$$

COV is determined from

$$COV = \frac{\sigma}{\mu} = \frac{\pi}{\sqrt{6}} \frac{1}{\frac{\beta}{\alpha} + 0,5772}$$

³² The extreme ambient wind speed standard deviation $\hat{\sigma}_{1ETM}$ may be derived using an appropriate extrapolation method, for example, the IFORM method, or estimated by:

- flow inclination;
- wind shear³³;
- air density.

Where there is no site data for the air density, it shall be assumed that the air density is consistent with ISO 2533, suitably corrected for annual average temperature.

The bin width of any wind speed used in the above shall be 2 m/s or less, and the wind direction sectors shall be 30° or less. All measurements, except air density, shall be available as function of wind direction, given as a 10 min average.

Attention should be given to wakes from significant structures and orographic obstacles within a distance from the wind turbine of 20 times the characteristic length of the structure or the orographic obstacle. The influence can be neglected if the bottom edge of the rotor is at least four times higher than the height of the structure or the orographic obstacle.

In regions prone to hurricanes, cyclones and typhoons, the extreme wind speed shall be evaluated by appropriate methods, for example as given in Annex J.

For cold climate, additional parameters should be derived for the position of the wind turbine. Icing condition may be assessed according to Annex L.

11.3.3 Measurement setup

The requirement for and use of measurements for wind turbine site suitability assessment and wind resource assessments differ in many respects, and therefore a balance needs to be found between the amount and the quality of measurements.³⁴ Furthermore, for the purposes of a wind turbine site suitability measurement campaign, additional criteria should be taken into consideration.

- The measurement system should be installed in locations broadly representative of the majority of site areas (e.g. forest, ridge lines, plains, valleys, slopes and obstacles).
- The exact number and location of measuring systems recommended is very site-specific and depends upon the terrain, extent and ground cover of the proposed wind farm as well as the expected complexity of the flow regime and the on-site validation of the flow model to be used in the analysis.
- The wind condition measurement heights as well as the number of sensors should be chosen to be representative. Measurements should be performed at a range of heights within the proposed turbine rotor's swept area. Consideration should be given to surrounding terrain and vegetation.
- The vertical separation distance between the sensors should enable a robust analysis of the vertical wind shear, for example a separation of at least one third of the rotor diameter.
- A temperature as well as pressure sensor should be installed.
- 10 minutes averaging time, based on at least 1 Hz (mean, standard deviation and maximum wind speed, mean of wind direction and mean temperature) should be used.
- If measurements are performed in a cold climate zone, then additional heated sensors should be used and their performance relative to unheated sensors considered.

$$\hat{\sigma}_{1\text{ETM}} = \hat{\sigma} + k_p \hat{\sigma}_{\sigma}; \quad k_p = 0,01 \left(\frac{V_{\text{ave}}}{(\text{m/s})} - 21 \right) \left(\frac{V_{\text{hub}}}{(\text{m/s})} - 5 \right) + 5$$

³³ Shear values with high variability have been reported for certain areas in connection with highly stratified flow, complex terrain or severe roughness changes. In this case using the average wind shear may not be sufficient.

³⁴ IEC 61400-12-1 and IEA Recommendation 11 illustrate best-practice guidelines for measurement equipment installation and setup.

- In complex terrain, all wind components should be measured, for example with a 3D-ultrasonic anemometer.

11.3.4 Data evaluation

The recommendations with respect to data coverage and period are the following.

- The measurement period can deviate depending on the quality of data and the reliability of the correlation to a reference long term source. Where seasonal variations contribute significantly to the wind conditions, the monitoring period should be long enough to include these effects (the minimum to capture seasonal effects would be 12 months).
- The data coverage in each month should be sufficiently high to adequately represent the monthly variation in wind conditions.

During data evaluation, a quality check and filtering should be performed and documented. A measure-correlate-predict (MCP) procedure may be performed to extend the data.

The average value of the wind speed standard deviation $\hat{\sigma}$, i.e. the standard deviation of the longitudinal turbulence component, and its standard deviation $\hat{\sigma}_{\sigma}$ shall be determined using appropriate statistical techniques applied to measured and preferably linearly de-trended data.

A long-term assessment is normally required for the estimation of the extreme wind speed, long-term mean wind speed as well as air density, but only if the available long term source is appropriate and sufficiently reliable.

Alternative methods can be used. These methods should aim to improve the representativeness of the measurements for the site.

The above mentioned methods and procedures shall be documented.

11.4 Assessment of wake effects from neighbouring wind turbines

Wake effects from neighbouring wind turbines during power production shall be considered. The assessment of the suitability of the wind turbine at a site in a wind farm shall take into account the deterministic and turbulent flow characteristics associated with single or multiple wakes from upwind machines, including the effects of the spacing between the machines, for all ambient wind speeds and wind directions relevant to power production.

The increase in loading generally assumed to result from wake effects may be accounted for by the use of an added turbulence approach, or by using more detailed wake models. In either case, the wake model shall include adequate representation of the effect on loading of ambient turbulence and discrete and turbulent wake effects.

For fatigue calculations, the effective turbulence intensity I_{eff} may be derived according to Annex E.

The added turbulence for fatigue and ultimate loads may be assumed to be the same.

The DWM model described in Annex E is generally applicable to both fatigue and extreme load cases.

11.5 Assessment of other environmental conditions

The following environmental conditions shall be assessed for comparison with the assumptions made in the design of a wind turbine:

- normal and extreme temperature ranges;

- icing, hail and snow;
- humidity;
- lightning;
- solar radiation;
- chemically active substances;
- salinity.

11.6 Assessment of earthquake conditions

There are no earthquake resistance requirements for standard class turbines because such events are only design driving in a few regions of the world. No earthquake assessment analysis is required for sites already excluded by the applicable local seismic code due to their weak seismic action. For locations where the seismic load cases described below are critical, the engineering integrity shall be demonstrated for the wind turbine site conditions. The assessment may be based on Annex D. The evaluation of load shall take into account the combination of seismic loading with other significant, frequently occurring operational loads.

The seismic loading shall depend on ground acceleration and response spectrum requirements as defined in local codes. If a local code is not available or does not give the ground acceleration and response spectrum, an appropriate evaluation of these parameters shall be carried out.

The ground acceleration shall be evaluated for a 475-year return period.

The earthquake loading shall be superposed with operational load that shall be the largest of

- a) mean loads during normal power production determined at V_r ,
- b) loads during emergency stop at V_r , and
- c) loads during idling or parked condition at no wind and V_{out} .

The partial safety factor for load for all load components shall be 1,0. The material safety factor for steel can be set to 1,0.

The seismic load evaluation may be carried out through response spectrum methods, in which case the operational load is added using the SRSS (square-root-sum-of-squares) or equivalent load combination arising from the seismic loading.

The seismic load evaluation may be carried out through time-domain methods, in which case sufficient simulations shall be undertaken to ensure that the operational load is representative of the time averaged values referred to above.

The number of tower natural vibration modes used in either of the above evaluations shall be selected in accordance with a recognized seismic code. In the absence of such a code, consecutive modes with a total modal mass of 85 % of the total mass shall be used.

The evaluation of the resistance of the structure may assume elastic response only, or ductile energy dissipation. However, it is important that the latter is assessed correctly for the specific type of structure in use, in particular for lattice structures and bolted joints.

The acceleration response spectrum at the engineering bedrock and seismic response evaluation method are described in Annex D. The response spectrum method shall not be used if it is possible that seismic action will cause significant loading of structures other than the tower.

11.7 Assessment of electrical network conditions

The external electrical conditions at the wind turbine terminals at a proposed site shall be assessed to ensure compatibility with the electrical design conditions. The external electrical conditions shall include the following³⁵:

- normal voltage and range including requirements for remaining connected or disconnecting through specified voltage range and duration;
- normal frequency, range and rate of change, including requirements for remaining connected or disconnecting through specified frequency range and duration;
- voltage imbalance specified as a percentage negative phase-sequence voltage for symmetric and unsymmetrical faults;
- method of neutral grounding;
- method of ground fault detection/protection;
- annual number of network outages;
- auto-reclosing cycles;
- required reactive compensation schedule;
- fault currents and duration;
- phase-phase and phase-ground short-circuit impedance at the wind turbine terminals;
- background harmonic voltage distortion of the network;
- presence of power line carrier signalling if any and frequency of same;
- fault profiles for ride-through requirements;
- power factor control requirements;
- ramp rate requirements; and
- other grid compatibility requirements.

11.8 Assessment of soil conditions

The soil properties at a proposed site shall be assessed by a professionally qualified geotechnical engineer, with reference to available local building codes.

11.9 Assessment of structural integrity by reference to wind data

11.9.1 General

It is possible to complete the assessment of structural integrity by comparison of the wind parameter values for the site to those used in design. The assessment can be performed separately for the fatigue load suitability and the ultimate load suitability.

11.9.2 Assessment of the fatigue load suitability by reference to wind data

A wind turbine is suitable for a site with respect to fatigue loading when the following conditions are all satisfied.

- a) The site value of the wind speed probability density function at hub height $p(V_{\text{hub}})$ shall be less than or equal to the design probability density function at all values of V_{hub} between the wind speeds V_{ave} and $2V_{\text{ave}}$. If the turbine has been designed with the wind speed distribution in 6.3.2.1 and the shape parameter k of the site-specific Weibull wind speed distribution is greater than or equal to 1,4, then, k shall fulfil the following equation, which

³⁵ The turbine designer may need to take account of grid compatibility conditions. The list represents a set of minimum requirements. Local and national grid compatibility requirements need to be anticipated at the design stage.

depends on the site-specific mean wind speed at hub height normalized by the design mean wind speed, see Figure 12:

$$6,5 \times \frac{V_{ave,site}}{V_{ave,design}} - 4,5 \leq k \leq -6,0 \times \frac{V_{ave,site}}{V_{ave,design}} + 8,0 \quad (35)$$

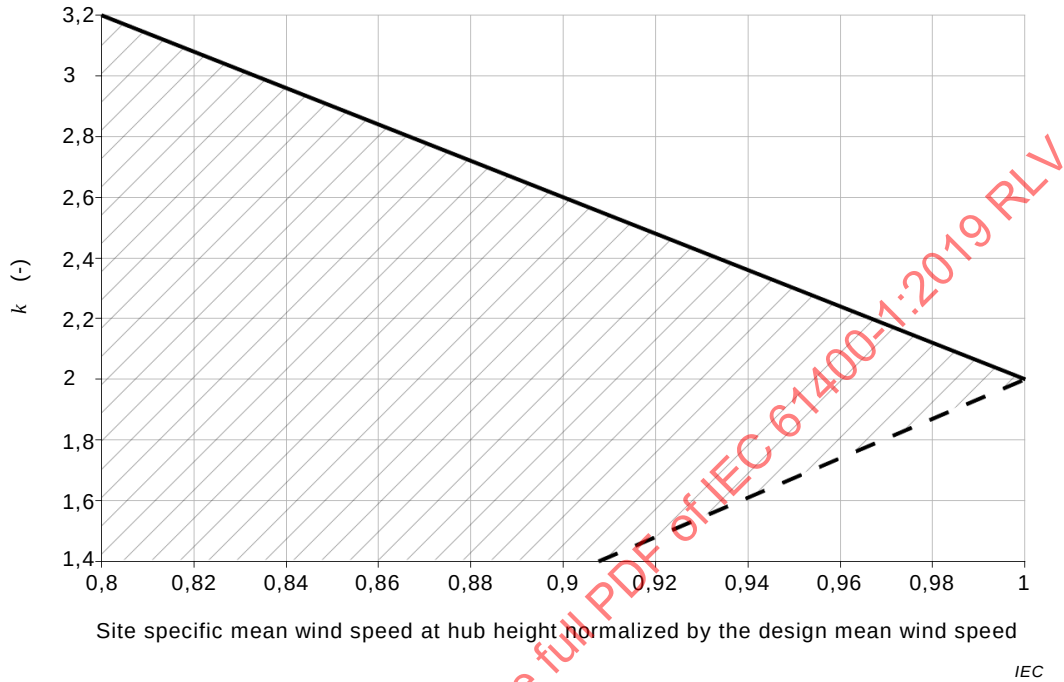


Figure 12 – Possible combinations of normalized mean wind speed and Weibull shape parameter k (shaded area)

- b) An adequate assessment of the ambient turbulence intensity and wake effects can be performed by verifying that the wind speed standard deviation σ_1 from the normal turbulence model (NTM) used in design is greater than or equal to the effective wind speed standard deviation $\hat{\sigma}_{eff}$ (see Annex E) between the wind speeds V_{ave} and $2V_{ave}$, i.e.

$$\sigma_1 > \hat{\sigma}_{eff} (= I_{eff} V_{hub}) \quad (36)$$

Guidance for calculating I_{eff} can be found in Annex E. In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation, i.e. $\hat{\sigma}_c$, shall be increased in order to account for the distortion of the turbulent flow. This can be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

- c) The site flow inclination, taken as the wind energy weighted mean from all directions, shall be between -8° and $+8^\circ$. Where there are no site data or calculations for the flow inclination, it shall be assumed that the flow inclination is equal to the slope, θ , for the 30° sector within a distance of $5z_{hub}$ or the $5z_{hub}$ area extended by $2z_{hub}$ downwind of the wind turbine position from the wind turbine, see 11.2.
- d) The energy weighted average over all wind directions and wind speeds during power production of the vertical site wind shear exponent α shall be in the range of 0,05 to 0,25. Where there are no site data for the wind shear, it shall be calculated taking topography and roughness of the surrounding terrain into account.
- e) The average site air density shall be less than the one specified in 6.4.2 for wind speeds greater than or equal to V_r . As an alternative, for an air density greater than the one specified in 6.4, it shall be demonstrated that the following condition applies:

$$\rho_{\text{design}} \times V_{\text{ave,design}}^2 \geq \rho_{\text{site}} \times V_{\text{ave,site}}^2 \quad (37)$$

11.9.3 Assessment of the ultimate load suitability by reference to wind data

A wind turbine is suitable for a site with respect to ultimate loading when the following conditions are all satisfied.

- a) The design value of the wind speed standard deviation, σ_1 , (see Equation (10)) shall be greater than or equal to the site value of the estimated 90 % quantile³⁶ of the wind speed standard deviation at all values of V_{hub} between the wind speeds $0,6 V_r$ and $1,6 V_r$, i.e.

$$\sigma_1 \geq \hat{\sigma} + 1,28 \hat{\sigma}_{\sigma} \quad (38)$$

In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation shall be increased in order to account for the distortion of the turbulent flow. This may be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

- b) The site estimate of the extreme 10-min average wind speed V_{50} at hub height with a return period of 50 years shall be less than or equal to V_{ref} . Alternatively, the wind turbine site central estimate of extreme 3 s average wind speed at hub height with a return period of 50 years shall be less than V_{e50} . For Class S turbines, both the extreme 3 s average wind speed and the extreme 10 min average wind speed shall be assessed. V_{50} shall be modified according to Footnote 24 when the coefficient of variation of the annual maximum wind speed is larger than 15 %. If the average site air density is different from the one specified in 6.4.2, it shall be demonstrated that the following condition applies:

$$\rho_{\text{design}} \times V_{\text{ref}}^2 \geq \rho_{\text{site}} \times V_{50,\text{hub}}^2 \quad (39)$$

- c) It shall be demonstrated that the site-specific extreme ambient wind speed standard deviation does not exceed the ETM model in 6.3.3.4.
- d) In case of wake situations, it shall be demonstrated that the maximum centre-wake wind speed standard deviation in the most severe direction does not exceed the ETM model in 6.3.3.4. Alternatively, it can be demonstrated that the ambient site-specific extreme turbulence does not exceed the ETM model used for DLC 1.6 in Annex B and that the minimum site-specific inter-turbine distance does not fall below S_{min} from DLC 1.6. For determination of the site-specific turbulence, the site-specific conditions, the frequency of the wake situations and the wind farm layout shall be accounted for.

11.10 Assessment of structural integrity by load calculations with reference to site-specific conditions

The demonstration shall comprise a comparison of loads and deflections calculated for the specific wind turbine site conditions with those calculated during design, taking account of the reserve margins and the influence of the environment on structural resistance. The calculations shall account for variations of wind conditions with mean wind direction and speed as well as for wake effects, vertical wind shear, mean wind flow angle, etc.

For the fatigue loading, a comparison of damage equivalent moments and damage equivalent load of the load duration distribution of the driving torque is sufficient for verification of components. For ultimate loading a comparison of contemporaneous loads is not required.

Turbulence structure shall be based on site-specific values. Where there are no site data for the components of turbulence and the terrain is complex, values for the ratios of the

³⁶ The right hand side of Equation (38) represents an approximation of the 90 % quantile.

components assigned for each complexity category in 11.2 may be used. As an alternative, the longitudinal turbulence intensity may be increased by the C_{CT} factor.

In the case of wake effects, it shall be verified that structural integrity is not compromised. This may be performed using a wake model, for example see Annex E, with the turbulence model adjusted to the site-specific parameters.

Since for fatigue load calculations, I_{eff} as defined in Annex E depends on the Wöhler curve exponent m of the material of the considered component, the loads on structural components with other material properties shall either be recalculated or assessed with the appropriate value of m .

Fatigue load calculations shall be performed, if one of the criteria in 11.9.2 fails.

Ultimate limit state analyses shall be performed if one of the criteria in 11.9.3 fails. As a minimum, the following ultimate design load cases shall be assessed: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. If the design load cases for the standard classes are adequate, no further evaluations need to be performed.

Annex B provides definitions of the aforementioned ultimate and fatigue load cases for site-specific conditions. If relevant, other load cases in design situations 1), 6), and 7) in Table B.1 should be considered. Design situations 2), 3), 4), 5), and 8) in Table B.1 only need to be considered when the control system behaviour and transport, assembly, maintenance and repair procedures are site-dependent.

12 Assembly, installation and erection

12.1 General

The manufacturer of a wind turbine shall provide an installation manual clearly describing installation requirements for the wind turbine structure and equipment. The installation of a wind turbine shall be performed by personnel trained or instructed in these activities.

The site of a wind turbine facility shall be prepared, maintained, operated and managed so that work can be performed in a safe and efficient manner. This should include procedures to prevent unauthorized access where appropriate. The operator should identify and eliminate existing and potential hazards.

Checklists of planned activities shall be prepared, and logs of completed work and results of that work should be kept.

When appropriate, installation personnel shall use approved eye, foot, hearing, and head protection. All personnel climbing towers, or working above ground or water level, should be trained in such work and shall use approved safety harnesses, safety climbing aids or other safety devices. When appropriate, a buoyancy aid should be used around water.

All equipment shall be kept in good repair and be suitable for the task for which it is intended. Cranes, hoists and lifting equipment, including all slings, hooks and other apparatus, shall be adequate for safe lifting.

Particular consideration should be given to installation of the wind turbine under unusual conditions, such as hail, lightning, high winds, earthquake, icing.

In the case of a tower standing without a nacelle, appropriate means shall be taken to avoid critical wind speeds for vortex-generated transverse vibrations unless the appropriate fatigue design load case has been analysed, or the resulting loads shall be included in the fatigue

analysis. The critical wind speeds and precaution measures shall be included in the installation manual.

12.2 Planning

The assembly, erection and installation of wind turbine and associated equipment shall be planned in order that the work is carried out safely and in accordance with local and national regulations. In addition to procedures for quality assurance, the planning shall include, where appropriate, consideration of the following:

- rules for safe execution of excavation work;
- detailed drawings and specifications of the work and inspection plan;
- rules for the proper handling of embedded items, such as foundations, bolts, anchors and reinforcement steel;
- rules for concrete composition, delivery, sampling, pouring, finishing and placement of conduits;
- safety rules for blasting;
- procedures for installation of towers and other anchors.

12.3 Installation conditions

During the installation of a wind turbine, the site shall be maintained in such a state that it does not present safety risks.

12.4 Site access

Access to a site shall be safe and the following shall be taken into account:

- barriers and routes of travel;
- traffic;
- road surface;
- road width;
- clearance;
- access weight bearing capacity;
- movement of equipment at the site.

12.5 Environmental conditions

During installation, environmental limits specified by the manufacturer shall be observed. Items such as the following should be considered:

- wind speed;
- snow and ice;
- ambient temperature;
- blowing sand;
- lightning;
- visibility;
- rain.

12.6 Documentation

The manufacturer of a wind turbine shall provide drawings, specifications and instructions for assembly procedures, installation and erection of the wind turbine. The manufacturer shall

provide details of all loads, weights, lifting points and special tools and procedures necessary for the handling and installation of the wind turbine.

12.7 Receiving, handling and storage

Handling and transport of wind turbine generator equipment during installation shall be performed with equipment confirmed to be suitable to the task and in accordance with the manufacturer's recommended practice.

Wind turbines are often sited on hilly terrain. Therefore, heavy equipment shall be set down in such a manner that it cannot shift. A suitably-sized, level lay-down area is preferred for all handling and assembly operations. Where this cannot be provided, all heavy equipment shall be securely blocked in a stable position.

Where there is risk of movement caused by the wind with risk of consequent damage, blades, nacelles, other aerodynamic parts and light crates shall be secured with ropes and stakes, or ground anchors.

12.8 Foundation/anchor systems

Where specified by the manufacturer for safe installation or assembly, special tools, jigs and fixtures and other apparatus shall be used.

12.9 Assembly of wind turbine

A wind turbine shall be assembled according to the manufacturer's instructions. Inspection shall be carried out to confirm proper lubrication and pre-service conditioning of all components.

12.10 Erection of wind turbine

A wind turbine shall be erected by personnel trained and instructed in proper and safe erection practices.

No part of a wind turbine electrical system shall be energized during erection unless it is necessary for the erection process. In this case, the energization of such equipment shall be carried out in accordance with a written procedure to be provided by the wind turbine supplier.

All elements where motion (rotation or translation) may result in a potential hazard shall be secured from unintentional motion throughout the erection process.

12.11 Fasteners and attachments

Threaded fasteners and other attachment devices shall be installed according to the wind turbine manufacturer's recommended torque and/or other instructions. Fasteners identified as critical shall be checked and procedures for confirming installation torque and other requirements shall be obtained and used.

In particular, inspection shall be carried out to confirm the following:

- proper assembly and connection of guys, cables, turn buckles, gin poles and other apparatus and devices;
- proper attachment of lifting devices required for safe erection.

12.12 Cranes, hoists and lifting equipment

Cranes, hoists and lifting equipment, including all hoisting slings, hooks and other apparatus required for safe erection, shall be adequate for safe lifting and final placement of the loads. Manufacturer's instructions and documentation with respect to erection and handling should

provide information on expected loads and safe lifting points for components and/or assemblies. All hoisting equipment, slings and hooks shall be tested and certified for safe load.

13 Commissioning, operation and maintenance

13.1 General

The commissioning, operation, inspection, and maintenance procedures shall be specified in the wind turbine manual with due consideration of the safety of personnel.

The design shall incorporate provisions for safe access for inspection and maintenance of all components.

The requirements of Clause 10 also cover electrical measurement equipment temporarily installed in the wind turbine for the purpose of measurements.

When appropriate, operation and maintenance personnel shall use approved eye, foot, hearing and head protection. All personnel climbing towers, or working above ground or water level, shall be trained in such work and shall use approved safety belt, safety climbing aids or other safety devices. When appropriate, a buoyancy aid should be used around water.

13.2 Design requirements for safe operation, inspection and maintenance

The normal operation of a wind turbine by the operating personnel shall be possible at ground level. A tagged, local, manual override on the automatic/remote control system shall be provided.

External events detected as faults but not critical for the future safety of a wind turbine, such as loss and reinstatement of the electrical load, may allow automatic return to normal operation after completion of the shutdown cycle.

Guards designed to protect personnel from accidental contact with moving components shall be fixed, unless frequent access is foreseen where they may be movable.

Guards shall

- a) be of robust construction,
- b) not be easy to by-pass, and
- c) where possible, enable essential maintenance work to be carried out without their dismantling.

Provisions shall be made in the design for use of diagnostic fault-finding equipment.

In order to ensure the safety of inspection and maintenance personnel, the design shall incorporate

- safe access paths and working places for inspection and routine maintenance,
- adequate means to protect personnel from accidental contact with rotating components or moving parts,
- provision for securing lifelines and safety harnesses or other approved protection devices when climbing or working above ground level,
- provisions for blocking rotation of the rotor and yawing mechanism or other mechanical motion, such as blade pitching, during servicing according to wind conditions and design situations specified in DLC 8.1, as well as provisions for safe unblocking,
- warning signs for live conductors,

- suitable devices for the discharge of accumulated electricity,
- suitable fire protection for personnel, and
- an alternative escape route from the nacelle.

Maintenance procedures shall require safety provisions for personnel entering any enclosed working space, such as hub or blade interior, that ensure any dangerous situation will be known by standby personnel to immediately initiate rescue procedures if necessary.

13.3 Instructions concerning commissioning

13.3.1 General

The manufacturer shall provide instructions for commissioning.

13.3.2 Energization

The manufacturer's instructions shall include a procedure for initial energization of the wind turbine electrical system.

13.3.3 Commissioning tests

The manufacturer's instructions shall include the procedures for wind turbine testing after installation, to confirm proper, safe and functional operation of all devices, controls and apparatus. These shall include, but not be limited to,

- safe start-up,
- safe shutdown,
- safe emergency stop,
- safe shutdown from overspeed or representative simulation thereof, and
- test of protection functions, see Clause 8.

13.3.4 Records

The manufacturer's instructions shall include the instruction that proper records shall be kept describing testing, commissioning, control parameters and results.

13.3.5 Post commissioning activities

At the completion of installation, and following operation for the manufacturer recommended running-in period, the specific actions that may be required by the manufacturer shall be completed.

These can include, but are not limited to, preloading of fasteners, changing of lubrication fluids, checking other components for proper setting and operation and proper adjustment of control parameters.

The wind turbine site should be refurbished to remove hazards and prevent erosion.

13.4 Operator's instruction manual

13.4.1 General

An operator's instruction manual shall be supplied by the wind turbine manufacturer and augmented with information on special local conditions at the time of commissioning as appropriate. The manual shall include, but not be limited to

- any requirements that the operation shall be performed by personnel suitably trained or instructed in this activity,

- safe operating limits and system descriptions,
- start-up and shutdown procedures,
- an alarms action list,
- emergency procedures plan, and
- stated requirements that
 - when appropriate, approved eye, feet, hearing and head protection shall be used,
 - when appropriate, all personnel climbing towers, or working above ground or water level, shall be trained in such work and shall use approved safety harness, safety climbing aids or other safety devices,
 - when appropriate, a buoyancy aid should be used around water, and
 - the manual shall be available to the operation and maintenance personnel in a language that can be read and understood by the operator.

13.4.2 Instructions for operations and maintenance records

The manual shall state that operations and maintenance records shall be kept and should include the following:

- wind turbine identification;
- energy produced;
- operating hours;
- shutdown hours;
- date and time of fault reported;
- date and time of service or repair;
- nature of fault or service;
- action taken;
- parts replaced.

13.4.3 Instructions for unscheduled automatic shutdown

The manual shall require that following any unscheduled automatic shutdown caused by a fault or malfunction, unless specified otherwise in the operations manual or instructions, the operator shall investigate the cause before a wind turbine is restarted. All unscheduled automatic shutdowns should be recorded.

13.4.4 Instructions for diminished reliability

The manual shall require that action shall be taken to eliminate the root cause of any indication or warning of abnormality or diminished reliability.

13.4.5 Work procedures plan

The manual shall require that the wind turbine shall be operated according to safe working procedures, taking account of the following:

- electrical systems operation;
- co-ordination of operation and maintenance;
- utility clearance procedures;
- tower climbing procedures;
- equipment handling procedures;
- activity during bad weather;

- communications procedures and emergency plans.

13.4.6 Emergency procedures plan

Probable emergency situations shall be identified in the operations manual and the required actions of the operating personnel prescribed.

The manual shall require that where there is a fire or apparent risk of structural damage to the wind turbine or its components, no one should approach the wind turbine unless the risk is specifically evaluated.

In preparing the emergency procedures plan, it shall be taken into account that the risk for structural damage may be increased by situations such as the following:

- overspeeding;
- icing conditions;
- lightning storms;
- earthquakes;
- broken or loose guy-wires;
- brake failure;
- rotor imbalance;
- loose fasteners;
- lubrication defects;
- sandstorms;
- fire, flooding;
- other component failures.

13.5 Maintenance manual

Each wind turbine model shall have a maintenance manual, which at a minimum consists of the maintenance requirements and emergency procedures specified by the wind turbine manufacturer. The manual shall also provide for unscheduled maintenance.

The maintenance manual shall identify parts subject to wear and indicate criteria for replacement.

Subjects which should also be covered in the manual include the following:

- any requirement that inspection and maintenance shall be carried out by personnel suitably trained or instructed in this activity, at the intervals specified in and in compliance with the instructions in the wind turbine maintenance manual;
- description of the subsystems of the wind turbine and their operation;
- lubrication schedule prescribing frequency of lubrication and types of lubricants or any other special fluids;
- recommissioning procedure;
- maintenance inspection periods and procedures;
- procedures for functional check of protection subsystems;
- complete wiring and interconnection diagram;
- guy cable inspection and re-tensioning schedules and bolt inspection and preloading schedules, including tension and torque loadings;
- diagnostic procedures and trouble-shooting guide;

- recommended spare parts list;
- set of field assembly and installation drawings;
- tooling list.

14 Cold climate

14.1 General

Cold climate (CC) weather conditions are defined as icing climate (IC) and/or low temperature climate (LTC). LTC is for temperatures below the normal environmental conditions (6.4.2). IC is defined as meteorological icing leading to rime and/or glaze ice accretion on the wind turbine. For ice type definitions, see ISO 12494. For simplicity, cold climate conditions will be treated here as IC and LTC conditions unless stated otherwise.

The impact of cold climate on the structural integrity or safety systems of the wind turbine shall be assessed.

14.2 Low temperature and icing climate

As a minimum, the following effects on a wind turbine from a LTC shall be considered:

- a) component materials;
- b) air density;
- c) start-up procedures;
- d) viscosity of oils and lubricants.

As a minimum, the following effects from an IC shall be considered:

- reduced turbine performance due to iced blades;
- inhomogeneous ice distribution on wind turbine blades;
- ice shedding from blades;
- icing effects on wind measurements;
- increased sound levels;
- prolonged standstills.

14.3 External conditions for cold climate

14.3.1 General

The external conditions for cold climate deviate from normal climate external conditions (6.4.2) in terms of ambient temperature, air density, and icing.

14.3.2 Wind turbine class for cold climate

The external conditions to be considered for design are dependent on the intended site or site type for a wind turbine installation. As a consequence of LTC effects in cold climate conditions, minimum ambient temperature conditions shall be assumed which are intended to represent many different sites and do not give a precise representation of any specific site. Wind turbine class for cold climate is defined in terms of ambient temperature as follows:

$\theta_{\min, \text{operation}} = -30 \text{ }^{\circ}\text{C}$	Minimum allowable ambient temperature for wind turbine operation (instantaneous value)
$\theta_{1\text{year}, \min} = -40 \text{ }^{\circ}\text{C}$	Minimum ambient temperature to be expected in hourly average (return period 1)

year) = minimum dimensioning temperature

$$\theta_{\text{mean}} = -5 \text{ }^{\circ}\text{C}$$

Yearly mean ambient temperature

Other environmental conditions are according to normal environmental conditions (6.4.2).

14.4 Structural design

For LTC, the air density of 1,225 kg/m³ shall be used for structural design in order to allow the use of wind turbines designed according to standard wind turbine classes.

The effect of the actual air density at the site³⁷, as influenced by temperature and altitude, shall be considered during the site suitability analysis.

14.5 Design situations and load cases

14.5.1 General

Cold climate conditions result in specific design situations for a wind turbine. In IC, the effect of ice accretion on blade aerodynamic coefficients and on the blade mass distribution needs to be considered. In LTC, low ambient temperatures (14.3.2) resulting in higher air densities than in normal climate conditions (6.4.2), selection of suitable materials (14.5.3) and the resulting consequences shall be taken into account in turbine design.

Ice accretion on rotor blades often occurs for temperatures higher than minimum ambient temperatures (14.3.2).

In cold climate conditions, altered turbine performance resulting to a shift in turbine operational point shall be assessed. As a minimum, the following shall be considered:

- unfavourable turbine controller behaviour, for example, due to incorrect generator torque and pitch setpoints caused by different aerodynamic performances of the blades;
- increase in start-stop cycles;
- change in stall behaviour of turbine blades;
- eigenfrequency changes due to additional blade ice mass.

Higher loading may be a consequence of aforementioned effects. Higher loading during icing may also be a consequence of imbalances resulting from altered rotor aerodynamics and additional ice mass. Further guidance can be found in Annex L.

14.5.2 Load calculations

For cold climate conditions, the turbine controller behaviour and loads are primarily affected by IC effects resulting from ice accretion on the rotor blades and LTC effects resulting from increased air density. Further guidance can be found in Annex L.

14.5.3 Selection of suitable materials

For LTC effects in cold climate, all load calculation shall be matched to the modified temperature range to take material properties into account. One air density according to 14.4 may be used for all cold climate temperature ranges.

Ultimate strength verifications for components³⁸ that are exposed to the ambient temperature shall be considered for $\theta_{\text{min,operation}}$ except for loads derived from DLC 7.1, 8.1 and 8.2 to be

³⁷ An air density of 1,3 kg/m³ may be more representative for sea-level sites.

considered with $\theta_{1\text{year,min}}$. Alternatively, the minimum temperature for DLC 8.1 may also be defined by the manufacturer. Fatigue strength verifications shall be considered for θ_{mean} .

14.6 Control systems

In addition to normal climate requirements for control systems stated in Clause 8, the components of the control system shall be designed under consideration of a shift in turbine operational point due to icing of the turbine, the specified ambient temperatures during operation and standstill as defined in 14.3.2. Cold climate conditions are especially to be considered in the following situations:

- when ensuring safety of the turbine controller behaviour during cold climate conditions;
- when a start procedure shall be implemented to set the wind turbine safely back on-line after an event leading to the turbine being cooled off to minimum ambient operation temperature $\theta_{\text{min,operation}}$ or below (due to grid failure, maintenance, or other);
- when the effect on wind turbine dynamics of different air density values shall be taken into account;
- in case of safety critical energy storages, for example in the hub;
- in case of ice/low temperature effects on sensors and data processing.

If operation of the iced turbine is not considered in the load assumptions, measures have to be taken to prevent operation of the iced turbine. These measures need to be redundant; a single failure shall not lead to unintended operation of an iced turbine.

14.7 Mechanical systems

In addition to normal climate requirements for mechanical systems stated in Clause 9, the mechanical systems of the wind turbine shall be designed under consideration of the ambient temperatures during operation and standstill as defined in 14.3.2.

It shall be assured that the oil temperature in the gearbox has reached a temperature to avoid damage before power can be transmitted. For a cold start procedure, see 14.6.

14.8 Electrical systems

In addition to normal climate requirements for electrical systems stated in Clause 10, the electrical installation of the wind turbine shall be designed under consideration of the ambient temperatures during operation and standstill as defined in 14.3.2.

Cold climate conditions are especially to be considered in the following areas:

- materials in the electrical components;
- grid return at minimum standstill ambient temperature $\theta_{1\text{year,min}}$, as defined in 14.3.2;
- start procedure as defined in 14.6.

³⁸ Minimum temperature and corresponding load cases for components that are not exposed to the ambient conditions shall be defined by the manufacturer.

Annex A (normative)

Design parameters for external conditions

A.1 Design parameters for describing wind turbine class S

A.1.1 General

For wind turbines designed to site-specific or special conditions, i.e. class S turbines, the following information shall be given in the design documentation for all conditions that differ from conditions for the wind turbine classes as defined in 6.2. Remaining conditions may be stated by reference to the appropriate wind turbine class.

A.1.2 Machine parameters

Rated power	[kW]
Hub height operating wind speed range $V_{in} - V_{out}$	[m/s]
Design life time	[years]

A.1.3 Wind conditions

General:

Air density	[kg/m ³]
Hub height extreme wind speeds V_{e1} and V_{e50}	[m/s]
Turbulence model and parameters	
Turbulence intensity mean and standard deviation as a function of mean wind speed	
Extreme gust model and parameters for 1- and 50-year return periods	
Extreme direction change model and parameters for 1- and 50-year return periods	
Extreme coherent gust model and parameters	
Extreme coherent gust with direction change model and parameters	
Extreme wind shear model and parameters	

Aggregated or sector-wise (30° or less):

Annual average wind speed	[m/s]
Flow inclination	[°]
Wind speed distribution (Weibull, Rayleigh, measured, other)	
Wind profile model and parameters	
Sector turbulence intensity mean and standard deviation as a function of mean wind speed	
Wake effect model and parameters (effective turbulence intensity or dynamic wake meandering)	

A.1.4 Electrical network conditions

Normal supply voltage and range	[V]
Normal supply frequency and range	[Hz]
Voltage imbalance	[V]
Method of neutral grounding	
Method of ground fault detection/protection	

Annual number and maximum duration of network outages
 Auto-reclosing cycles
 Required reactive compensation schedule
 Fault currents and duration
 Phase-phase and phase-ground short-circuit impedance at the wind turbine terminals
 Background harmonic voltage distortion of the network
 Presence of power line carrier signalling if any and frequency of same
 Fault profiles for ride-through requirements
 Power factor control requirements
 Ramp rate requirements
 Other grid compatibility requirements

A.1.5 Other environmental conditions (where taken into account)

Normal and extreme temperature ranges [°C]
 Relative humidity of the air [%]
 Solar radiation [W/m²]
 Rain, hail and snow
 Icing model and parameters
 Chemically active substances
 Mechanically active particles
 Lightning, including description of lightning protection system
 Salinity [g/m³]

Foundation:

Foundation stiffness and damping

Earthquake model and parameters:

A.2 Additional design parameters for describing cold climate wind turbine class S (CC-S)

See Table A.1

Table A.1 – Design parameters for describing cold climate wind turbine class S (CC-S)

External conditions		
Symbol	Unit	Description
$\theta_{\min, \text{operation}}$	[K]	Minimum allowable ambient temperature for wind turbine operation
$\theta_{1\text{year}, \min}$	[K]	Minimum ambient temperature to be expected in hourly average
$\rho(\theta_{\min, \text{operation}})$	[kg/m ³]	Air density for cold climate design load cases associated with the minimum allowable ambient temperature for wind turbine operation $\theta_{\min, \text{operation}}$
$\rho(\theta_{1\text{year}, \min})$	[kg/m ³]	Air density for cold climate design load cases associated with the minimum ambient temperature to be expected in hourly average $\theta_{1\text{year}, \min}$

The air densities used for load calculation and in the determination of the power curve should be calculated by applying the ideal gas law³⁹.

The following equation applies:

$$\rho(\theta) = \frac{p}{R_0 \times \theta} \quad (\text{A.1})$$

with

$p = 101\,325 \text{ N/m}^2$ (at sea level);

$R_0 = 287 \text{ J/(kg} \cdot \text{K)}$;

$\theta = \theta_{1\text{year,min}} + 35 \text{ K}$ to calculate $\rho(\theta_{1\text{year,min}})$;

$\theta = \theta_{\text{min,operation}} + 25 \text{ K}$ to calculate $\rho(\theta_{\text{min,operation}})$.

Corrections for different altitudes can be applied.

The air density of $1,225 \text{ kg/m}^3$ can be used for structural design in order to allow the use of wind turbines designed according to standard wind turbine classes.

The effect of the actual air density at the site, as influenced by temperature and altitude, shall be considered during the site suitability analysis.

³⁹ The temperature value $\theta_{1\text{year,min}}$ can be set to $\theta_{1\text{year,min}} + 35 \text{ K}$ and $\theta_{\text{min,operation}}$ can be set to $\theta_{\text{min,operation}} + 25 \text{ K}$ for determining the air density accordingly. This increase by $+35 \text{ K}$ and $+25 \text{ K}$, respectively, is equivalent to definitions of the normal climate conditions in 6.4.2 and 6.4.3.2. The standard air density for normal climate conditions is $1,225 \text{ kg/m}^3$ referring to $+15 \text{ }^\circ\text{C}$. The ambient temperature range for normal climate is $-10 \text{ }^\circ\text{C}$ to $+40 \text{ }^\circ\text{C}$, being $+15 \text{ }^\circ\text{C} \pm 25 \text{ K}$. The extreme temperature range for normal climate is $-20 \text{ }^\circ\text{C}$ to $+50 \text{ }^\circ\text{C}$, being $+15 \text{ }^\circ\text{C} \pm 35 \text{ K}$.

Annex B (informative)

Design load cases for special class S wind turbine design or site suitability assessment

B.1 General

The design load cases for special class S wind turbine design or site suitability assessment are determined from the combination of operational modes or design situations with the applicable class S external conditions with design parameters as specified in Annex A.

In design situation power production, the analysis for NTM_S and ETM_S may be performed for each sector with wind conditions determined for each sector or for all sectors using aggregated wind conditions. For other design situations, the analysis is performed for all sectors using aggregated wind conditions. The aggregation of wind conditions shall be carried out such that proper fatigue and extreme loads are maintained, or the design parameters shall be chosen conservatively. Consideration should be given to the potential variation in wind shear, density and other parameters that can affect fatigue loading on the wind turbine.

Wake effects, earthquake loading and icing shall be considered in load cases as specified for other conditions, if appropriate.

When a wind speed range is indicated in Table B.1, wind speeds leading to the most adverse condition for wind turbine design shall be considered. The range of wind speeds may be represented by a set of discrete values, in which case the resolution shall be sufficient to assure accuracy of the calculation.⁴⁰ In the definition of the design load cases, reference is made to the wind conditions described in Clause 6.

As stated in 11.10, for site suitability assessment, the following ultimate design load cases shall be assessed as minimum: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. If the design load cases for the standard classes are adequate, no further evaluations need to be performed. If relevant, other load cases in design situations 1), 6), and 7) in Table B.1 should be considered. Design situations 2), 3), 4), 5), and 8) in Table B.1 only need to be considered when the control system behaviour and transport, assembly, maintenance and repair procedures are site-dependent.

B.2 Power production (DLC 1.1 to 1.9)

In this design situation, a wind turbine is running and connected to the electric load. The assumed wind turbine configuration shall take into account rotor imbalance. The maximum mass and aerodynamic imbalances (e.g. blade pitch and twist deviations) specified for rotor manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating situations, such as yaw misalignment and control system tracking errors, shall be taken into account in the analyses of operational loads.

Design load cases (DLC) 1.1 and 1.2 embody the requirements for loads resulting from site-specific atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime (NTM). For DLC 1.2, wake effects are additionally considered – see Annex E for guidance. DLC 1.3 embodies the requirements for ultimate loading resulting from

⁴⁰ In general, a resolution of 2 m/s is considered sufficient.

extreme site-specific turbulence conditions. DLC 1.4 and 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine.

The statistical analysis of DLC 1.1 simulation data shall include at least the calculation of extreme values of the blade root in-plane moment and out-of-plane moment and tip deflection. If the extreme design values of the blade root moments derived from DLC 1.1 are exceeded by the extreme design values derived for DLC 1.3, the further analysis of DLC 1.1 may be omitted.

If the extreme design values of the blade root moments derived from DLC 1.1 are not exceeded by the extreme design values derived for DLC 1.3, the factor c in Equation (20) for the extreme turbulence model used in DLC 1.3 may be increased until the extreme design values of the blade root moments computed in DLC 1.3 are equal to or exceed the relevant extremes. The characteristic values of the loads relevant for other turbine components may be determined from this analysis based on DLC 1.3 with the increased extreme turbulence. As an alternative to this analysis, the appropriate characteristic values of all load components relevant for each specific turbine component determined from the simulation may be directly extrapolated.

Table B.1 – Design load cases

Design situation	DLC	Wind condition ⁴¹	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM _s $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM _s $V_{in} < V_{hub} < V_{out}$	Wake effects	F	*
	1.3	ETM _s $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD _s $V_{hub} = V_r - 2 \text{ m/s},$ $V_r, V_r + 2 \text{ m/s}$		U	N
	1.5	EWS _s $V_{in} < V_{hub} < V_{out}$		U	N
	1.6	ETM _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	Wake effects	U	N
	1.7	NTM _s $V_{in} < V_{hub} < V_{out}$	Ice formation Wake effects	U	N
	1.8	NTM _s $V_{hub} = V_r$	Earthquake plus grid loss	U	N
2) Power production plus occurrence of fault	2.1	NTM _s $V_{in} < V_{hub} < V_{out}$	Normal control system fault or loss of electrical network or primary layer control function fault (see 7.4.3)	U	N
	2.2	NTM _s $V_{in} < V_{hub} < V_{out}$	Abnormal control system fault or secondary layer protection function related fault (see 7.4.3)	U	A
	2.3	EOG _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM _s $V_{in} < V_{hub} < V_{out}$	Control system fault, electrical fault or loss of electrical network	F	*

⁴¹ For Class S design, the wind conditions (gust amplitudes, turbulence intensity, etc.) are defined by the designer, as stated in Annex A.

Design situation	DLC	Wind condition ⁴¹	Other conditions	Type of analysis	Partial safety factors
	2.5	NWP $V_{in} < V_{hub} < V_{out}$	Low voltage ride through	U	N
3) Start-up	3.1	NWP _s $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
	3.3	EDC _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
4) Normal shutdown	4.1	NWP _s $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
5) Emergency stop	5.1	NTM _s $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM _s 50-year return period		U	N
	6.2	EWM _s 50-year return period	Loss of electrical network connection	U	A
	6.3	EWM _s 1-year return period	Extreme yaw misalignment	U	N
	6.4	NTM _s $V_{hub} < 0,7 V_{ref}$		F	*
	6.4	NTM _s $V_{hub} < 0,7 V_{ref}$	Ice formation	U	N
	6.6	NTM _s $V_{hub} < 0,7 V_{ref}$	Extreme temperature range	U	N
	6.7	NTM _s $V_{hub} < 0,7 V_{ref}$	Earthquake plus grid loss	U	N
7) Parked and fault conditions	7.1	EWM _s 1-year return period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM _s V_{maint} to be stated by the manufacturer		U	N
	8.2	EWM _s 1-year return period		U	A

The following abbreviations are used:

DLC	Design load case
ECD_s	Site-specific extreme coherent gust with direction change. When site-specific values are not available, it may be assumed to be identical to the ECD defined in 6.3.3.6.
EDC_s	Site-specific extreme direction change. When site-specific values are not available, Equations (21) and (22) in 6.3.3.5 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1 .
EOG_s	Site-specific extreme operating gust. When site-specific values are not available, Equations (18) and (19) in 6.3.3.3 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1 .
EWM_s	Site-specific extreme wind speed. When site-specific values are not available, Equations (13) through (17) in 6.3.3.2 may be used, with site-specific extreme wind speed with 50 years return period in place of V_{ref} .
EWS_s	Site-specific extreme wind shear. When site-specific values are not available, Equations (27) and (28) in 6.3.3.7 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1 and site-specific wind shear exponent in place of $\alpha = 0,2$.
NTM_s	Site-specific representative ambient turbulence intensity, as a function of hub height wind speed, $\hat{\sigma}_c / V_{hub}$ (see 6.3.2.3).
ETM_s	Site-specific extreme ambient turbulence intensity as a function of hub height wind speed $\hat{\sigma}_{1,ETM} / V_{hub}$ (see 6.3.2.3 and footnote 25).
NWP_s	Site-specific wind profile model. When site-specific wind speed profile is not available, Equation (9) in 6.3.2.2 may be used with the site-specific wind shear exponent at hub height in place of $\alpha = 0,2$.
$V_r \pm 2 \text{ m/s}$	Sensitivity to all wind speeds in the range shall be analysed.
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
*	Partial safety for fatigue (see 7.6.3)

In DLC 1.6, the assessment of loads resulting from the ambient site-specific ETM_s model in combination with an inter-turbine wake condition shall be assessed. The inter-turbine spacing S shall cover the worst loading conditions between a minimum spacing S_{min} (to be defined by the manufacturer) and $S = 20D$, where D is the turbine rotor diameter.

Annex E provides guidance on the use of appropriate wake models for DLC 1.6. If an added wake turbulence model is used, the maximum centre-line wake turbulence intensity shall be applied. The use of a meandering wake model (e.g. DWM) shall consider at least five mean wake offset angles $\theta_{wake} = 0^\circ; \pm \theta_{hub-tip}; \pm \theta_{hub-tip} \times 1,5$, where $\theta_{hub-tip} = \sin^{-1}\left(\frac{D}{2S}\right)$.

The number of transient events for DLC 2.4, DLC 3.1 and DLC 4.2 may be site-dependent, and that should be considered in the analysis of site-specific loads. If there is no information available, the number of events suggested in 7.4.3, 7.4.4 and 7.4.5 (footnotes 7, 9 and 10) may be used.

Annex C (informative)

Turbulence models

C.1 General

Two turbulence models are given here for design load calculations. The turbulent velocity fluctuations are assumed to be a stationary, random vector field whose components have zero-mean Gaussian statistics. The first model is recommended.

- 1) Mann uniform shear model.
- 2) Kaimal spectral and exponential coherence model.

Parameters for the models have been selected to satisfy the general turbulence requirements given in 6.3.

C.2 Mann [3] uniform shear turbulence model

The description of this model differs somewhat from the previous models in that a three-dimensional velocity spectral tensor is defined. The model assumes that the isotropic von Karman [2] energy spectrum is rapidly distorted by a uniform, mean velocity shear. The resulting spectral tensor components are given by

$$\Phi_{11}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^4} \left(k_0^2 - k_1^2 - 2k_1(k_3 + \beta(k)k_1)\zeta_1 + (k_1^2 + k_2^2)\zeta_1^2 \right) \quad (C.1)$$

$$\Phi_{22}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^4} \left(k_0^2 - k_2^2 - 2k_2(k_3 + \beta(k)k_1)\zeta_2 + (k_1^2 + k_2^2)\zeta_2^2 \right) \quad (C.2)$$

$$\Phi_{33}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k^4} \left(k_1^2 + k_2^2 \right) \quad (C.3)$$

$$\Phi_{12}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^4} \left(-k_1k_2 - k_1(k_3 + \beta(k)k_1)\zeta_2 - k_2(k_3 + \beta(k)k_1)\zeta_1 + (k_1^2 + k_2^2)\zeta_1\zeta_2 \right) \quad (C.4)$$

$$\Phi_{13}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^2 k^2} \left(-k_1(k_3 + \beta(k)k_1) + (k_1^2 + k_2^2)\zeta_1 \right) \quad (C.5)$$

$$\Phi_{23}(k_1, k_2, k_3) = \frac{E(k_0)}{4\pi k_0^2 k^2} \left(-k_2(k_3 + \beta(k)k_1) + (k_1^2 + k_2^2)\zeta_2 \right) \quad (C.6)$$

where

$$\Phi_{ij}(k_1, k_2, k_3) = \Phi_{ji}^*(k_1, k_2, k_3) = \frac{1}{8\pi^3} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} R_{ij}(\delta_1, \delta_2, \delta_3) e^{-ik_1\delta_1} e^{-ik_2\delta_2} e^{-ik_3\delta_3} d\delta_1 d\delta_2 d\delta_3 ;$$

$$R_{ij}(\delta_1, \delta_2, \delta_3) = \frac{1}{\sigma_{\text{iso}}^2} E \left\langle u_i(x_1, x_2, x_3) u_j(x_1 + \ell \delta_1, x_2 + \ell \delta_2, x_3 + \ell \delta_3) \right\rangle$$

= a non-dimensional correlation tensor;

u_1, u_2, u_3 = the longitudinal, lateral, and upward velocity components, respectively;

$\delta_1, \delta_2, \delta_3$ = the non-dimensional spatial separation vector components;

k_1, k_2, k_3 = the non-dimensional spatial wave numbers for the three component directions;

$k = \sqrt{k_1^2 + k_2^2 + k_3^2}$ = the magnitude of the non-dimensional wave number vector;

$k_0 = \sqrt{k^2 + 2\beta(k)k_1k_3 + (\beta(k)k_1)^2}$ = the magnitude before shear distortion;

$$\zeta_1 = C_1 - \frac{k_2}{k_1} C_2, \quad \zeta_2 = \frac{k_2}{k_1} C_1 + C_2;$$

$$C_1 = \frac{\beta(k)k_1^2(k_1^2 + k_2^2 - k_3(k_3 + \beta(k)k_1))}{k^2(k_1^2 + k_2^2)};$$

$$C_2 = \frac{k_2 k_0^2}{(k_1^2 + k_2^2)^{3/2}} \arctan \left(\frac{\beta(k)k_1 \sqrt{k_1^2 + k_2^2}}{k_0^2 - (k_3 + \beta(k)k_1)k_1 \beta(k)} \right);$$

$E(k) = \frac{1.453k^4}{(1+k^2)^{17/6}}$ = the non-dimensional, von Karman isotropic energy spectrum;

$$\beta(k) = \frac{\gamma}{k^{2/3} \sqrt{{}_2F_1\left(\frac{1}{3}, \frac{17}{6}, \frac{4}{3}, -k^{-2}\right)}}$$

= a non-dimensional distortion time inversely proportional to $\sqrt{k^2 \int_k^\infty E(p) dp}$;

${}_2F_1$ = Hypergeometric function;

$\sigma_{\text{iso}}^2, \ell$ = the unsheared, isotropic variance and scale parameters respectively;

γ = a non-dimensional shear distortion parameter.

While this model is more complex than the von Karman isotropic model, it contains only one additional parameter, namely the shear distortion parameter, γ . When this parameter is zero, the isotropic model is recovered. As this parameter is increased, the longitudinal and lateral velocity component variances increase while the upward velocity component variance decreases. The resulting turbulent eddy structure is stretched in the longitudinal direction and tilted relative to the 1-2 plane.

Assuming that the random velocity field generated by the model is convected past the turbine at the hub-height wind speed, the velocity component spectra observed at a point may be computed by integrating the spectral tensor components. In particular, the non-dimensional, one-sided spectra are given by

$$\frac{f S_i(f)}{\sigma_i^2} = \frac{\sigma_{\text{iso}}^2}{\sigma_i^2} \left(\frac{4\pi \ell f}{V_{\text{hub}}} \right) \psi_{ii} \left(\frac{2\pi \ell f}{V_{\text{hub}}} \right) \quad (\text{C.7})$$

where

$$\Psi_{ij}(k_1) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Phi_{ij}(k_1, k_2, k_3) dk_2 dk_3$$

= the one-dimensional, wave number autospectrum for $i = j$, or cross-spectrum for $i \neq j$, and

$$\sigma_i^2 = \sigma_{\text{iso}}^2 \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} \Phi_{ii}(k_1, k_2, k_3) dk_1 dk_2 dk_3 = \text{the component variance.}$$

Similarly, for spatial separations normal to the longitudinal direction the coherence is given by

$$\text{Coh}_{ij}(f, \ell \delta_2, \ell \delta_3) = \frac{\left| \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \Phi_{ij}\left(\frac{2\pi \ell f}{V_{\text{hub}}}, k_2, k_3\right) e^{-i k_2 \delta_2} e^{-i k_3 \delta_3} dk_2 dk_3 \right|}{\sqrt{\Psi_{ii}\left(\frac{2\pi \ell f}{V_{\text{hub}}}\right) \Psi_{jj}\left(\frac{2\pi \ell f}{V_{\text{hub}}}\right)}} \quad (\text{C.8})$$

Unfortunately, the resulting integrals do not have known analytical forms and shall be carried out numerically for a specific value of the parameter, γ . Mann [4] carried out such integrations and compared the results to the Kaimal spectral model. A least squares fit to the Kaimal model gave the shear parameter

$$\gamma = 3,9 \quad (\text{C.9})$$

with the resulting variance relations

$$\left. \begin{aligned} \sigma_1^2 &= 3,25 \sigma_{\text{iso}}^2 \\ \sigma_2^2 &= 1,65 \sigma_{\text{iso}}^2 \\ \sigma_3^2 &= 0,85 \sigma_{\text{iso}}^2 \end{aligned} \right\} \Rightarrow \begin{cases} \frac{\sigma_2}{\sigma_1} \approx 0,7 \\ \frac{\sigma_3}{\sigma_1} \approx 0,5 \end{cases} \quad (\text{C.10})$$

Note the resulting lateral variance is slightly less than given in Table C.1. The scale parameter may be found by equating the asymptotic, inertial-sub-range longitudinal spectra. Thus,

$$S_1(f) \rightarrow 0,475 \sigma_{\text{iso}}^2 \left(\frac{2\pi \ell}{V_{\text{hub}}} \right)^{-2/3} f^{-5/3} = 0,05 \sigma_1^2 \left(\frac{A_1}{V_{\text{hub}}} \right)^{-2/3} f^{-5/3} \Rightarrow \ell \approx 0,8 A_1 \quad (\text{C.11})$$

In summary, the three parameters required in the Mann model are given by

$$\begin{aligned} \gamma &= 3,9 \\ \sigma_{\text{iso}} &= 0,55 \sigma_1 \\ l &= 0,8 A_1 \end{aligned} \quad (\text{C.12})$$

where σ_1 and A_1 are specified in 6.3.

For three dimensional turbulent velocity simulations, the velocity components are determined from a decomposition of the spectral tensor and an approximation by the discrete Fourier

transform. Thus, the three-dimensional spatial domain is divided into equally spaced discrete points and the velocity vector at each point is given by

$$\begin{bmatrix} u_1(x, y, z) \\ u_2(x, y, z) \\ u_3(x, y, z) \end{bmatrix} = \sum_{k_1, k_2, k_3} e^{i \frac{xk_1 + yk_2 + zk_3}{\ell}} \begin{bmatrix} C(k_1, k_2, k_3) \end{bmatrix} \begin{bmatrix} n_1(k_1, k_2, k_3) \\ n_2(k_1, k_2, k_3) \\ n_3(k_1, k_2, k_3) \end{bmatrix} \quad (\text{C.13})$$

where

$$\begin{bmatrix} C(k_1, k_2, k_3) \end{bmatrix} \approx \sigma_{\text{iso}} \sqrt{\frac{2\pi^2 \ell^3 E(k_0)}{N_1 N_2 N_3 \Delta^3 k_0^4}} \begin{bmatrix} k_2 \zeta_1 & k_3 - k_1 \zeta_1 + \beta k_1 & -k_2 \\ k_2 \zeta_2 - k_3 - \beta k_1 & -k_1 \zeta_2 & k_1 \\ \frac{k_0^2 k_2}{k^2} & -\frac{k_0^2 k_1}{k^2} & 0 \end{bmatrix}$$

- u_1, u_2, u_3 = complex vector components whose real and imaginary parts are independent realizations of the turbulent velocity field;
- n_1, n_2, n_3 = complex Gaussian random values that are independent for each different wave number and have real and imaginary parts with unit variance;
- x, y, z = coordinates of the spatial grid points;
- N_1, N_2, N_3 = the number of spatial grid points in the three directions;
- Δ = the spatial grid resolution.

In this expression, the notation $\sum_{k_1, k_2, k_3}$ means the summation over all dimensionless wave numbers in the grid and may be accomplished using FFT techniques. In cases when the spatial domain is smaller than 8ℓ in any dimension, an adjustment is recommended for the spectral tensor factorization, $[C(k_1, k_2, k_3)]$. This procedure is detailed in Mann [4].

The Mann model parameters derived herein to represent the Mann sheared turbulence model are based on conforming to the external conditions defined in Clause 6 and whereby the resulting wind spectra are equivalent to the Kaimal spectra.

For site-specific analysis, the shear distortion (anisotropy) parameter γ , dissipation factor, $\alpha \epsilon^{2/3}$ and the length scale, l , may be determined based on high frequency site-specific measurements of the wind spectra $F_u(kl)$, $F_v(kl)$, $F_w(kl)$ and $F_{uw}(kl)$ at one fixed point. The Mann model turbulent wind field needs to be then generated based on the three model parameters derived from the measured spectra.

C.3 Kaimal [1]⁴² spectrum and exponential coherence model

The component power spectral densities are given in non-dimensional form by Equation (C.14):

⁴² Note that the turbulence component variance ratios in Table C.1 and the equation form for the upward velocity component differ somewhat from the original Kaimal spectral model. The longitudinal scale has been chosen to approximate the original Kaimal spectrum and, for the lateral and upward scales, to satisfy the spectral requirements in 6.3 for the asymptotic inertial subrange and the variance ratios given in Table C.1.

$$\frac{f S_k(f)}{\sigma_k^2} = \frac{4 f L_k / V_{\text{hub}}}{(1 + 6 f L_k / V_{\text{hub}})^{5/3}} \quad (\text{C.14})$$

where

f is the frequency, in hertz;

k is the index referring to the velocity component direction (i.e. 1 = longitudinal, 2 = lateral, and 3 = upward);

S_k is the single-sided velocity component spectrum;

σ_k is the velocity component standard deviation;

L_k is the velocity component integral scale parameter;

and with

$$\sigma_k^2 = \int_0^{\infty} S_k(f) df \quad (\text{C.15})$$

The turbulence spectral parameters are given in Table C.1.

Table C.1 – Turbulence spectral parameters for the Kaimal model

	Velocity component index, k		
	1	2	3
Standard deviation, σ_k	σ_1	$0,8 \sigma_1$	$0,5 \sigma_1$
Integral scale, L_k	$8,1 A_1$	$2,7 A_1$	$0,66 A_1$
σ_1 and A_1 are the standard deviation and scale parameters, respectively, of the turbulence as specified in 6.3.			

The following exponential coherence model may be used in conjunction with the Kaimal autospectrum to account for the spatial correlation structure of the longitudinal velocity component:

$$\text{Coh}(r, f) = \exp \left[-12 \left((f r / V_{\text{hub}})^2 + (0,12 r / L_c)^2 \right)^{0,5} \right] \quad (\text{C.16})$$

where

$\text{Coh}(r, f)$ is the coherence function defined by the complex magnitude of the cross-spectral density of the longitudinal wind velocity components at two spatially separated points divided by the autospectrum function;

r is the magnitude of the projection of the separation vector between the two points on to a plane normal to the average wind direction;

f is the frequency, in hertz;

$L_c = 8,1 A_1$ is the coherence scale parameter.

C.4 Reference documents

- [1] J.C. Kaimal, J.C. Wyngaard, Y. Izumi, and O.R. Cote, Spectral characteristics of surface-layer turbulence, *Q.J.R. Meteorol. Soc.*, v. 98, 1972, p. 563-598
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- [4] J. Mann, Wind field simulation, *Prob. Engng. Mech.*, v. 13, no. 4, 1998, p. 269-282

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Annex D (informative)

Assessment of earthquake loading

D.1 General

There are two approaches to evaluate the seismic loading on wind turbine. One approach is the dynamic simulation in time domain and the other approach is the response spectrum method (RSM). In time domain approach, the ground acceleration at the surface is estimated from the response spectrum at the engineering bedrock, or the time history of the ground motion specified in the local building codes. The site-specific parameters of the response spectrum may be based on local building codes [1-7]. Special care is required when response spectrum method is used for wind turbine support structures due to its low damping ratio [8]. In Annex D, the design response spectrum is first presented in Clause D.2 followed by the description of the structure model in Clause D.3, seismic load evaluation methods in Clause D.4 and additional load in Clause D.5. An example of time domain simulation is described in [9-10].

D.2 Design response spectrum

The acceleration response spectrum shall be selected at the engineering bedrock for a 475-year return period. In general, the response spectrum is given by local codes.

The acceleration response spectrum may be defined according to Equation (D.1):

$$S_{a0}(T) = \begin{cases} a_0 \left[1 + (\beta_0 - 1) \frac{T}{T_B} \right] & (0 \leq T < T_B) \\ a_0 \beta_0 & (T_B \leq T < T_C) \\ a_0 \beta_0 \left(\frac{T_C}{T} \right)^{K_1} & (T_C \leq T < T_D) \\ a_0 \beta_0 \left(\frac{T_C}{T_D} \right)^{K_1} \left(\frac{T_D}{T} \right)^{K_2} & (T_D \leq T) \end{cases} \quad (D.1)$$

where a_0 is the peak ground acceleration at the engineering bedrock for a 475-year return period; β_0 is the acceleration response magnification ratio for the region where acceleration response becomes constant and may be taken as 2 to 3; T is the fundamental natural period of the structure; T_B , T_C , K_1 and K_2 are dependent on tectonic, geological and soil condition. T_B may be taken as 1/5 to 1/2 of T_C . T_C can be taken as 0,3 s to 0,5 s for stiff and hard soil conditions, 0,5 s to 0,8 s for intermediate soil conditions and 0,8 s to 1,2 s for loose and soft soil conditions. K_1 and K_2 are the exponents that can vary between 1/3 and 2. These parameters can be determined by local design codes as shown in references [2], [3], [4].

The design response spectrum can be written as in Equation (D.2) [2].

$$S_a(T, \zeta) = \begin{cases} a_0 G_s \left[1 + (F_\zeta \beta_0 - 1) \frac{T}{T_B} \right] & (0 \leq T < T_B) \\ a_0 G_s F_\zeta \beta_0 & (T_B \leq T < T_C) \\ a_0 G_s F_\zeta \beta_0 \left(\frac{T_C}{T} \right)^{K_1} & (T_C \leq T < T_D) \\ a_0 G_s F_\zeta \beta_0 \left(\frac{T_C}{T_D} \right)^{K_1} \left(\frac{T_D}{T} \right)^{K_2} & (T_D \leq T) \end{cases} \quad (D.2)$$

where G_s is the soil amplification factor and F_ζ is the damping correction factor of the structure. These parameters are described in Clause D.2.

Soil amplification factor G_s explains the difference of seismic wave amplification during its propagation through the soil where a structure is built. Local design codes usually define typical soil types and their amplification factor. Those valued in local design code may be used for the seismic load evaluation of the wind turbine.

The following damping correction factor may be used for the seismic response analysis of wind turbine [8]:

$$\begin{cases} F_\zeta(\zeta, T, \gamma) = \left(\frac{7}{2 + 100\zeta} \right)^{(-0,07T + 0,7r + 0,5)} & (\zeta \leq 5\%) \\ F_\zeta(\zeta, T, \gamma) = \left(\frac{2}{-3 + 100\zeta} \right)^{\left(0,15 \log_{10} \frac{T}{1,5\gamma} + 0,3 \right)} & (\zeta > 5\%) \end{cases} \quad (D.3)$$

where γ is a value to consider uncertainty in seismic loading, and a value between 0,5 and 0,85 can be used considering local requirement.

D.3 Structure model

For the estimation of seismic load on wind turbine, simplified N degree of freedom model (Figure D.1) can be used in which the mass and the inertia moment of rotor, gear box and generator are lumped at the top of tower (node N), and tower mass is distributed along the tower. The bottom of the tower can be fixed to the ground for the load estimation of tower. More complicated model may be needed for the load estimation of the foundation, which is out of scope of Annex D.

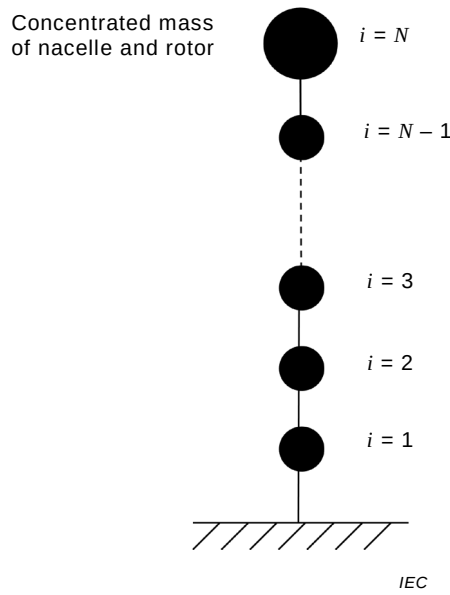


Figure D.1 – Structure model for response spectrum method

D.4 Seismic load evaluation

Using the response spectrum, maximum acceleration (A_{ij}), force (F_{ij}) and displacement (D_{ij}) corresponding to j^{th} mode at i^{th} node can be calculated as follows.

$$A_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta_j) \quad (\text{D.4})$$

$$F_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta_j) m_i \quad (\text{D.5})$$

$$D_{ij} = \gamma_j X_{ij} S_a(T_j, \zeta_j) \left(\frac{T_j}{2\pi} \right)^2 \quad (\text{D.6})$$

where X_{ij} is the j^{th} mode shape obtained from eigenvalue analysis, $S_a(T_j, \zeta_j)$ is the amplitude of response spectrum for natural period T_j and damping ratio ζ_j of j^{th} mode, and γ_j is the modal participation factor for j^{th} mode.

$$\gamma_j = \frac{\sum_{i=1}^N X_{ij}}{\sum_{i=1}^N X_{ij}^2} \quad (\text{D.7})$$

where N is the number of nodes in the model.

The total acceleration (A_i^{total}), displacement (D_i^{total}), shear force (Q_i^{total}) and bending moment (M_i^{total}) considering all the relevant modes at i^{th} node can be calculated by using complete quadratic combination (CQC) method [Equations (D.8) to (D.11)].

$$A_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} A_{ij} A_{il}} \quad (\text{D.8})$$

$$D_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} D_{ij} D_{il}} \quad (\text{D.9})$$

$$Q_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} \left(\sum_{k=i}^N F_{kj} \right) \left(\sum_{k=i}^N F_{kl} \right)} \quad (\text{D.10})$$

$$M_i^{\text{total}} = \sqrt{\sum_{j=1}^M \sum_{l=1}^M \rho_{jl} \left[\sum_{k=i}^N F_{kj} (z_N - z_k) \right] \left[\sum_{k=i}^N F_{kl} (z_N - z_k) \right]} \quad (\text{D.11})$$

where

$$\rho_{jl} = \frac{8\sqrt{\zeta_j \zeta_l} (\zeta_j + X_{jl} \zeta_l) X_{jl}^{3/2}}{(1 - X_{jl}^2)^2 + 4\zeta_j \zeta_l X_{jl} (1 + X_{jl}^2) + 4(\zeta_j^2 + \zeta_l^2) X_{jl}^2} \quad (\text{D.12})$$

where ζ_j and ζ_l are the damping ratios for j^{th} and l^{th} modes, respectively, and X is the ratio of the j^{th} mode natural frequency to the l^{th} mode natural frequency.

D.5 Additional load

The torsional moment of the tower (M^t) can be calculated by using Equation (D.13) [8].

Additional bending moment caused by geometrical non-linearity, such as $p - \Delta$ effect, can be calculated by using maximum displacement, see [8].

$$M^t = 11M_n A_n L_e \quad (\text{D.13})$$

where M_n is the mass of the nacelle and rotor, A_n is the maximum acceleration at the nacelle and L_e is the distance between rotor centre and centre of gravity of the nacelle and rotor.

D.6 Reference documents

- [1] ISO 3010, *Basis for design of structures – Seismic actions on structures*
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Annex E (informative)

Wake and wind farm turbulence

E.1 Added wake turbulence method

Wake effects from neighbouring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity I_{eff} , [1]. The effective turbulence intensity – conditioned on hub height mean wind speed V_{hub} – may be defined as

$$I_{\text{eff}}(V_{\text{hub}}) = \left\{ \int_0^{2\pi} p(\theta|V_{\text{hub}}) I^m(\theta|V_{\text{hub}}) d\theta \right\}^{\frac{1}{m}} \quad (\text{E.1})$$

where

p is the probability density function of wind direction;

I is the turbulence intensity of the combined ambient and wake flows from wind direction θ , and

m is the Wöhler curve exponent corresponding to the material of the considered structural component.

The approach is applicable for regular as well as irregular wind farm layouts.

In the following, a uniform distribution $p(\theta|V_{\text{hub}})$ and a regular rectangular wind farm layout are assumed. It is acceptable to adjust the formulas for other layouts and other than uniform distribution.⁴³ No reduction in mean wind speed inside the wind farm shall be assumed.

If $\min\{d_i\} \geq 10D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_c}{V_{\text{hub}}} \quad (\text{E.2})$$

If $\min\{d_i\} < 10D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_{\text{eff}}}{V_{\text{hub}}} = \frac{1}{V_{\text{hub}}} \left[(1 - N p_w) \hat{\sigma}_c^m + p_w \sum_{i=1}^N \hat{\sigma}_T^m(d_i) \right]^{\frac{1}{m}}; p_w = 0,06 \quad (\text{E.3})$$

where

D is turbine diameter;

$\hat{\sigma}_c = \hat{\sigma} + 1,28\hat{\sigma}_\sigma$ is the representative ambient turbulence standard deviation;

$\hat{\sigma}$ is the estimated ambient turbulence standard deviation;

⁴³ In the case of non-uniform distribution or non-grid wind farm layout, the formula should be modified accordingly, maintaining the concept implied in the more general Formula (E.1). It should be taken into consideration for each neighbour affecting wind turbine, the sector disturbed and their associated probability of occurrence conditioned on hub height mean wind speed.

$\hat{\sigma}_\sigma$	is the estimated standard deviation of the ambient turbulence standard deviation;
$\hat{\sigma}_T = \sqrt{\frac{V_{hub}^2}{\left(1,5 + \frac{0,8d_i}{\sqrt{C_T}}\right)^2} + \hat{\sigma}_c^2}$	is the representative value of the maximum centre-wake, hub height turbulence standard deviation ($\hat{\sigma}_c$ shall not account for farm generated ambient turbulence);
C_T	is the characteristic value of the wind turbine thrust coefficient for the corresponding hub height wind velocity. If the thrust coefficient for the neighbouring wind turbines are not known, a generic value $C_T = 7 c / V_{hub}$, can be used;
d_i	is the distance, normalized by rotor diameter, to neighbouring wind turbine no. i ;
c	is a constant equal to 1 m/s;
I_{eff}	is the effective turbulence intensity;
N	is the number of neighbouring wind turbines, see Table E.1.

Wake effects from wind turbines "hidden" behind other machines need not be considered, for example in a row only wakes from the two units closest to the machine in question are to be taken into account. Dependent on wind farm configuration, the number of nearest wind turbines to be included in the calculation of I_{eff} is as given in Table E.1.

Table E.1 – Number (N) of neighbouring wind turbines

Wind farm configuration	N
2 wind turbines	1
1 row	2
2 rows	5
Inside a wind farm with more than 2 rows	8

The wind farm configuration is illustrated in Figure E.1 for the case "Inside a wind farm with more than 2 rows" and a regular layout.

Inside large wind farms, wind turbines tend to generate their own "wind farm ambient" turbulence. Thus, when

- the number of wind turbines from the considered unit to the "edge" of the wind farm is more than 5, or
- the spacing in the rows perpendicular to the predominant wind direction is less than $3D$,

then the following representative wind farm ambient turbulence shall be assumed instead of $\hat{\sigma}_c$ except in the expression for $\hat{\sigma}_T$:

$$\hat{\sigma}'_c = \frac{1}{2} \left(\sqrt{\hat{\sigma}_w^2 + \hat{\sigma}^2} + \hat{\sigma} \right) + 1,28 \hat{\sigma}_\sigma \quad (E.4)$$

where

$$\hat{\sigma}_w = \frac{0,36 V_{hub}}{1 + 0,2 \sqrt{d_r d_f / C_T}} \quad (E.5)$$

in which d_r and d_f are separations in rotor diameters in rows and separation between rows, respectively.

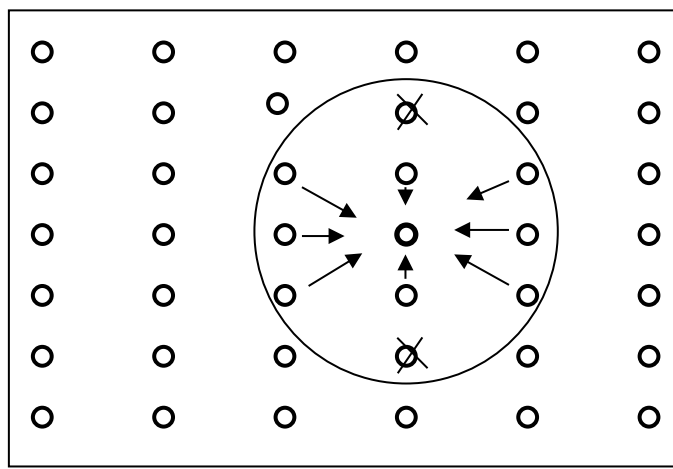


Figure E.1 – Configuration – Inside a wind farm with more than 2 rows

E.2 Dynamic wake meandering model

E.2.1 General

Wake effects from neighboring wind turbines may be taken into account for fatigue and ULS calculations by application of the Dynamic Wake Meandering (DWM) model [2], [3] and [4]. It describes the changes in the mean flow field over the wind farm as well as the changes in the turbulence intensity and turbulence structure compared to ambient conditions.

The DWM model is composed of three parts, see Figure E.2:

- 1) a model of the wake deficit formulated in the meandering frame of reference;
- 2) a stochastic model of the downstream wake meandering process;
- 3) a model of the self-induced wake turbulence described in the meandering frame of reference.

A summary description of recommended sub-models, their synthesis and their extension to the multiple wake case are given in the following.

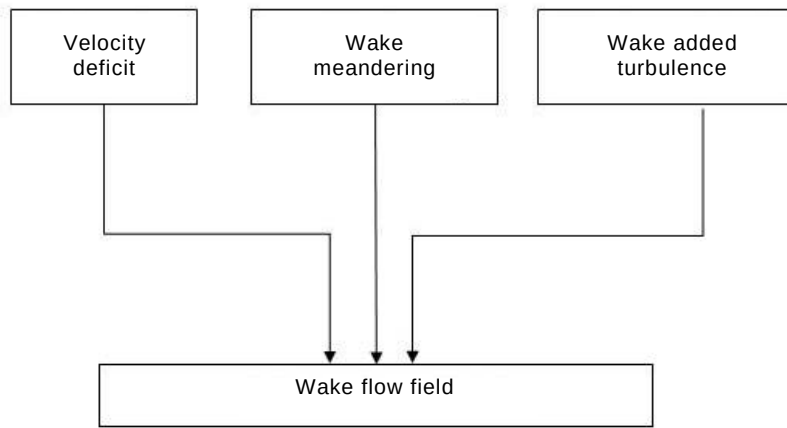


Figure E.2 – The three fundamental parts of the DWM model

E.2.2 Wake deficit

The mean wake deficit expands and attenuates with downstream distance from the wake generating rotor. The recommended modelling of the wake deficit is based on the thin shear layer approximation of the Navier-Stokes equations in their rotational symmetric form with the pressure term disregarded. Taking an eddy viscosity approach for the Reynolds stresses, the system of equations to be solved is:

$$\frac{1}{r} \frac{\partial}{\partial r} (rV(r,x)) + \frac{\partial U(r,x)}{\partial x} = 0 \quad (\text{E.6})$$

$$U \frac{\partial U(r,x)}{\partial x} + V(r,x) \frac{\partial U(r,x)}{\partial r} = \frac{\nu_T}{r} \frac{\partial}{\partial r} \left(r \frac{\partial U(r,x)}{\partial r} \right) \quad (\text{E.7})$$

where U and V denote the mean wake velocities in the axial and radial directions, respectively. The eddy viscosity, ν_T , includes contributions from both the ambient turbulence and the wake self-generated wake turbulence:

$$\frac{2\nu_T}{DV_{\text{hub}}} = 0,023 F_1(\tilde{x}) \left(\frac{\sigma}{V_{\text{hub}}} \right)^{0,3} + 0,016 F_2(\tilde{x}) \frac{R_w(\tilde{x})}{D} \left(1 - \frac{U_{\text{min}}(\tilde{x})}{V_{\text{hub}}} \right) \quad (\text{E.8})$$

where normalized spatial variables are introduced as

$$\tilde{r} = \frac{2r}{D} ; \tilde{x} = \frac{2x}{D} \quad (\text{E.9})$$

and F_1 and F_2 are filter functions depending on the axial coordinate, R_w is the wake radius, and U_{min} is the minimum wake velocity. The empirical filter functions, accounting for the near field pressure influence (i.e. F_2) and the lack of equilibrium between the mean shear flow field and the turbulence field in the near and intermediate wake regime (i.e. F_1), are given by

$$F_1(\tilde{x}) = \begin{cases} \left(\frac{\tilde{x}}{8}\right)^{3/2} - \frac{\sin(2\pi \tilde{x}^{3/2} / 8^{3/2})}{2\pi} & ; 0 \leq \tilde{x} < 8 \\ 1 & ; \tilde{x} \geq 8 \end{cases} \quad (\text{E.10})$$

$$F_2(\tilde{x}) = \begin{cases} 0,0625 & ; 0 \leq \tilde{x} < 4 \\ 0,025 \tilde{x} - 0,0375 & ; 4 \leq \tilde{x} < 12 \\ 0,00105 (\tilde{x} - 12)^3 + 0,025 \tilde{x} - 0,0375 & ; 12 \leq \tilde{x} < 20 \\ 1 & ; 20 \leq \tilde{x} \end{cases} \quad (\text{E.11})$$

The pressure influence is implicitly taken into account by the introduction of F_2 and further by including the part of the wake expansion dictated by the pressure recovery in the boundary conditions associated with the system of differential Equations (E.6) and (E.7). Thus, the initial wake radius is approximated by

$$R_w(0) = D(1 - 0,45 a_m^2) \sqrt{\frac{1+m}{8}} \quad (\text{E.12})$$

where a_m denotes the mean induction over the rotor, and

$$m = \frac{1}{\sqrt{1 - C_T}} \quad (\text{E.13})$$

with C_T being the rotor thrust coefficient. The initial wake deficit to be developed downstream using Equations (E.6) and (E.7) is thus obtained from a blade element momentum far-field induction prediction combined with the radial scaling given by Equation (E.12).

E.2.3 Meandering

The wake meandering part is based on the fundamental presumption that the transport of wakes in the atmospheric boundary layer can be modelled by considering the wakes to act as passive tracers driven by the large-scale turbulence structures. Modelling of the meandering process consequently includes considerations of a suitable description of the "carrier" stochastic transport media (i.e. the large scale turbulence field) as well as of a suitable definition of the cut-off frequency defining large-scale turbulence structures in this context.

The stochastic modelling of wake meandering is established by considering a cascade of wake deficit releases "emitted" at consecutive time instants in agreement with the passive tracer analogy. The propagation of each "emitted" wake deficit is subsequently modelled, and the collective description of these constitutes the wake meandering model in space and time.

Adopting Taylor's hypothesis, the downstream advection of each wake deficit "release" is dictated by a suitable advection velocity often taken as the ambient mean wind speed. As for the dynamics in the lateral and vertical directions, each considered wake cascade-element is successively displaced according to the large scale lateral and vertical turbulence velocities at the instantaneous wake deficit position. In mathematical terms, the wake deficit dynamics in the lateral direction, y , and in the vertical direction, z , are thus described by the following differential equation system:

$$\frac{dy}{dt} = v_c(y, z, t) \quad (\text{E.14})$$

$$\frac{dz}{dt} = w_c(y, z, t) \quad (\text{E.15})$$

where v_c and w_c are the spatially dependent large scale turbulent velocities at time t .

The recommended spatial averaging, defining the large scale part of the turbulence, may be expressed in terms of a cut off frequency using Taylor's frozen hypothesis:

$$f_c = \frac{U_u}{4R} \quad (\text{E.16})$$

Note that with this formulation the large scale part of the turbulence is assumed unaffected by the presence of the wind farm.

E.2.4 Wake induced turbulence

Wake induced turbulence includes contributions from conventional mechanically generated turbulence, caused by the wake shear, as well as from the blade shed and trailed vortices mainly in terms of tip and root vortices gradually breaking down downstream of the wake generating rotor. Thus, this turbulence contribution is considered independent of the ambient turbulence.

With a length scale comparable with the characteristic size of the wake deficit, the basic DWM split in scales implies that the wake induced turbulence meanders with the wake deficit. The induced small scale turbulence is consequently formulated in the meandering frame of reference. Although violating the second order statistics (i.e. the cross correlation), the in-homogeneity of the induced turbulence is approximated by simple scaling of a homogeneous and isotropic turbulence field with a length scale equal to one rotor diameter and a turbulence standard deviation equal to 1 m/s. Rotational symmetry of the induced wake turbulence intensity is assumed, resulting in a scaling coefficient that for a given downstream distance only depends on the radial coordinate. The empirical scaling factor, k_{wt} , depends on the deficit depth, $(V_{hub} - U_{min})$, at the considered downstream distance, as well as on the wake deficit radial gradient $\partial U / \partial r$:

$$k_{wt}(\tilde{x}, \tilde{r}) = 0,6 \left| 1 - \frac{U(\tilde{x}, \tilde{r})}{V_{hub}} \right| + \frac{0,35}{V_{hub}} \left| \frac{\partial U(\tilde{x}, \tilde{r})}{\partial \tilde{r}} \right| \quad (\text{E.17})$$

E.2.5 Wake superposition

Wake superposition is important when dealing with wind farm flow fields. This is a complicated process that calls for simplification. Wakes (including associated small scale wake induced turbulence) from the turbines in question are treated individually, and their correlated meandering is then subsequently modelled. Referring to ambient wind speed conditions, two different approaches are applied for the wind regimes corresponding to below and above rated power, respectively.

- **Below rated wind speed:** For a turbine with the rotor centre located at the spatial position, x , within the wind farm, the temporally varying flow field at the rotor polar coordinate (r, θ) is determined by the dominating wake among contributions from all upstream turbines at any time:

$$U_t(r, \theta, t | x) = \min_i (U_{t,i}(r, \theta, t | x)) \quad (\text{E.18})$$

where $(r, \theta, t | x)$ denotes a temporal coordinate combined with a spatial coordinate in a polar frame of reference centred at the spatial position x , and where each individual wake flow

field is given by $U_{t,i} = (U_i + u_i)e_1 + v_ie_2 + w_ie_3$, with e_j , $j = 1, 2, 3$, being unit normal vectors in the longitudinal, transversal and vertical flow directions. The parameter i includes all upstream turbines relative to the spatial position x for a given mean wind direction. Note that with the recipe formulated in Equation (E.18), the induced small scale turbulence, associated with the wakes contributing to U_t , is aggregated in a non-consistent manner. However, since the induced turbulence contributions are small scale this does not compromise the present application.

- *Above rated wind speed:* Using the nomenclature introduced above, Equation (E.18) is replaced by a summation of the deficit contributions of all upstream turbines:

$$U_t(r, \theta, t | x) = \sum_i U_{t,i}(r, \theta, t | x) \quad (\text{E.19})$$

E.2.6 Model synthesis

For each rotor in a wind farm, the inflow wind field is composed of the ambient, undisturbed wind field with relevant (see Equation (E.18)) wake deficits and wake induced small scale turbulence linearly superimposed. The undisturbed wind field is the site-specific mean wind speed consisting of a deterministic part (i.e. the mean wind shear) and the conventional turbulent part with ambient turbulence characteristics. The resulting inflow wake effects to be superimposed consist of stochastically moving wake deficits, $(V_{\text{hub}} - U)$, and associated wake induced turbulence contributions, respectively, and added according to the recipe formulated in Equation (E.18). Note that the wake deficit meandering is by far the dominating wake effect.

E.3 Reference documents

- [1] S. Frandsen (2007) Turbulence and turbulence generated structural loading in wind turbine clusters, Risø report R-1188
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Annex F (informative)

Prediction of wind distribution for wind turbine sites by measure-correlate-predict (MCP) methods

F.1 General

The assessment of the suitability of a wind turbine for a specific site requires the evaluation of the design-critical wind speed parameters at a site. Frequently, there is insufficient data even at a single point within a wind farm to carry out the evaluation. However, the extended data record can be synthesized by extrapolation based on a long-term record for another location. The MCP methods are a means to create that extended record. The following explanation is taken from [2]. Further information can be found in [3], [4] and [5].

F.2 Measure-correlate-predict (MCP)

The MCP method takes a number of forms in which the averaging period and directional nature of the data vary. One version is described here, based upon the concurrent hourly data from the wind turbine site and a nearby reference meteorological station (Met. Station). These data are cross-plotted and used to derive sector-wise linear regression equations; the sectors being consistent with those used by the Met. Station, typically 30° sectors. The data sets used for deriving the regression equations should be as long as possible, at least conservatively covering the conservative part of any seasonal variations.

F.3 Application to annual mean wind speed and distribution

The above regression equations are applied to the long-term Met. Station record sector by sector, for a period sufficiently long to eliminate short-term variations, probably at least seven years. The result is an hourly mean record for the site, which may be processed into a probability distribution for site assessment.

F.4 Application to extreme wind speed

The classical method for the prediction of the extreme wind speed is a Gumbel analysis modified to improve accuracy (e.g. Best Leiblein Unbiased Estimators (BLUE) method described in [1]). The minimum recommended length of data set is ten years.

It is also possible to apply the method of independent storms (MIS), a derivative of the Gumbel method, which utilizes more than one data point per year from a data set, also described by Cook [1]. This method can be used for data sets that are as short as four years. MIS selects individual storms' peak wind speeds by application of thresholds and time filters to ensure that all values are from independent events.

The sector-specific regression coefficients are applied to a table of the maximum hourly wind speed at the Met. Station, by year for basic Gumbel and by storm event for MIS, and by sector. A similar table is therefore built up for the wind turbine site. The maximum value in each year for the candidate site is extracted for use in a Gumbel analysis.

The use of the coefficients is appropriate here since they have been formed from hourly mean data and are being applied to hourly mean data. In this method, there is no assumption that the maximum value at the candidate site occurs in the same sector as the maximum at the reference site. By using the sector-specific regression coefficients, the maximum at the candidate site can be more accurately determined, taking account of the inter-site relationships.

The selection of the relevant return period in the extreme value analysis should account for the number of events per annum.

The gust factors should be estimated from the site-measured data, or by theoretical methods.

Users of these methods for estimation of extreme wind speed should note that the resulting accuracy depends significantly on data quality and actual local conditions compared to the reference station. As a result, correlations from a regression analysis may be poor. In cases where existing local codes are recognized as applicable by authorities having jurisdiction, the extreme values obtained using such codes should be considered as minimum values for design in preference to MCP.

F.5 Reference documents

- [1] N.J. Cook, The designers guide to wind loading of building structures, Butterworths, 1995
- [2] National Wind Power and Climatic Research Unit of the University of East Anglia, Prediction of extreme wind speed at wind energy sites, a set of guidelines prepared under ETSU contract W/11/00427/00
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- [4] D.C. Quarton, Wind Farms in Hostile Terrain, Final Report, A report prepared under ETSU contract W/43/00501/00/00, July 1999
- [5] R.I. Harris, The accuracy of design values predicted from extreme value analysis, Journal of Wind Engineering and Industrial Aerodynamics, 89 (2001) p. 153-164

Annex G (informative)

Statistical extrapolation of loads for ultimate strength analysis

G.1 General

Failure of a structure occurs when the stress at a critical location exceeds the resistance capacity of the component material. Assuming that local stresses are related to the loading so that the stress progressively increases with increased loading, the strength of a structural component can be defined in terms of an ultimate load that causes failure. Given the service loading, the adequacy of the structure can be assessed by comparing the extreme values of the loading with the ultimate load resistance, applying suitable factors of safety.

For wind turbines, loading depends on the turbulent wind inflow for a variety of wind conditions. Thus, it is necessary to analyse the extreme values of the loading on a statistical basis in order to determine a suitable characteristic load.

For a given wind condition, it is reasonable to model the short-term load response as a stationary random process. Given that loads can be represented as such processes, methods are described in the following for the extraction of data for extrapolation and load extrapolation. Convergence criteria also are proposed and an alternative for estimating the long-term loads using the inverse first-order reliability method (IFORM) is given.

The methods have been tested for a 3-bladed horizontal-axis upwind turbine. Special attention may be necessary for other wind turbine concepts and/or control schemes including load feedback. More information and guidance can be found in [1].

G.2 Data extraction for extrapolation

Data used in extrapolation methods are extracted from time series of turbine simulation over the operating range of the turbine in specified wind conditions. Data may be extracted by choosing the global individual response extremes from each simulation or some subset created by breaking the simulation into blocks of equal time or ensuring a minimum time separation between extremes.

Establishing independence among the individual load response extremes is important for some methods of extrapolation. When extracting, the designer should consider the effect of independence between peaks on the extrapolation and minimize dependence when possible. If the method chosen for extrapolation is sensitive to independence assumption (e.g. the method involves transforming probability functions between time bases), the designer should attempt to statistically test for independence.

A simple approach to ensure independence is to assume that the global extreme in each ten-minute simulation or local extremes from intervals no shorter than three response cycles are independent and thus require a minimum time separation between individual response extremes of three response cycles (defined by three mean crossings over the block size). If a systematic statistical approach is desired, the designer may test for independence using standard estimation techniques (e.g. [5], [6]) and then minimize dependence in a controlled manner.

Peak over threshold methods may also be employed, but the designer should be careful that truncation errors and correlation introduced by the threshold do not influence the shape of the empirical distribution dramatically.

G.3 Load extrapolation methods

G.3.1 General

The 50-year return period load of a wind turbine may be defined as the extreme loading that has an annual probability of exceedance of $\frac{1}{50 \text{ years}} = 0,02$ per year.

The suggested approaches of extrapolation of extreme events for determination of the 50-year load can be divided into the following procedures.

1) Parametric fitting and aggregation afterwards

- Subdivide the operational range of the turbine into discrete wind speeds and perform time domain simulations at the normal turbulence (NTM) level.
- Estimate an extreme value (parametric) distribution [2] for every wind speed realization.
- Aggregate all distributions according to the long-term distribution function of the mean wind speed.
- Predict the 50-year value of the aggregated distribution function.

For global extreme from ten-minute simulations, the probability of the 50-year load is approximately $3,8 \times 10^{-7}$.

2) Data aggregation first and fitting afterwards

- Subdivide the operational range of the turbine into discrete wind speeds and performance of time domain simulations at normal turbulence (NTM) level.
- Aggregate all relevant extremes from all time series according to the long-term distribution function of the mean wind speed within the operational range of the turbine.
- Estimate one (aggregated) distribution function for all extremes.
- Predict the 50-year value from the resulting distribution function.

Two different cases are regarded for aggregation of simulated short-term distributions of extremes for a specific observation period T into an empirical distribution of the long-term extremes for the same period: extrapolation from global extremes, and from local extremes.

G.3.2 Global extremes

The short-term distribution of global extremes in the observation period, T , is denoted

$$F_{\text{Short-term}}(s|V;T) \quad (\text{G.1})$$

where s stands for load response and V is the mean wind speed for the observation period. Using the long-term distribution of the mean wind speeds, the long-term distribution of extreme values is obtained:

$$F_{\text{long-term}}(s;T) = e^{-\int_{V_{\text{in}}}^{V_{\text{out}}} \ln(F_{\text{Short-term}}(s|V;T)) f(V) dV} \quad (\text{G.2})$$

This equation is derived assuming that the exceedances of the value s form a composite Poisson point process with independent increments. The extreme load response, s_r , of the desired return period, T_r , is obtained from Equation (G.3):

$$F_{\text{long-term}}(s; T) = \left(1 - \frac{1\text{yr}}{T_r}\right)^{\frac{T}{1\text{yr}}} \approx 1 - \frac{T}{T_r} \quad (\text{G.3})$$

for sufficiently small values of $\frac{T}{T_r}$.

The practical implementation of these formulas would typically be to use discrete wind speed values. Then one has

$$F_{\text{long-term}}(s; T) \approx \prod_{k=1}^M \left(F_{\text{short-term}}(s|V_k; T)\right)^{p_k},$$

$$p_k = f(V_k) \Delta V_k, \quad V_{\text{in}} \leq V_1 < \dots < V_M \leq V_{\text{out}} \quad (\text{G.4})$$

For small short-term exceedance probabilities, this may be conservatively approximated as

$$F_{\text{long-term}}(s; T) \approx 1 - \sum_{k=1}^M (1 - F_{\text{short-term}}(s|V_k; T)) p_k$$

$$= \sum_{k=1}^M F_{\text{short-term}}(s|V_k; T) p_k \quad (\text{G.5})$$

The latter equivalence results because the exceedance probability outside the operating range is assumed to be zero.

The distribution $F_{\text{short-term}}$ may be obtained by fitting to the empirical distribution

$$\hat{F}_{\text{short-term}}(s_{ki}|V_k) = \frac{r_i}{n_k + 1}, \quad i = 1, \dots, n_k \quad (\text{G.6})$$

where s_{ki} denotes the i th extreme value sample from wind speed k and r_i is s_{ki} 's rank among the n_k extremes arising from wind speed k . For the following developments, it is worth noting that an equivalent expression for the empirical distribution by use of a summation is

$$\hat{F}_{\text{short-term}}(s_{ki}|V_k) = \sum_{j=1}^{n_k} \frac{1}{n_k + 1} I(s_{kj} - s_{ki}), \quad i = 1, \dots, n_k \quad (\text{G.7})$$

where an indicator function $I(x)$ has the expression

$$I(x) = \begin{cases} 1 & \text{for } x \leq 0 \\ 0 & \text{for } x > 0 \end{cases} \quad (\text{G.8})$$

The task of the indicator function is to pick out all values less than or equal to s_{ki} in order that they can contribute to the empirical probability of having values less than or equal to s_{ki} . Note

that the specific definition of the indicator function ensures that the event that identical extreme values should be realized is accounted for.

G.3.3 Local extremes

Now the short-term distribution of global extremes in the observation period, T , is obtained from $n(V)$ independent local extreme values in the period (assuming the extremes are positive, otherwise a change of sign may be made):

$$F_{\text{short-term}}(s|V;T) = F_{\text{local}}(s|V;T)^{n(V)} \quad (\text{G.9})$$

The long-term distribution, defined in Equation (G.9), and the extreme load response, s_r , of the desired return period, T_r , are established as described in G.3.2. Strictly, n should be a random number for which a distribution (dependent on V) should be assumed. However, n has for wind turbine applications limited variation compared to its mean value. Consequently, replacing n by its mean value (conditional on V), as implicitly done above, is sufficiently accurate. The approximation may be accepted if, when applying the formulas proposed in the following, one uses an s -value representative of the wind speeds that contribute most to the specific load response under consideration. Based on the approximation, one has the following expression:

$$F_{\text{long-term}}(s;T) = e^{\int_{V_{\text{in}}}^{V_{\text{out}}} n(V) \ln(F_{\text{local}}(s|V;T)) f(V) dV} \quad (\text{G.10})$$

G.3.4 Long-term empirical distributions

There are advantages to aggregating data from all wind speeds and then fitting a distribution to the combined data. One method for accomplishing this is to compute a number of simulations, where the number of simulations per bin is determined by the Weibull (or appropriate) distribution of wind speed.

$$N_{\text{sims}}(V_k) \approx N_{\text{total}} p_k, \quad p_k = f(V_k) \Delta V_k, \quad V_{\text{in}} \leq V_1 < \dots < V_M \leq V_{\text{out}} \quad (\text{G.11})$$

Once simulations are completed and maxima are extracted, all maxima from all wind speeds are combined into a single distribution and ranked such that

$$\hat{F}_{\text{long-term}}(s_i) = \frac{r_i}{n_k + 1}, \quad i = 1, \dots, n_{\text{total}} \quad (\text{G.12})$$

where s_i denotes the i th extreme value sample over all wind speeds and r_i is s_i 's rank among the n_{total} extremes arising from the combined distribution.

One potential disadvantage of this method is that loads that are dominated by high wind speeds may have very few simulations from which to extract large extreme values in the tail of the empirical distribution. To address this issue, additional long-term distributions can be calculated using additional simulations for the low probability wind speed bins. The total simulation time per bin should follow the original wind speed distribution. But, a number of new long-term empirical distributions can be formed using randomly bootstrapped data from all bins, in which a large number of simulations are available. Once a number of long-term distributions are formed, they can be averaged to form a single aggregate long-term distribution that can be used for extrapolation to lower probability levels.

G.4 Convergence criteria

G.4.1 General

In the context of turbine extreme loads, the importance of different wind speeds varies depending on the load that is being extrapolated. Some loads are dominated by wind speeds near rated while others are dominated near cut-out or other wind speeds. It is important that the designer examine the dominant wind speeds closely to ensure that a sufficient number of simulations are carried out to ensure stability of the method. A minimum of 15 simulations is necessary for each wind speed from ($V_r - 2$ m/s) to cut-out and six simulations are necessary for each wind speed with V below ($V_r - 2$ m/s).

In addition to a minimum number of simulations for the wind speeds ($V_r - 2$ m/s) to cut-out, an additional convergence criterion shall also be applied according to 7.6.2. The recommended number of simulations is determined by calculating a confidence interval for the resulting empirical distribution. The number of simulations deemed sufficient is that for which the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile. This interval may be estimated using bootstrapping methods [3], the binomial estimation method [4], or it may be inherently estimated as a part of the extrapolation method employed.

If the extremes are obtained using any other method (e.g. block maxima) that results in m extremes per 10-minute simulation, on average, then the 84 % fractile above needs to be replaced by p^* where

$$p^* = (0,84)^{\frac{1}{m}} \quad (\text{G.13})$$

The convergence criterion⁴⁴ should be applied individually to each short-term load distribution whether the long-term distribution is to be established using aggregation of wind speed data before fitting or whether fitting parametric distributions to data from each wind speed is carried out before aggregation.

In the procedure that involves aggregation before fitting, empirical long-term distributions for the loads following aggregation of all wind speed bins can be established by making use of similar convergence criteria as proposed above for short-term distributions. The appropriate fractile at which to impose the convergence criterion should be higher than the fractile corresponding to any apparent "knee" (often observed) in the empirical long-term distribution to ensure that convergence is checked closer to the tail of this empirical distribution.

G.4.2 Load fractile estimate

The desired load fractile, $\hat{L}_p$, corresponding to a non-exceedance probability, P , is estimated as follows.

Rank order all the loads data such that $S_1 \leq S_2 \leq \dots \leq S_m$ if we have m such values from simulations. Note that m will be equal to the number of simulations if global maxima are used.

For any specified p , make sure it is possible to find some integer i (where $2 \leq i \leq m$), such that

⁴⁴ The criterion should only be evaluated where the 84 % fractile is much larger than 0. For example, blade flap moments away from tower for outboard sections might be problematic at certain wind speeds; i.e. criterion should be handled with a certain engineering judgement.

$$\frac{i-1}{m+1} \leq p \leq \frac{i}{m+1} \quad (\text{G.14})$$

A sufficient number of extremes, m , should be available (for which a sufficient number of simulations will have to be run) so that the above inequality results and a value of i found.

The load fractile estimate is then computed by (linear) interpolation as follows:

$$\hat{S}_p = S_{i-1} + [p(m+1) - (i-1)](S_i - S_{i-1}); \text{ where } 2 \leq i \leq m \quad (\text{G.15})$$

G.4.3 Confidence bounds

Confidence bounds are estimated such that the 90 % confidence interval on the 84 % fractile, $\hat{S}_{0,84}$, is as follows:

$$\frac{\hat{S}_{0,84;0,05} - \hat{S}_{0,84;0,95}}{\hat{S}_{0,84}} < 0,15 \quad (\text{G.16})$$

The interval, $\langle \hat{S}_{0,84;0,05}, \hat{S}_{0,84;0,95} \rangle$, represents the desired 90 % confidence interval.

G.4.4 Confidence intervals based on bootstrapping

Using the bootstrap procedure to form confidence intervals [3, 7] begins with taking the initial set of data on p global maxima ($m_1, m_2, m_3, m_4, m_5 \dots m_p$) and randomly resampling these data with replacement to form a new set ($m_1^*, m_2^*, m_3^*, m_4^*, m_5^* \dots m_p^*$) or a bootstrap resampling of the same size as the original sample. Note that bootstrap resamplings will be composed of repeated values from the original sample since, for each resampling, data are sampled randomly with replacement. The process is repeated so as to form a large number, N_b , of bootstrap resamplings. From each of these sets of p data, individual estimates of the 84 % fractile can be obtained. From these N_b estimates, constituting the set, ($l_1, l_2, l_3, l_4, l_5, \dots, l_{N_b}$), confidence intervals can be found in the usual manner by ordering the data. These can then be used for the numerator of Equation (G.16). The estimate of the 84 % fractile that is obtained from the original data represents the denominator of Equation (G.16).

A minimum number of 25 bootstrap resamplings may be sufficient to determine a reasonable estimate of confidence bounds. However, a larger number closer to 5 000 will lead to more reliable estimates.

G.4.5 Confidence intervals based on the binomial distribution

Confidence intervals based on the binomial distribution [7] are computationally less intensive than those computed using the bootstrap procedure. This saving is simplified by tabulating parameters for calculating a binomial confidence interval that will result for most common situations. For the load fractile equal to 0,84 and 90 % confidence interval, Table G.1 provides values of k^* and l^* as well as two other values, A and B , needed for interpolating the estimate confidence bounds in Equation (G.17), below. The number of simulations is of the order of 15 to 35 for each wind speed bin.

Table G.1 – Parameters needed to establish binomial-based confidence intervals

For 90 % confidence interval on the 84th percentile load	No. of sims.	k^*	l^*	A	B
	15	9	14	0,50	0,32
	16	10	15	0,27	0,19
	17	11	16	0,10	0,03
	18	11	16	0,87	0,96
	19	12	17	0,58	0,90
	20	13	18	0,35	0,83
	21	14	19	0,16	0,76
	22	14	20	1,00	0,69
	23	15	21	0,69	0,60
	24	16	22	0,45	0,50
	25	17	23	0,25	0,39
	26	18	24	0,08	0,26
	27	18	25	0,85	0,12
	28	19	25	0,58	0,98
	29	20	26	0,36	0,91
	30	21	27	0,18	0,83
	31	22	28	0,02	0,75
	32	22	29	0,75	0,66
	33	23	30	0,51	0,56
	34	24	31	0,31	0,44
	35	25	32	0,13	0,32

The parameters in Table G.1 are used with a design equation that is tailored to give the 90 % confidence interval for the 84th percentile ten-minute maximum. The design equation can be written as follows:

$$(x_l - x_k) = (x_{l^*} - x_{k^*}) + B \left(x_{(l+1)^*} - x_{l^*} \right) - A \left(x_{(k+1)^*} - x_{k^*} \right) \quad (\text{G.17})$$

where l^* , k^* , A , and B are as given in Table G.1 as a function of the number of simulations run and x_{l^*} , $x_{(l+1)^*}$, x_{k^*} , and $x_{(k+1)^*}$ are obtained from the rank-ordered simulated extremes. This estimate can then be inserted into Equation (G.16) to determine if the convergence criteria are met, where

$$\hat{S}_{0,84;0,05} - \hat{S}_{0,84;0,95} \approx x_l - x_k \quad (\text{G.18})$$

G.5 Inverse first-order reliability method (IFORM)

An alternative to typical loads extrapolation methods is the use of IFORM to estimate long-term loads. In this method, turbulence and wind turbine response simulations are carried out for NTM conditions. A minimum of 15 simulations should be carried out for wind speeds ($V_r - 2$ m/s) to cut-out. The wind speed(s) that yields the highest load is (are) then identified.

Extrapolation of the short-term load distributions to a probability level consistent with the definition of a 50-year return period yields the 50-year load for use with DLC 1.1.

The convergence criteria for IFORM should be the same as for the other extrapolation methods, except that the designer need only estimate confidence intervals for the load distributions from identified important wind speeds (often only one).

The theory for the use of the inverse FORM (IFORM) technique (which relies on transformation of physical random variables to standard normal random variables [8]) is well-documented, see for example [9], and can be applied to estimate long-term wind turbine loading under NTM conditions.

In order to implement IFORM for wind turbine extreme loads, use the following steps.

- a) Carry out 15 simulations for the wind speed bins ($V_r - 2$ m/s) to cut-out.
- b) Identify which bins yield the largest load maxima.
- c) Refine the search by performing another 15 simulations for the bins identified in step b). Again, identify the design dominating wind speed(s), v^* , which produce the largest loads. Ensure that the number of simulations at the important wind speed(s) is sufficient such that the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile.
- d) Perform short-term analysis only for the bin(s) identified in step c). The desired fractile of the load distribution for this bin is derived and depends on the target probability level.
 - Using Rayleigh CDF, compute $U_1 = \Phi^{-1}[P_R(v^*)]$.
 - For probability of exceedance in 10 min once in 50 years, $p_T = 3,8 \times 10^{-7}$. This corresponds to $\beta = 4,95$.
 - Solve $U_2 = [\beta^2 - U_1^2]^{1/2}$.
 - Derive the load fractile $P_S = \Phi(U_2)$, see Table G.2.
 - The long term load is the P_S fractile of the short-term distribution for the wind speed bin, v^* . To reach the appropriate fractile, extrapolation may be required.

Table G.2 – Short-term load exceedance probabilities as a function of hub-height wind speed for different wind turbine classes for use with the IFORM procedure

v^* [m/s]	$1-P_{S, \text{class I}}$	$1-P_{S, \text{class II}}$	$1-P_{S, \text{class III}}$
5	5,91E-07	4,95E-07	4,42E-07
6	4,86E-07	4,24E-07	3,94E-07
7	4,26E-07	3,90E-07	3,80E-07
8	3,94E-07	3,80E-07	3,91E-07
9	3,81E-07	3,90E-07	4,24E-07
10	3,83E-07	4,17E-07	4,84E-07
11	3,97E-07	4,64E-07	5,78E-07
12	4,24E-07	5,35E-07	7,20E-07
13	4,66E-07	6,38E-07	9,33E-07
14	5,26E-07	7,85E-07	1,26E-06
15	6,08E-07	9,97E-07	1,75E-06
16	7,20E-07	1,30E-06	2,54E-06
17	8,71E-07	1,75E-06	3,82E-06
18	1,08E-06	2,43E-06	5,93E-06
19	1,36E-06	3,46E-06	9,54E-06
20	1,75E-06	5,06E-06	1,59E-05
21	2,31E-06	7,60E-06	2,74E-05
22	3,10E-06	1,17E-05	4,89E-05
23	4,25E-06	1,86E-05	9,02E-05
24	5,93E-06	3,03E-05	1,73E-04
25	8,45E-06	5,06E-05	3,42E-04

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Annex H (informative)

Fatigue analysis using Miner's rule with load extrapolation

H.1 Fatigue analysis

Fatigue failure results from an accumulation of damage due to fluctuating loads. For this kind of macroscopic view of fatigue, there is general agreement that an increment of damage results from each hysteresis cycle displayed in the local stress-strain diagram. Thus, each local maximum of the load time history is paired with the local minimum that completes a full cycle (rain-flow cycle counting, see [1] or [2]). Each of these cycles is characterized by the paired extreme values (or equivalently by the range and midpoint values, i.e. the difference between and the mean of the two paired cycle extremes). If the damage accumulates linearly and independently for each cycle [5, 3] then the total damage, D , will be given by⁴⁵

$$D = \sum_i \frac{1}{N(S_i)} \quad (\text{H.1})$$

where S_i is the load range for the i th cycle, and $N(\)$ is the number of cycles to failure for a constant amplitude loading with the range given by the argument (i.e. the S-N curve). In this expression, it has been further assumed that the local stress at the failure location is linearly related to the loading. Typically, for fatigue analysis, the S-N curve selected for design is associated with a given survival probability (often 95 %) and level of confidence (often 95 %) in determining the curve from materials data. Thus, the desired minimum level of reliability may be expected when the damage sums to unity.

For the life of a wind turbine, there will be many cycles of varying sizes resulting from a broad range of wind conditions. Therefore, for design purposes, a load spectrum should be estimated. The largest cycles for this spectrum will be estimated from a smooth fit to the data obtained from simulations or testing of a duration that is significantly shorter than the turbine lifetime. For each wind condition, it may be assumed that the load is modelled by a stationary random process. Thus, the expected damage for a given wind speed, V , and a specific time period, T , will be given by

$$E\langle D|V,T \rangle = \int_0^\infty \frac{n_{ST}(S|V,T)}{N(S)} dS \quad (\text{H.2})$$

where $n_{ST}(S|V,T)$ is the short term load spectrum defined as a density function for the number of cycles. In this case, the expected number of cycles in any load range interval

(S_A, S_B) during the time period T is given by $\int_{S_A}^{S_B} n_{ST}(S|V,T) dS$. The expected damage from

normal operating loads for the whole turbine life is then given by extending the time interval to the full lifetime and integrating over the range of operating wind speeds, so that

⁴⁵ For ease of presentation, the effect of variation in the midpoint load level for each cycle is neglected. This restriction is eliminated later when the issue of varying midpoint levels is addressed through the use of an equivalent cyclic range.

$$E\langle D \rangle = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} E\langle D|V, T \rangle p(V) dV = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} \int_0^{\infty} \frac{n_{\text{ST}}(S|V, T)}{N(S)} p(V) dS dV \quad (\text{H.3})$$

where $p(V)$ is the probability density function for the hub-height wind speed prescribed for the standard wind turbine classes in 6.3.2.1.

Now, defining the long-term load spectrum

$$n_{\text{LT}}(S) = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} n_{\text{ST}}(S|V, T) p(V) dV \quad (\text{H.4})$$

then gives

$$E\langle D \rangle = \int_0^{\infty} \frac{n_{\text{LT}}(S)}{N(S)} dS \quad (\text{H.5})$$

In many cases, it is convenient, for practical purposes, to divide the ranges of load and wind speed values into discrete bins. In this case, the expected damage can be approximated by

$$E\langle D \rangle \approx \sum_{j,k} \frac{n_{jk}}{N(S_k)} \quad (\text{H.6})$$

where n_{jk} is the expected number of lifetime load cycles in the j^{th} wind speed and the k^{th} load bins, and S_k is the centre value for the k^{th} load bin. Thus, from the above definition,

$$n_{jk} = \frac{\text{Lifetime}}{T} \int_{V_j - \Delta V_j/2}^{V_j + \Delta V_j/2} \int_{S_k - \Delta S_k/2}^{S_k + \Delta S_k/2} n_{\text{ST}}(S|V, T) p(V) dS dV \quad (\text{H.7})$$

where ΔV_j is the width of the j^{th} wind speed bin and ΔS_k is the width of the k^{th} load bin.

Utilizing these results, and considering the requirement from 7.6.3 that the safety factors be applied to the load, the limit state relation for fatigue analysis becomes

$$\int_0^{\infty} \frac{n_{\text{LT}}(S)}{N(\gamma S)} dS \leq 1 \quad (\text{H.8})$$

where $\gamma = \gamma_f \gamma_m \gamma_n$ is the product of all three general partial safety factors for load, materials, and consequences of failure, respectively. In discrete terms, this equation results in

$$\sum_{j,k} \frac{n_{jk}}{N(\gamma S_k)} \leq 1 \quad (\text{H.9})$$

In cases where significant damage occurs in more than one load case from Table 2, the damage fractions for all the load cases, computed using the left side of Equation (H.9), should sum to be less than or equal to one.

The formulation up to this point has ignored the effect of the variability in the midpoint levels for each load cycle. One simple way of dealing with this variability is to define damage equivalent load cycles with a fixed midpoint value. In this case, the damage done by the equivalent cycles is exactly the same as that done by the cycles with varying midpoints. Thus, failure will occur (on average) for the same number of constant amplitude cycles for the equivalent cyclic range, S_{eq} , as for cycles at any given cyclic range and midpoint value. Thus, defining a family of S-N curves for varying midpoint values, $N(S,M)$, the equivalent damage equation

$$N(S_{eq}, M_0) = N(S, M) \quad (H.10)$$

is solved for S_{eq} given values for S, M and the selected constant midpoint level M_0 . In mathematical terms, this can be stated as

$$S_{eq} = N^{-1}(N(S, M), M_0) \quad (H.11)$$

where the inverse refers to solution for the first argument in the function, N , given the second argument. Typically, M_0 is chosen to give R values (the ratio of maximum load to minimum load) for the equivalent load cycles that are in the middle of the range of values observed directly in the load data. Often, an acceptable value is the mean load considering all operating wind speeds. Fortunately, in most cases where the S-N curves are defined analytically (e.g. power law or exponential forms), the equivalent cyclic load range is easily computed. Care should be taken, however, as the range becomes large. Depending on the midpoint value, the maximum or minimum load value for the given cycle can get close to the static strength, in which case the simple, high-cycle S-N curve may not be applicable. Also, for larger range values, the local stress or strain may transition from a compression-compression or tension-tension dominated case to a tension-compression case, which could have a different analytical S-N curve representation. It is important to utilize the proper S-N relation in determining the equivalent cyclic range. For a given load time history, the rain flow cycles are first identified. Then a set of equivalent constant-midpoint cycles is computed considering the proper S-N relation for each cycle. The distribution of these equivalent cycles is then estimated giving a new short-term equivalent load spectrum. This new spectrum is then used to define the number of cycles used for the damage fraction for each load and wind speed bin. The main advantage of using this method is that the estimation of the equivalent spectrum is statistically more robust than tracking the midpoint levels as an independent variable. This advantage results because many more load cycles are counted from typical time series load data for each load and wind speed bin than when midpoint bins are also tracked separately.

An additional practical issue that arises in determining the short-term load spectrum is the large number of small cycles determined by the rain-flow method. These small cycles can often occur at nearby points in time and may therefore be correlated. The small cycles can also distort the shape of analytical approximations to the tail of the distribution. It is therefore recommended to only consider cycles above a threshold when approximating the tail of the short-term distribution. A threshold value of at least the 95th percentile typically works well in practice. Lower threshold values may be appropriate if the small cycles have been eliminated or if the increased number of data points used for the fitting process is expected to yield significant additional statistical reliability.

For practical wind turbine design applications, it is necessary to estimate the short-term equivalent load spectrum from dynamic simulation data and then compute the lifetime damage. One method of accomplishing this task is given by the following procedure.

- a) Select the reference midpoint level as the mean load level considering all wind speeds.

From the simulation data for a given wind speed, extract the sequence of local maxima and minima. The sequences of local maxima and minima from multiple time series for the same wind conditions may be concatenated into a single series.

- b) Use the rain flow method to identify the midpoint and range for each simulated load cycle.
- c) Determine the equivalent range for each load cycle in relation to the selected reference midpoint level.
- d) Determine an analytical fit for the short-term probability distribution of equivalent load cycles, $F_{ST}(S|V,T)$ for the data above the selected threshold. Guidance for one method for fitting the distribution may be found in [4]. The distribution type selected should be checked to see if the fit to the data is acceptable and whether there is sufficient data for reliable estimation of the behaviour of the tail compared to the data.
- e) Determine the expected number of lifetime cycles in each bin using the data when the load bin is below the threshold and the fitted load distribution when the load bin is above the threshold. This results in

$$n_{jk} \approx \left(\frac{\text{Lifetime}}{T} \right) P_j \left\{ \begin{array}{ll} m_{jk} & \text{if } S_k \text{ is below the } j^{\text{th}} \text{ threshold} \\ M_j \left(F \left(S_k + \frac{\Delta S_k}{2} | V_j, T \right) - F \left(S_k - \frac{\Delta S_k}{2} | V_j, T \right) \right) & \text{if } S_k \text{ is above the } j^{\text{th}} \text{ threshold} \end{array} \right\} \quad (\text{H.12})$$

where m_{jk} is the number of simulation fatigue cycles counted in the data for the j^{th} wind speed bin and k^{th} load bin below the threshold, M_j is the number of fatigue cycles counted in the simulation above the threshold, and

$$P_j = e^{-\pi \left(\frac{V_j - \Delta V_j / 2}{2V_{\text{ave}}} \right)^2} - e^{-\pi \left(\frac{V_j + \Delta V_j / 2}{2V_{\text{ave}}} \right)^2}$$

is the fraction of time the wind speed is in bin j for the assumed Rayleigh wind speed distribution.

- 1) Sum the damage using the left hand side of Equation (G.9).
- 2) Sum the total lifetime damage from all fatigue load cases.

In using this procedure, care should be taken that

- the resolution of the wind speed and load range bins is sufficient for the desired numerical precision, and
- sufficiently large values of load range are used to adequately represent the tail of the long-term load distribution.

The first issue may be addressed by approximating the error as half the difference between results computed by two different bin resolutions skipping data from every other wind speed or load range. An alternative would be to compute the damage summation using the endpoints for the bin values instead of the central values to bound the result. The second issue may be addressed by progressively increasing the highest load range bin value until a negligible

increase in the lifetime damage is observed. Note because the ratio $\frac{\text{Lifetime}}{T}$ is a large number, the largest required load bin may be significantly larger than the largest cycle observed in the simulation data. This results because the total simulated load time history is much smaller than the turbine lifetime, and statistical extrapolation is required to accurately estimate damage from the tail of the long-term load distribution.

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Annex I (informative)

Contemporaneous loads

I.1 General

Detailed structural analyses of wind turbine components commonly use a finite element or other suitable model for determination of the local stress or strain resulting from the loading applied to the component. Such analyses often define a suitable interface plane where the applied loads are acting (e.g. the yaw bearing interface, defining the tower top loading). In this case, there are six load components defining the boundary conditions for loading, three forces, F_x , F_y , and F_z , and three moments, M_x , M_y , and M_z . For convenience here, the x, y axes are taken to be in the loading plane and the z axis normal to the plane. To describe the extreme loading situations, a load matrix is often defined as shown in Table I.1.

Table I.1 – Extreme loading matrix

	F_x	F_y	F_z	M_x	M_y	M_z	F_R	θ_F	M_R	θ_M
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Max.										

In this table, each column represents a load component value delineated by the heading at the top. Each row represents contemporaneous values (i.e. all values occurring at the same time) and the shaded cell shows the specific component that has either a maximum or minimum value as indicated on the left. These maximum and minimum values are intended to cover the full range of values for that particular load component. The detailed structural model is then exercised using each of the rows to determine resulting local stress or strain values, which are compared to an appropriate failure criterion. When the structural stiffness and strength in response to loading in the plane is similar for the different loading directions, the most extreme loading can result when both x and y components are large in magnitude but not at their very largest values. Thus, the in-plane vector resultant values are also displayed in the additional columns on the right and the rows at the bottom. These in-plane resultants are defined as

$$F_R = \sqrt{F_x^2 + F_y^2} \quad \text{and} \quad M_R = \sqrt{M_x^2 + M_y^2} \quad (\text{I.1})$$

The angular directions of these resultants are also defined as

$$\theta_F = \arctan(F_x / F_y) \text{ and } \theta_M = \arctan(M_x / M_y) \quad (1.2)$$

The values in the table are determined by post-processing analysis of the time series for the six load components determined as the outputs from the complete wind turbine dynamic simulation code. In this analysis, the time series are searched for the maximum and minimum values for each component as well as the maxima for the resultants. The contemporaneous values associated with each of these corresponding time points are then inserted in the rows of the table. Each of the load cases defined in Clause 7 are analysed in this way and the most extreme loading in each row from the different load cases is then used to define an overall loads envelope for that part of the wind turbine.

In Clauses I.2 and I.3, two approaches are given. Note that caution should be exercised in order to obtain conservative contemporaneous loads.

I.2 Scaling

- For each cross section and load component, one bin of the considered load case delivers the largest among candidate characteristic loads.
- A time series from this bin being close with its maximum within $\pm 5\%$ to this characteristic load is selected.
- The maximum of this time series is scaled to the characteristic load. The obtained scaling factor is then also applied to all contemporaneous load components to this selected maximum of this time series.
- For each load component, one load case series is obtained to be used for extreme design load analysis.
- For minimum values, a corresponding procedure is applied considering appropriate scaling of magnitude.

I.3 Averaging

- For a load case consisting of more than one realization, the candidate characteristic maximum load is calculated as the mean of the maximum of all realizations.
- Contemporaneous loads are calculated as the mean of the absolute contemporaneous values of each realization. Signs on the contemporaneous loads are applied in accordance with the signs of the contemporaneous loads of the realization with the highest load.
- The candidate characteristic minimum load is calculated as the mean of the minimum of each realization. Contemporaneous loads are calculated in the same manner as in the positive case.
- The ultimate maximum and minimum characteristic loads are determined as the maximum and minimum, respectively, of the candidate characteristic loads described above with the corresponding contemporaneous values.

Annex J (informative)

Prediction of the extreme wind speed of tropical cyclones by using Monte Carlo simulation method

J.1 General

In the areas where the strong wind is dominated by extratropical cyclones, the extreme wind speed can be estimated by using the Gumbel method for extended data obtained from a nearby reference meteorological station with the measure-correlate-predict (MCP) approach as described in Annex F. On the other hand, tropical and subtropical regions, where both tropical and extratropical cyclones are dominant, are known as mixed climates and the examination of each significant wind-producing meteorological phenomenon is required as mentioned by [2]. It was noticed that the MCP method without consideration for different type of storms underestimates the extreme wind speed in mixed climate regions.

Annex J describes a Monte Carlo simulation (MCS) method for the prediction of tropical cyclone induced extreme wind speeds. Refer to [1] for the detail of the MCS method.

J.2 Prediction of tropical cyclone induced extreme wind speeds

J.2.1 General

Monte Carlo simulation of tropical cyclones has been proposed (e.g. [3]) in order to obtain reliable statistical wind speed induced by tropical cyclones. The prediction of strong wind induced by tropical cyclones should be performed as follows.

J.2.2 Evaluation of tropical cyclone parameters

The number of tropical cyclones per year at specific site λ can be defined as the number of the tropical cyclones whose passes are included within the simulation circle (usually, the radius of which is 500 km) per year and obtained from the track records of past tropical cyclones. For each tropical cyclone, four tropical cyclone parameters, namely, the central pressure p_c , the translation speed C , the translation angle q measured counterclockwise positive from east and the minimum distance $d_{\min}$ when the cyclone approached the site of the interest most closely, are obtained from the historical track record of the tropical cyclones. The other tropical cyclone parameter is the radius of maximum wind speed R_m , which can be identified by the pressure field model proposed by [4].

$$\frac{p(r) - p_c}{p_\infty - p_c} = \exp\left(-\frac{R_m}{r}\right)^B \quad (\text{J.1})$$

where $p(r)$ is the sea surface pressure at the distance r from the centre of the tropical cyclone. R_m can be identified by the least square method using the measured sea surface pressure at the meteorological stations, and periphery pressure p_∞ can be assumed to be 1 013 hPa or identified simultaneously. The central pressure difference is defined as Δ or $i_\infty - p_c$. In the case of $B = 1,0$, this relationship becomes the formulae proposed by [5].

These six parameters are approximated by analytical functions: Δh , R_m and C can be approximated by mixed probability density functions based on lognormal and Weibull distribution (e.g. [6]), q by normal or bi-normal distribution (e.g. [7]), $d_{\min}$ by a polynomial function and λ by Poisson's distribution. The correlations between these parameters except for λ should also be calculated.

J.2.3 Generation of synthetic tropical cyclones

Synthetic tropical cyclones are generated for long period to satisfy the modelled probability distribution functions and the correlations. The change in the pressure field of the tropical cyclones can be neglected since the wind speed and direction are estimated only when the tropical cyclone is located inside the simulation circle with the radius of 500 km.

A modified orthogonal decomposition (MOD) method should be used to satisfy the statistical distribution functions of the tropical cyclone parameters and the correlations between them at the same time, as proposed by [6]. The detailed procedure of the MOD method is described below.

Five parameters describing a tropical cyclone are normalized and written in vector form as follows.

$$\mathbf{x}^T = \{\ln(\Delta p), \ln(R_m), \ln(C), \theta, d_{\min}\} \quad (\text{J.2})$$

The covariance matrix of $\mathbf{x}$ is defined as $\mathbf{S}$. The eigenvalues $\lambda^{(k)}$ and the eigenvectors $\Phi^{(k)}$ are calculated by solving the following equation.

$$[\mathbf{S} - \lambda^{(k)}\mathbf{E}]\Phi^{(k)} = 0 \quad (\text{J.3})$$

The independent parameters $\mathbf{z}_i$ with five components are then generated following the approximated distributions to the intended ones for specified years and the number of the generated vectors following the estimated annual occurrence rate. The correlated parameters $\mathbf{x}_i$ can be obtained by the following equation.

$$\mathbf{x}_i = [\Phi^{(1)} \quad \Phi^{(2)} \quad \dots \quad \Phi^{(5)}]^{-1} \mathbf{z}_i \quad (\text{J.4})$$

These vectors $\mathbf{x}_i$ should be considered as the set of parameters for tropical cyclones. Note that although the correlations between each component of $\mathbf{x}_i$ satisfy the intended correlations, the probability distributions of them do not follow the intended ones.

Finally, $\mathbf{x}_i$ should be rearranged in an ascending order and modified so that its probability distribution follows the intended probability distributions. This operation hardly affects the correlations because it does not change the set of parameters.

J.2.4 Prediction of wind speeds in the tropical cyclone boundary

A tropical cyclone induced wind at the site of interest $\vec{\mathbf{x}}$ is affected by local topography. Wind speed $u_T(\vec{\mathbf{x}})$ and direction $\theta_T(\vec{\mathbf{x}})$ at the hub height can be written as

$$u_T(\vec{\mathbf{x}}) = S_t E_p u_g(\vec{\mathbf{x}}) \quad (\text{J.5})$$

$$\theta_T(\vec{\mathbf{x}}) = \theta_g(\vec{\mathbf{x}}) - \gamma_p + D_t \quad (\text{J.6})$$

where $u_g(\vec{\mathbf{x}})$ and $\theta_g(\vec{\mathbf{x}})$ are the gradient wind speed and direction (clockwise positive from south), E_p and γ_p are the wind profile factor and the inflow angle measured counterclockwise positive from the gradient wind velocity vector, S_t and D_t are the speed up ratio and the

difference in wind direction due to local topography as functions of the wind direction $(\theta_g(\vec{x}) - \gamma_p)$ over flat terrain.

The gradient wind speed and direction at the site $\vec{x}(r, \phi)$ can be calculated from the pressure field of the tropical cyclone assuming the balance among pressure gradient force, centrifugal force and Coriolis force.

$$u_g(\vec{x}) = \frac{-C \sin(\phi - \theta) - fr}{2} + \sqrt{\left(\frac{-C \sin(\phi - \theta) - fr}{2} \right)^2 + \frac{r}{\rho} \frac{\partial p(r)}{\partial r}} \quad (J.7)$$

$$\theta_g(\vec{x}) = \pi - \phi \quad (J.8)$$

where r is the distance from the centre of the tropical cyclone, ϕ is the angle measured counterclockwise positive from east, f is the Coriolis parameter, u_g and θ_g are the functions of time due to the motion of tropical cyclones.

The wind profile factor E_p and the inflow angle γ_p are used to calculate the wind speed at the hub height above the ground, which can be estimated by semi-theoretical formulae (e.g. [6]) or computational fluid dynamics (CFD). The speed up ratio S_t and the difference in wind direction D_t show the effect of local topography on the wind speed and direction. These factors are defined as functions of the wind direction over flat terrain and can be calculated by CFD (e.g. [8]).

Ten-minute average wind speed can be predicted by adding random values to the wind speed estimated by the wind field models. These random values are assumed to follow the lognormal distribution with the mean value of zero and the standard deviation of σ_a , which can be modelled as

$$\sigma_a = \gamma \times u_T(\vec{x}) \quad (J.9)$$

Here, 0,1 was used for γ as proposed by [9].

J.3 Prediction of extreme wind speed in mixed climate regions

J.3.1 General

The relation between the return period R and the probability distribution of annual maximum wind speed $F(u)$ can be written as follows:

$$F(u) = 1 - 1/R \quad (J.10)$$

In mixed climate regions, the probability distributions should be evaluated separately for extratropical cyclones and tropical cyclones, and then combined probability distribution should be predicted.

J.3.2 Extreme wind distributions of extratropical cyclones by the MCP method

The extreme wind distribution (i.e. the probability distribution of annual maximum wind speed) of extratropical cyclones can be estimated by the MCP method from limited length of measurement data for N years at nearby reference meteorological station as follows.

- a) First, the time series of the wind speed at the site for N years can be obtained from wind records at nearby reference station by using the MCP method or CFD method.
- b) Next, the maximum wind speed $u_{E,i}$ caused by extratropical cyclones in each calendar year at the site is extracted and ranked in ascending order from $u_{E,1}$ to $u_{E,N}$, for which a probability distribution of annual maximum wind speed induced by extratropical cyclones defined as Equation (J.11) is assigned.

$$F_E(u_{E,i}) = \frac{i}{N+1} \quad (\text{J.11})$$

- c) Then, $u_{E,i}$ is plotted against a reduced variate $y_{E,i}$, expressed as

$$y_{E,i} = -\ln(-\ln(F_E(u_{E,i}))) \quad (\text{J.12})$$

A best fitting function can be obtained by the least square method, and the extreme wind speed with specified return period can be predicted from this function.

J.3.3 Extreme wind distributions of tropical cyclones by the MCS method

The extreme wind distribution of tropical cyclones can be estimated from the M years of Monte Carlo simulation described in Clause J.2. The procedure is as follows:

- a) From M years of Monte Carlo simulation of tropical cyclones, annual maximum wind speed can be extracted and ranked in the ascending order from $u_{T,1}$ to $u_{T,M}$. A probability distribution $F_T(u_T)$ is assigned, and reduced variate $y_{T,i}$ is calculated similarly.
- b) Then, $u_{T,i}$ is plotted against the reduced variate $y_{T,i}$. In case of the MCS method, extrapolation of $F_T(u_T)$ by the best fitting is not necessary since sufficient data are obtained.

J.3.4 Determination of extreme wind speed in a mixed climate region

The combined probability distribution of annual maximum wind speed can be obtained considering both extratropical and tropical cyclones. Assuming that wind speeds induced by extratropical cyclones and tropical cyclones are independent events, the combined probability distribution can be estimated by

$$F_C(u_C) = F_E(u_E)F_T(u_T) \quad (\text{J.13})$$

where $F_C(u_C)$ denotes the combined probability distribution. It should be made sure that the predicted extreme wind speeds have comparable values with the measurement.

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Annex K (informative)

Calibration of structural material safety factors and structural design assisted by testing

K.1 Overview and field of application

Annex K provides guidance on selection of partial safety factors for materials in Clauses K.2 to K.6 and on statistical analysis of tests for material parameters and resistances in Clauses K.7 to K.12.

K.2 Target reliability level

For calibration of partial safety factors, a measure of reliability should be identified with the survival probability $P_S = (1 - P_F)$, where P_F is the probability of failure⁴⁶ for the considered failure mode within an appropriate reference period. If the calculated failure probability is larger than a pre-set target value P_0 , the structure should be considered to be unsafe.

An alternative measure of reliability is conventionally defined by the reliability index β which is related to P_F by

$$P_F = \Phi(-\beta) \quad (\text{K.1})$$

where $\Phi()$ is the cumulative distribution function of the standardized normal distribution.

A target value for the nominal failure probability for structural design for extreme and fatigue failure modes for a reference period of one year is

$$P_F^t = 5 \times 10^{-4} \quad (\text{K.2})$$

The corresponding target value for the reliability index is $\beta^t = 3,3$. Application of this target value assumes that the risk to human lives is negligible in case of failure of a structural element, see [5]. The target reliability level is assumed to correspond to component class 2.

K.3 Safety formats

The resistance model is assumed to be obtained by the following general model:

$$R = b \delta R(X, a) \quad (\text{K.3})$$

where

$R(X, a)$ is the resistance model as defined in a relevant structural and materials standard;
 X is the strength (and stiffness) material parameter(s). Each of the strength parameters is modelled as a lognormal stochastic variable with coefficient of variation V_X ;

⁴⁶ The probability of failure and its corresponding reliability index are notional values that do not necessarily represent the actual failure rates but are used as operational values for code calibration purposes and comparison of reliability levels of structures.

- a is the geometrical parameter(s);
- δ is the model uncertainty related to resistance model (can be determined using the method in Clause K.12). δ is modelled as a lognormal stochastic variable with mean value 1 and coefficient of variation V_δ ;
- b is the bias in resistance model. b can be determined using the method in Clause K.12.

The design value of the resistance, R_d can be determined by different models⁴⁷.

- a) Model 1 where design values are determined for the material strength parameters:

$$R_d = \frac{R(X_d, a_d)}{\gamma_\Delta} \quad (\text{K.4})$$

where

- a_d is the design value for geometrical data;
- X_d is the design values for strength parameters;
- γ_Δ is the partial safety factor related to the model uncertainty for the resistance model including bias in resistance model.

If more than one strength parameter is used in the resistance model, then design values are applied for each strength parameter in Equation (K.4).

The design value of a strength parameter(s) X_d is determined by

$$X_d = \eta \frac{X_k}{\gamma_m} \quad (\text{K.5})$$

where

- η is the conversion factor taking into account load duration effects, moisture, temperature, scale effects;
- X_k is the characteristic value of strength parameter generally defined by the 5 % quantile;
- γ_m is the partial safety factor for strength parameter depending on the coefficient of variation V_X .

If the resistance model is linear in the strength parameters, then $R_d = R(X_d, a_d)$ and X_d for each of the strength parameters is obtained using a partial safety factor $\gamma_M = \gamma_m \gamma_\Delta$.

The partial safety factor γ_Δ depends on the uncertainty of the resistance model, including bias:

$$\gamma_\Delta = \frac{\gamma_\delta}{b} \quad (\text{K.6})$$

where

- γ_δ is the partial safety factor depending on the model uncertainty with coefficient of variation V_δ without taking into account bias in the resistance model.

- b) Model 2 where a characteristic resistance is obtained using characteristic values of the material strength parameters, and the design value of the resistance is obtained from:

$$R_d = \frac{R(\eta X_k, a_k)}{\gamma_M} \quad (\text{K.7})$$

⁴⁷ The following three models correspond to the basic resistance models in the Eurocodes [2].

where

γ_M is the partial safety factor for the resistance related to the uncertainty of the resistance including uncertainty in material parameters, uncertainty in resistance model and bias.

The total uncertainty of the resistance depends on the model uncertainty δ , the bias of the resistance model and the uncertainty related to the strength parameters X through the resistance function $R(X,a)$. The material partial safety factors are correspondingly obtained from

$$\gamma_M = \frac{\gamma_\delta \gamma_{Rm}}{b} \quad (K.8)$$

where

γ_{Rm} is the partial safety factor depending on the resistance uncertainty with coefficient of variation V_{Rm} from the strength parameters through the resistance function $R(X,a)$;

γ_δ is the partial safety factor depending on the model uncertainty with coefficient of variation V_δ .

c) Model 3 where a characteristic resistance is estimated based on tests:

$$R_d = \frac{R_k}{\gamma_M} \quad (K.9)$$

where

R_k is the characteristic resistance estimated based on tests, see Clause K.12. R_k is generally defined by the 5 % quantile;

γ_M is the partial safety factor for the resistance related to uncertainty of the resistance obtained based on tests, V_R .

The material partial safety factors should be calibrated such that failure probabilities for the relevant failure modes are close to the target reliability level in Equation (K.2) – see Clause K.4 – where relevant statistical uncertainty and uncertainty related to transformation from laboratory to real structure should be included.

K.4 Reliability-based calibration

The partial safety factors for loads and resistances are determined such that the failure probability obtained using the limit state function

$$g = R - S \quad (K.10)$$

is less than the target failure probability P_F^t . In Equation (K.10), the resistance is modelled by Equation (K.3) and S is the load effect. The corresponding design equation is

$$R_d - \gamma_f S_k \geq 0 \quad (K.11)$$

where R_d is the design value of the resistance and S_k is the characteristic value of the load effect defined usually as the 98 % quantile in the distribution function for the annual maximum load effect corresponding to a 50 year return period. Other reference periods might also be used in some cases. γ_f is the load partial safety factor.

Table K.1 – Partial safety factor for model uncertainty, γ_δ ⁴⁸

Coefficient of variation for model uncertainty for resistance model in model 1, V_δ	≤ 5 %	10 %	15 %	20 %
γ_δ	1,20	1,25	1,35	1,45

If the load partial safety factors for ULS in 7.6 are used, then the partial safety factors are calibrated for a failure mode such that the reliability level becomes equal to the target reliability level R_F^t specified by Equation (K.2), see [5]. The recommended partial safety factors for Models 1 and 2 are $\gamma_m = 1,0$, $\gamma_{Rm} = 1,0$ and γ_δ as shown in Table K.1^{49 50}. For Model 3, the recommended partial safety factor is $\gamma_M = 1,2$, corresponding to the value of γ_δ for $V_\delta \leq 5 \%$ in Table K.1.

K.5 Calibration using the design value format

Alternatively, to the reliability-based method in Clause K.4 for calibration of partial safety factors, the design value format can be applied, see ISO 2394.

K.6 Partial safety factors for fatigue for welded details in steel structures

The SN-approach is assumed to be used together with the Miner's rule for linear fatigue accumulation⁵¹.

For linear SN-curves, the number of cycles, N , to failure with constant stress range, $\Delta\sigma$, is written

$$N(\Delta\sigma) = \left(\frac{\Delta\sigma}{\Delta\sigma_C} \right)^{-m} 2 \times 10^6 = K \Delta\sigma^{-m} \quad (\text{K.12})$$

where

$\Delta\sigma_C$ is the characteristic fatigue strength defined as the 5 % quantile;

m is the slope of SN-curve (Wöhler exponent);

K is the SN-curve parameter.

For variable amplitude fatigue loading, the design value of the Miner's sum should fulfil

⁴⁸ The partial safety factors in Table K.1 are calibrated without taking into account the bias b and with the characteristic value for the model uncertainty equal to 1.

⁴⁹ The reason that $\gamma_m = 1,0$ and $\gamma_{Rm} = 1,0$ is that the partial safety factor for resistance becomes independent of the uncertainty of the strength parameters because the 5 % quantile used to define the characteristic values covers the influence of this uncertainty. The characteristic value of the model uncertainty is defined as the mean value and therefore γ_δ depends on V_δ . V_δ should be determined from tests, see Clause K.12 (design assisted by testing) or from the literature.

⁵⁰ The partial safety factor for a steel component with a yielding failure criteria becomes $\gamma_M = 1,1$ using coefficients of variation for yield strength equal to 5 % and for resistance model equal to 5 %, and bias equal to 1,1 (yield strength is less than 90 % of the tensile or compression strength).

The parametric formulas based on membrane theory in [6] for shell buckling applicable to tubular steel towers with $D/t < 300$ include a bias (design buckling curve is 85 % of the mean value of experimental values) and a model uncertainty with a coefficient of variation equal to 13 % implying that γ_M for buckling becomes 1,1.

⁵¹ Fatigue failure of welded details is considered in Clause K.6. The same principles could be used for fatigue failure of other fatigue critical details made by other materials such as composites and cast steel where the mean value of the fatigue load can be important.

$$\sum_i \frac{n_i}{2 \times 10^6} \left(\frac{\gamma_n \gamma_{Ff} \Delta \sigma_i}{\Delta \sigma_C / \gamma_{Mf}} \right)^m \leq 1 \quad (\text{K.13})$$

where

- γ_n is the consequence of failure factor, see 7.6.1.3;
- γ_{Ff} is the partial factor for fatigue load depending on uncertainties related to fatigue stresses;
- γ_{Mf} is the partial factor for fatigue strength depending on uncertainties related to the SN-curve and the Miner's rule;
- n_i is the number of cycles with fatigue stress range $\Delta \sigma_i$.

For non-linear SN-curves, the design value of the Miner's sum should fulfil

$$\sum_i \frac{n_i}{N(\gamma_n \gamma_{Mf} \gamma_{Ff} \Delta \sigma_i)} \leq 1 \quad (\text{K.14})$$

The partial safety factors γ_{Mf} and γ_{Ff} in Tables K.2 and K.3 are calibrated such that failure probabilities for the relevant failure modes are close to the target reliability level in Clause K.2 for a welded structural detail in component class 2. The partial safety factor γ_{Ff} depends on the coefficient of variation, V_{Ff} , for the fatigue stresses.

The fatigue strength parameter, $\log K$, can be assumed normal distributed with coefficient depending on the actual SN-curve, but typically 0,2 for welded details. The Miner sum can be assumed lognormal distributed with coefficient of variation equal to 0,3. The uncertainty for the fatigue stress ranges can be assumed lognormal distributed with a coefficient of variation representing the uncertainty for the assessment of the fatigue load and the uncertainty for the calculation of stress ranges given the fatigue loading, see [5]. Normally, the coefficient of variation V_{Ff} can be taken as 0,15 to 0,20, see [5].

The required reliability can be achieved as follows.

a) Damage tolerant method:

- selecting details, materials and stress levels so that in the event of the formation of cracks a low rate of crack propagation and a long critical crack length would result;
- provision of multiple load path;
- provision of crack-arresting details;
- provision of readily inspectable details during regular inspections.

b) Safe-life method:

- selecting details and stress levels resulting in a fatigue life sufficient to achieve the target value β^t at the end of the design service life. No inspections are required.

**Table K.2 – Recommended values for partial safety factor
for fatigue strength, γ_{Mf}**

Assessment method	γ_{Mf}
Damage tolerant	1,10
Safe-life	1,25

**Table K.3 – Recommended partial safety factor
for fatigue stresses, γ_{Ff}**

Coefficient of variation, V_{Ff} , for fatigue stress ranges	15 % to 20 %	20 % to 25 %	25 % to 30 %
γ_{Ff}	1,00	1,10	1,20

K.7 Types of tests for materials⁵²

A distinction needs to be made between the following types of tests:

- tests to establish directly the ultimate resistance or serviceability properties of structures or structural members for given loading conditions;
- tests to obtain specific material properties using specified testing procedures; for instance, coupon tests for material properties for blades;
- tests to reduce uncertainties in parameters used in resistance models; for instance by subcomponent and full-scale tests.

K.8 Planning of tests

K.8.1 General

Prior to the carrying out of tests, a test plan should be agreed with the testing organization. This plan should contain the objectives of the test and all specifications necessary for the selection or production of the test specimens, the execution of the tests and the test evaluation. The test plan should cover the following:

- objectives and scope;
- prediction of test results;
- specification of test specimens and sampling;
- loading specifications;
- testing arrangement;
- measurements;
- evaluation and reporting of the tests.

K.8.2 Objectives and scope

The objective of the tests should be clearly stated, for example the required properties, the influence of certain design parameters varied during the test and the range of validity. Limitations of the test and required conversions (e.g. scaling effects) should be specified.

K.8.3 Prediction of test results

All properties and circumstances that can influence the prediction of test results should be taken into account, including

- geometrical parameters and their variability,
- geometrical imperfections,
- material properties,

⁵² Clauses K.8 to K.11 are based on ISO 2394:2015 [3] and EN 1990:2002 [2].

- parameters influenced by fabrication and execution procedures, and
- scale effects of environmental conditions taking into account, and if relevant, any sequencing.

The expected modes of failure and/or calculation models, together with the corresponding variables should be described. If there is a significant doubt about which failure modes might be critical, then the test plan should be developed on the basis of accompanying pilot tests.⁵³

K.8.4 Specification of test specimen and sampling

Test specimens should be specified, or obtained by sampling, in such a way as to represent the conditions of the real structure.

Factors to be taken into account include

- dimensions and tolerances,
- material and fabrication of prototypes,
- number of test specimens,
- sampling procedures, and
- restraints.

The objective of the sampling procedure should be to obtain a statistically representative sample. Attention should be drawn to any difference between the test specimens and the product population that could influence the test results.

K.8.5 Loading specifications

The loading and environmental conditions to be specified for the test should include

- loading points,
- loading history,
- restraints,
- temperatures,
- relative humidity,
- loading by deformation or force control, etc.

Load sequencing should be selected to represent the anticipated use of the structural member, under both normal and severe conditions of use. Interactions between the structural response and the apparatus used to apply the load should be taken into account where relevant.

Where structural behaviour depends upon the effects of one or more actions that will not be varied systematically, then those effects should be specified by their representative values.

K.8.6 Testing arrangement

The test equipment should be relevant for the type of tests and the expected range of measurements. Special attention should be given to measures to obtain sufficient strength and stiffness of the loading and supporting rigs, and clearance for deflections, etc.

⁵³ Attention needs to be given to the fact that a structural member can possess a number of fundamentally different failure modes.

K.8.7 Measurements

Prior to the testing, all relevant properties to be measured for each individual test specimen should be listed. Additionally, a list should be made

- a) of measurement-locations, and
- b) of procedures for recording results, including if relevant,
 - 1) time histories of displacements,
 - 2) velocities,
 - 3) accelerations,
 - 4) strains,
 - 5) forces and pressures,
 - 6) required frequency,
 - 7) accuracy of measurements, and
 - 8) appropriate measuring devices.

K.8.8 Evaluation and reporting the test

For specific guidance, see Clause K.9. Any standards on which the tests are based should be reported.

K.9 General principles for statistical evaluations

When evaluating test results, the behaviour of test specimens and failure modes should be compared with theoretical predictions. When significant deviations from a prediction occur, an explanation should be sought: this might involve additional testing, perhaps under different conditions, or modification of the theoretical model.

The evaluation of test results should be based on statistical methods, with the use of available (statistical) information about the type of distribution to be used and its associated parameters. The methods given in Annex K may be used only when the following conditions are satisfied:

- a) the statistical data (including prior information) are taken from identified populations which are sufficiently homogeneous; and
- b) a sufficient number of observations is available.

At the level of interpretation of test results, three main categories can be distinguished.

- Where one test only (or very few tests) is (are) performed, no classical statistical interpretation is possible. Only the use of extensive prior information, associated with hypotheses about the relative degrees of importance of this information and of the test results, make it possible to present an interpretation as statistical (Bayesian procedures, see ISO 12491 [4]).
- If a larger series of tests is performed to evaluate a parameter, a classical statistical interpretation might be possible. This interpretation will still need to use some prior information about the parameter; however, this will normally be less than above.
- When a series of tests is carried out in order to calibrate a model (as a function) and one or more associated parameters, a classical statistical interpretation is possible.

The result of a test evaluation should be considered valid only for the specifications and load characteristics considered in the tests. If the results are to be extrapolated to cover other design parameters and loading, additional information from previous tests or from theoretical bases should be used.

K.10 Derivation of characteristic values

The derivation of a characteristic value from tests should take into account

- a) the scatter of test data,
- b) statistical uncertainty associated with the number of tests, and
- c) prior statistical knowledge.

If the response of the structure or structural member or the resistance of the material depends on influences not sufficiently covered by the tests such as

- time and duration effects,
- scale and size effects,
- different environmental, loading and boundary conditions, and
- resistance effects,

then the calculation model should take such influences into account as appropriate.

K.11 Statistical determination of characteristic value for a single property

Clause K.11 gives expressions for deriving characteristic values from (a) test types and (b) a single property (for example, a strength)⁵⁴.

NOTE The expressions presented here, which use Bayesian procedures with "vague" prior distributions, lead to almost the same results as classical statistics with confidence levels equal to 75 %.

The table and expressions below are based on the following assumptions:

- a) all variables follow either a normal or a lognormal distribution;
- b) there is no prior knowledge about the value of the mean;
- c) for the case " V_X unknown", there is no prior knowledge about the coefficient of variation;
- d) for the case " V_X known", there is full knowledge of the coefficient of variation.

In practice, it is often preferable to use the case " V_X known" together with a conservative upper estimate of V_X , rather than to apply the rules given for the case " V_X unknown". Moreover, V_X , when unknown, should be assumed to be not smaller than 0,10.

The characteristic value of a property X should be found by using

$$X_k = m_X (1 - k_n V_X) \quad (\text{K.15})$$

where m_X is the sample mean and the value of k_n can be found from Table K.4.

When using Table K.4, one of two cases should be considered as follows.

- The row " V_X known" should be used if the coefficient of variation, V_X , or a realistic upper bound of it, is known from prior knowledge⁵⁵.
- The row " V_X unknown" should be used if the coefficient of variation V_X is not known from prior knowledge and so needs to be estimated from the sample as:

⁵⁴ Adopting a lognormal distribution for certain variables has the advantage that no negative values can occur as for example for geometrical and resistance variables.

⁵⁵ Prior knowledge can come from the evaluation of previous tests in comparable situations. What is "comparable" needs to be determined by engineering judgement.

$$m_x = \frac{1}{n} \sum x_i \quad (\text{K.16})$$

$$s_x^2 = \frac{1}{n-1} \sum (x_i - m_x)^2 \quad (\text{K.17})$$

$$V_x = \frac{s_x}{m_x} \quad (\text{K.18})$$

Table K.4 – Values of k_n for the 5 % characteristic value

N	1	2	3	4	5	6	8	10	20	30	∞
V_x known	2,31	2,01	1,89	1,83	1,80	1,77	1,74	1,72	1,68	1,67	1,64
V_x unknown	-	-	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

Table K.4 is based on the normal distribution. With a lognormal distribution expression, Equation (K.15) becomes:

$$X_k = \exp(m_y - k_n s_y)$$

where

$$m_y = \frac{1}{n} \sum \ln(x_i)$$

If V_x is known from prior knowledge, $s_y = \sqrt{\ln(V_x^2 + 1)} \cong V_x$

If V_x is unknown from prior knowledge, $s_y = \sqrt{\frac{1}{n-1} \sum (\ln x_i - m_y)^2}$

K.12 Statistical determination of characteristic value for resistance models

K.12.1 General

Clause K.12 is mainly intended to define procedures (methods) for calibrating resistance models and for deriving design values from test type c), see Clause K.7. Use will be made of available prior information (knowledge or assumptions).

Based on the observation of actual behaviour in tests and on theoretical considerations, a "design model" should be developed, leading to the derivation of a resistance function. The validity of this model should then be checked by means of a statistical interpretation of all available test data. If necessary, the design model is adjusted until sufficient correlation is achieved between the theoretical values and the test data.

Deviation in the predictions obtained by using the design model should also be determined from the tests. This deviation will need to be combined with the deviations of the other variables in the resistance function in order to obtain an overall indication of deviation. These other variables include:

- deviation in material strength and stiffness;

- deviation in geometrical properties.

The characteristic resistance should be determined by taking account of the deviations of all the variables.

The method is presented as a number of discrete steps, and some assumptions regarding the test population are made and explained; these assumptions are to be considered to be no more than recommendations covering some of the most common cases.

For the standard evaluation procedure, the following assumptions are made:

- a) the resistance function is a function of a number of independent variables X ;
- b) a sufficient number of test results is available;
- c) all relevant geometrical and material properties are measured;
- d) there is no correlation (statistical dependence) between the variables in the resistance function;
- e) all variables follow either a normal or a lognormal distribution⁵⁶.

The standard procedure comprises seven steps, see K.12.2 to K.12.8.

K.12.2 Step 1: Develop a design model

Develop a design model for the theoretical resistance r_t of the member or structural detail considered, represented by the resistance function:

$$r_t = g_t(\underline{X}) \quad (\text{K.19})$$

The resistance function should cover all relevant basic variables $\underline{X}$ that affect the resistance at the relevant limit state.

All basic parameters should be measured for each test specimen and should be available for use in the evaluation.

K.12.3 Step 2: Compare experimental and theoretical values

Substitute the actual measured properties into the resistance function so as to obtain theoretical values r_{ti} to form the basis of a comparison with the experimental values r_{ei} from the tests.

The points representing pairs of corresponding values (r_{ti}, r_{ei}) should be plotted on a diagram, as indicated in Figure K.1.

⁵⁶ Adopting a lognormal distribution for a variable has the advantage that no negative values can occur.

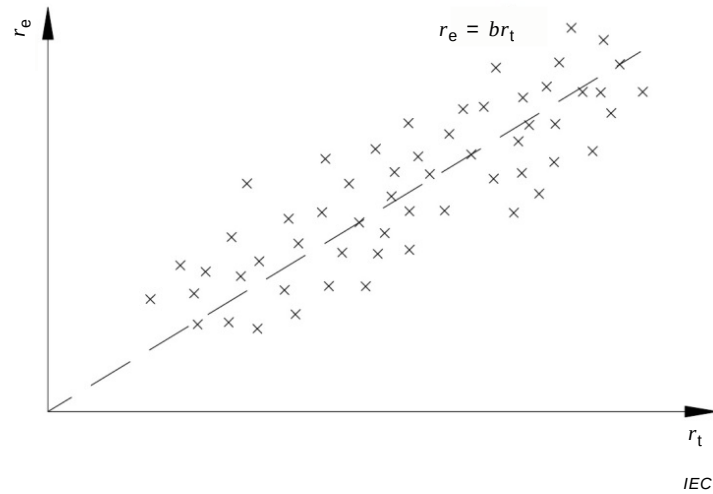


Figure K.1 – r_e - r_t diagram

If the resistance function is exact and complete, then all of the points will lie on the line with $b = 1$. In practice, the points will show some scatter, but the causes of any systematic deviation from that line should be investigated to check whether this indicates errors in the test procedures or in the resistance function.

K.12.4 Step 3: Estimate the mean value correction factor (bias) b

Represent the probabilistic model of the resistance r in the format

$$r = b r_t \delta \quad (\text{K.20})$$

where

b is the least squares best-fit to the slope, given by

$$b = \frac{\sum r_{ei} r_{ti}}{\sum r_{ti}^2} \quad (\text{K.21})$$

The mean value of the theoretical resistance function, calculated using the mean values $\underline{X}_m$ of the basic variables, can be obtained from

$$r_m = b r_t(\underline{X}_m) \delta = b g_{r_t}(\underline{X}_m) \delta \quad (\text{K.22})$$

K.12.5 Step 4: Estimate the coefficient of variation of the errors

The error term δ_i for each experimental value r_{ei} should be determined from the expression

$$\delta_i = \frac{r_{ei}}{b r_{ti}} \quad (\text{K.23})$$

From the values of δ_i an estimated value for V_δ should be determined by defining

$$A_i = \ln(\delta_i) \quad (\text{K.24})$$

The estimated value $\bar{A}$ for $E(A)$ should be obtained from

$$\bar{A} = \frac{1}{n} \sum A_i \quad (\text{K.25})$$

The estimated value s_A^2 for σ_A^2 should be obtained from

$$s_A^2 = \frac{1}{n-1} \sum (A_i - \bar{A})^2 \quad (\text{K.26})$$

The expression

$$V_\delta = \sqrt{\exp(s_A^2) - 1} \quad (\text{K.27})$$

may be used as the coefficient of variation V_δ of the δ_i error terms.

K.12.6 Step 5: Analyse compatibility

The compatibility of the test population with the assumptions made in the resistance function should be analysed.

If the scatter of the (r_{ti}, r_{ei}) values is too high to give economical design resistance functions, this scatter may be reduced in one of the following ways:

- by correcting the design model to take into account parameters which had previously been ignored;
- by modifying b and V_δ by dividing the total test population into appropriate subsets for which the influence of such additional parameters may be considered to be constant.

To determine which parameters have most influence on the scatter, the test results may be split into subsets with respect to these parameters.⁵⁷

When determining the fractile factors k_n (see step 7), the k_n value for the subsets may be determined on the basis of the total number of the tests in the original series.

K.12.7 Step 6: Determine the coefficients of variation V_{Xi} of the basic variables

If it can be shown that the test population is fully representative of the variation in reality, then the coefficients of variation V_{Xi} of the basic variables in the resistance function may be determined from the test data. However, since this is not generally the case, the coefficients of variation V_{Xi} will normally need to be determined on the basis of some prior knowledge.

K.12.8 Step 7: Determine the characteristic value r_k of the resistance

If the resistance function is of the form

⁵⁷ The purpose is to improve the resistance function per subset by analysing each subset using the standard procedure. The disadvantage of splitting the test results into subsets is that the number of test results in each subset can become very small.

$$r = b \, r_t \, \delta = b \, g_{r_t} \left(\underline{X_1, \dots, X_j} \right) \delta \quad (\text{K.28})$$

the mean value may be obtained from

$$E(r) = b \, g_{r_t} \left(E(X_1), \dots, E(X_j) \right) \delta = b \, g_{r_t} \left(\underline{X_m} \right) \delta \quad (\text{K.29})$$

and the coefficient of variation V_r may be approximated by

$$V_r^2 \cong V_\delta^2 + V_{r_t}^2 \quad (\text{K.30})$$

where V_δ is obtained from Equation (K.30)⁵⁸ and the coefficient of variation V_{r_t} may be obtained from

$$V_{r_t}^2 = \frac{1}{g_{r_t}(\underline{X_m})^2} \sum_{i=1}^j \left(\frac{\partial g_{r_t}(\underline{X})}{\partial X_i} \sigma_i \right)^2 \quad (\text{K.31})$$

where

σ_i is the standard deviation of X_i .

If the number of tests is limited (say $n < 100$), allowance should be made in the distribution of Δ for statistical uncertainties. The distribution should be considered as a central t-distribution with the parameters $\bar{\Delta}$, V_Δ and n .

The characteristic (5 % fractile) resistance r_k should be obtained from

$$r_k = b \, g_{r_t}(\underline{X_m}) \exp \left(-k_\infty \alpha_{\ln r_t} \sigma_{\ln r_t} - k_n \alpha_{\ln \delta} \sigma_{\ln \delta} - 0,5 \sigma_{\ln r}^2 \right) \quad (\text{K.32})$$

with

$$\sigma_{\ln r} = \sqrt{\ln(V_r^2 + 1)}$$

$$\sigma_{\ln r_t} = \sqrt{\ln(V_{r_t}^2 + 1)}$$

$$\sigma_{\ln \delta} = \sqrt{\ln(V_\delta^2 + 1)}$$

$$\alpha_{\ln r_t} = \frac{\sigma_{\ln r_t}}{\sigma_{\ln r}}$$

⁵⁸ The value of V_δ is estimated from the test sample under consideration.

$$\alpha_{\ln \delta} = \frac{\sigma_{\ln \delta}}{\sigma_{\ln r}}$$

where

k_n is the characteristic fractile factor from Table 5 with V_X unknown;

k_∞ is the value of k_n for $n \rightarrow \infty$ [$k_\infty = 1,64$];

$\alpha_{\ln r_t}$ is the weighting factor for $\sigma_{\ln r_t}$;

$\alpha_{\ln \delta}$ is the weighting factor for $\sigma_{\ln \delta}$.

K.13 Reference documents

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Annex L **(informative)**

Cold climate: assessment and effects of icing climate

L.1 Assessment of icing climate conditions

L.1.1 General

In icing climate conditions, meteorological icing is defined as the accretion of ice or snow on structures which are exposed to the atmosphere. In general, two different types of atmospheric icing that impact wind turbines can be distinguished: in-cloud icing (rime ice or glaze ice) and precipitation icing (freezing rain or drizzle, wet snow, see [1]). Typically in-cloud icing is more common and in many cases the frequency of in-cloud icing increases with increasing altitude. This is due to a higher probability of a structure being inside clouds and due to lower temperature.

Icing climate conditions can be assessed using various methods and measurement sensors. In order to assess icing climate effects for a wind turbine, the severity and duration of expected long-term rotor icing needs to be assessed. Clause L.1 describes some methods that can be used to assess expected rotor icing effects.

It is recommended to assess icing near blade tip or hub height (if necessary, extrapolate assessed icing to representative rotor icing height as presented in Equation (L.1)), use multiple ice detection methods in parallel for increased availability and reliability and use long-term site-specific data (preferably 10 years or more) to assess icing whenever possible as observed icing frequency may have a high inter-annual variation.

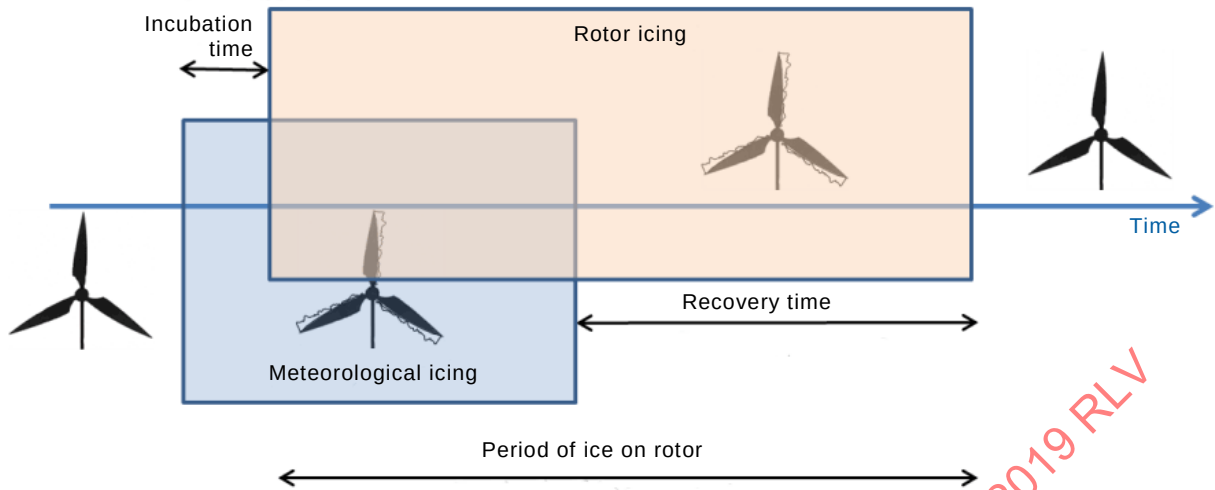
Additional information for guidance can be found in [3], [4], [5] and [6].

L.1.2 Icing climate

In general, an icing event can be described with the following expressions applicable to wind turbines exposed to meteorological icing (see Figure L.1).

- Meteorological icing: Period during which the meteorological conditions for ice accretion are favourable (active ice formation).
- Rotor icing⁵⁹: Period during which a wind turbine rotor is disturbed by ice.
- Incubation time: Delay between the start of meteorological icing and the start of rotor icing (dependent on the surface, the temperature of the structure and the wind turbine operating point).
- Recovery time: Delay between the end of meteorological icing and the end of rotor icing (period during which the ice remains but is not actively formed).

⁵⁹ The term "rotor icing" is used in this document instead of typical literature term "instrumental icing" because "rotor icing" specifies the phenomenon more accurately in case ice is affecting a rotating turbine rotor. For the rotating turbine rotor, high flow velocity and blade vibrations result to typically shorter incubation and recovery times than for stationary instruments.



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Figure L.1 – Definition of meteorological icing and rotor icing

L.1.3 Rotor icing

Rotor icing is defined as the period during which the wind turbine rotor is disturbed by ice. Ice is accreted continuously on a wind turbine rotor until the meteorological conditions for icing are not present anymore (end of the meteorological icing). Ice will remain at the wind turbine for a certain time – the recovery time – until ice erodes, sublimates, melts or sheds away from the rotor (end of the rotor icing).

In general, the frequency of meteorological in-cloud icing conditions increases significantly with altitude, thus a representative height above ground level for a wind turbine rotor is required to take these effects in to account. This representative height, rotor icing height (h_{ri}), is defined as:

$$h_{ri} = z_{hub} + \frac{1}{3}D \quad (L.1)$$

where

z_{hub} is hub height of the wind turbine [m];

D is the rotor diameter [m].

Figure L.2 illustrates the definition of rotor icing height. For cloud heights below the rotor icing height, it may be assumed that the complete rotor above is in cloud.

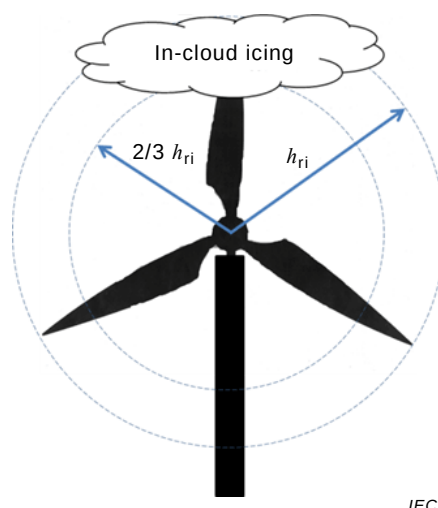


Figure L.2 – Representative ice affected rotor area as defined by rotor icing height

L.1.4 Measurement methods

Icing climate conditions may be assessed with following methods:

- use of dedicated ice detectors that measure severity and/or duration of meteorological and/or instrumental icing conditions;
- use pair of heated/unheated cup anemometers, which can be used to approximate the duration of instrumental icing;
- synoptic or camera system on stationary, for example met mast, or rotating component such as blades;
- measurements or observations via cloud base height and/or visibility and temperature;
- other validated method to assess meteorological icing.

Measurement equipment and/or the wind turbine may also be affected by a phenomenon called secondary icing. Secondary icing is formed through the process of ice accretion, melting and refreezing. Secondary icing may affect, for example, instrument availability and reliability.

Finally assessment of icing climate (IC) effects for wind turbines in terms of expected long-term rotor icing is needed. Typical severity and duration of IC effects on rotor blades presented in Clauses L.2 and L.3 may be used if no further data is available.

L.1.5 Profile coefficients modification for ice

Ice accretion on rotor blades deteriorates the airfoil aerodynamic performance characteristics versus clean airfoil performance. To account for the changes in airfoil performance, the following procedure for modifying the static airfoil characteristics may be used. It should be noted that the below mentioned range is arbitrary and should be chosen and evaluated according to the specific polar. Especially the merging into the background polar should be handled with care.

Airfoil penalty factors are to be multiplied with clean airfoil lift (C_L) and drag (C_D) coefficients for angles of attack from -2° to $\alpha = \alpha_{C_{lmax}}$. Coefficients outside this range may be extrapolated e.g. by Viterna [2] or similar method. The lift and drag penalties are a function of airfoil angle of attack as follows:

$$C_{L,pen}(\alpha) = -0,0014\alpha^2 - 0,0017\alpha + 0,9509 \quad (L.2)$$

$$C_{D,pen}(\alpha) = 0,0191 \alpha + 3,1151;$$

$$C_{L,iced} = C_{L,pen} \times C_{L,clean}$$

$$C_{D,iced} = C_{D,pen} \times C_{D,clean}$$

where

$C_{L,pen}$ is the clean airfoil lift coefficient penalty factor [-];

$C_{D,pen}$ is the clean airfoil drag coefficient penalty factor [-];

α is the angle of attack [°].

There is no modification applied for moment coefficient (C_m). It should be noted that the angle of attack range from -2° is arbitrary and should be adjusted according to angle of attack definition. This value could be adjusted to approximately the mid-point between $\alpha_{C_{lmax}}$ and $\alpha_{C_{lmin}}$.

Figure L.3 illustrates the penalty factors for iced airfoils. In the figure equations, x refers to the angle of attack, α , and y to the penalty factor.

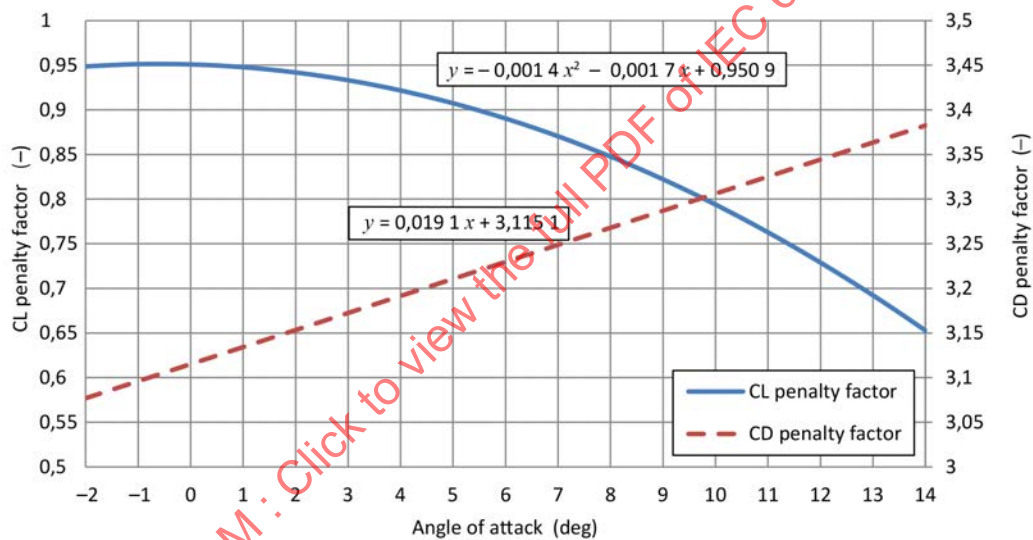


Figure L.3 – Iced airfoil lift and drag penalty factors

L.2 Ice mass effects on wind turbine blades

The duration ice remains on a rotor varies significantly geographically and from one year to another. It is recommended to assess the icing climate effects for a wind turbine with site measurements, see more guidance in Clause L.1. If no other information is available, 750 h of annual expected long-term rotor icing may be assumed.

The ice mass distribution (mass / unit length) for a wind turbine blade shall be assumed at the leading edge. It increases linearly from zero in the rotor axis to the maximum value at the rotor tip. The ice load distribution is calculated as follows:

$$M(r) = A \times C_{85\%} \times r \quad (L.4)$$

where

M is the mass distribution on the leading edge of the rotor blade [kg/m];

- A is 0,125 [kg/m³];
 $C_{85\%}$ is the chord length at 85 % rotor radius [m];
 r is the radial position from rotor axis [m].

L.3 Cold climate design situations and load case

L.3.1 General

Additional load cases according to cold climate conditions are listed in Table L.1.

Table L.1 – Cold climate design load cases

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1. Power production	1.6	NTM $V_{in} < V_{hub} < V_{out}$	Ice formation	F / U	N
6. Parked (standstill or idling)	6.5	NTM $V_{hub} < 0,7 V_{ref}$	Ice formation	F / U	N
7. Parked and fault conditions	7.1	EWM 1-year return period	Ice formation	U	A

The duration ice remains on a rotor varies significantly geographically and from one year to another. It is recommended to assess the icing climate effects for a wind turbine with site measurements, see more guidance in Clause L.1. If no other information is available, 750 h of annual expected long-term rotor icing may be assumed.

L.3.2 Power production (DLC 1.1 to 1.6)

If icing of the blades can be expected and not actively prevented, safety of the turbine controller behaviour and turbine performance (Clause L.2) due to iced blades needs to be evaluated.

L.3.3 Parked (standstill or idling) (DLC 6.1 to 6.5)

For DLC 6.5 iced turbine idling, safety of the turbine controller behaviour needs to be evaluated.

L.3.4 Parked and fault conditions (DLC 7.1)

If no autonomous energy supply exists for the wind turbine, a cooling of the wind turbine down to $\theta_{1\text{year,min}}$ is to be assumed in case of grid failure. It shall be observed that low oil sump temperatures lead to significantly increased power train losses and damping, which obstruct free idling of the rotor. Iced turbine idling safety regarding turbine controller behaviour needs to be evaluated.

L.4 Cold climate load calculations

All load calculations are mainly for investigations regarding the behaviour and safety of turbine controller. Simulations with aerodynamic penalties according to Clause L.2 and ice induced rotor masses according to Clause L.3 may be implemented in the absence of other information. For ultimate load analysis, ice mass formation on all rotor blades except one and aerodynamic penalties on all rotor blades should be investigated. For fatigue analysis, ice mass on all rotor blades except one rotor blade where 50 % of the ice mass should be considered, in addition to aerodynamic penalties on all rotor blades, should be investigated.

Increased air density according to 14.4 shall be used.⁶⁰ The approach is summarized in Table L.2.

For fatigue load analysis, ice mass distribution according to Equation (L.4) may be used. For ultimate load analysis, Formula (L.4) is to be increased by a factor of two.

Table L.2 – Blade ice mass and airfoil penalty factors used in different analysis types

Analysis Type	Blade No. 1	Blade No. 2	Blade No. <i>N</i>	Airfoil penalty factor, applied for all blades
Ultimate	Equation (L.4)	Equation (L.4)	-	Equations (L.2) and (L.3)
Fatigue	Equation (L.4)	Equation (L.4)	Equation (L.4) – 50 %	Equations (L.2) and (L.3)

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⁶⁰ Special care should be taken to investigate different lateral (perpendicular to main wind direction) stiffness and damping coefficients especially for foundations. Variations in these properties might significantly influence the effects of rotor mass imbalances.

Annex M (informative)

Medium wind turbines

M.1 Overview

There is a significant market for the deployment of turbines in a size category smaller than typical utility size and larger than the category dealt with in IEC 61400-2. This category is referred to as "medium wind turbines". Depending on the application, it may be appropriate to use design requirements that differ from those in the main text.

Annex M provides information on design requirements that may be appropriate to medium wind turbines as defined in 3.29. All requirements described in this document shall be met with the following optional additions and clarifications for medium wind turbine systems.

M.2 External conditions

M.2.1 General

External conditions as defined in Clause 6 apply to medium wind turbine systems with the following clarifications.

Medium wind turbines may be installed in more complex terrain and/or near industrial areas. Therefore, it may be more appropriate to use a turbulence intensity class A+ or A for wind turbines in these environments.

M.2.2 Wind shear

On some medium wind turbine sites, higher shear exponents can arise in combination with high turbulence levels at such sites. Therefore, for a medium wind turbine, it may be appropriate to use a shear exponent, α , larger than 0,2. A shear exponent of $\alpha = 0,3$ provides a more conservative value of the wind profile for such sites.

A generic class wind turbine may also be designated with an "M" sub-class. If a value of $\alpha > 0,2$ is needed, the value shall be stated in the design documentation and the load analysis shall be executed with this value.

M.3 Assembly, installation and erection

Assembly, installation and erection of medium wind turbine systems shall meet the requirements described in Clause 12 with the following optional additional paragraphs.

12.6 Documentation

Additional paragraphs:

Information on the how to install, assemble and erect the turbine shall be specified in the documentation provided to the installer. This could include, but is not be limited to:

- details on the correct sequencing and assembly of the turbine installation;
- any general or specific training or competence standards recommended or mandated to enable contractors to undertake the installation safely and in accordance with local rules;
- technical and health and safety information regarding foundation installation, in case the turbine manufacturer is responsible for the foundation – if not, turbine loads and turbine-

foundation interface details, as well as any other turbine requirement to be taken into account for the correct foundation design and construction;

- technical and health and safety information regarding tower, blade and nacelle installation;
- technical and health and safety information regarding any other structure or system being installed (e.g. gearbox);
- technical and health and safety information regarding the installation of anchors or any equivalent systems;
- advice on site management, site access and the receiving handling and storage of the turbine and associate equipment to enable the protection of workers and others including the turbine and its components during the installation of the turbine;
- any specified loads or environmental conditions (e.g. wind speeds), including specified limits that need to be observed or not exceeded with specific reference to the installation of the tower and blades;
- technical and health and safety information necessary to enable the safe use of any specified equipment (e.g. cranes and lifting equipment) as part of the installation of the turbine;
- any additional or alternative requirements to safely decommission the turbine; and
- all necessary information to record and communicate the final as installed information to customers or end users.

Unless specific installation equipment is supplied by the manufacturer, the final selection of any equipment used or systems of work applied shall be the responsibility of the installer.

Any specific regulatory requirements or obligations relevant to the turbine and any duties mandated to fulfil national regulations in the jurisdiction supplied may be specified in the documentation provided.

Any specific standards or codes relevant to the turbine and any duties mandated to fulfil national standards and codes in the jurisdiction supplied may be specified in the documentation provided.

M.4 Commissioning, operation and maintenance

Commissioning, operation and maintenance of medium wind turbine systems shall meet the requirements described in Clause 13 with the following optional paragraphs.

13.1 General

Additional paragraphs:

Information and instruction on the how to operate and maintain the turbine shall be specified in the documentation provided to the operator. This shall include, but not be limited to:

- drawings, diagrams, descriptions and explanations necessary for the operation, maintenance, repair and testing of the wind turbine;
- instructions for training of operators and maintenance personnel, which shall indicate important aspects to be covered – as a minimum, description of access and egress to the wind turbine, climbing instructions, use of the lift, instructions about safe access to electrical installations and emergency escape procedures, maximum maintenance wind speed and the maximum number of persons allowed inside the nacelle or working on it;
- information about the maximum number of people allowed in different parts of the wind turbine at the same time;
- information about the protective measures to be taken by the operator including, where appropriate, the personal protective equipment (PPE) to be provided;

- requirements for maintenance, inspection and testing of safety critical components and systems;
- details of control and operating modes of the turbine control system;
- specification of rescue equipment;
- list of potential danger zones and specification of hazards associated with each potential danger zone;
- specification of fire extinguishers and their location;
- description of essential special tools to be used during maintenance and repair; and
- recommended service intervals for the turbine and the key components and systems;
- limits of stability during operation, maintenance, repair and breakdown. This includes description of the environmental limits to enter the turbine for maintenance work.

13.2 Design requirements for safe operation, inspection and maintenance

Additional paragraphs:

The protective measures that have been incorporated into the turbine shall be documented. This could include, but not be limited to:

- a description of significant hazards that may exist;
- specification of the limits of the wind turbine, including
 - the intended use of the wind turbine including different operating modes and intervention procedures for the operators,
 - the space limits defining working areas and access to them, operator-machine interfaces and machine-power supply interfaces,
 - any time limits specifying the design life of components critical to safety;
- details of the safety requirements and protective measures including the control systems that the turbine design has taken into account; and
- details of any residual risks that need to be brought to the attention of the buyer or operator of the turbine.

M.5 Documentation

All necessary manuals, diagrams, specifications, instructions, drawings or safety instructions sufficient to enable the safe and correct supply, assembly, installation, operation and maintenance of the wind turbine structure and equipment shall be provided as appropriate. The final scope and content of all information provided shall take into account:

- a) risk assessments performed by the manufacturer;
- b) the size and configuration of the turbine;
- c) the applicable class and load characteristics of the turbine as supplied; and
- d) site and environmental conditions for which the turbine is appropriate.

Documentation provided to the buyer shall be written in the English language and one or more official languages of the country in which the turbine is to be installed if English is not one of them. It shall include:

- the name of the manufacturer and its local representative, if a separate organization;
- the designation of the wind turbine, including name, model and class;
- any specified declarations of conformity; and
- a clear statement regarding the limitations regarding the operations that can be carried out by the buyer/user and those which should be entrusted to specialized/authorized

companies/technicians and the evidences these companies/technicians shall show to be allowed to carry out these operations.

All the documentation shall be arranged in a logical order and it shall be updated when new information becomes available. The content of the documentation shall also cover reasonably foreseeable misuse.

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⁶¹ Under preparation. Stage at the time of publication: IEC CDV 61400-3-1:2017.

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COMMISSION ÉLECTROTECHNIQUE INTERNATIONALE

SYSTÈMES DE GÉNÉRATION D'ÉNERGIE ÉOLIENNE –

Partie 1: Exigences de conception

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La Norme internationale IEC 61400-1 a été établie par le comité d'études 88 de l'IEC: Systèmes de génération d'énergie éolienne.

Cette quatrième édition annule et remplace la troisième édition, parue en 2005, et son Amendement 1:2010. Cette édition constitue une révision technique.

Cette édition inclut les modifications techniques majeures suivantes par rapport à l'édition précédente:

- a) mise à jour générale et clarification des références et des exigences;
- b) extension des classes d'éoliennes pour les adapter aux cyclones tropicaux et aux fortes turbulences;
- c) loi de Weibull de l'écart type de la turbulence pour le modèle de turbulence normale (NTM);

- d) cas de charge pour la conception (DLC) mis à jour, en particulier les DLC 2.1 et 2.2;
- e) révision des spécifications du facteur de sécurité partielle;
- f) révision majeure des Articles 8, 10 et 11;
- g) introduction des exigences relatives au climat froid, Article 14;
- h) nouvelle Annexe B sur les cas de charge pour la conception d'éolienne de classe S spécifique au site ou particulière ou à l'évaluation d'adaptabilité au site;
- i) nouvelle Annexe J sur les prévisions de vitesse de vent extrême des cyclones tropicaux par la méthode de simulation de Monte-Carlo;
- j) nouvelle Annexe K sur l'étalonnage des facteurs de sécurité des matériaux de structure et à la conception structurelle assistée par des essais;
- k) nouvelle Annexe L sur l'évaluation et aux effets du climat givrant;
- l) nouvelle Annexe M sur les éoliennes moyennes.

La présente version bilingue (2020-03) correspond à la version anglaise monolingue publiée en 2019-02.

La version française de cette norme n'a pas été soumise au vote.

Ce document a été rédigé selon les Directives ISO/IEC, Partie 2.

Une liste de toutes les parties de la série IEC 61400, publiées sous le titre général *Systèmes de génération d'énergie éolienne*, peut être consultée sur le site web de l'IEC.

Les futures normes de cette série porteront dorénavant le nouveau titre général cité ci-dessus. Le titre des normes existant déjà dans cette série sera mis à jour lors de la prochaine édition.

Le comité a décidé que le contenu de ce document ne sera pas modifié avant la date de stabilité indiquée sur le site web de l'IEC sous « <http://webstore.iec.ch> » dans les données relatives au document recherché. À cette date, le document sera

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Le contenu du corrigendum de septembre 2019 a été inclus dans cette copie.

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INTRODUCTION

Cette partie de l'IEC 61400 expose les exigences minimales de conception des éoliennes et n'est pas destinée à servir de spécification intégrale de conception ou de manuel d'instruction.

Toute exigence du présent document peut être modifiée s'il peut être démontré de manière adéquate que la sécurité du système n'est pas compromise. Cette disposition, cependant, ne s'applique pas à la classification et aux définitions associées des conditions externes de l'Article 6. La conformité au présent document ne dégage pas toute personne, organisation ou personne morale de sa responsabilité d'observer d'autres réglementations applicables.

Le présent document n'est pas destiné à donner des exigences pour les éoliennes installées en pleine mer, en particulier pour la structure de support. Pour les installations en pleine mer, il est fait référence à la série IEC 61400-3.

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SYSTÈMES DE GÉNÉRATION D'ÉNERGIE ÉOLIENNE –

Partie 1: Exigences de conception

1 Domaine d'application

La présente partie de l'IEC 61400 spécifie les exigences de conception essentielles pour assurer l'intégrité structurelle des éoliennes. Elle a pour objet de fournir un niveau de protection approprié contre les dommages causés par tous les dangers pendant la durée de vie prévue.

Le présent document concerne tous les sous-systèmes des éoliennes tels que les fonctions de commande et de protection, les systèmes électriques internes, les systèmes mécaniques et les structures de support.

Le présent document s'applique aux éoliennes de toutes dimensions. Pour les petites éoliennes, l'IEC 61400-2 peut s'appliquer. L'IEC 61400-3-1 donne les exigences supplémentaires relatives aux installations d'éoliennes en pleine mer.

Le présent document est destiné à être utilisé avec les normes IEC et ISO appropriées mentionnées à l'Article 2.

2 Références normatives

Les documents suivants sont cités dans le texte de sorte qu'ils constituent, pour tout ou partie de leur contenu, des exigences du présent document. Pour les références datées, seule l'édition citée s'applique. Pour les références non datées, la dernière édition du document de référence s'applique (y compris les éventuels amendements).

IEC 60034 (toutes les parties), *Machines électriques tournantes*

IEC 60038, *Tensions normales de la CEI*

IEC 60071-1, *Coordination de l'isolement – Partie 1: Définitions, principes et règles*

IEC 60071-2, *Coordination de l'isolement – Partie 2: Lignes directrices en matière d'application*

IEC 60076 (toutes les parties), *Transformateurs de puissance*

IEC 60204-1, *Sécurité des machines – Équipement électrique des machines – Partie 1: Exigences générales*

IEC 60204-11:2000, *Sécurité des machines – Équipement électrique des machines – Partie 11: Prescriptions pour les équipements HT fonctionnant à des tensions supérieures à 1 000 V c.a. ou 1 500 V c.c. et ne dépassant pas 36 kV*

IEC 60364 (toutes les parties), *Installations électriques à basse tension*

IEC 60529, *Degrés de protection procurés par les enveloppes (Code IP)*

IEC 60664-1, *Coordination de l'isolement des matériels dans les systèmes (réseaux) à basse tension - Partie 1: Principes, exigences et essais*

IEC 60664-3, *Coordination de l'isolement des matériels dans les systèmes (réseaux) à basse tension - Partie 3: Utilisation de revêtement, d'empotage ou de moulage pour la protection contre la pollution*

IEC 60721 (toutes les parties), *Classification des conditions d'environnement*

IEC 61000-6-2, *Compatibilité électromagnétique (CEM) – Partie 6-2: Normes génériques – Norme d'immunité pour les environnements industriels*

IEC 61400-3, *Wind turbines - Part 3 : design requirements for offshore wind turbines* (disponible en anglais seulement)

IEC 61400-4, *Wind Turbines – Part 4: Design requirements for wind turbine gearboxes* (disponible en anglais seulement)

IEC 61400-24, *Wind turbines – Part 24: Lightning protection* (disponible en anglais seulement)

IEC 61439 (toutes les parties), *Ensembles d'appareillage à basse tension*

IEC 61800-4, *Entraînements électriques de puissance à vitesse variable – Partie 4: Exigences générales - Spécifications de dimensionnement pour systèmes d'entraînements de puissance en courant alternatif de tension supérieure à 1 000 V alternatif et ne dépassant pas 35 kV*

IEC 61800-5-1, *Entraînements électriques de puissance à vitesse variable – Partie 5-1: Exigences de sécurité - Électrique, thermique et énergétique*

IEC 62271 (toutes les parties), *Appareillage à haute tension*

IEC 62305-3, *Protection against lightning – Part 3: Physical damage to structures and life hazard* (disponible en anglais seulement)

IEC 62305-4, *Protection against lightning – Part 4: Electrical and electronic systems within structures* (disponible en anglais seulement)

IEC 62477-1:2012, *Exigences de sécurité applicables aux systèmes et matériels électroniques de conversion de puissance - Partie 1: Généralités*

ISO 76, *Roulements – Charges statiques de base*

ISO 281, *Roulements – Charges dynamiques de base et durée nominale*

ISO 2394, *Principes généraux de la fiabilité des constructions*

ISO 2533, *Atmosphère Type*

ISO 4354, *Actions du vent sur les structures*

ISO 6336-2, *Calcul de la capacité de charge des engrenages cylindriques à dentures droite et hélicoïdale - Partie 2: Calcul de la résistance à la pression de contact (piqûre).*

ISO 6336-3:2006, *Calcul de la capacité de charge des engrenages cylindriques à dentures droite et hélicoïdale - Partie 3: Calcul de la résistance à la flexion en pied de dent*

ISO 12494:2001, *Charges sur les structures dues à la glace*

ISO 13850, *Sécurité des machines - Fonction d'arrêt d'urgence - Principes de conception*

ISO/TS 16281, *Roulements - Méthodes de calcul de la durée nominale de référence corrigée pour les roulements chargés universellement*

3 Termes et définitions

Pour les besoins du présent document, les termes et définitions suivants s'appliquent.

L'ISO et l'IEC tiennent à jour des bases de données terminologiques destinées à être utilisées en normalisation, consultables aux adresses suivantes:

- IEC Electropedia: disponible à l'adresse <http://www.electropedia.org/>
- ISO Online browsing platform: disponible à l'adresse <http://www.iso.org/obp>

3.1

moyenne annuelle valeur moyenne d'un ensemble de données mesurées de taille et de durée suffisantes destinée à l'estimation de la valeur attendue de la grandeur

Note 1 à l'article: Il convient que l'intervalle de temps moyen soit un nombre entier d'années (10, par exemple) qui représente la moyenne des effets non permanents tels que la saisonnalité..

3.2

vitesse moyenne annuelle du vent

V_{ave}

vitesse du vent moyennée conformément à la définition de la moyenne annuelle

3.3

cycle de refermeture automatique

événement dont la durée varie d'approximativement 0,01 s à quelques secondes, pendant lesquelles un disjoncteur déclenché après un défaut sur le réseau est automatiquement refermé et la ligne électrique est reconnectée au réseau

3.4

blocage

<éoliennes> utilisation d'une broche ou d'un autre mécanisme (autre que le frein mécanique normal) qui ne peut pas être déclenché(e) accidentellement pour empêcher le mouvement, par exemple, de l'arbre du rotor ou du dispositif d'orientation

3.5

frein

<éoliennes> dispositif capable de réduire la vitesse du rotor ou d'arrêter la rotation

Note 1 à l'article: Le frein peut fonctionner, par exemple, selon des principes aérodynamiques, mécaniques ou électriques.

3.6

valeur caractéristique

valeur ayant une probabilité prescrite de ne pouvoir être atteinte (c'est-à-dire une probabilité de dépassement inférieure ou égale à une quantité prescrite)

3.7

terrain complexe

terrain environnant qui présente des variations topographiques notables et des obstacles pouvant entraîner une distorsion de l'écoulement de l'air

3.8

fonctions de commande

<éoliennes> fonctions du système de commande qui, fondées sur des informations relatives à l'état de l'éolienne et/ou son environnement, règlent l'éolienne afin de la maintenir dans ses limites de fonctionnement

3.9

système de commande

<éoliennes> système mettant en œuvre les fonctions de commande de l'éolienne, comprenant les capteurs, les éléments logiques, les actionneurs, les réseaux de communication et les alimentations électriques

Note 1 à l'article: Le système de commande a pour objet de commander le fonctionnement de l'éolienne par des moyens actifs et passifs, et de maintenir les paramètres de fonctionnement dans les limites indiquées dans la conception structurelle. Le système de commande est susceptible d'inclure des boucles de commande pour le fonctionnement normal, ainsi que des alarmes et des mécanismes d'arrêt visant à assurer que les limites ne sont pas dépassées.

3.10

vitesse de démarrage

V_{in}

vitesse du vent sur 10 min la plus basse à hauteur du moyeu à partir de laquelle l'éolienne commence à fournir une puissance en cas de vent constant sans turbulence

3.11

vitesse de coupure

V_{out}

vitesse du vent sur 10 min la plus élevée à hauteur du moyeu pour laquelle l'éolienne a été conçue pour fournir de la puissance en cas de vent constant sans turbulence

3.12

limites de conception

paramètres maximaux ou minimaux utilisés lors de la conception

3.13

panne latente

défaillance d'un composant ou d'un système qui n'est pas détectée en fonctionnement normal

3.14

sous le vent

dans la direction du vecteur vent principal

3.15

réseau d'alimentation électrique

installations, sous-stations, lignes ou câbles particuliers destinés à la transmission et à la distribution de l'électricité

Note 1 à l'article: Les limites des différentes parties de ce réseau sont définies par des critères appropriés, tels que la situation géographique, le propriétaire, la tension.

3.16

arrêt d'urgence

<éoliennes> arrêt rapide de l'éolienne provoqué par une intervention manuelle

3.17

conditions d'environnement

caractéristiques de l'environnement (vent, altitude, température, humidité, etc.) qui peuvent affecter le comportement de l'éolienne

3.18**conditions externes**

<éoliennes> facteurs affectant le fonctionnement d'une éolienne, dont les conditions d'environnement (température, neige, glace, etc.) et l'état du réseau électrique

3.19**vitesse de vent extrême**

valeur de la vitesse du vent la plus élevée, moyennée sur t en secondes, avec une probabilité annuelle de dépassement de $1/N$ (« période de retour »: N années)

Note 1 à l'article: Des périodes de retour de $N = 50$ ans et $N = 1$ an et des intervalles de temps de moyennage de $t = 3$ s et $t = 10$ min sont utilisés dans le présent document. En langage courant, le terme moins précis de « vitesse de survie » est souvent utilisé. Dans le présent document, cependant, l'éolienne est conçue en utilisant des vitesses de vent extrêmes pour les cas de charge pour la conception.

3.20**sécurité intrinsèque**

qualifie une entité qui est conçue en vue d'éviter que ses défaillances n'entraînent des pannes critiques

3.21**rafale**

changement temporaire de la vitesse du vent

Note 1 à l'article: Une rafale peut être caractérisée par son temps de front, son amplitude et sa durée.

3.22**éolienne à axe horizontal**

éolienne pourvue d'un rotor dont l'axe est sensiblement horizontal

3.23**moyeu**

élément servant à attacher les pales ou l'assemblage des pales à l'arbre du rotor

3.24**hauteur du moyeu**

z_{hub}

<éoliennes> hauteur du centre de la surface balayée (3.57) du rotor de l'éolienne par rapport au sol

3.25**ralenti**

<éoliennes> état d'une éolienne en rotation lente sans production d'énergie

3.26**sous-domaine inertiel**

intervalle de fréquence du spectre de la turbulence, dans lequel les tourbillons – après avoir atteint l'isotropie – subissent une dispersion avec une dissipation négligeable d'énergie

Note 1 à l'article: À une vitesse du vent typique de 10 m/s, le sous-domaine inertiel est environ de 0,2 Hz jusqu'à 1 kHz.

3.27**état limite**

état d'une structure et des charges qui agissent sur elle, au-delà duquel la structure ne satisfait plus aux exigences de conception

Note 1 à l'article: Le but des calculs de conception (c'est-à-dire l'exigence de conception pour l'état-limite) est de limiter la probabilité qu'un état-limite puisse être atteint au-dessous d'une certaine valeur prescrite pour le type de structure concerné (voir l'ISO 2394).

3.28

vitesse moyenne du vent

moyenne statistique des valeurs instantanées de la vitesse du vent, pendant un intervalle de temps déterminé qui peut varier de quelques secondes à de nombreuses années

3.29

éolienne moyenne

éolienne dont la surface balayée par le rotor ou, dans le cas d'une éolienne carénée, la plus grande surface d'entrée et de sortie du carénage, est supérieure à 200 m² et inférieure ou égale à 1 000 m²

3.30

nacelle

carter contenant la transmission et d'autres éléments, placé au sommet du mât d'une éolienne à axe horizontal

3.31

point de connexion au réseau électrique

<éoliennes>bornes du câble d'une éolienne ou, pour une centrale éolienne, point de connexion au jeu de barres du système de collecte de puissance du site

3.32

perte du raccordement au réseau

perte du raccordement au réseau électrique (réseau) pendant une période dépassant toute durée prévue dans le système de commande de l'éolienne

3.33

arrêt normal

<éoliennes>arrêt dans lequel toutes les étapes sont sous le contrôle du système de commande

3.34

limites de fonctionnement

ensemble de conditions définies par le concepteur de l'éolienne qui régit l'activation des fonctions de commande de l'éolienne

3.35

éolienne immobilisée

éolienne qui est soit à l'arrêt soit au ralenti, selon la conception de l'éolienne

3.36

niveau de performance

PL

niveau discret utilisé pour spécifier la capacité des parties relatives à la sécurité des systèmes de commande à accomplir une fonction de sécurité dans des conditions prévisibles

Note 1 à l'article: L'abréviation «PL» est dérivée du terme anglais développé correspondant «performance level».

3.37

système de collecte de puissance

<éoliennes>système électrique qui récupère l'énergie produite par une ou plusieurs éoliennes

Note 1 à l'article: Il comprend tous les équipements électriques raccordés entre les bornes des éoliennes et le point de connexion au réseau.

3.38

puissance restituée

courant fourni par un dispositif sous une forme spécifique et pour un objectif spécifique

Note 1 à l'article: Pour une éolienne, il s'agit du courant électrique qu'elle fournit.

3.39

fonction de protection de la couche principale

fonction de protection (3.40) d'un système de protection dont au moins deux couches indépendantes peuvent être mises en œuvre comme partie intégrante du système de commande de l'éolienne, et qui est distincte d'une fonction de protection de couche secondaire (3.52) dont l'objectif est similaire

3.40

fonctions de protection

<éolienne>fonctions du système de commande qui assurent qu'une éolienne reste dans les limites de conception

3.41

puissance assignée

quantité de puissance assignée, généralement par un fabricant, dans des conditions de fonctionnement définies d'un composant, d'un dispositif ou d'un équipement

Note 1 à l'article: Pour une éolienne, il s'agit de la puissance électrique maximale qu'une éolienne est conçue pour fournir en permanence, dans les conditions normales de fonctionnement et dans les conditions externes.

3.42

vitesse du vent assignée

V_r

vitesse du vent minimale à hauteur du moyeu pour laquelle une éolienne atteint sa puissance assignée en cas de vent constant sans turbulence

3.43

loi de Rayleigh

P_R

fonction de distribution de la probabilité

Note 1 à l'article: Voir 3.68.

3.44

vitesse du vent de référence

V_{ref}

paramètre de base de la vitesse du vent utilisé pour définir les classes d'éoliennes

Note 1 à l'article: D'autres paramètres climatiques de conception sont dérivés de la vitesse du vent de référence et d'autres paramètres de catégories d'éoliennes de base (voir Article 6)

Note 2 à l'article: Une éolienne conçue pour une classe d'éoliennes avec une vitesse du vent de référence V_{ref} est dimensionnée afin de résister à des climats pour lesquels la vitesse moyenne du vent extrême établie sur 10 min à hauteur du moyeu, avec une période de retour possible de 50 ans, est inférieure ou égale à V_{ref} .

3.45

facteur de sécurité partielle de résistance

γ_M

facteur qui tient compte des possibles écarts/incertitudes défavorables des paramètres de résistance du matériau et du modèle de résistance, y compris la polarisation dans le modèle de résistance

3.46

vitesse vectorielle du vent échantillonnée en rotation

vitesse vectorielle du vent rencontrée en un point déterminé du rotor de l'éolienne en rotation

Note 1 à l'article: Le spectre de turbulence de la vitesse de vent échantillonnée en rotation est nettement différent du spectre normal de la turbulence. Les pales, en tournant, traversent le flux du vent qui varie dans l'espace. En conséquence, le spectre de turbulence résultant présente une variance importante à la fréquence de rotation et à ses harmoniques.

3.47

vitesse du rotor

<éoliennes> vitesse de rotation du rotor d'une éolienne autour de son axe

3.48

longueur de la rugosité

z_0

hauteur extrapolée à laquelle la vitesse moyenne du vent est égale à zéro en partant du principe que le profil vertical du vent varie de manière logarithmique avec sa hauteur

3.49

durée de vie assurée

propriété de conception d'un système critique qui est soit très difficile à réparer ou qui peut mettre la vie en danger ou endommager gravement les biens

Note 1 à l'article: Ce type de systèmes est conçu pour fonctionner sur toute la durée de vie du système sans exigence de réparation ou d'examens.

3.50

niveau d'intégrité de sécurité

SIL

niveau discret (parmi quatre possibles), correspondant à une plage de valeurs d'intégrité de sécurité, le niveau 4 étant le niveau le plus élevé et le niveau 1 étant le niveau le plus faible

Note 1 à l'article: Les mesures de défaillance cible des quatre niveaux d'intégrité de sécurité sont définies dans les Tableaux 2 et 3 de l'IEC 61508-1:2010. Ces niveaux peuvent être utilisés pour spécifier les exigences d'intégrité de sécurité des fonctions de sécurité attribuées aux systèmes. Un SIL n'est pas une propriété d'un système, d'un sous-système, d'un élément ou d'un composant. Comme indiqué dans l'IEC 61508-1, la phrase « système relatif à la sécurité à SIL n » (où n est égal à 1, 2, 3 ou 4) signifie que le système est potentiellement capable de prendre en charge des fonctions de sécurité avec un niveau d'intégrité de sécurité jusqu'à n .

Note 2 à l'article: L'abréviation «SIL» est dérivée du terme anglais développé correspondant «safety integrity level».

3.51

maintenance programmée

maintenance préventive effectuée conformément à un planning établi

3.52

fonction de protection de couche secondaire

fonction de protection dédiée qui fonctionne au moyen d'une couche de surveillance et de logique séparée d'une fonction de protection de couche principale (voir 3.39) dont l'objet est similaire

3.53

données du site

données environnementales, sismiques, sur le sol et le réseau électrique pour le site de l'éolienne

Note 1 à l'article: Les données du vent doivent être les statistiques d'échantillons sur 10 min, sauf indication contraire.

3.54

arrêt

état d'une éolienne immobilisée

3.55

structure de support

<éoliennes> éléments d'une éolienne comprenant le mât et les fondations

3.56**vitesse de survie**

vitesse maximale du vent qu'une construction est conçue pour supporter

Note 1 à l'article: Il s'agit d'une expression courante qui n'est pas utilisée dans le présent document. Les conditions de conception se rapportent plutôt à la vitesse de vent extrême (3.19).

3.57**surface balayée**

surface projetée perpendiculaire à la direction du vent qu'un rotor décrira pendant une rotation complète

3.58**intensité de la turbulence**

I

rapport entre l'écart type de la vitesse du vent et la vitesse moyenne du vent, déterminé à partir des mêmes ensembles d'échantillons de données mesurés de la vitesse du vent, et établi sur une durée définie

3.59**paramètre d'échelle de la turbulence**

λ_1

longueur d'onde pour laquelle la densité spectrale de puissance longitudinale sans dimension est égale à 0,05

Note 1 à l'article: La longueur d'onde est ainsi définie comme suit: $\lambda_1 = V_{\text{hub}}/f_0$, où $f_0 S_1(f_0)/\sigma_1^2 = 0,05$.

3.60**écart type de la turbulence**

σ_1

écart type de la composante longitudinale de la vitesse du vent turbulent à hauteur du moyeu

3.61**état limite ultime**

états limites qui correspondent en règle générale à une capacité maximale à supporter des charges

3.62**maintenance non programmée**

maintenance qui n'est pas effectuée conformément à un échéancier, mais par suite d'une indication relative à l'état d'une entité

3.63**au vent**

dans la direction opposée au vecteur vent principal

3.64**éolienne à axe vertical**

éolienne pourvue d'un rotor dont l'axe est vertical

3.65**loi de Weibul**

P_w

fonction de distribution de la probabilité

Note 1 à l'article: Voir 3.68.

3.66
centrale éolienne
parc éolien
groupe(s) d'éoliennes

3.67
profil du vent
loi du cisaillement du vent

expression mathématique de la variation prise pour hypothèse pour la vitesse du vent dont la hauteur est située au-dessus du sol

Note 1 à l'article: Les profils couramment utilisés sont le profil logarithmique (Équation 1) ou le profil de la loi de puissance (Équation 2).

$$V(z) = V(z_r) \cdot \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \quad (1)$$

$$V(z) = V(z_r) \cdot \left(\frac{z}{z_r} \right)^\alpha \quad (2)$$

où

- $V(z)$ est la vitesse du vent à la hauteur z ;
 z est la hauteur au-dessus du sol;
 z_r est une hauteur de référence au-dessus du sol utilisée pour adapter le profil;
 z_0 est la longueur de rugosité;
 α est l'exposant du cisaillement du vent (ou de la loi de puissance).

3.68
distribution de la vitesse du vent

fonction de la loi de probabilité, utilisée pour décrire la distribution des vitesses du vent sur une longue durée

Note 1 à l'article: Les fonctions de la distribution souvent utilisées sont les fonctions de Rayleigh, $P_R(V_0)$ et de Weibull, $P_W(V_0)$.

$$\begin{aligned} P_R(V_0) &= 1 - \exp \left[-\pi (V_0 / 2V_{ave})^2 \right] \\ P_W(V_0) &= 1 - \exp \left[-(V_0 / C)^k \right] \end{aligned} \quad (3)$$

$$\text{with } V_{ave} = \begin{cases} C \Gamma(1 + \frac{1}{k}) \\ C \sqrt{\pi} / 2, \text{ if } k = 2 \end{cases} \quad (4)$$

Anglais	Français
With $V_{ave} =$	Avec $V_{ave} =$

où

- $P(V_0)$ est la fonction de probabilité cumulée, c'est-à-dire la probabilité selon laquelle $V < V_0$;
 V_0 est la vitesse du vent (limite);
 V_{ave} est la valeur moyenne de V ;
 C est le paramètre d'échelle de la fonction de Weibull;
 k est le paramètre de forme de la fonction de Weibull;

Γ est la fonction gamma.

Aussi bien C et k peuvent être évalués à partir de données réelles. La fonction de Rayleigh est identique à la fonction de Weibull si $k = 2$ est choisi et que C et V_{ave} satisfont à la condition figurant dans l'Équation 4 pour $k = 2$.

Les fonctions de distribution expriment la probabilité cumulée selon laquelle la vitesse du vent est inférieure à V_0 . Ainsi $(P(V_1) - P(V_2))$, si son évaluation est effectuée entre les limites définies V_1 et V_2 , indique la fraction de temps durant laquelle la vitesse du vent se trouve dans ces limites. La différenciation des fonctions de distribution permet d'obtenir les fonctions de densité de probabilité correspondantes.

3.69

cisaillement du vent

variation de la vitesse du vent dans le plan perpendiculaire à la direction du vent

3.70

vitesse du vent

V

vitesse de déplacement d'une minuscule quantité d'air entourant un point spécifique de l'espace

Note 1 à l'article: Elle est aussi égale à l'amplitude de la vitesse vectorielle locale du vent (voir 3.73).

3.71

aérogénérateur

<éolienne> système destiné à convertir l'énergie cinétique présente dans le vent en énergie électrique

3.72

site de l'éolienne

emplacement d'une éolienne individuelle soit seule, soit dans un parc éolien

3.73

vitesse vectorielle du vent

vecteur pointant dans la direction de déplacement d'une minuscule quantité d'air entourant le point à l'étude, l'amplitude du vecteur étant égale à la vitesse de déplacement de cet « élément » d'air (c'est-à-dire la vitesse locale du vent)

Note 1 à l'article: Ainsi, ce vecteur, en un point donné, est la dérivée par rapport au temps du vecteur de position de l'« élément » d'air passant par ce point.

3.74

système électrique d'une éolienne

équipements électriques internes aux éoliennes, allant jusqu'aux bornes des éoliennes et les comprenant, dont les équipements destinés à la mise à la terre, aux liaisons et aux communications

Note 1 à l'article: Les conducteurs situés dans les éoliennes, qui sont destinés à fournir un réseau de raccordement à la terre spécifiquement pour les éoliennes, sont inclus.

3.75

bornes de l'éolienne

point(s) identifié(s) par le fournisseur d'éoliennes au niveau duquel (desquels) les éoliennes peuvent être raccordées au système de collecte de puissance

Note 1 à l'article: Cela inclut le raccordement permettant de transporter l'énergie et de transmettre les communications.

3.76

orientation

rotation de l'axe du rotor autour d'un axe vertical

Note 1 à l'article: Pour les éoliennes à axe horizontal uniquement.

3.77

désalignement d'orientation

écart horizontal de l'axe du rotor de l'éolienne à partir de la direction du vent

4 Symboles et abréviations

4.1 Symboles et unités

C	paramètre d'échelle de la fonction de loi de Weibull	[m/s]
C_{CT}	paramètre de correction de la structure de turbulence	
C_T	coefficient de poussée	[-]
Coh	fonction de cohérence	[-]
D	diamètre du rotor	[m]
$D_{TV,i}$	écart type de la variation du terrain Δz en i^{e} secteur de 30°	[m]
$D_{TV,360}$	écart type de la variation du terrain Δz de la surface du cercle à 360°	[m]
f	fréquence	[s ⁻¹]
f_d	valeur de conception de la résistance du matériau	[-]
f_k	valeur caractéristique de la résistance du matériau	[-]
F_d	valeur de conception des charges	[-]
F_k	valeur caractéristique des charges	[-]
I_{ref}	valeur de référence de l'intensité de la turbulence correspondant au quantile à 70 % à 15 m/s	[-]
I_{eff}	intensité effective de la turbulence	[-]
k	paramètre de forme de la fonction de loi de Weibull	[-]
k_1	facteur d'ajustement empirique pour TSI360, $k_1 = 5/3$	[-]
k_2	facteur d'ajustement empirique pour TVI360, $k_2 = 3$	[-]
K	fonction de Bessel modifiée	[-]
L	paramètre d'échelle intégrale de la turbulence isotrope	[m]
L_e	paramètre d'échelle de cohérence	[m]
L_k	paramètre d'échelle intégrale de la composante de la vitesse	[m]
m	exposant de la courbe de Wöhler	[-]
n_i	nombre de cycles de fatigue en rééchantillonnage de la charge i	[-]
$N(.)$	nombre de cycles jusqu'à la défaillance en fonction de la contrainte (ou déformation) indiquée par l'argument (c'est-à-dire la courbe caractéristique S-N)	[-]
N	période de retour lors des situations extrêmes	[years]
p	pression de l'air	[N/m ²]
$P(V_0)$	loi de probabilité, c'est-à-dire la probabilité selon laquelle $V < V_0$	[-]
$P_R(V_0)$	loi de probabilité de Rayleigh, c'est-à-dire la probabilité selon laquelle $V < V_0$	[-]
P_s	probabilité de survie	[-]
$P_W(V_0)$	loi de probabilité de Weibull	[-]
r	amplitude de la projection du vecteur de séparation	[m]
R	rayon du segment de cercle	[m]

R_0	constante des gaz	[J/(kg·K)]
S	fonction de charge	[-]
s_i	niveau de contrainte (ou de déformation) associé au nombre de cycles en bin i	[-]
$S_1(f)$	fonction de la densité spectrale de puissance pour la composante longitudinale de la vitesse du vent	[m ² /s]
$S_{F,min}$	valeur minimale du facteur de sécurité pour la rupture de dent	[-]
$S_{H,min}$	valeur minimale du facteur de sécurité pour les piqures	[-]
$S_k(f)$	fonction de la densité spectrale de puissance dans un sens donné pour la composante de la vitesse du vent k : $k = 1$ composante longitudinale $k = 2$ composante latérale $k = 3$ composante verticale	[m ² /s]
T	durée caractéristique de la rafale	[s]
t	temps	[s]
V	vitesse du vent	[m/s]
$V(z)$	vitesse du vent à la hauteur z	[m/s]
V_{ave}	vitesse moyenne annuelle du vent à hauteur du moyeu	[m/s]
V_{cg}	amplitude de la rafale extrême cohérente sur toute la surface balayée par le rotor	[m/s]
V_{eN}	vitesse du vent extrême prévue (moyennée sur trois secondes), avec un intervalle de temps de récurrence de N années. V_{e1} et V_{e50} pendant 1 an et 50 ans, respectivement	[m/s]
V_{gust}	amplitude de la rafale la plus importante avec une période de retour prévue de 50 années	[m/s]
V_{hub}	vitesse du vent à la hauteur du moyeu	[m/s]
V_{in}	vitesse de démarrage	[m/s]
V_0	vitesse du vent limite selon le modèle de distribution de la vitesse du vent	[m/s]
V_{50}	vitesse du vent extrême (moyennée sur 10 minutes) avec un intervalle de récurrence de 50 années.	[m/s]
V_{100}	vitesse du vent extrême (moyennée sur 10 minutes) avec un intervalle de récurrence de 100 années.	[m/s]
V_{out}	vitesse de coupure	[m/s]
V_r	vitesse du vent assignée	[m/s]
V_{ref}	vitesse du vent de référence	[m/s]
$V_{ref,T}$	vitesse du vent de référence pour les conditions proches des conditions tropicales	[m/s]
$V(y,z,t)$	composante de la vitesse longitudinale du vent permettant de décrire le cisaillement du vent horizontal transitoire	[m/s]
$V(z,t)$	composante de la vitesse longitudinale du vent permettant de décrire la variation transitoire des conditions de cisaillement et de rafale extrême	[m/s]
x, y, z	système de coordonnées utilisé à des fins de description du champ éolien; le long du vent (longitudinal), à travers le vent (latéral) et hauteur, respectivement	[m]

Z_{NT}	facteur de durée pour la pression d'engrènement dans les conditions d'essai de référence	[-]
z_{hub}	hauteur du moyeu de l'éolienne	[m]
z_r	hauteur de référence au-dessus du sol	[m]
z_0	longueur de rugosité du profil du vent logarithmique	[m]
α	exposant de la loi de puissance du cisaillement du vent	[-]
β	paramètre du modèle de changement de direction extrême	[-]
δ	coefficient de variation	[-]
Γ	fonction gamma	[-]
γ_f	facteur de sécurité partielle des charges	[-]
γ_M	facteur de sécurité partielle des résistances	[-]
γ_n	facteur de sécurité partielle des conséquences de défaillance	[-]
$\theta(t)$	transitoire de changement de direction du vent	[deg]
θ_{cg}	angle de l'écart maximal à partir de la direction de la vitesse moyenne du vent dans des conditions de rafale	[deg]
θ_{eN}	changement de direction extrême avec une période de retour de N années	[deg]
θ_i	pente du plan de montage pour $i^{\text{è}}$ secteur de 30°	[deg]
θ_{360}	pente du plan de montage à 360°	[deg]
$\theta_{1\text{year,min}}$	température ambiante minimale à prévoir, en moyenne horaire	[K]
$\theta_{\text{min,operation}}$	température ambiante minimale admise pour le fonctionnement de l'éolienne	[K]
Λ_1	paramètre d'échelle de la turbulence défini comme la longueur d'onde où la densité spectrale de puissance longitudinale sans dimension, $fS_1(f)/\sigma_v^2$, est égale à 0,05	[m]
ρ	masse volumique de l'air	[kg/m ³]
$\hat{\sigma}$	écart type estimé de la vitesse du vent	[m/s]
$\hat{\sigma}_c$	écart type de la turbulence ambiante représentative	[m/s]
$\hat{\sigma}_{\text{eff}}$	écart type de la vitesse du vent estimée effective	[m/s]
σ_{sillage}	écart type de la vitesse du vent dans le sillage	[m/s]
$\hat{\sigma}_T$	écart type de la vitesse du vent de sillage central maximal	[m/s]
$\hat{\sigma}_\sigma$	écart type de l'écart type estimé de la vitesse du vent $\hat{\sigma}$	[m/s]
$\hat{\sigma}_{1\text{ETM}}$	écart type de la turbulence ambiante extrême	[m/s]
σ_1	écart type de la vitesse longitudinale du vent à hauteur du moyeu	[m/s]
σ_2	écart type de la vitesse du vent latéral à hauteur du moyeu	[m/s]
σ_3	écart type de la vitesse du vent ascendant à hauteur du moyeu	[m/s]
Φ	fonction normale de probabilité normalisée	[-]
$E[]$	valeur attendue du paramètre entre crochets	[-]
$\text{Var}[]$	variance du paramètre entre crochets	[-]

4.2 Abréviations

A	anormal (pour facteurs de sécurité partielle)
AC	alternating current (courant alternatif)
DC	direct current (courant continu)
CC	cold climate (climat froid)
COV	coefficient of variation (coefficient de variation)
DLC	design load case (cas de charge pour la conception)
DWM	dynamic wake meandering (déstabilisation du sillage dynamique)
ECD	extreme coherent gust with direction change (rafale extrême cohérente avec changement de direction)
EDC	extreme wind direction change (changement de direction du vent extrême)
EOG	extreme operating gust (rafale extrême de fonctionnement)
ETM	extreme turbulence model (modèle de turbulence extrême)
EWM	extreme wind speed model (modèle de vitesse extrême du vent)
EWS	extreme wind shear (cisaillement du vent extrême)
F	fatigue
AMDE	analyse des modes de défaillance et de leurs effets
HT	haute tension
IAC	internal arc classification (classification de l'arc interne)
IC	icing climate (climat givrant)
LTC	low temperature climate (climat de température basse)
LVRT	low voltage ride through (alimentation continue basse tension)
N	normal et extrême (pour facteurs de sécurité partielle)
NWP	normal wind profile model (modèle de profil normal du vent)
NTM	normal turbulence model (modèle de turbulence normale)
S	classe d'éoliennes spécifiques à l'IEC
T	transport et levage (pour facteurs de sécurité partielle)
TSI	terrain slope index (indice de pente du terrain)
TVI	terrain variation index (indice de variation du terrain)
U	ultime
ULS	ultimate limit state (état limite ultime)

5 Éléments principaux

5.1 Généralités

Les exigences techniques et mécaniques permettant de garantir la sécurité des systèmes structurels, mécaniques, électriques et de commande des éoliennes sont précisées dans les articles suivants. Cette spécification relative aux exigences s'applique à la conception, la fabrication, l'installation et aux manuels de fonctionnement et de maintenance des éoliennes et aux processus de gestion de la qualité correspondants. En outre, les procédures de sécurité qui ont été établies pour les différentes pratiques utilisées dans l'installation, le fonctionnement et la maintenance des éoliennes sont prises en considération.

5.2 Méthodes relatives à la conception

Le présent document exige l'utilisation d'un modèle dynamique aéroélastique en vue de prévoir les charges de conception. Un tel modèle doit être utilisé afin de déterminer les

charges relatives à une plage donnée des vitesses du vent, en ayant recours, pour ce faire, aux conditions de turbulence et autres conditions de vent spécifiées à l'Article 6, et aux situations relatives à la conception définies à l'Article 7. Toutes les combinaisons pertinentes se rapportant aux conditions extérieures et situations relatives à la conception doivent faire l'objet d'une analyse. Un ensemble minimal de telles combinaisons a été défini, au sein du présent document, en tant que cas de charge.

Les données obtenues à partir des essais réalisés à l'échelle réelle d'une éolienne doivent être utilisées afin de renforcer la confiance vis-à-vis des valeurs relatives à la conception ainsi prédites et de vérifier les modèles de dynamique structurelle ainsi que les situations liées à la conception (voir 7.2).

La vérification de l'adéquation de la conception doit être réalisée par des calculs et/ou par des essais. Si les résultats d'essai sont utilisés dans le cadre de la vérification, les conditions externes présentes au cours de l'essai doivent être indiquées afin de refléter les valeurs caractéristiques et les situations relatives à la conception définies dans le présent document. Le choix des conditions d'essai, y compris les charges d'essai, doit tenir compte des facteurs de sécurité correspondants.

5.3 Classes de sécurité

Une éolienne doit être conçue conformément à l'une des deux classes de sécurité suivantes:

- une classe de sécurité standard s'appliquant lorsqu'une défaillance peut entraîner un risque de dommage corporel ou avoir d'autres conséquences sociales ou économiques;
- une classe de sécurité spécifique s'appliquant lorsque les exigences en matière de sécurité sont fixées par les réglementations locales et/ou lorsque les exigences en matière de sécurité font l'objet d'un accord entre le fabricant et le client.

Les facteurs de sécurité partielle, relatifs aux éoliennes de classe de sécurité standard, sont spécifiés en 7.6.

Les facteurs de sécurité partielle, relatifs aux éoliennes de classe de sécurité spécifique, doivent faire l'objet d'un accord entre le fabricant et le client. Une éolienne conçue conformément à une classe de sécurité spécifique doit correspondre à une éolienne de classe S, telle que définie en 6.2.

5.4 Assurance qualité

L'assurance qualité doit faire partie intégrante de la conception, de l'approvisionnement, de la fabrication, de l'installation, du fonctionnement et de la maintenance des éoliennes et de l'ensemble de leurs composants.

Il est recommandé que le système d'assurance qualité satisfasse aux exigences de l'ISO 9001.

5.5 Marquage des éoliennes

Les informations suivantes doivent, au moins, figurer de manière visible, lisible et indélébile sur la plaque signalétique de l'éolienne:

- fabricant de l'éolienne et pays;
- modèle et numéro de série;
- année de fabrication;
- puissance assignée;
- vitesse du vent de référence, V_{ref} ;
- plage de vitesses du vent en fonctionnement à hauteur du moyeu, $V_{in} - V_{out}$;

- plage de températures ambiantes de fonctionnement;
- éoliennes, classe IEC (voir le Tableau 1);
- tension assignée aux bornes de l'éolienne;
- fréquence aux bornes de l'éolienne ou plage de fréquences dans le cas où l'amplitude de variation nominale est supérieure à 2 %.

6 Conditions externes

6.1 Généralités

Les conditions externes décrites à l'Article 6 doivent être prises en considération dans la conception d'une éolienne.

Les éoliennes sont soumises à des conditions d'environnement et électriques qui peuvent affecter leur charge, leur durabilité et leur fonctionnement. Afin de garantir un niveau adéquat de sécurité et de fiabilité, les paramètres liés à l'environnement, à l'électricité et au sol doivent être pris en compte lors de la conception et doivent figurer de manière explicite dans les documents de conception.

Les conditions d'environnement se subdivisent, en outre, en conditions de vent et autres conditions d'environnement. Les conditions électriques se rapportent aux conditions du réseau d'alimentation électrique. Les propriétés du sol revêtent une importance significative dans la conception des fondations de l'éolienne.

Les conditions externes sont subdivisées en catégories normales et extrêmes. Les conditions externes normales concernent, en règle générale, les conditions de charges structurales récurrentes, tandis que les conditions externes extrêmes représentent les conditions externes de conception peu fréquentes. Les cas de charge pour la conception doivent consister en des combinaisons potentiellement critiques de ces conditions externes et des modes de fonctionnement des éoliennes et d'autres situations de conception.

Les conditions de vent constituent les conditions externes principales affectant l'intégrité structurale. D'autres conditions d'environnement affectent également les caractéristiques de conception, telles que la fonction du système de commande, la durabilité, la corrosion.

Les conditions normales et extrêmes qui doivent être prises en considération dans la conception, conformément aux classes d'éoliennes, sont spécifiées de 6.2 à 6.4.

6.2 Classes d'éoliennes

Les conditions externes à prendre en considération lors de la conception dépendent du site envisagé ou du type de site retenu pour l'installation d'une éolienne. Les classes d'éoliennes se définissent selon les paramètres de vitesses de vent, de classes d'éoliennes I, II et III, de turbulence et de catégories de turbulence A+, A, B et C. L'objectif de ces classes est de couvrir la plupart des applications. Les valeurs relatives aux paramètres de vitesses de vent et de turbulence ont pour objectif de représenter de nombreux sites différents et ne sont pas spécifiquement représentatives d'un site particulier, voir 11.3. La classification des éoliennes présente une plage de robustesse clairement définie selon les paramètres de vitesses de vent et de turbulence. Pour pouvoir utiliser les classes d'éoliennes pour certaines zones, qui peuvent être exposées à des vents extrêmement puissants dans un climat de vent par ailleurs modéré, une vitesse du vent de référence de classe T est incluse. Ce type de conditions peut être observé dans des zones soumises à ces cyclones tropicaux. Cette vitesse du vent de référence peut être utilisée avec la vitesse moyenne du vent de la classe I à la classe III et

dans les catégories de turbulence A+ à C¹. Le Tableau 1 indique les paramètres de base définissant les classes d'éoliennes.

Tableau 1 – Paramètres de base pour les classes d'éoliennes

Classe d'éoliennes		I	II	III	S
V_{ave} (m/s)		10	8,5	7,5	Valeurs spécifiées par le concepteur
V_{ref}	(m/s)	50	42,5	37,5	
	Tropical (m/s) $V_{ref,T}$	57	57	57	
A+	I_{ref} (-)	0,18			
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			
Les valeurs des paramètres s'appliquent à la hauteur du moyeu, et					
V_{ave} est la vitesse moyenne annuelle du vent;					
V_{ref} est la moyenne de la vitesse du vent de référence sur 10 min;					
$V_{ref,T}$ est la moyenne de la vitesse du vent de référence sur 10 min applicable pour les zones soumises aux cyclones tropicaux;					
A+ désigne la catégorie relative aux caractéristiques de turbulence très élevée;					
A désigne la catégorie relative aux caractéristiques de turbulence plus élevée;					
B désigne la catégorie relative aux caractéristiques de turbulence moyenne;					
C désigne la catégorie relative aux caractéristiques de turbulence plus faible; et					
I_{ref} est une valeur de référence de l'intensité de la turbulence (voir 6.3.2.3).					

La classe T prend pour hypothèse que tous les paramètres du modèle de vent sont les mêmes et permet de combiner $V_{ref,T}$ avec toutes les catégories de turbulences. Elle ne couvre pas toutes les zones sujettes aux cyclones tropicaux. Une évaluation sur site est nécessaire en s'appuyant sur l'Article 11, en déterminant au moins que V_{50} est inférieur à V_{ref} de la classe T ($V_{ref,T}$).

Une classe d'éoliennes CC facultative, qui peut être utilisée dans des zones au climat froid, est définie à l'Article 14. La classe d'éoliennes facultative spécifie des exigences et paramètres supplémentaires correspondant aux éléments de l'Article 6.

Une catégorie supplémentaire d'éoliennes, la classe S, peut être utilisée lorsque des conditions de vent spécifiques ou d'autres conditions externes ou encore une classe de sécurité spécifique (voir 5.3) sont exigées par le concepteur et/ou le client. Les valeurs de conception relatives à la classe S des éoliennes doivent être sélectionnées par le concepteur et mentionnées dans les documents de conception. Concernant des conceptions spécifiques de ce type, les valeurs sélectionnées pour les conditions de conception doivent refléter un environnement au moins aussi hostile qu'initialement prévu pour l'utilisation des éoliennes.

Les éoliennes prévues pour des conditions spécifiques au site ou des conditions extrêmes peuvent exiger une conception de classe S.

Outre les paramètres de base présentés dans le Tableau 1, plusieurs autres paramètres importants sont nécessaires afin d'indiquer de manière exhaustive les conditions externes à

¹ Une classe d'éoliennes utilisant, par exemple, la vitesse moyenne annuelle du vent de classe II et la catégorie de turbulence B avec la vitesse du vent de référence de classe T est appelée classe IIB,T.

retenir dans la conception des éoliennes. Dans le cas des classes d'éoliennes I_{A+} à III_C, ces dernières étant mentionnées en tant que classes standards d'éoliennes, les valeurs de ces paramètres supplémentaires sont spécifiées en 6.3, 6.4 et 6.5.

La durée de vie prévue à la conception pour les classes I à III d'éoliennes doit être d'au moins 20 ans.

Concernant la classe S des éoliennes, le fabricant doit décrire, dans les documents de conception, les modèles utilisés ainsi que les valeurs des paramètres de conception. Lorsque les modèles figurant à l'Article 6 sont approuvés et retenus, la déclaration des valeurs des paramètres est suffisante. Les documents de conception, relatifs à la classe S des éoliennes, doivent intégrer les informations indiquées à l'Annexe A. Des recommandations relatives aux cas de charge pour la conception des éoliennes de classe S sont données à l'Annexe B.

Les abréviations ajoutées entre parenthèses dans les intitulés de 6.3.2.2 à 6.3.3.7 sont utilisées afin de décrire les conditions de vent s'appliquant aux cas de charge pour la conception stipulés en 7.4.

6.3 Conditions de vent

6.3.1 Généralités

Une éolienne doit être conçue afin de résister en toute sécurité aux conditions de vent définies par la classe d'éoliennes ayant été retenue.

Les valeurs de conception relatives aux conditions de vent doivent être clairement spécifiées dans les documents de conception.

Le régime des vents, pour ce qui concerne les charges et la sécurité, se subdivise en conditions normales de vent, se présentant fréquemment en phase normale de fonctionnement d'une éolienne, et en conditions extrêmes de vent, lesquelles sont définies comme présentant une période de retour tous les ans ou tous les 50 ans.

Les conditions de vent comprennent un débit moyen constant combiné, dans de nombreux cas, avec un profil de rafale déterministe variable ou avec des turbulences. Dans tous les cas, l'influence d'une inclinaison du débit moyen par rapport à un plan horizontal de 8° doit être prise en considération. Cet angle d'inclinaison du débit doit par hypothèse ne pas varier avec la hauteur.

Les conditions de vent comprennent un débit moyen constant combiné, dans de nombreux cas, avec un profil de rafale déterministe variable ou avec des turbulences. Dans tous les cas, l'influence d'une inclinaison du débit moyen par rapport à un plan horizontal de 8° doit être prise en compte. Cet angle d'inclinaison du débit doit par hypothèse ne pas varier avec la hauteur.

L'expression « turbulence » indique des variations aléatoires de la vitesse du vent à partir de moyennes établies sur 10 min. Le modèle de turbulence, lorsqu'il est utilisé, doit inclure les effets de la variation de la vitesse du vent, des cisaillements et de la direction et permettre un échantillonnage rotationnel en variant les cisaillements. Les trois composantes vectorielles de la vitesse du vent turbulent sont définies comme suit:

- longitudinale – le long de la direction de la vitesse moyenne du vent,
- latérale – horizontale et perpendiculaire à la direction longitudinale, et
- ascendante – perpendiculaire aux directions longitudinale et latérale, c'est-à-dire inclinée à partir de la verticale par l'angle d'inclinaison du débit moyen.

Concernant les classes standards d'éoliennes, le champ de vitesse aléatoire du vent pour les modèles de turbulence doit satisfaire au modèle de Kaimal et au modèle de cohérence décrit à l'Annexe C. Ce modèle satisfait aux exigences ci-dessous.

- m) L'écart type de la turbulence, σ_1 , avec les valeurs données dans les paragraphes suivants, doit par hypothèse ne pas varier avec la hauteur. Les composantes perpendiculaires à la direction moyenne du vent doivent avoir les écarts types minimaux suivants²:
- composante latérale: $\sigma_2 \geq 0,7 \sigma_1$;
 - composante ascendante: $\sigma_3 \geq 0,5 \sigma_1$;
- n) Le paramètre d'échelle de la turbulence longitudinale, A_1 , à la hauteur du moyeu z doit être donné par

$$A_1 = \begin{cases} 0,7z & z \leq 60m \\ 42m & z \geq 60m \end{cases} \quad (5)$$

Les densités spectrales de puissance des trois composantes orthogonales, $S_1(f)$, $S_2(f)$ et $S_3(f)$ doivent, de manière asymptotique, s'approcher des formules suivantes à mesure que la fréquence dans le sous-domaine inertiel augmente:

$$S_1(f) = 0,05 \sigma_1^2 (A_1 / V_{\text{hub}})^{-2/3} f^{-5/3} \quad (6)$$

$$S_2(f) = S_3(f) = \frac{1}{3} S_1(f) \quad (7)$$

- o) Un modèle reconnu pour la cohérence, défini comme l'amplitude du co-spectre divisée par l'autospectre pour les composantes de la vitesse longitudinale en des points séparés dans l'espace dans un plan perpendiculaire à la direction longitudinale, doit être utilisé.

En variante, le modèle de Mann correspondant peut être appliqué (voir l'Annexe C).

D'autres modèles de turbulence peuvent être appliqués. Toutefois, pour les classes standards d'éoliennes (I à III), le modèle de turbulence doit satisfaire aux exigences a) à c) et donner lieu également à des charges dues à la fatigue supérieures ou égales à celles générées à l'aide des modèles de l'Annexe C. Pour la classe S, un modèle de turbulence validé peut être appliqué.

6.3.2 Conditions normales de vent

6.3.2.1 Distribution de la vitesse du vent

La distribution de la vitesse du vent est significative pour la conception des éoliennes puisqu'elle détermine la fréquence d'occurrence des conditions individuelles de charge pour les situations conceptuelles normales. La valeur moyenne de la vitesse du vent sur une période de moyennage de 10 min doit par hypothèse suivre une loi de Rayleigh à hauteur du moyeu donnée par:

$$P_R(V_{\text{hub}}) = 1 - \exp\left[-\pi(V_{\text{hub}} / 2V_{\text{ave}})^2\right] \quad (8)$$

où, dans les classes standards d'éoliennes, V_{ave} doit être choisie depuis le Tableau 1.

² Les valeurs réelles peuvent dépendre du choix du modèle de turbulence et des exigences de b).

6.3.2.2 Modèle de profil normal du vent (NWP)

Le profil du vent, $V(z)$, indique la vitesse moyenne du vent en fonction de la hauteur, z , au-dessus du sol. Dans le cas des classes standards d'éoliennes, le profil normal de la vitesse du vent doit être donné par la loi de puissance:

$$V(z) = V_{\text{hub}} \left(z/z_{\text{hub}} \right)^{\alpha} \quad (9)$$

L'exposant de la loi de puissance, α , doit par hypothèse être équivalent à 0,2.

Le profil de vent retenu par hypothèse est utilisé afin de définir le cisaillement vertical moyen du vent à travers la surface balayée par le rotor.

6.3.2.3 Modèle de turbulence normale (NTM)

Pour le modèle de turbulence normale, la valeur représentative de l'écart type de la turbulence, σ_1 , doit être donnée par le quantile à 90 % pour la vitesse du vent donnée à hauteur du moyeu. Cette valeur pour les classes standards d'éoliennes doit être donnée par:

$$\sigma_1 = I_{\text{ref}} (0,75V_{\text{hub}} + b); \quad b = 5,6 \text{ m/s} \quad (10)$$

Les valeurs pour l'écart type de la turbulence σ_1 et l'intensité de la turbulence σ_1/V_{hub} sont présentées à la Figure 1.

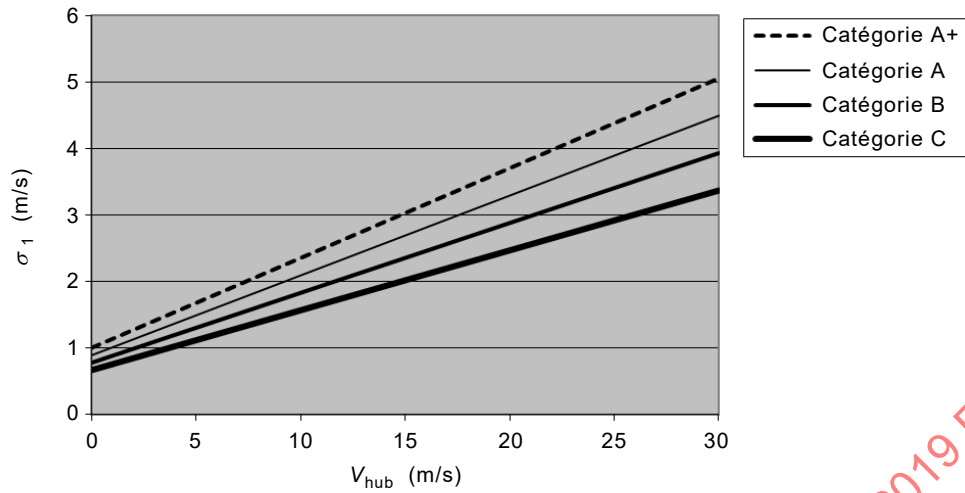


Figure 1a – Écart type de la turbulence

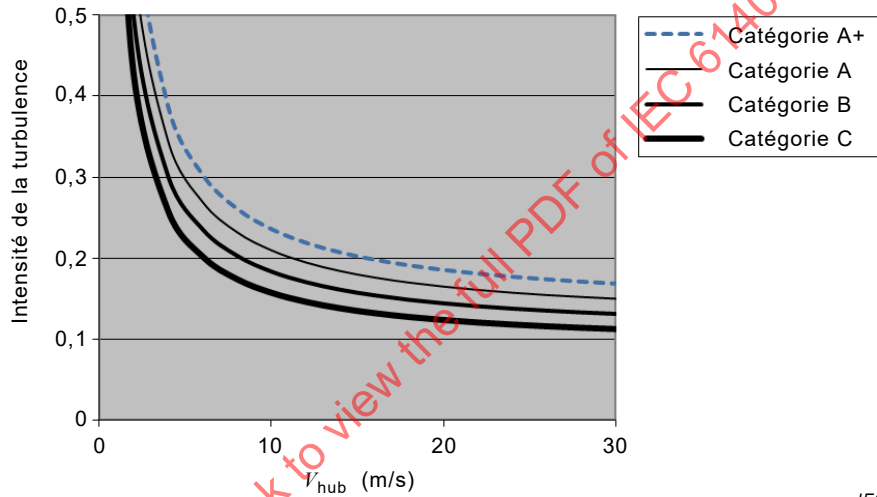


Figure 1b – Intensité de la turbulence

Figure 1 – Écart type de la turbulence et intensité de la turbulence pour le modèle de turbulence normale (NTM)

Les valeurs pour I_{ref} sont données dans le Tableau 1.

En variante à l'Équation (10), une loi de Weibull doit être prise pour hypothèse pour σ_1 avec des paramètres d'échelle et de forme de Weibull:

$$P_W(\sigma_1 < \sigma_0) = 1 - \exp \left[- \left(\frac{\sigma_0}{C} \right)^k \right] \quad (11)$$

où

$$k = 0,27 V_{\text{hub}} (\text{s/m}) + 1,4$$

$$C = I_{\text{ref}} (0,75 V_{\text{hub}} + 3,3 \text{ m/s}) \quad (12)$$

6.3.3 Conditions extrêmes de vent

6.3.3.1 Généralités

Les conditions extrêmes de vent comprennent les événements de cisaillement du vent, ainsi que les vitesses de pointe du vent dues aux tempêtes et changements brusques de la vitesse et de la direction du vent.

6.3.3.2 Modèle de vitesse extrême du vent (EWM)

Le modèle de vitesse extrême du vent doit être un modèle de vent soit constant soit turbulent. Les modèles de vents doivent être fondés sur la vitesse du vent de référence, V_{ref} , et un écart type de turbulence, σ_1 . Si le type d'éolienne est conçu pour une vitesse du vent de référence de classe T, V_{ref} doit être remplacée par $V_{\text{ref,T}}$ dans le modèle de vitesse extrême du vent en conservant d'autres paramètres.

Pour le modèle de vent extrême constant, la vitesse de vent extrême, V_{e50} , avec une période de retour de 50 ans, et la vitesse de vent extrême, V_{e1} , avec une période de retour de 1 an, doivent être calculées en fonction de la hauteur, z , à l'aide des équations suivantes:

$$V_{\text{e50}}(z) = 1,4 V_{\text{ref}} \left(\frac{z}{z_{\text{hub}}} \right)^{0,11} \quad (13)$$

et

$$V_{\text{e1}}(z) = 0,8 V_{\text{e50}}(z) \quad (14)$$

Dans le modèle de vent extrême constant, il faut tenir compte des écarts à court terme de la direction moyenne du vent en retenant par hypothèse un désalignement d'orientation constant dans la plage de $\pm 15^\circ$.

Pour le modèle de vitesse de vent turbulent extrême, les vitesses moyennes du vent établies sur 10 min en fonction de z avec des périodes de retour de 50 ans et 1 an, respectivement, doivent être fournies par:

$$V_{50}(z) = V_{\text{ref}} \left(\frac{z}{z_{\text{hub}}} \right)^{0,11} \quad (15)$$

$$V_1(z) = 0,8 V_{50}(z) \quad (16)$$

L'écart type de la turbulence longitudinale³ doit être:

$$\sigma_1 = 0,11 V_{\text{hub}} \quad (17)$$

6.3.3.3 Rafale extrême de fonctionnement (EOG)

L'amplitude de la rafale à hauteur du moyeu V_{gust}^4 doit être donnée pour les classes standards d'éoliennes par la relation suivante:

³ L'écart type de la turbulence pour le modèle de vent extrême turbulent n'est pas lié au modèle de turbulence normale (NTM) ni au modèle de turbulence extrême (ETM). Le modèle de vent extrême constant est lié au modèle de vent extrême turbulent par un facteur de crête d'environ 3,5.

$$V_{\text{gust}} = \text{Min} \left\{ 1,35(V_{\text{e1}} - V_{\text{hub}}); 3,3 \left(\frac{\sigma_1}{1 + 0,1 \left(\frac{D}{A_1} \right)} \right) \right\} \quad (18)$$

où

σ_1 est donné dans l'Équation (10);

A_1 est le paramètre d'échelle de la turbulence, conformément à l'Équation (5);

D est le diamètre du rotor.

La vitesse du vent doit être définie par l'Équation (19):

$$V(z,t) = \begin{cases} V(z) - 0,37 V_{\text{gust}} \sin(3\pi t / T) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V(z) & \text{otherwise} \end{cases} \quad (19)$$

Anglais	Français
for $0 \leq t \leq T$	pour $0 \leq t \leq T$
$V(z)$ otherwise	sinon $V(z)$

où

$V(z)$ est défini par l'Équation (9);

$T = 10,5$ s.

Un exemple de rafale extrême de fonctionnement ($V_{\text{hub}} = 25$ m/s, Classe I_A, $D = 42$ m est donné à la Figure 2.

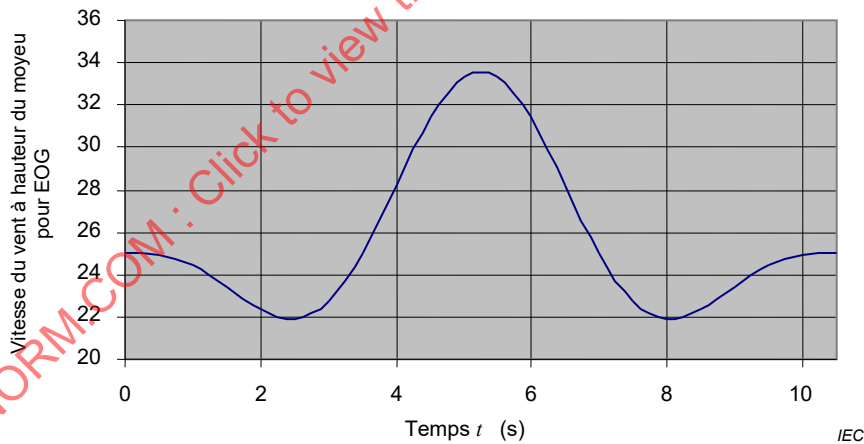


Figure 2 – Exemple de rafale extrême de fonctionnement

6.3.3.4 Modèle de turbulence extrême (ETM)

Le modèle de turbulence extrême doit utiliser le modèle de profil normal du vent de 6.3.2.2 et la turbulence avec l'écart type de la composante longitudinale donné par:

$$\sigma_1 = c I_{\text{ref}} \left(0,072 \left(\frac{V_{\text{ave}}}{c} + 3 \right) \left(\frac{V_{\text{hub}}}{c} - 4 \right) + 10 \right); \quad c = 2 \text{ m/s}. \quad (20)$$

4 L'amplitude de la rafale est étalonnée avec la probabilité de fonctionnements, par exemple des démarrages et des arrêts, pour donner une période de retour de 50 ans.

6.3.3.5 Changement de direction extrême (EDC)

L'amplitude de changement de direction extrême, θ_e , doit être calculée à l'aide de la relation suivante:

$$\theta_e = \pm 4 \arctan \left(\frac{\sigma_1}{V_{\text{hub}} \left(1 + 0,1 \left(\frac{D}{A_1} \right) \right)} \right) \quad (21)$$

où

σ_1 est donné par l'Équation (10) pour le modèle de turbulence normale;

θ_e est limitée à l'intervalle $\pm 180^\circ$;

A_1 est le paramètre d'échelle de la turbulence, conformément à l'Équation (5);

D est le diamètre du rotor.

La phase transitoire de changement de direction extrême, $\theta(t)$, doit être donnée par:

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0,5\theta_e(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ \theta_e & \text{for } t > T \end{cases} \quad (22)$$

Anglais	Français
for	pour

où $T = 6$ s est la durée du changement de direction extrême. Le signe doit être choisi de sorte que la charge transitoire la plus défavorable se produise. À la fin de la phase transitoire de changement de direction, la direction est réputée demeurer inchangée. La vitesse du vent doit suivre le modèle de profil normal du vent de 6.3.2.2.

À titre d'exemple, l'amplitude du changement de direction extrême avec la catégorie de turbulence A, $D = 42$ m, $z_{\text{hub}} = 30$ m est représentée à la Figure 3 pour faire varier V_{hub} . La transitoire correspondante pour $V_{\text{hub}} = 25$ m/s est représentée à la Figure 4.

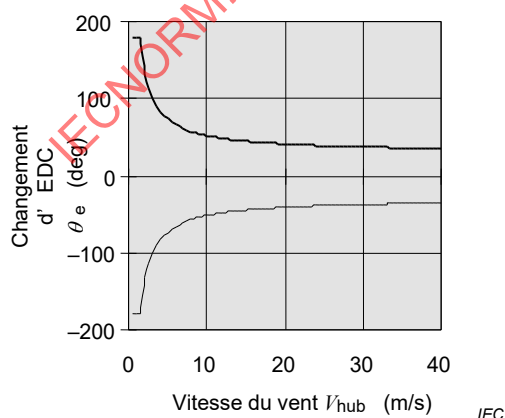


Figure 3 – Exemple d'amplitude de changement de direction extrême

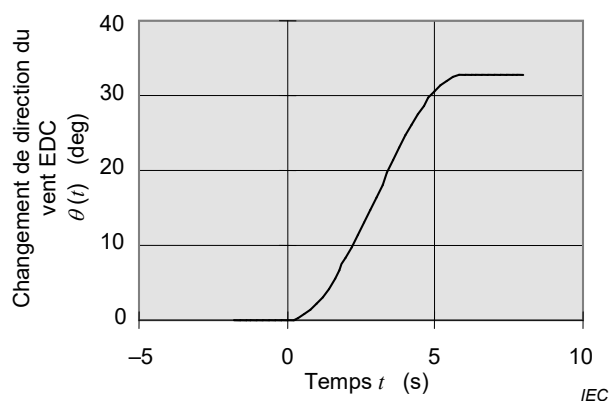


Figure 4 – Exemple de phase transitoire de changement de direction extrême

6.3.3.6 Rafale extrême cohérente avec changement de direction (ECD)

La rafale extrême cohérente avec changement de direction doit avoir une amplitude de:

$$V_{cg} = 15 \text{ m/s} \quad (23)$$

La vitesse du vent doit être définie par:

$$V(z, t) = \begin{cases} V(z) & \text{for } t \leq 0 \\ V(z) + 0,5 V_{cg} (1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ V(z) + V_{cg} & \text{for } t \geq T \end{cases} \quad (24)$$

Anglais	Français
for	pour

où $T = 10 \text{ s}$ est le temps d'accroissement et la vitesse du vent $V(z)$ est donnée par le modèle de profil normal du vent de 6.3.2.2. L'accroissement de la vitesse du vent au cours de la rafale extrême cohérente est représenté à la Figure 5 pour $V_{hub} = 25 \text{ m/s}$.

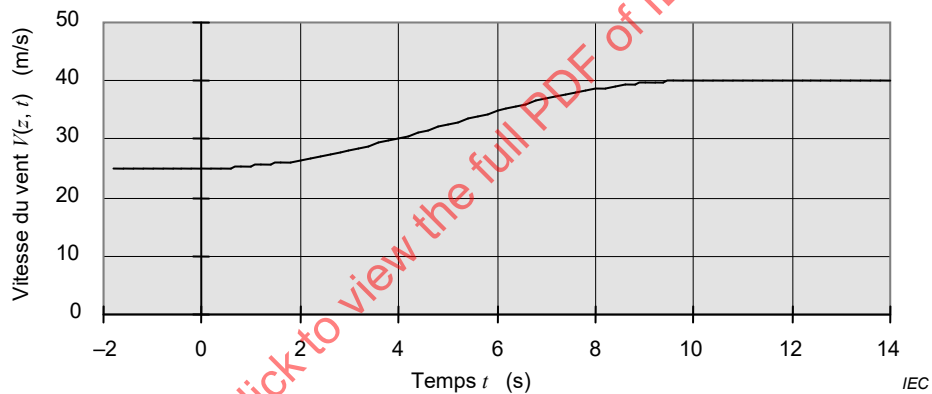


Figure 5 – Exemple d'amplitude de rafale extrême cohérente pour ECD

L'accroissement de la vitesse du vent doit par hypothèse se produire simultanément avec le changement de direction θ de 0° jusqu'à θ_{cg} inclus, où l'amplitude θ_{cg} est définie par:

$$\theta_{cg}(V_{hub}) = \begin{cases} 180^\circ & \text{for } V_{hub} < 4 \text{ m/s} \\ \frac{720^\circ (m/s)}{V_{hub}} & \text{for } 4 \text{ m/s} < V_{hub} < V_{ref} \end{cases} \quad (25)$$

Anglais	Français
for	pour

Le changement simultané de direction est alors donné par:

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0,5 \theta_{cg} (1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ \pm \theta_{cg} & \text{for } t > T \end{cases} \quad (26)$$

Anglais	Français
for	pour

où $T = 10$ s est le temps d'accroissement.

L'amplitude de changement de direction, θ_{cg} et le changement de direction $\theta(t)$ sont représentés à la Figure 6 et à la Figure 7, en fonction de V_{hub} et en fonction du temps pour $V_{hub} = 25$ m/s, respectivement.

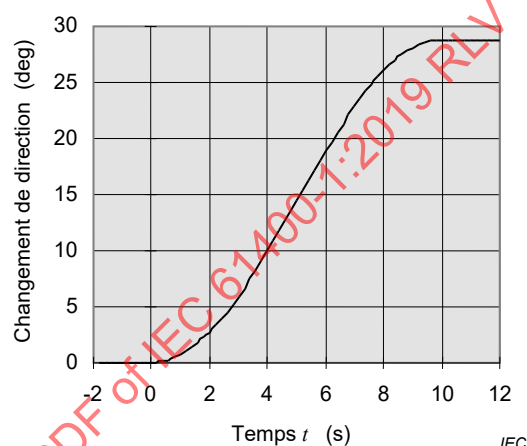
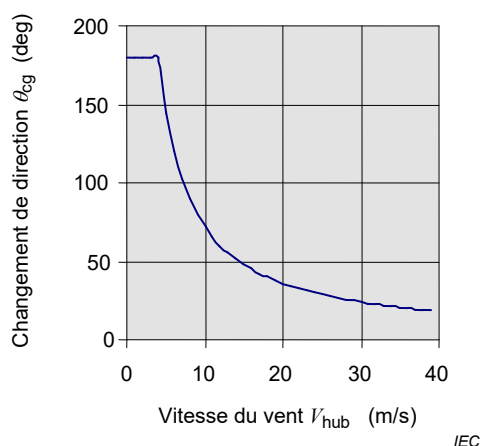


Figure 6 – Changement de direction pour ECD

Figure 7 – Exemple de phase transitoire de changement de direction

6.3.3.7 Cisaillement du vent extrême (EWS)

Le cisaillement du vent extrême doit être pris en compte en utilisant les transitoires de vitesses du vent suivantes.

Cisaillement vertical transitoire (positif et négatif):

$$V(z, t) = \begin{cases} V_{hub} \left(\frac{z}{z_{hub}} \right)^{\alpha} \pm \left(\frac{z - z_{hub}}{D} \right) \left(2,5[\text{m/s}] + 0,2\beta\sigma_1 \left(\frac{D}{A_1} \right)^{1/4} \right) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V_{hub} \left(\frac{z}{z_{hub}} \right)^{\alpha} & \text{otherwise} \end{cases} \quad (27)$$

Cisaillement horizontal transitoire:

$$V(y, z, t) = \begin{cases} V_{hub} \left(\frac{z}{z_{hub}} \right)^{\alpha} \pm \left(\frac{y}{D} \right) \left(2,5[\text{m/s}] + 0,2\beta\sigma_1 \left(\frac{D}{A_1} \right)^{1/4} \right) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V_{hub} \left(\frac{z}{z_{hub}} \right)^{\alpha} & \text{otherwise} \end{cases} \quad (28)$$

Anglais	Français
for	pour

V hub....otherwise	sinon V hub....

où, pour les cisaillements vertical et horizontal:

$$\alpha = 0,2; \beta = 6,4; T = 12 \text{ s};$$

σ_1 est donné par l'Équation (10) pour le modèle de turbulence normale;

A_1 est le paramètre d'échelle de la turbulence, conformément à l'Équation (5);

D est le diamètre du rotor.

Le signe correspondant à la transitoire de cisaillement horizontal du vent doit être choisi de sorte que la charge transitoire la plus défavorable se produise. Les deux cisaillements extrêmes du vent ne sont pas appliqués simultanément.

À titre d'exemple, le cisaillement vertical extrême du vent (catégorie de turbulence A, $z_{\text{hub}} = 30 \text{ m}$, $V_{\text{hub}} = 25 \text{ m/s}$, $D = 42 \text{ m}$) est illustré à la Figure 8, qui représente les profils du vent avant le début de l'événement extrême ($t = 0 \text{ s}$) et lors du cisaillement maximal ($t = 6 \text{ s}$). La Figure 9 représente les vitesses du vent au niveau des parties supérieure et inférieure du rotor en vue de représenter le déroulement temporel du cisaillement (hypothèses comme à la Figure 8).

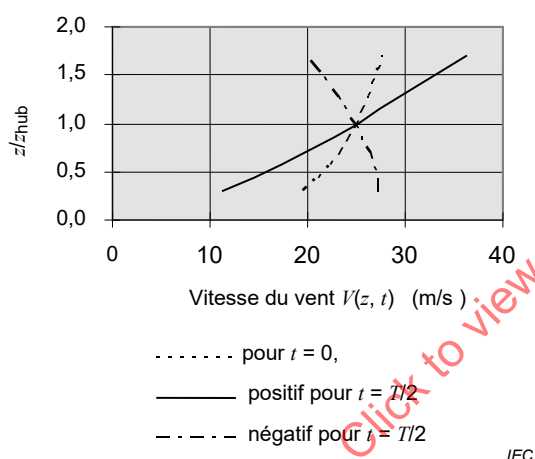


Figure 8 – Exemples de cisaillement vertical extrême du vent positif et négatif, profil du vent avant début de l'événement ($t = 0$, ligne en pointillés) et lors du cisaillement maximal ($t = 6 \text{ s}$, ligne continue)

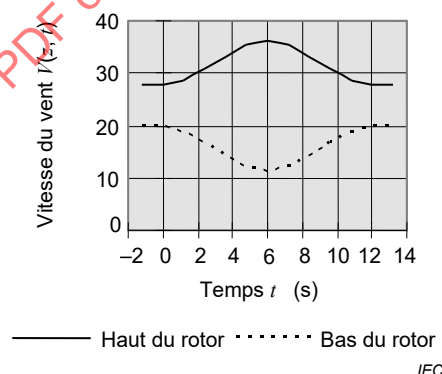


Figure 9 – Exemples de vitesses du vent au niveau des parties supérieure et inférieure du rotor, respectivement, qui illustrent le cisaillement positif transitoire du vent

6.4 Autres conditions d'environnement

6.4.1 Généralités

Des conditions d'environnement (climatiques) autres que le vent peuvent affecter l'intégrité et la sécurité des éoliennes sous l'effet d'une action thermique, photochimique, corrosive, mécanique, électrique ou physique. D'autre part, la combinaison des conditions climatiques peut accroître leurs effets.

Les autres conditions d'environnement suivantes doivent, au moins, être prises en compte et l'action résultante doit être stipulée dans les documents de conception:

- la température;
- l'humidité;

- la masse volumique de l'air;
- le rayonnement solaire;
- la pluie, la grêle, la neige et la glace;
- les substances chimiques actives;
- les particules mécaniques actives;
- la salinité;
- la foudre;
- les tremblements de terre.

Un environnement marin exige des considérations supplémentaires, conformément à l'IEC 61400-3.

Une classe de climat froid facultative est définie à l'Article 14.

Les conditions climatiques prises en compte doivent être définies selon des valeurs représentatives ou des limites des conditions variables. La probabilité d'occurrence simultanée des conditions climatiques doit être prise en compte lors du choix des valeurs inhérentes à la conception.

Les variations des conditions climatiques, dans la fourchette des limites normales correspondant à une période de retour d'un an, ne doivent pas interférer avec le fonctionnement normal pour lequel l'éolienne est conçue.

À moins qu'une corrélation n'existe, d'autres conditions d'environnement extrêmes, conformément à 6.4.3, doivent être associées aux conditions normales de vent, conformément à 6.3.2. Une description générale de la manière de combiner les situations conceptuelles aux conditions externes est donnée en 7.4.

6.4.2 Autres conditions d'environnement normales

Les valeurs relatives aux autres conditions d'environnement normales qui doivent être prises en compte sont les suivantes:

- une plage de températures ambiantes comprise entre -10 °C et $+40\text{ °C}$;
- une humidité relative jusqu'à 95 %;
- un contenu atmosphérique identique à celui d'une atmosphère intérieure au pays non polluée (voir IEC 60721-2-1);
- une intensité du rayonnement solaire de $1\,000\text{ W/m}^2$;
- une masse volumique de l'air de $1,225\text{ kg/m}^3$.

Lorsque des conditions externes complémentaires sont spécifiées par le concepteur, les paramètres et leurs valeurs doivent figurer dans les documents de conception et satisfaire aux exigences de l'IEC 60721-2-1.

6.4.3 Autres conditions d'environnement extrêmes

6.4.3.1 Généralités

Les autres conditions d'environnement extrêmes qui doivent être prises en considération dans la conception des éoliennes sont la température, la foudre, la glace et les tremblements de terre (voir 11.6 pour l'évaluation des conditions de tremblements de terre).

6.4.3.2 Température

La plage de températures extrêmes pour les classes standards d'éoliennes doit être au moins comprise entre $-20\text{ }^{\circ}\text{C}$ et $+50\text{ }^{\circ}\text{C}$.

6.4.3.3 Foudre

Les dispositions relatives à la protection nécessaire contre la foudre exigée en 10.7 peuvent être considérées comme adéquates pour les conceptions d'éoliennes associées aux classes standards d'éoliennes.

6.4.3.4 Glace

Aucune exigence minimale de protection contre la glace n'est indiquée concernant les classes standards d'éoliennes. Pour les climats froids, les exigences en matière de glace sont données à l'Article 14 et à l'Annexe L.

6.4.3.5 Tremblements de terre

Aucune exigence minimale de protection contre les tremblements de terre n'est indiquée concernant les classes standards d'éoliennes. Pour la prise en considération des conditions et des effets des tremblements de terre, voir 11.6 et l'Annexe D.

6.5 Conditions relatives au réseau d'alimentation électrique

Les conditions normales, au niveau des bornes des éoliennes, à prendre en considération, sont énumérées ci-dessous.

Les conditions normales, relatives au réseau d'alimentation électrique, s'appliquent lorsque les paramètres suivants sont compris dans les plages données ci-dessous.

- Tension – valeur nominale (conformément à l'IEC 60038) $\pm 10\%$.
- Fréquence – valeur nominale $\pm 2\%$.
- Déséquilibre de tension – le rapport de la composante inverse de tension n'est pas supérieur à 2% .
- Cycles de refermeture automatique – les cycles de refermeture automatique compris entre $0,1\text{ s}$ et 5 s pour la première fermeture et entre 10 s et 90 s pour une deuxième fermeture doivent être pris en considération.
- Défaillances électriques – les défaillances du réseau électrique doivent par hypothèse se produire 20 fois par an. Une défaillance électrique d'une durée maximale de 6 h^5 doit être considérée comme une condition normale. Une défaillance électrique d'une durée maximale d'une semaine doit être considérée comme une condition extrême.

7 Conception structurelle

7.1 Généralités

L'intégrité des composants supportant les charges de la structure de l'éolienne doit être vérifiée et un niveau de sécurité acceptable doit être déterminé. La résistance ultime et à la fatigue des parties structurelles doit être vérifiée par des calculs et/ou des essais afin de démontrer l'intégrité structurelle d'une éolienne avec le niveau de sécurité approprié.

L'analyse structurelle doit être fondée sur l'ISO 2394.

⁵ Une durée de fonctionnement de six heures correspond par hypothèse à la durée de la partie la plus critique d'une tempête.

Les calculs doivent être réalisés à l'aide des méthodes appropriées. Les descriptions des méthodes de calcul doivent être fournies dans les documents de conception. Les descriptions doivent comporter des preuves de la validité des méthodes de calcul ou des références aux études de vérification adaptées. Le niveau de charge dans tout essai de vérification de résistance doit correspondre aux facteurs de sécurité appropriés pour les charges caractéristiques conformément à 7.6.

Les résonances dans le mât, le rotor et les éléments de transmission doivent être identifiées pour la plage de fréquences jusqu'à 2 fois inclus l'excitation de fréquence de passage de la pale. Les éventuelles résonances doivent être examinées aux niveaux de turbulence de 30 % de la turbulence conceptuelle NTM de catégorie C pour DLC 1.2 (voir 7.4.2). Si des charges résonantes élevées sont détectées à faible turbulence, des moyens doivent être mis en place pour les éviter ou doivent être inclus dans les charges pour la conception.

7.2 Méthodologie conceptuelle

Il faut vérifier que les états limites ne sont pas dépassés pour la conception de l'éolienne. Les essais de modèle et de prototype peuvent également être utilisés comme une méthode de substitution au calcul afin de vérifier la conception structurelle, comme cela est spécifié dans l'ISO 2394.

Les calculs de conception doivent s'appuyer sur des méthodes validées et des codes reconnus.

La méthodologie conceptuelle part du principe que le modèle de simulation aéroélastique utilisé pour les calculs de conception spécifiques est ensuite validé par des mesurages. Ces mesurages doivent être réalisés sur une éolienne similaire d'un point de vue dynamique et structurel à l'éolienne conçue, ses caractéristiques pouvant toutefois être différentes (conceptions de mât différentes, par exemple). Les exigences relatives aux mesurages de charge peuvent être consultées dans l'IEC 61400-13.

7.3 Charges

7.3.1 Généralités

Les charges décrites de 7.3.2 à 7.3.5 doivent être prises en considération dans les calculs de conception.

7.3.2 Charges d'inertie et gravitationnelles

Les charges d'inertie et gravitationnelles sont des charges statiques et dynamiques qui résultent de la gravité, la vibration, la rotation et l'activité sismique.

Les tolérances admises en matière de verticalité des mâts doivent être indiquées dans les documents de conception et doivent inclure les effets initiaux et à long terme dus à la subsidence permanente des sols. Les effets de la verticalité du mât sur les charges gravitationnelles doivent être pris en compte séparément lors de l'analyse structurelle du mât et des fondations.

7.3.3 Charges aérodynamiques

Les charges aérodynamiques sont des charges statiques et dynamiques provoquées par l'écoulement de l'air et son interaction avec les pièces fixes et mobiles des éoliennes.

L'écoulement de l'air dépend de la vitesse moyenne du vent et de la turbulence à travers le plan du rotor, de la vitesse de rotation du rotor, de la masse volumique de l'air et des formes aérodynamiques des composants de l'éolienne et de leurs effets interactifs, y compris les effets aéroélastiques.

Dans les calculs de charges aérodynamiques, il n'est pas exigé de tenir compte des tolérances géométriques d'une verticalité de mât inférieure ou égale à 3°.

7.3.4 Charges de manœuvre

Les charges de manœuvre résultent du fonctionnement et de la commande des éoliennes. Elles se situent dans plusieurs catégories, comprenant la commande du couple provenant d'un générateur et/ou d'un onduleur, les charges de manœuvre du dispositif d'orientation et de calage et les charges de freinage mécanique. Dans chaque cas, il est important, dans le calcul de la réponse et des charges, de prendre en compte la plage des forces de manœuvre disponibles, y compris les frottements. En particulier, pour les freins mécaniques, la plage de frottement, la force ou la pression de ressort influencée par la température et le vieillissement doivent être prises en compte dans la vérification de la réponse et des charges au cours de tout événement de freinage.

7.3.5 Autres charges

Les autres charges telles que les charges de sillage, les charges d'impact, les charges de gel, les charges de mât résultant, par exemple, de vibrations induites par tourbillon, peuvent se produire et doivent être prises en considération, le cas échéant. Pour les autres charges liées aux climats froids, voir l'Article 14 et l'Annexe L.

7.4 Situations conceptuelles et cas de charge pour la conception

7.4.1 Généralités

Le paragraphe 7.4 décrit les cas de charge pour la conception pour une éolienne et spécifie un nombre minimal à prendre en considération.

Au titre de la conception, la durée de vie d'une éolienne peut être représentée par un ensemble de situations conceptuelles couvrant les conditions les plus vraisemblables que l'éolienne peut subir.

Les cas de charge doivent être déterminés à partir de la combinaison de modes de fonctionnement ou d'autres situations conceptuelles, telles que les conditions d'assemblage spécifique, de levage ou de maintenance avec les conditions externes. Tous les cas de charge pertinents avec une probabilité raisonnable de survenance doivent être pris en considération avec le comportement du système de commande. Les cas de charge pour la conception utilisés pour vérifier l'intégrité structurelle d'une éolienne doivent être calculés en combinant les éléments suivants:

- les situations conceptuelles normales et les conditions externes normales ou extrêmes appropriées;
- les situations conceptuelles défaillantes et les conditions externes appropriées;
- les situations conceptuelles inhérentes au transport, à l'installation et à la maintenance et les conditions externes appropriées.

S'il existe une corrélation entre une condition externe extrême et une situation défaillante, une combinaison réaliste des deux doit être considérée comme un cas de charge pour la conception.

Au sein de chaque situation conceptuelle, plusieurs cas de charge pour la conception doivent être pris en considération. Les cas de charge pour la conception du Tableau 2 doivent au moins être pris en considération. Dans ce tableau, les cas de charge pour la conception sont spécifiés pour chaque situation conceptuelle par la description des conditions de vent, des conditions électriques et d'autres conditions externes.

Si le régulateur de l'éolienne peut, au cours des cas de charge pour la conception, avec un modèle de vent déterministe, entraîner l'arrêt de l'éolienne avant qu'elle n'ait atteint l'angle

d'orientation maximal et/ou la vitesse du vent maximale, il doit alors être prouvé que l'éolienne peut s'arrêter de manière fiable dans des conditions de turbulence avec le même changement de condition de vent déterministe.

D'autres cas de charge pour la conception doivent être pris en considération, s'ils sont relatifs à l'intégrité structurelle de la conception d'éolienne spécifique.

Pour chaque cas de charge pour la conception, le type d'analyse approprié est indiqué par « F » et « U » dans le Tableau 2. « F » se rapporte à l'analyse des charges dues à la fatigue, à utiliser dans l'évaluation de la résistance à la fatigue. « U » se rapporte à l'analyse des charges ultimes par rapport à la résistance du matériau, à la déviation de l'extrémité de pale et à la stabilité structurelle.

Les cas de charge pour la conception indiqués par un « U » sont classés comme normaux (N) ou anormaux (A). Les cas de charge pour la conception normaux sont réputés se produire souvent. L'éolienne se trouve dans un état normal ou peut avoir subi des défaillances ou des anomalies mineures. Les situations conceptuelles anormales sont moins susceptibles de survenir. Elles correspondent habituellement à des situations conceptuelles avec des défaillances graves qui entraînent l'activation des fonctions de protection du système. Le type de situation conceptuelle, N ou A, détermine le facteur de sécurité partielle γ_f à appliquer aux charges ultimes. Ces facteurs sont donnés dans le Tableau 3.

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Tableau 2 – Cas de charge pour la conception (DLC)

Situation conceptuelle	DLC	Condition de vent	Autres conditions	Type d'analyse	Facteurs de sécurité partielle
1) Production électrique	1.1	NTM $V_{in} < V_{hub} < V_{out}$	Pour l'extrapolation des événements extrêmes	U	N
	1.2	NTM $V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD $V_{hub} = V_r - 2 \text{ m/s}$, V_r , $V_r + 2 \text{ m/s}$		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$		U	N
2) Production d'électricité plus survenance de la panne	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Panne normale du système de commande, perte du réseau électrique ou défaillance de la fonction de commande de couche principale (voir 7.4.3)	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Panne anormale du système de commande ou défaillance liée à la fonction de protection de couche secondaire (voir 7.4.3)	U	A
	2.3	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ et V_{out}	Panne électrique externe ou interne comprenant la perte du réseau électrique	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	Panne du système de commande, panne électrique ou perte du réseau électrique	F	*
	2.5	NWP $V_{in} < V_{hub} < V_{out}$	Maintien d'alimentation en cas de sous-tension	U	N
3) Démarrage	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG $V_{hub} = V_{in}$, $V_r \pm 2 \text{ m/s}$ et V_{out}		U	N
	3.3	EDC $V_{hub} = V_{in}$, $V_r \pm 2 \text{ m/s}$ et V_{out}		U	N
4) Arrêt normal	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ et V_{out}		U	N
5) Arrêt d'urgence	5.1	NTM $V_{hub} = V_r \pm 2 \text{ m/s}$ et V_{out}		U	N
6) Immobilisation (arrêt ou ralenti)	6.1	EWM Période de retour de 50 ans		U	N
	6.2	EWM Période de retour de 50 ans	Perte du raccordement au réseau électrique	U	A
	6.3	EWM Période de retour de 1 an	Désalignement d'orientation extrême	U	N
	6.4	NTM $V_{hub} < 0,7 V_{ref}$		F	*
7) Immobilisation et conditions de panne	7.1	EWM Période de retour de 1 an		U	A
8) Transport, assemblage, maintenance et réparation	8.1	NTM V_{maint} à indiquer par le fabricant		U	N
	8.2	EWM Période de retour de 1 an		U	A

Légende	
DLC	Cas de charge pour la conception
ECD	Rafale extrême cohérente avec changement de direction (voir 6.3.3.6)
EDC	Changement de direction extrême (voir 6.3.3.5)
EOG	Rafale extrême de fonctionnement (voir 6.3.3.3)
EWM	Modèle de vitesse du vent extrême (voir 6.3.3.2)
EWS	Cisaillement du vent extrême (voir 6.3.3.7)
NTM	Modèle normal de turbulence (voir 6.3.2.3)
ETM	Modèle de turbulence extrême (voir 6.3.3.4)
NWP	Modèle de profil normal du vent (voir 6.3.2.2)
$V_r \pm 2$ m/s	La sensibilité à toutes les vitesses du vent dans la plage doit être analysée
F	Fatigue (voir 7.6.3)
U	Résistance ultime (voir 7.6.2)
N	Normal
A	Anormal
*	Sécurité partielle en matière de fatigue (voir 7.6.3)

Lorsqu'une plage de vitesses de vent est indiquée dans le Tableau 2, les vitesses du vent menant à l'état le plus défavorable pour la conception de l'éolienne doivent être prises en considération. La plage de vitesses du vent peut être représentée par un ensemble de valeurs discrètes, auquel cas la résolution doit être suffisante pour assurer l'exactitude du calcul⁶. Dans la définition des cas de charge pour la conception, il est fait référence aux conditions de vent décrites à l'Article 6.

Dans les autres spécifications des cas de charge pour la conception (DLC) de 7.4.2 à 7.4.9, certains DLC admettent d'autres formulations. Si des variantes sont indiquées, la partie en charge de la conception du présent document doit choisir celle qui doit être utilisée tout au long de l'analyse du DLC.

7.4.2 Production d'électricité (DLC 1.1 à 1.5)

Dans cette situation conceptuelle, une éolienne fonctionne et est raccordée à la charge électrique. Par hypothèse, la configuration de l'éolienne doit prendre en compte le balourd du rotor. La masse maximale et les balourds aérodynamiques (par exemple calage de pale et déviations dues à la torsion) spécifiés pour la fabrication du rotor doivent être utilisés dans les calculs inhérents à la conception.

Par ailleurs, les écarts par rapport aux situations de fonctionnement de l'optimum théorique tels que le désalignement d'orientation et les erreurs de traçage du système de commande doivent être pris en compte dans les analyses des charges opérationnelles.

Les cas de charge pour la conception (DLC) 1.1 et 1.2 intègrent les exigences pour des charges résultant de la turbulence atmosphérique qui se produit au cours du fonctionnement normal d'une éolienne pendant toute sa durée de vie (NTM). DLC 1.3 intègre les exigences pour des charges ultimes résultant de conditions de turbulence extrême. DLC 1.4 et 1.5 spécifient des cas transitoires qui ont été retenus comme des événements potentiellement critiques dans la vie d'une éolienne.

L'analyse statistique des données de simulation de DLC 1.1 (voir 7.6.2.2 et l'Annexe G) doit au moins inclure le calcul des valeurs extrêmes dans le plan et hors plan du pied de pale et de la déviation de l'extrémité. Si les valeurs extrêmes relatives à la conception de ces

⁶ En général, une résolution de 2 m/s est considérée comme suffisante. Toutefois, dans la plage de vitesses du vent dans laquelle la courbe de puissance augmente rapidement, des intervalles de 2 m/s peuvent être trop importants pour assurer l'exactitude.

moments d'emplanture sont dépassées par les valeurs extrêmes relatives à la conception obtenues pour DLC 1.3, l'analyse supplémentaire de DLC 1.1 peut être omise.

Si les valeurs extrêmes relatives à la conception des moments d'emplanture obtenues pour DLC 1.1 ne sont pas dépassées par les valeurs extrêmes relatives à la conception obtenues pour DLC 1.3, le facteur c de l'Équation (20) peut être augmenté jusqu'à ce que les valeurs extrêmes relatives à la conception des moments d'emplanture calculés dans DLC 1.3 soient supérieures ou égales aux valeurs extrêmes correspondantes. Les valeurs caractéristiques des charges pertinentes pour d'autres composants de l'éolienne peuvent être déterminées dans le cadre de cette analyse en fonction de DLC 1.3 avec la valeur c augmentée. En variante à cette analyse, les valeurs caractéristiques appropriées de toutes les composantes de charge pertinentes pour chaque éolienne spécifique peuvent être directement déterminées ou extrapolées à partir de la simulation.

7.4.3 Production d'électricité et survenance de panne ou perte du raccordement au réseau électrique (DLC 2.1 à 2.5)

7.4.3.1 Généralités

Cette situation conceptuelle implique un événement transitoire déclenché par une panne ou par la perte du raccordement au réseau électrique pendant que l'éolienne produit de l'électricité. Toute panne survenant sur le système de commande ou toute défaillance interne du système électrique, importante pour la charge de l'éolienne (telle que le court-circuit du générateur), doit être prise en considération. Cette situation conceptuelle est également considérée comme étant pertinente pour l'analyse de fatigue (voir DLC 2.4).

Une analyse des modes de défaillance et de leurs effets (AMDE) ou une analyse de pannes équivalente doit être réalisée pour déterminer les événements de panne pertinents pour la charge de l'éolienne.

La position d'azimut du rotor au moment d'une panne peut avoir un impact significatif sur le niveau de charge. Il convient que la position d'azimut au moment de la survenue d'une panne soit aléatoire.

Les pannes dans le système de commande doivent être prises en considération dans DLC 2.1 et DLC 2.2 (voir 7.4.3.2). Pour les architectures dans lesquelles la sécurité de l'éolienne est assurée par deux ensembles indépendants de fonctions (par l'intermédiaire des fonctions de commande de couche principale et des fonctions de protection de couche secondaire, respectivement), la méthode décrite en 7.4.3.3 peut être utilisée. Voir l'Article 8 pour les recommandations relatives à l'identification des modes de défaillance, à l'évaluation des périodes de retour de mode de défaillance, aux exclusions de défaut et aux mesures visant à éviter les défaillances de cause commune.

7.4.3.2 Défaillance du système de commande (DLC 2.1 et DLC 2.2) – Approche quantitative

Pour DLC 2.1, les éléments suivants doivent être considérés comme des événements normaux:

- a) événements liés à la défaillance du système de commande dont la période de retour prévue du mode de défaillance est inférieure ou égale à 50 ans;
- b) événements liés à la défaillance du système de commande dont la période de retour prévue du mode de défaillance ne peut pas être obtenue;
- c) perte du raccordement au réseau électrique.

Pour les événements dont les périodes de retour prévues du mode de défaillance sont comprises entre 10 et 50 ans, le facteur de charge partielle appliqué est déterminé en fonction de la période de retour du mode de défaillance indiqué dans le Tableau 3.

Pour DLC 2.2, les événements liés à la défaillance du système de commande ou les pannes électriques internes et les pannes du système mécanique dont la période de retour prévue du mode de défaillance est supérieure à 50 ans doivent être considérés comme anormaux.

Les pannes dont la période de retour dépasse 2 000 ans et les pannes non pertinentes pour la charge de l'éolienne peuvent être ignorées. La période de retour d'événement de défaut repose sur le calcul statistique de la probabilité de survenue d'un événement par lequel une partie du système de commande ou du système électrique interne se trouve ou passe à l'état de défaut, tel qu'une défaillance structurelle puisse se produire.

7.4.3.3 Défaillance du système de commande (DLC 2.1 et DLC 2.2) – Approche à deux couches

Cette approche peut être utilisée pour les architectures de système de commande composées d'au moins deux couches indépendantes. Dans cette approche,

- a) les fonctions de commande et de protection de couche principale visent à maintenir les paramètres de fonctionnement de l'éolienne dans leurs limites normales de fonctionnement et de conception, respectivement, et
- b) les fonctions de protection de couche secondaire visent à maintenir les paramètres de fonctionnement de l'éolienne dans leurs limites de conception. Elles doivent être activées par suite d'une défaillance des fonctions de commande de couche principale ou aux effets d'une défaillance interne ou externe ou d'un événement dangereux.

Pour DLC 2.1, les défaillances de la fonction de commande de couche principale, l'activation des fonctions de protection de couche principale ou la perte du raccordement au réseau électrique doivent être considérées comme des événements normaux. Les défaillances de la fonction de commande qui se traduisent par un dépassement des limites et l'activation des fonctions de protection de couche secondaire doivent être incluses dans DLC 2.2.

Les défaillances de la fonction de commande de couche principale dans DLC 2.1 incluent en général celles relatives à la vitesse du rotor, à l'angle d'orientation et aux angles de calage de pale.

Pour DLC 2.2, les événements rares pertinents pour la charge de l'éolienne, y compris les défaillances liées à l'activation des fonctions de protection de couche secondaire, doivent être considérés comme anormaux. Ces défaillances peuvent inclure l'activation accidentelle des actionneurs, la non-activation des systèmes de freinage et le blocage du système de calage. Ce cas de charge doit au moins concerner ce qui suit: la protection indépendante contre les vitesses excessives, la protection du générateur contre les surcharges/les défaillances, la protection contre le calage non contrôlé de pale (emballement de calage de pale), la protection contre les orientations non contrôlées et la protection contre les vibrations et les chocs excessifs.

7.4.3.4 Autre production d'électricité et survenance de panne ou perte du raccordement au réseau électrique (DLC 2.3 à 2.5)

Pour DLC 2.3, l'événement de vent potentiellement significatif, la rafale extrême de fonctionnement (EOG), est combiné à la perte d'au moins une phase d'un raccordement au réseau électrique multiphase et est considéré comme un événement anormal. Dans ce cas, la chronologie de ces deux événements doit être choisie afin d'atteindre la charge la plus défavorable.

En variante à la spécification de DLC 2.3 ci-dessus et dans le Tableau 2, DLC 2.3 peut plutôt être considéré comme un événement normal (c'est-à-dire un facteur de sécurité partielle pour une charge de 1,35) à analyser à l'aide de simulations de vent stochastiques (NTM – $V_{in} < V_{hub} < V_{out}$) combinées à une panne électrique interne ou externe (y compris la perte du raccordement au réseau électrique). Dans ce cas, 12 simulations de réponse doivent être réalisées pour chaque vitesse moyenne du vent prise en considération. Pour chaque simulation de réponse, la réponse extrême est échantillonnée après survenue de la panne

électrique. La panne doit être introduite après que l'effet des conditions initiales est devenu négligeable. Pour chaque vitesse moyenne du vent, une réponse extrême nominale est évaluée comme étant la moyenne des 12 réponses extrêmes échantillonnées plus trois fois l'écart type des 12 échantillons. La valeur de réponse caractéristique pour DLC 2.3 est déterminée comme étant la valeur extrême parmi les réponses extrêmes nominales.

Si une panne ou la perte du raccordement au réseau électrique ne provoque pas d'arrêt immédiat et que la charge conséquente peut mener à des dommages importants par fatigue, la durée probable de cette situation, ainsi que les dommages par fatigue résultants dans des conditions de turbulence normale (NTM), doivent être évalués en DLC 2.4. Le fabricant doit estimer la durée/fréquence prévue des événements⁷.

Pour DLC 2.5, l'événement de maintien d'alimentation en cas de sous-tension (LVRT)⁸ est considéré comme normal. L'événement de maintien d'alimentation en cas de sous-tension de conception doit être spécifié par la chute de tension et la durée.

7.4.4 Démarrage (DLC 3.1 à 3.3)

Cette situation conceptuelle comprend tous les événements aboutissant à des charges sur une éolienne pendant les transitoires depuis une situation d'arrêt ou de ralenti à la production électrique. Le nombre de survenances doit être estimé en se fondant sur le comportement du système de commande⁹.

Pour DLC 3.2, au moins quatre événements de temporisation entre la rafale extrême de fonctionnement (EOG) et l'événement de démarrage doivent être pris en considération pour chaque vitesse du vent. La première temporisation doit être choisie de sorte que la rafale extrême de fonctionnement (EOG) commence lorsque la production d'électricité atteint 50 % de la puissance maximale. La dernière temporisation doit être choisie de sorte que la rafale extrême de fonctionnement (EOG) commence lorsque la production d'électricité atteint 95 % de la puissance maximale. Au moins deux temporisations supplémentaires doivent être choisies, réparties de manière uniforme dans l'intervalle comprise entre 50 % et 95 % de la puissance maximale.

Pour chaque vitesse du vent, la valeur caractéristique de la charge peut être calculée comme étant la valeur moyenne de la valeur transitoire calculée extrême pour les quatre points distincts dans le temps.

En variante à la rafale EOG, le DLC 3.2 peut être analysé à l'aide d'au moins 12 simulations de vent stochastiques pour chaque vitesse moyenne du vent avec le modèle de turbulence

⁷ En l'absence de données/informations pertinentes, la fréquence/durée suivante peut être appliquée pour les événements ci-dessous:

- 10 arrêts par an pour l'événement de vitesse excessive;
- 24 heures par année de fonctionnement pour les événements avec une erreur d'orientation;
- 24 heures par année de fonctionnement pour les événements avec une erreur de calage;
- 20 fois par an avec perte du raccordement au réseau électrique.

⁸ En principe, les situations de maintien d'alimentation en cas de sous-tension sont définies par les producteurs-fournisseurs d'électricité comme étant des situations de perturbations ou de défaillance du réseau auxquelles il convient que l'éolienne soit en mesure de faire face sans s'arrêter. L'arrêt des éoliennes (particulièrement dans les parcs éoliens) peut faire écrouler le réseau. C'est la raison pour laquelle un maintien d'alimentation est demandé.

⁹ En l'absence de données historiques relatives aux démarrages pour des éoliennes similaires, les fréquences annuelles suivantes pour DLC 3.1 peuvent être prises par hypothèse:

- 1 000 procédures de démarrage à V_{in} ;
- 50 procédures de démarrage à V_r ;
- 50 procédures de démarrage à la vitesse de démarrage du vent maximale.

extrême (ETM). Pour chaque vitesse moyenne du vent, une réponse extrême nominale est évaluée comme étant la moyenne des extrêmes simulés.

7.4.5 Arrêt normal (DLC 4.1 à 4.2)

Cette situation conceptuelle comprend tous les événements aboutissant à des charges sur une éolienne pendant les situations transitoires normales depuis une situation de production électrique à un état d'arrêt ou de ralenti. Le nombre de survenances doit être estimé en se fondant sur le comportement du système de commande.¹⁰

Pour DLC 4.2, la temporisation de la rafale et l'événement d'arrêt doivent être choisis de sorte que la rafale EOG commence à différents moments par rapport à l'arrêt, avec au moins six événements répartis de manière uniforme à partir de 10 s avant le début de l'arrêt jusqu'au moment auquel la puissance atteint 50 % du niveau initial de production d'électricité.

Au moins quatre positions d'azimut de rotor réparties de manière uniforme doivent être appliquées pour chaque point distinct dans le temps. Pour chaque vitesse du vent, la valeur caractéristique de la charge peut être calculée comme étant la valeur moyenne des charges calculées extrêmes parmi toutes les temporisations et positions d'azimut prises en considération.

Si, en raison du système de sécurité et de commande, un événement d'arrêt est automatiquement déclenché pendant la rafale EOG, cet événement doit également être pris en considération dans l'analyse.

En variante à la rafale EOG, le DLC 4.2 peut être analysé à l'aide d'au moins 12 simulations de vent stochastiques pour chaque vitesse moyenne du vent avec le modèle de turbulence extrême (ETM). Pour chaque vitesse moyenne du vent, une réponse extrême nominale est évaluée comme étant la moyenne des extrêmes simulés.

7.4.6 Arrêt d'urgence (DLC 5.1)

Les charges résultant de l'activation du bouton d'arrêt d'urgence doivent être prises en considération.

La position d'azimut du rotor au moment d'une panne peut avoir un impact significatif sur le niveau de charge. Il convient que la position d'azimut au moment de la survenue d'une panne soit aléatoire.

7.4.7 Immobilisation (arrêt ou ralenti) (DLC 6.1 à 6.4)

Dans cette situation conceptuelle, le rotor d'une éolienne immobilisée est soit en état d'arrêt soit au ralenti. Dans DLC 6.1, 6.2 et 6.3, cette situation doit être prise en considération avec le modèle de vitesse de vent extrême (EWM). Pour DLC 6.4, le modèle de turbulence normale (NTM) doit être pris en considération.

Pour les cas de charge pour la conception, pour lesquels les conditions de vent sont définies par l'EWM, soit le modèle de vent extrême constant, soit le modèle de vent extrême turbulent, peut être utilisé. Si le modèle de vent extrême turbulent est utilisé, la réponse doit être estimée à l'aide d'une simulation dynamique complète ou d'une analyse quasi constante avec des corrections appropriées pour les rafales et une réponse dynamique à l'aide de la

¹⁰ En l'absence de données historiques relatives aux arrêts pour des éoliennes similaires, les fréquences annuelles suivantes pour DLC 4.1 peuvent être prises par hypothèse:

- 1 000 procédures d'arrêt à V_{in} ;
- 50 procédures d'arrêt à V_r ;
- 50 procédures d'arrêt à V_{out} .

formulation de l'ISO 4354. Si le modèle de vent extrême constant est utilisé, les effets de la réponse de résonance doivent être estimés à partir de l'analyse quasi constante dont il est question ci-dessus. Si le rapport de la réponse de résonance sur la réponse en retour (R/B) est inférieur à 5 %, une analyse statique utilisant le modèle de vent extrême constant peut être utilisée. Si un glissement dans le système d'orientation de l'éolienne peut se produire à la charge caractéristique, le plus grand glissement défavorable possible doit être ajouté au désalignement d'orientation moyen. Si l'éolienne possède un système d'orientation où le mouvement d'orientation est attendu dans les situations de vent extrême (par exemple orientation libre, orientation passive ou orientation semi-libre), le modèle de vent turbulent doit être utilisé et le désalignement d'orientation dépend des changements de direction du vent turbulent et de la réponse dynamique de l'orientation de l'éolienne. De même, si l'éolienne est soumise à de grands mouvements d'orientation ou un changement d'équilibre pendant une augmentation de la vitesse du vent d'un fonctionnement normal à la situation extrême, ce comportement doit être inclus dans l'analyse.

Dans DLC 6.1, pour une éolienne avec un système d'orientation actif, un désalignement d'orientation pouvant atteindre $\pm 15^\circ$ doit être imposé en utilisant le modèle de vent extrême constant ou un désalignement d'orientation moyen de $\pm 8^\circ$ en utilisant le modèle de vent extrême turbulent, à condition qu'une limitation des glissements dans le système d'orientation puisse être assurée.

Dans DLC 6.2, une perte du réseau d'alimentation électrique doit par hypothèse se produire à un stade précoce d'une tempête présentant la situation de vent extrême. À moins que ne soit fournie une alimentation de secours pour le système de commande et d'orientation avec une capacité pour l'alignement d'orientation pendant au moins 6 h, l'effet d'un changement de direction du vent jusqu'à $\pm 180^\circ$ doit être analysé.

Les facteurs de sécurité partielle des charges pour DLC 6.1 et DLC 6.2 du Tableau 3 sont déduits en partant du principe que le coefficient de variation de la vitesse du vent maximale annuelle est inférieur à 15 %. Pour les autres coefficients de variation, voir la note de bas de page 31 de 11.3.2.

Dans DLC 6.3, le vent extrême avec une période de retour de 1 an doit être combiné avec un désalignement d'orientation extrême. Il faut prendre pour hypothèse un désalignement d'orientation extrême pouvant atteindre $\pm 30^\circ$ en utilisant le modèle de vent extrême constant ou un désalignement d'orientation moyen de $\pm 20^\circ$ en utilisant le modèle de vent turbulent.

Si, pour les cas DLC 6.1 avec le modèle de vent extrême constant, DLC 6.2 et DLC 6.3, le désalignement d'orientation est évalué à l'aide de valeurs discrètes, l'incrément de désalignement d'orientation ne doit pas être supérieur à 10° dans le secteur de la composante de portance maximale des pales.

Dans DLC 6.4, il faut tenir compte du nombre prévu d'heures de temps de production sans alimentation au niveau d'une charge variable appropriée pour chaque vitesse du vent où un dommage par fatigue significatif peut se produire sur un composant (par exemple du fait du poids des pales au ralenti).

7.4.8 Immobilisation et conditions de panne (DLC 7.1)

Les écarts par rapport au comportement normal d'une éolienne immobilisée, résultant de pannes survenant sur le réseau électrique ou au niveau de l'éolienne, doivent faire l'objet d'une analyse. Les défaillances des systèmes suivants doivent au moins être évaluées: système de freinage, système de calage et système d'orientation. L'état de panne doit être associé à l'EWM pendant une période de retour d'un an. Ces conditions doivent être soit turbulentes soit quasi constantes, avec une correction pour les rafales et une réponse dynamique.

En cas de panne dans le système d'orientation, un désalignement d'orientation de $\pm 180^\circ$ doit être pris en considération. Si, pour les cas DLC 7.1 avec une panne dans le système

d'orientation, le désalignement d'orientation est évalué à l'aide de valeurs discrètes, l'incrément de désalignement d'orientation ne doit pas être supérieur à 10° dans le secteur de la composante de portance maximale des pales. Pour toute autre panne, le désalignement d'orientation doit être cohérent avec DLC 6.1.

Si un glissement dans le système d'orientation peut se produire à la charge caractéristique observée en DLC 7.1, le plus grand glissement défavorable possible doit être pris en considération.

7.4.9 Transport, assemblage, maintenance et réparation (DLC 8.1 et 8.2)

Pour DLC 8.1, le fabricant doit mentionner toutes les conditions de vent et les situations conceptuelles prises par hypothèse pour le transport, l'assemblage sur site, la maintenance et la réparation d'une éolienne. Les conditions de vent maximales établies doivent être prises en considération dans la conception si elles peuvent exercer des charges significatives sur l'éolienne. Le fabricant doit prévoir une marge suffisante entre les conditions établies et les conditions de vent prises en considération dans la conception pour donner un niveau de sécurité acceptable. Une marge suffisante peut être obtenue en ajoutant 5 m/s à la condition de vent établie.

De plus, DLC 8.2 doit inclure tous les états de transport, d'assemblage, de maintenance et de réparation de l'éolienne qui peuvent persister pendant plus d'une semaine. Cela doit, le cas échéant, inclure un mât partiellement complété, le mât étant dressé sans nacelle et l'éolienne sans une ou plusieurs pales. Dans le cas d'un mât dressé sans nacelle, des moyens appropriés doivent être mis en œuvre afin d'éviter des vitesses de vent critiques pour des vibrations transversales générées par tourbillon ou le cas de charge pour la conception due à la fatigue approprié doit être ajouté¹¹. Le réseau électrique doit par hypothèse ne pas être connecté dans l'un de ces états. Des mesures peuvent être prises pour réduire les charges au cours de l'un de ces états, tant que ces mesures n'exigent pas le raccordement au réseau électrique.

Des dispositifs de blocage doivent pouvoir supporter les charges provenant de situations pertinentes en DLC 8.1. Des dispositifs de blocage non redondants doivent être conçus dans la classe de composants 3. En particulier, l'application de forces de manœuvre conceptuelles maximales doit être prise en compte. Le cas échéant, il est recommandé d'appliquer en outre les normes relatives aux appareils de levage, y compris les facteurs de sécurité/facteurs d'influence. À moins qu'ils ne soient installés de manière permanente, les appareils de levage eux-mêmes ne sont pas concernés par le présent document, et il convient de les concevoir et de les soumettre à l'essai selon les normes correspondantes en la matière.

7.5 Calculs de charge

Les charges telles que décrites de 7.3.2 à 7.3.5 doivent être prises en compte pour chaque cas de charge pour la conception. Si cela est approprié, les éléments suivants doivent également être pris en compte:

- les perturbations du champ éolien en raison de l'éolienne elle-même (vitesses induites par sillage, ombre portée du mât, etc.);
- l'influence du débit tridimensionnel sur les caractéristiques aérodynamiques de la pale (par exemple décrochage tridimensionnel et perte aérodynamique en extrémité de pale);
- les effets aérodynamiques instables;
- la dynamique structurelle et le couplage des modes de vibration;
- les effets aéroélastiques;

¹¹ Des recommandations relatives aux charges du mât provenant des vibrations induites par tourbillon peuvent être consultées dans l'IEC 61400-6 (en préparation, stade au moment de la publication: IEC CDV 61400-6:2017).

- le comportement du système de commande de l'éolienne.

Les simulations dynamiques utilisant un modèle de dynamique structurelle sont généralement utilisées pour calculer les charges de l'éolienne. Certains cas de charge ont une entrée de vent turbulent. La période totale des données de charge, pour ces cas, doit être suffisamment longue pour assurer une fiabilité statistique de l'estimation de la charge caractéristique. Au moins six réalisations stochastiques de 10 min (ou une période continue de 60 min) doivent être exigées pour chaque vitesse moyenne du vent à hauteur du moyeu utilisée dans les simulations. Cependant, pour DLC 2.1, 2.2 et 5.1, au moins 12 simulations doivent être effectuées pour chaque événement à la vitesse du vent donnée. Étant donné que les conditions initiales utilisées pour les simulations dynamiques ont généralement un effet sur les statistiques des charges pendant le début de la période de simulation, les 5 premières secondes de données (ou plus si nécessaire) ne doivent pas être prises en considération dans tout intervalle d'analyse impliquant une entrée de vent turbulent.

Il faut assurer que, pendant l'application d'un comptage de cycles sur la série chronologique de charges, les résidus de chaque série chronologique sont pris en considération par demi-cycles pour l'évaluation du mode de défaillance due à la fatigue. De plus, la discrétisation de la plage de charges doit assurer une résolution suffisante.

Si des vents turbulents sont utilisés pour les simulations dynamiques, il convient de veiller à la résolution du maillage eu égard à la résolution spatiale¹² et temporelle.

Dans de nombreux cas, les contraintes ou efforts locaux pour les emplacements critiques dans un composant donné d'éolienne sont fixés par des charges multiaxiales simultanées. Dans ce cas, des séries chronologiques de charges orthogonales résultant de simulations sont parfois utilisées pour spécifier des charges pour la conception. Lorsque de telles séries chronologiques de composantes orthogonales sont utilisées pour calculer les charges de fatigue et ultimes, elles doivent être combinées afin de préserver la phase et l'amplitude. Ainsi, la méthode directe repose sur la dérivée de la contrainte significative comme valeur en fonction du temps. Les méthodes de prédiction extrêmes et de fatigue peuvent alors être appliquées à ce signal unique, en évitant les problèmes de combinaison de charges.

Les composantes de charge ultime peuvent également être combinées de manière prudente en partant du principe que les valeurs des composantes extrêmes se produisent simultanément. Si cette option est adoptée, les valeurs de composantes extrêmes minimale et maximale doivent être appliquées dans toutes les combinaisons possibles pour éviter toute absence de conservatisme.

Des recommandations sur la dérivation des charges de conception extrêmes à partir de charges simultanées issues d'un certain nombre de réalisations sont données à l'Annexe I.

7.6 Analyse de l'état limite ultime

7.6.1 Méthode

7.6.1.1 Généralités

Les facteurs de sécurité partielle représentent les incertitudes et la variabilité des charges et des résistances, les incertitudes des méthodes d'analyse et l'importance des composants structurels par rapport aux conséquences de défaillance.

¹² Concernant la résolution spatiale, il convient que la distance maximale entre les points adjacents soit inférieure à 25 % de λ_1 (Équation (5)) et au maximum égale à 15 % du diamètre du rotor. La distance est en principe la distance diagonale entre les points dans chaque cellule du maillage définie par quatre points. Si le maillage n'est pas uniforme, une valeur moyenne, sur la surface du rotor, de la distance entre les points du maillage peut être considérée comme étant la résolution spatiale représentative, mais en général, cette distance diminue à mesure que l'extrémité de pale approche.

Pour l'analyse de l'état limite ultime de l'éolienne, les quatre types d'analyses suivants doivent être réalisés s'ils sont pertinents:

- l'analyse de la résistance ultime (voir 7.6.2);
- l'analyse de la défaillance due à la fatigue (voir 7.6.3);
- l'analyse de la stabilité (par exemple, flambement) (voir 7.6.4);
- l'analyse de la déviation critique (interférence mécanique entre la pale et le mât, etc.) (voir 7.6.5).

Chaque type d'analyse exige une formulation différente de la fonction de l'état limite et traite des différentes sources d'incertitudes par l'emploi de facteurs de sécurité.

7.6.1.2 Facteurs de sécurité partielle des charges et des résistances

Pour assurer des valeurs de conception sûres, les incertitudes et la variabilité des charges et des résistances (y compris la variabilité des matériaux) sont prises en compte par des facteurs de sécurité partielle tels que définis dans l'Équation (29) et l'Équation (30).

$$F_d = \gamma_f F_k \quad (29)$$

où

F_d est la valeur de conception de la charge interne agrégée ou la réponse de charge à des composantes de charges simultanées multiples provenant de différentes sources pour le cas de charge pour la conception donné;

γ_f est le facteur de sécurité partielle des charges;

F_k est la valeur caractéristique de la charge.

$$R_d = \frac{1}{\gamma_M} R_k \quad (30)$$

où

R_d sont les valeurs de conception des résistances (voir l'Annexe K);

γ_M sont les facteurs de sécurité partielle¹³ représentant les incertitudes des paramètres du matériau et des modèles de résistance (voir l'Annexe K);

R_k sont les valeurs caractéristiques des résistances, y compris les effets de la durée de charge, les effets d'échelle, etc. pris en compte par un facteur de conversion (voir l'Annexe K).

Les facteurs de sécurité partielle des charges utilisées dans le présent document prennent en compte:

- la possibilité d'écarts/incertitudes défavorables de la charge par rapport à la valeur caractéristique, et
- les incertitudes dans le modèle de charge.

Les facteurs de sécurité partielle des résistances γ_M utilisés dans le présent document, ainsi que dans l'ISO 2394, prennent en compte

- la possibilité d'écarts/incertitudes défavorables de la résistance du matériau par rapport à la valeur caractéristique,

¹³ En variante, le facteur de sécurité partielle de la résistance γ_M peut être inclus en tant que facteur de sécurité partielle lié à l'incertitude des paramètres du matériau et en tant que facteur de sécurité partielle lié à l'incertitude du modèle de résistance (voir l'Annexe K).

- la possibilité d'évaluation inexacte de la résistance des sections ou de la capacité des parties de la structure à supporter des charges,
- les incertitudes dans les paramètres géométriques,
- les incertitudes existant dans la relation entre les propriétés du matériau dans la structure et celles mesurées par des essais sur des échantillons de contrôle, et
- les incertitudes dans les facteurs de conversion.

Ces différentes incertitudes sont parfois représentées au moyen de facteurs de sécurité partielle individuels, mais, dans le présent document comme dans la plupart des autres, les facteurs associés à la charge sont combinés en un facteur γ_f et les facteurs associés au matériau et à la résistance en un facteur γ_M . Les valeurs de γ_f et de γ_M sont données de 7.6.2 à 7.6.5. Toutefois, ces valeurs peuvent être remplacées s'il peut être démontré que les hypothèses donnant lieu à ces valeurs sont conservatrices, auquel cas les facteurs de sécurité de charge et de résistance peuvent être étalonnés pour satisfaire au niveau de sécurité prévu dans le présent document¹⁴.

7.6.1.3 Facteur de sécurité partielle des conséquences de défaillance et des classes de composants

La conséquence du facteur de défaillance, γ_n , est présentée afin de faire la distinction entre:

- a) classe de composants 1: utilisée pour des composants structurels « à sécurité intégrée » dont la défaillance n'aboutit pas à la défaillance d'une partie importante d'une éolienne, par exemple roulements remplaçables avec surveillance;
- b) classe de composants 2: utilisée pour des composants structurels « à durée de vie assurée » dont la défaillance peut conduire à la défaillance d'une partie importante d'une éolienne;
- c) classe de composants 3: utilisée pour des composants mécaniques « à durée de vie assurée » qui relient des actionneurs et des freins aux composants structurels principaux afin de mettre en application des fonctions de protection uniques de l'éolienne. Concernant les dispositifs de blocage, voir 7.4.9.

Facteurs de sécurité partielle pour des conséquences de défaillance:

- classe de composants 1: $\gamma_n = 0,9$;
- classe de composants 2: $\gamma_n = 1,0$;
- classe de composants 3: $\gamma_n = 1,2$.

Les conséquences du facteur de défaillance doivent être incluses dans la charge d'essai lors de la réalisation des essais (essai de la pale réalisé à l'échelle réelle, par exemple).

D'autres valeurs de γ_n s'appliquent pour l'analyse de la déviation critique (voir 7.6.5.)

7.6.1.4 Application des codes de matériau reconnu

Lors de la détermination de l'intégrité structurelle des éléments d'une éolienne, des codes conceptuels nationaux ou internationaux pour le matériau correspondant peuvent être utilisés. Une attention particulière doit être prêtée lorsque des facteurs de sécurité partielle issus de codes conceptuels nationaux ou internationaux sont utilisés avec des facteurs de sécurité partielle provenant du présent document. Dans ce cas, le niveau de sécurité qui en résulte ne doit pas être inférieur au niveau de sécurité prévu dans le présent document.

Différents codes subdivisent les facteurs de sécurité partielle pour la résistance, γ_M , en plusieurs facteurs de matériaux représentant des types différents d'incertitudes, par exemple

¹⁴ L'Annexe K donne des lignes directrices relatives à l'étalonnage des facteurs de sécurité partielle du matériau.

la variabilité inhérente de la résistance du matériau, l'étendue du contrôle de la production ou de la méthode de production. Si le code donne des facteurs de sécurité partielle ou emploie des facteurs de réduction sur les valeurs caractéristiques pour représenter d'autres incertitudes, ces dernières doivent également être prises en compte.

Des codes individuels peuvent choisir différentes factorisations des facteurs de sécurité partielle sur la charge et les parties de matériau de la vérification conceptuelle. La répartition des facteurs souhaitée ici est celle définie dans l'ISO 2394. Si la répartition des facteurs dans le code retenu est différente de celle de l'ISO 2394, les réglages nécessaires dans le code retenu doivent être pris en compte dans la vérification conformément au présent document.

7.6.2 Analyse de la résistance ultime

7.6.2.1 Généralités

La fonction de l'état limite peut être séparée en fonctions de charge et de résistance S et R de telle sorte que la condition devienne

$$\gamma_n \cdot S(F_d) \leq R_d \quad (31)$$

La fonction S relative à l'analyse de la résistance ultime est habituellement définie comme étant la valeur la plus élevée de la réponse structurelle, d'où $S(F_d) = F_d$. L'équation devient alors:

$$\gamma_n \gamma_f F_k \leq \frac{1}{\gamma_M} R_k \quad (32)$$

Noter que γ_n est une conséquence du facteur de défaillance et ne doit pas être traitée comme un facteur de sécurité sur les matériaux.

Pour chaque composant d'éolienne évalué et pour chaque cas de charge du Tableau 2 dans lequel l'analyse de la résistance ultime est appropriée, la condition de l'état limite dans l'Équation (32) doit être vérifiée pour l'état limite le plus critique, identifié sur la base de la marge la plus faible.

7.6.2.2 Facteurs de sécurité partielle des charges

Pour DLC 1.1, une valeur caractéristique de la charge doit être déterminée par une analyse statistique de la charge extrême qui se produit pour les situations conceptuelles normales et doit correspondre à l'une des variantes ci-dessous.

- La valeur caractéristique est obtenue comme étant la plus grande (ou la plus petite) des valeurs moyennes des extrêmes sur 10 min déterminées pour chaque vitesse du vent dans la plage donnée, multipliée par 1,35. Cette méthode peut uniquement être appliquée pour calculer les valeurs extrêmes dans le plan du pied de pale et la déviation de l'extrémité.
- La valeur caractéristique est obtenue comme étant la plus grande (ou la plus petite) des valeurs du 99^e centile (ou du 1^{er} centile dans le cas de la valeur minimale) des extrêmes sur 10 min déterminées pour chaque vitesse du vent dans la plage donnée, multipliée par 1,2.
- La valeur caractéristique est obtenue comme étant la valeur correspondant à une période de retour de 50 ans, fondée sur des méthodes d'extrapolation de charge, en tenant compte de la distribution de vitesse du vent indiquée en 6.3.2.1 et du modèle de turbulence normale de 6.3.2.3. Des recommandations relatives à l'extrapolation de charge sont données à l'Annexe G.

La charge pour la conception est alors obtenue en multipliant les charges caractéristiques selon l'une de ces variantes par le facteur de sécurité partielle pour DLC 1.1 défini dans le Tableau 3.

Pour les trois variantes ci-dessus, les données utilisées dans l'analyse statistique doivent être extraites des séries chronologiques des simulations d'éolienne d'au moins 10 min sur la plage de fonctionnement de l'éolienne pour DLC 1.1. Au moins 15 simulations sont exigées pour chaque vitesse du vent entre $(V_r - 2 \text{ m/s})$ et la coupure, et six simulations sont exigées pour chaque vitesse du vent inférieure à $(V_r - 2 \text{ m/s})$. Lors de l'extraction des données, le concepteur doit tenir compte de l'effet de l'indépendance entre les crêtes sur l'analyse statistique et, dans la mesure du possible, réduire le plus possible la dépendance. Pour des recommandations relatives aux contrôles de dépendance, voir l'Annexe G.

Pour les cas de charge avec des événements de champ éolien déterministes spécifiés, la valeur caractéristique de la charge doit être la valeur transitoire calculée du cas le plus défavorable. Si d'autres simulations sont réalisées à une vitesse de vent donnée, représentant l'azimut du rotor, la valeur caractéristique pour le cas de charge est la valeur moyenne des valeurs transitoires calculées du cas le plus défavorable pour chaque azimut. Des recommandations relatives à la dérivée de la charge simultanée peuvent être consultées à l'Annexe I. Lorsqu'un débit turbulent est utilisé, la valeur moyenne parmi les charges calculées du cas le plus défavorable pour différentes réalisations stochastiques sur 10 min doit être prise, sauf pour DLC 2.1, DLC 2.2 et DLC 5.1, où la valeur caractéristique de la charge doit être la valeur moyenne de la moitié la plus grande des charges maximales.

Les facteurs de sécurité partielle des charges doivent être au moins les valeurs spécifiées dans le Tableau 3.

L'approche de 7.6.1.2, pour laquelle le facteur de sécurité partielle des charges est appliqué à la réponse de charge, part du principe qu'une représentation correcte de la réponse dynamique est primordiale. Si une représentation correcte du comportement non linéaire du matériau et/ou des non-linéarités géométriques (comme, par exemple, pour les fondations) est primordiale, la réponse de charge de conception S_d doit être obtenue dans le cadre d'une analyse structurelle de la combinaison des charges de conception F_d , où la charge de conception est obtenue en multipliant les charges caractéristiques F_k par le facteur de charge partielle γ_f pour les charges favorables et défavorables:

$$F_d = \gamma_f F_k \quad (33)$$

Les réponses de charge dans le mât au niveau de l'interface (efforts de cisaillement et moments de flexion) factorisées par γ_f (Tableau 3) doivent être appliquées comme étant les conditions aux limites.

Tableau 3 – Facteurs de sécurité partielle des charges γ_f

Charges défavorables		Charges favorables ¹⁵
Type de situation conceptuelle (voir le Tableau 2)		Toutes les situations conceptuelles
Normale (N)	Anormale (A)	
1,35 ^a	1,1	0,9

^a Pour le cas de charge pour la conception DLC 1.1, le facteur de sécurité partielle doit être $\gamma_f = 1,25$.

Si, pour les situations conceptuelles normales, la valeur caractéristique de la réponse de charge $F_{gravity}$ due à la gravité peut être calculée pour la situation conceptuelle en question, et si la gravité est une charge défavorable, le facteur de charge partielle pour la charge combinée provenant de la gravité et d'autres sources peut avoir la valeur:

$$\gamma_f = 1,1 + \varphi \zeta^2 \text{ and } \varphi = \begin{cases} 0,15 \text{ for DLC 1.1} \\ 0,25 \text{ otherwise} \end{cases}$$

$$\zeta = \begin{cases} 1 - \left| \frac{F_{gravity}}{F_k} \right|; & |F_{gravity}| \leq |F_k| \\ 0; & |F_{gravity}| > |F_k| \end{cases}$$

Anglais	Français
and $\varphi =$	et $\varphi =$
0,15 for DLC 1.1	0,15 pour DLC 1.1
0,25 otherwise	sinon 0,25

Pour le cas de charge pour la conception DLC 2.1, le facteur de sécurité partielle peut être calculé à partir de l'expression suivante si la durée moyenne entre les défaillances (MTBF), en années, pour le mode de défaillance pris en considération a été évaluée (voir 7.4.3.2):

$$\gamma_f = \begin{cases} 1,35 & \text{MTBF} \leq 10 \\ 1,71 - 0,155 \ln(\text{MTBF}) & 10 < \text{MTBF} \leq 50 \\ 1,10 & \text{MTBF} > 50 \end{cases}$$

Pour le cas de charge pour la conception DLC 2.5, le facteur de sécurité partielle doit être 1,2.

L'utilisation de facteurs de sécurité partielle des charges pour les situations conceptuelles normales et anormales spécifiées dans le Tableau 3 exige que le modèle de calcul de charge soit validé par les mesurages de charge. Ces mesurages doivent être réalisés sur une éolienne similaire à la conception d'éolienne à l'étude en ce qui concerne l'aérodynamique, le contrôle et la réponse dynamique.

7.6.2.3 Facteurs de sécurité partielle des fondations en dalle

Pour les fondations en dalle, les états limites tenant compte de la stabilité générale (mouvement de corps rigide sans défaillance du sol) et la capacité de charge du sol et des fondations doivent être analysés et calculés selon une norme reconnue. En règle générale, un facteur de sécurité partielle de $\gamma_f = 1,1$ pour les charges de gravité défavorables et de $\gamma_f = 0,9$ pour les charges de gravité favorables doit être appliqué pour la charge sur les fondations, le remblaiement et la flottabilité. S'il peut être démontré par une gestion et une surveillance respectives de la qualité que les densités du matériau des fondations spécifiées dans les documents de conception sont respectées sur le site, un facteur de sécurité partielle pour la charge des fondations en dalle $\gamma_f = 1,0$ peut être utilisé pour les états limites en ce qui concerne la capacité de charge du sol et des fondations. Si la flottabilité est calculée comme étant égale à un niveau d'eau du terrain, un facteur de sécurité partielle pour la flottabilité $\gamma_f = 1,0$ peut être appliqué.

¹⁵ Les charges de prétension et de gravité, qui diminuent de façon significative la réponse de charge totale, sont considérées comme des charges favorables. Dans le cas de charges à la fois favorables et défavorables, l'Équation (32) devient:

$$\gamma_n S(\gamma_{f,unfav} F_{k,unfav}, \gamma_{f,fav} F_{k,fav}) \leq R(f_d)$$

En variante, la vérification de la capacité du sol et des fondations peut reposer sur un facteur de sécurité partielle $\gamma_f = 1,0$ pour les charges de gravité tant favorables que défavorables, et la vérification de la stabilité générale peut reposer sur un facteur de sécurité partielle de $\gamma_f = 1,1$ pour les charges de gravité défavorables et de $\gamma_f = 0,9$ pour les charges de gravité favorables, en utilisant toutes les estimations prudentes de masses ou de densités des différents cas définis en fractiles à 5 %/95 %. Le fractile inférieur doit être utilisé lorsque la charge est favorable. Sinon, le fractile supérieur doit être utilisé.

7.6.2.4 Facteurs de sécurité partielle pour des résistances dont les codes de conception reconnus ne sont pas disponibles

Les facteurs de sécurité partielle des résistances doivent être sélectionnés en fonction de l'adéquation des données d'essai de propriétés du matériau disponibles. Dans le présent document, le niveau de sécurité correspond à un facteur de sécurité partielle pour les résistances, $\gamma_M = 1,2$ lorsqu'il est appliqué à des propriétés de matériau caractéristiques présentant une probabilité de survie de 95 %¹⁶. Cette valeur ne prend pour hypothèse aucun biais (en général un conservatisme systématique dans le modèle de résistance) et une petite incertitude liée au modèle de résistance (coefficient de variation inférieur à 5%) (voir l'Annexe K) et s'applique aux composants présentant un comportement ductile, dont la défaillance peut conduire à la défaillance d'une partie importante d'une éolienne.

Pour déduire les valeurs de conception pour les résistances, il est nécessaire de tenir compte des effets d'échelle, des tolérances et de la dégradation due à des actions externes (le rayonnement ultraviolet ou l'humidité, par exemple). Ces effets peuvent être pris en compte par des facteurs supplémentaires au facteur de sécurité partielle pour la résistance ou par un facteur de conversion utilisé pour obtenir la valeur caractéristique de la résistance (voir l'Annexe K).

Dans les cas suivants avec les modes de défaillance ductile, le facteur de sécurité partielle pour la résistance, γ_M , ne doit pas être inférieur à

- 1,1 pour les matériaux présentant une limite d'élasticité bien définie (la limite d'élasticité maximale est égale à 90 % de la résistance ultime), et
- 1,1 pour la rupture des boulons dans un raccordement avec un nombre suffisant de boulons pour assurer un mode de défaillance ductile.

Pour les composants mécaniques/structurels « à durée de vie assurée » avec un comportement non ductile, dont la défaillance conduit rapidement à la défaillance d'une partie importante d'une éolienne, le facteur de sécurité partielle pour la résistance, γ_M , ne doit pas être inférieur à:

- 1,3 si les matériaux ne présentant pas de limite d'élasticité bien définie (la limite d'élasticité est supérieure à 90 % de la résistance à la traction ou la compression) sont utilisés, et
- 1,2 pour le flambement global des boîtiers courbés tels que les mâts tubulaires et les pales.¹⁷

¹⁶ En variante, les paramètres de résistance caractéristique peuvent être sélectionnés comme le fractile à 95% à l'aide de l'approche de Bayesian (voir l'Annexe K et l'ISO 2394). Il convient que les paramètres de résistance caractéristique soient sélectionnés comme le fractile à 95 % (déterminé avec une confiance de 75 %) ou selon les valeurs du certificat pour les matériaux avec des procédures établies pour les essais d'échantillons représentatifs.

¹⁷ Les formules paramétriques fondées sur la théorie M de l'Eurocode 3 Partie 6 (EN 1993-1-6) pour le flambement des boîtiers applicable aux mâts en acier tubulaires avec $D/t < 300$ incluent un biais qui peut être pris en compte en réduisant γ_M pour le flambement à 1,1.

7.6.2.5 Facteurs de sécurité partielle des matériaux dont les codes de conception reconnus sont disponibles

Les facteurs combinés de sécurité partielle des charges, de la résistance et des conséquences de défaillance, γ_f , γ_M et γ_n , ne doivent pas être inférieurs à ceux spécifiés en 7.6.1.3, 7.6.2.2 et 7.6.2.4.

7.6.3 Défaillance due la fatigue

7.6.3.1 Généralités

Les dommages causés par fatigue doivent être estimés à l'aide d'un calcul approprié de dommages dus à la fatigue. Par exemple, dans le cas de la règle de Miner, l'état limite est atteint lorsque les dommages cumulés dépassent 1. Ainsi, dans ce cas, les dommages cumulés au cours de la durée de vie prévue à la conception d'une éolienne doivent être inférieurs ou égaux à 1. Les calculs des dommages dus à fatigue doivent prendre en considération la formulation, y compris les effets des niveaux de la plage cyclique et des niveaux moyens de déformation (ou de contrainte). Tous les facteurs de sécurité partielle (charge, matériau et conséquences de défaillance) doivent être appliqués à la plage cyclique de déformation (ou de contrainte) pour évaluer l'incrément de dommages associés à chaque cycle de fatigue. Un exemple de formulation est donné pour la règle de Miner à l'Annexe H.

7.6.3.2 Facteur de sécurité partielle des charges

Le facteur de sécurité partielle des charges, γ_f , doit être de 1,0.

7.6.3.3 Facteurs de sécurité partielle pour des résistances dont les codes reconnus ne sont pas disponibles

Le facteur de sécurité partielle pour les résistances γ_M doit être d'au moins 1,7, à condition que la courbe SN repose sur des probabilités de survie de 50 % et un coefficient de variation < 15 %. Pour les composants avec un coefficient élevé de variation pour la résistance à la fatigue¹⁸, c'est-à-dire 15 % à 20 % (comme pour de nombreux composants constitués de matériaux composites, par exemple béton armé ou matériaux composites renforcés par des fibres), γ_M doit être augmenté en conséquence et au moins jusqu'à 2,0.

Les résistances à la fatigue doivent être dérivées à partir d'un nombre d'essais significatif sur le plan statistique et la dérivation des valeurs caractéristiques doit représenter des effets d'échelle, des tolérances, la dégradation en raison d'actions externes, par exemple le rayonnement ultraviolet et les défauts qui ne seraient pas détectés normalement.

Pour l'acier soudé et de construction, la probabilité de survie de 97,7 % est généralement utilisée comme base pour les courbes SN. Dans ce cas, γ_M peut être égal à 1,25, ce qui correspond à une approche d'évaluation de durée de vie assurée (voir l'Annexe K). S'il s'avère possible de détecter le développement de fissures critiques par l'introduction d'un programme d'examen périodique, une plus faible valeur de γ_M peut être utilisée, ce qui correspond à une approche d'évaluation de tolérance aux dommages (voir l'Annexe K). Dans tous les cas, γ_M doit être supérieur à 1,0.

Pour les matériaux composites renforcés par des fibres, la distribution de résistance doit être établie à partir de données d'essai pour le matériau réel. La probabilité de survie de 95 % doit être utilisée comme une base pour la courbe SN. Dans ce cas, γ_M peut être égal à 1,35. La même approche peut être utilisée pour d'autres matériaux.

¹⁸ La résistance à la fatigue est définie ici comme des plages de contraintes associées à des nombres donnés de cycles.

7.6.3.4 Facteurs de matériaux partiels dont les codes de conception reconnus sont disponibles

Les facteurs combinés de sécurité partielle des charges, des matériaux et des conséquences de défaillance ne doivent pas être inférieurs à ceux spécifiés en 7.6.3.2 et 7.6.3.3, en veillant à prendre en considération les quantiles spécifiés dans le code.

7.6.4 Stabilité

Les parties porteuses de charge des composants « sans sécurité intégrée » ne doivent pas flamber en charge pour la conception. Pour tous les autres composants, un flambement élastique en charge pour la conception est acceptable. Le flambement ne doit pas se produire dans tout composant soumis à une charge caractéristique.

Une valeur minimale du facteur de sécurité partielle des charges, γ_f , doit être retenue conformément à 7.6.2.2, afin d'obtenir la valeur de conception. Les facteurs de sécurité partielle des matériaux ne doivent pas être inférieurs à ceux spécifiés en 7.6.2.4.

7.6.5 Analyse de la déviation critique

7.6.5.1 Généralités

Il faut vérifier qu'aucune déviation affectant l'intégrité structurelle ne survient dans les conditions de conception détaillées dans le Tableau 2. La déviation élastique maximale dans le sens défavorable doit être déterminée pour les cas de charge détaillés dans le Tableau 2. Une valeur caractéristique des déviations résultantes est déterminée de manière cohérente avec les autres composants de charge. La déviation caractéristique qui en résulte est alors multipliée par le facteur combiné de sécurité partielle des charges, des matériaux et des conséquences de défaillance.

7.6.5.2 Facteur de sécurité partielle des charges

Les valeurs de γ_f doivent être choisies depuis le Tableau 3.

7.6.5.3 Facteur de sécurité partielle des propriétés élastiques des matériaux

La valeur de γ_M doit être de 1,1 sauf lorsque les propriétés élastiques du composant en question ont été déterminées par des essais et des surveillances, auquel cas elle peut être réduite à 1,0. Une attention particulière doit être prêtée aux incertitudes géométriques et à l'exactitude de la méthode de calcul de la déviation.

7.6.5.4 Facteur de sécurité partielle pour les conséquences de défaillance

Le facteur de sécurité partielle pour les conséquences de défaillance, γ_n , doit être de 1,0.

La déviation élastique doit ensuite être ajoutée à la position non déviée dans le sens le plus défavorable et la position résultante comparée à l'exigence de non-interférence.

7.6.5.5 Déviation de l'extrémité de pale

L'un des aspects les plus importants est de vérifier qu'aucune interférence mécanique ne survient entre la pale et le mât. Le facteur de sécurité combiné $\gamma_f \gamma_n \gamma_m$ pour la distance d'isolement pale-mât ne doit pas être inférieur à 1,15.

En règle générale, les déviations de pale doivent être calculées pour les cas de charge ultime. Les déviations provoquées par les cas de charge ultime peuvent être calculées selon des modèles à poutre, des modèles à éléments finis ou des modèles équivalents. Tous les cas de charge pertinents du Tableau 2 doivent être pris en compte avec les facteurs de sécurité de charge partielle correspondants.

De plus, pour DLC 1.1, une analyse statistique de la déviation de pale maximale ou de la distance d'isolement minimale de mât est obligatoire conformément à 7.4.2. Ici, l'analyse de la déviation dynamique directe ou de la distance d'isolement de mât peut être utilisée. La probabilité dans le sens le plus défavorable doit être la même pour cette valeur caractéristique que pour la charge caractéristique sur les pales. Pour une analyse de déviation, la déviation caractéristique doit alors être multipliée par les facteurs partiels combinés des charges, des matériaux et des conséquences de défaillance, et être ajoutée à la position non déviée dans le sens le plus défavorable et la position résultante comparée à l'exigence de non-interférence. Dans le cas d'une analyse de la distance d'isolement de mât dynamique directe, le dégagement minimal admis est déterminé en multipliant le dégagement de mât nominal non dévié par le rapport des facteurs partiels combinés des charges, des matériaux et des conséquences de défaillance moins un au facteur partiel combiné (c'est-à-dire $\frac{\gamma_f \gamma_n \gamma_m - 1}{\gamma_f \gamma_n \gamma_m}$).

7.6.6 Facteurs spéciaux de sécurité partielle

Les facteurs inférieurs de sécurité partielle des charges peuvent être utilisés lorsque l'amplitude des charges a été établie par mesurage ou par analyse confirmée par mesurage à un degré de confiance supérieur à la normale. Les valeurs de tous les facteurs de sécurité partielle utilisés doivent être mentionnées dans les documents de conception.

8 Système de commande

8.1 Généralités

Le fonctionnement d'une éolienne doit être régi par un système de commande qui satisfait aux exigences de l'Article 8.

Le domaine d'application de l'Article 8 se limite à assurer que le système de commande offre un niveau approprié de protection contre les défaillances structurelles des composants principaux de l'éolienne.¹⁹

Pour les exigences particulières relatives aux climats froids, voir 14.6.

8.2 Fonctions de commande

Les fonctions de commande d'une éolienne doivent commander le fonctionnement par des moyens actifs ou passifs et conserver les paramètres de fonctionnement dans l'enveloppe prise par hypothèse dans la conception structurelle.

Les fonctions de commande peuvent régir ou autrement limiter les fonctions ou les paramètres tels que:

- la puissance,
- la vitesse du rotor,
- le raccordement de la charge électrique,
- les procédures de démarrage et d'arrêt,
- la torsion des câbles,

¹⁹ Les appréciations du risque peuvent donner lieu à des exigences de fonctionnalité supplémentaire du système de commande nécessaires à la sécurité des personnes. Il convient que ces fonctions soient conçues et évaluées selon les méthodes et principes de conception reconnus, comme ceux spécifiés dans l'ISO 13849 ou l'IEC 62061.

- les vibrations excessives,
- l'alignement dans le sens du vent, et
- l'angle de calage de pale.

L'aptitude des fonctions de commande à contrôler l'éolienne pendant un fonctionnement sans défaillance des fonctions de commande doit être démontrée dans les cas de charge pour la conception (mais à l'exclusion des cas de charge DLC 2.1 et DLC 2.2).

En cas de défaillance de la fonction de commande, l'éolienne doit rester en mode de fonctionnement sûr, qui peut inclure le maintien du fonctionnement ou l'arrêt de l'éolienne.

Le comportement de l'éolienne après une panne des fonctions de commande doit être clairement défini, y compris les procédures de redémarrage automatique ou manuel (voir 8.7).

8.3 Fonctions de protection

Le système de commande doit utiliser les fonctions de protection afin d'éviter la surcharge structurelle de l'éolienne en raison des modes de défaillance. Ces fonctions de protection peuvent être mises en œuvre soit en tant que fonctions de commande qui appliquent des mesures de prévention intrinsèque²⁰, soit en tant que fonctions de protection de couche secondaire séparée.

Si une fonction de protection de couche secondaire est utilisée pour amener l'éolienne dans un mode de fonctionnement sûr, elle doit l'emporter sur la fonction de commande de couche principale.

Les fonctions de protection contre la surcharge structurelle doivent être mises en œuvre au moyen d'architectures multicanaux²¹ dont la couverture du diagnostic permet d'obtenir une durée moyenne entre les défaillances suffisamment élevée.

L'aptitude des fonctions de protection à protéger contre la surcharge structurelle doit être démontrée dans les cas de charge pour la conception DLC 2.1 et DLC 2.2 (voir 7.4.3).

8.4 Analyse des défaillances du système de commande

8.4.1 Généralités

Les pannes ou erreurs dans les systèmes qui mettent en œuvre les fonctions de commande et de protection peuvent entraîner un certain nombre de modes de défaillance, un mode de défaillance étant défini comme le comportement du système de commande en cas de panne ou d'erreur. Ce type de modes de défaillance peut entraîner des événements ayant un impact sur la structure de l'éolienne.

EXEMPLE Un capteur peut déclencher une action de calage inopportune (le mode de défaillance), qui peut elle-même entraîner une vitesse excessive du rotor (l'événement).

Les modes de défaillance du système de commande doivent être identifiés conformément aux exigences du présent article et évalués selon celles de 7.4.3.

Une analyse des modes de défaillance et de leurs effets (AMDE) ou une analyse de pannes équivalente doit être réalisée pour déterminer les événements de panne pertinents pour la

²⁰ L'ISO 12100:2010, 6.2.11 et 6.2.12 donne des recommandations relatives à l'application des mesures de prévention intrinsèque aux systèmes de commande.

²¹ Les architectures multicanaux incluent, entre autres, l'utilisation de la redondance. Un seul canal fonctionnel avec une couverture du diagnostic élevée fourni par un canal d'essai distinct peut suffire si le temps moyen avant défaillance dangereuse qui en résulte est suffisamment élevé. L'architecture conçue pour les systèmes de Catégorie 2 conformes à l'ISO 13849-1 représente ce type d'architecture.

charge de l'éolienne. Il peut s'agir d'une analyse par arbre de panne ou de méthodes similaires visant à identifier des défaillances de cause commune.

L'ensemble des événements présentés dans l'analyse de pannes doit inclure au moins les éléments suivants:

- a) vitesse excessive du rotor;
- b) vibrations excessives;
- c) production électrique excessive;
- d) pannes de l'actionneur (pannes d'actionnement de calage et d'orientation, par exemple).

8.4.2 Indépendance et défaillances de cause commune

Par hypothèse, les pannes indépendantes peuvent ne pas se produire en même temps. Si par hypothèse, des pannes indépendantes sont prises en compte, des mesures doivent être mises en œuvre contre les défaillances de cause commune, et la couverture du diagnostic doit être suffisante pour assurer la protection contre les défaillances dormantes.²²

8.4.3 Exclusions de défaut

Les défaillances du système de commande faisant l'objet d'exclusions de défaut²³ (voir les normes reconnues) peuvent être ignorées.

Tous les composants mécaniques du système de commande dans lesquels des exclusions de défaut sont appliquées doivent relever de la classe de composants 3 avec les conséquences appropriées du facteur de défaillance de sécurité partielle définies en 7.6. Tous les composants critiques doivent être analysés en ce qui concerne la résistance ultime, la fatigue, le flambement et la déviation critique.

8.4.4 Périodes de retour du mode de défaillance

Si des périodes de retour de mode de défaillance sont revendiquées dans les calculs de charge (voir 7.4.3.2), elles doivent être démontrées par des méthodes reconnues.²⁴

Pour les composants mécaniques, il est uniquement nécessaire d'établir les périodes de retour du mode de défaillance si aucune exclusion de défaut ne s'applique.

8.4.5 Défaillances systématiques

Pour les fonctions de protection et les fonctions de commande pour lesquelles des périodes de retour du mode de défaillance supérieures à 10 ans sont revendiquées, des mesures permettant d'éviter les défaillances systématiques²⁵ (y compris des défaillances logicielles) décrites par des normes reconnues doivent être appliquées.

²² L'ISO 13849-1 peut être utilisée pour juger de la suffisance des mesures prises contre les défaillances de cause commune

²³ Les exclusions de défaut sont décrites dans les normes comme l'ISO 13849-2. Pour les composants mécaniques, les exclusions de défaut concernent les composants "à durée de vie assurée".

²⁴ Voir l'IEC 61508-6 ou l'IEC 62061 pour des méthodes adaptées de démonstration des taux de défaillance (les arbres de pannes, les modèles de Markov, etc.). De même, l'ISO 13849-1 donne des méthodes simplifiées d'évaluation des taux de défaillance, y compris les valeurs génériques pour les composants.

²⁵ Les mesures permettant d'éviter les défaillances systématiques et les défaillances logicielles sont présentées en 6.4, 6.10 et 6.11 de l'IEC 62061:2005, l'IEC 62061:2005/AMD1:2012 et l'IEC 62061:2005/AMD2:2015 ou en 4.6, à l'Annexe G et à l'Annexe J de l'ISO 13849-1:2015.

8.5 Fonctionnement manuel

L'intervention manuelle ou automatique ne doit pas compromettre l'aptitude du système de commande à maintenir l'éolienne dans les limites. Un dispositif permettant une intervention manuelle doit être clairement visible et identifiable par un marquage approprié si nécessaire.

Si le mode de commande peut être sélectionné (pour la maintenance, par exemple), la sélection du mode doit être commandée par un sélecteur, qui peut être verrouillé dans chaque position correspondant à un mode unique.

Les réglages du système de commande doivent être protégés contre toute interférence non autorisée.

8.6 Fonction du bouton d'arrêt d'urgence

Une fonction du bouton d'arrêt d'urgence doit être mise en œuvre à l'aide de méthodes et de principes de conception reconnus (ceux de l'ISO 13850, par exemple, qui donne des recommandations relatives à la disponibilité, à l'emplacement, au choix de la fonctionnalité d'arrêt et au comportement de réinitialisation du bouton d'arrêt d'urgence).

La catégorie d'arrêt choisie doit être spécifiée. De plus, une fonctionnalité exigée du système de commande doit être spécifiée lors de l'activation d'arrêt d'urgence.²⁶

Le comportement de tous les systèmes ayant un impact sur la charge structurelle lors de l'activation du bouton d'arrêt d'urgence doit être clairement spécifié.

EXEMPLE 1 La déconnexion des systèmes électriques peut avoir un impact sur la charge de la transmission.

Si le comportement de la fonction d'arrêt d'urgence dépend des conditions de fonctionnement, ces dépendances doivent être clairement définies.

EXEMPLE 2 L'application du frein à disque mécanique en cas d'activation du bouton d'urgence peut être conditionnée à la vitesse de rotation et/ou la vitesse du vent, etc.

Les effets de l'activation du bouton d'arrêt d'urgence doivent être évalués dans le D.LC 5.1 pour tous les scénarii de fonctionnement pertinents (voir 7.4).

8.7 Redémarrage manuel, automatique et à distance

Les mécanismes de redémarrage de l'éolienne après un arrêt doivent être clairement définis et doivent satisfaire aux exigences suivantes.

Le comportement au redémarrage de l'éolienne et les procédures de redémarrage²⁷ après une défaillance de la fonction de commande doivent être définis dans le cadre d'une analyse du mode de défaillance (une analyse par arbre de panne, par exemple).

Si des défaillances de fonctions qui définissent si un redémarrage peut avoir lieu peuvent avoir un impact sur les charges d'éolienne, il convient de considérer ces défauts comme des événements de défaut du système de commande (voir 8.4.1).

Le comportement après une défaillance du système de commande peut être défini par des procédures automatiques ou manuelles, exécutées en local ou à distance. Dans le cas d'un

²⁶ L'exigence ci-dessus est particulièrement importante lorsque la catégorie d'arrêt 1 (arrêt commandé) est choisie.

²⁷ Une procédure de redémarrage nécessite de tenir compte des raisons de l'arrêt de l'éolienne afin de justifier qu'il est sûr de la redémarrer. Par exemple, un redémarrage peut ne pas être considéré comme étant sûr sans la réalisation d'un examen si l'éolienne s'est arrêtée en raison d'un choc mécanique important.

redémarrage à distance, cela doit inclure tous les examens à distance nécessaires (à l'aide, par exemple, de caméras à distance et/ou de données SCADA) et les critères adaptés qu'il est nécessaire de respecter avant que le redémarrage à distance ne soit considéré comme étant sûr.

Le redémarrage automatique ne doit pas être permis si les diagnostics automatiques et les critères nécessaires permettant de garantir la sécurité de l'éolienne (c'est-à-dire dans les limites d'un risque acceptable des dommages de l'éolienne) après le redémarrage n'ont pas été définis.

EXEMPLE Ce type de diagnostics peut consister à justifier automatiquement que les limites de conception structurelle de la vitesse du rotor et de l'accélération du sommet du mât n'ont pas été dépassées.

Les risques et conséquences d'un redémarrage à distance intempestif (dû à une erreur du système de communication, par exemple) doivent être pris en considération.

Une éolienne disposant d'une fonction de redémarrage automatique ou à distance doit comporter des moyens de désactivation et de verrouillage en local de la fonction de redémarrage automatique et de la fonction de redémarrage à distance.

L'éolienne ne doit pas redémarrer de manière intempestive en raison de facteurs externes comme une perte (et un rétablissement) d'alimentation du réseau, des charges externes ou des actions de maintenance.

Le nombre et la fréquence des redémarrages à distance ou automatiques admis doivent être clairement définis en fonction des hypothèses d'arrêt contenues dans l'évaluation des charges de conception. La fonction de redémarrage doit permettre d'assurer que ces limites ne sont pas dépassées.

L'évaluation des charges de conception doit prendre en considération les conséquences de redémarrages répétés jusqu'aux limites définies ci-dessus.

Des facteurs externes comme la perte (et le rétablissement) d'alimentation du réseau, les charges externes ou les actions de maintenance ne doivent pas affecter de manière intempestive la fonctionnalité de contrôle du nombre et de la fréquence des redémarrages à distance ou automatiques admis.

8.8 Système de freinage

Le rotor doit pouvoir être amené au mode ralenti ou à un arrêt complet à partir de n'importe quelle condition de fonctionnement, y compris la perte de puissance.

Des moyens doivent être fournis afin d'amener le rotor à un arrêt complet à n'importe quelle vitesse de vent inférieure à la limite de vitesse de vent définie pour la maintenance et la réparation (voir 7.4.9), sauf si elle est explicitement réduite en fonction des résultats d'une appréciation du risque.

Il est recommandé qu'au moins un système de freinage fonctionne selon un principe aérodynamique, agissant à ce titre directement sur le rotor. Si cette recommandation n'est pas satisfaite, au moins un système de freinage doit agir sur l'arbre directement relié au rotor ou sur le rotor de l'éolienne.

Si un système de freinage est conçu pour amener le rotor à l'arrêt en cas d'activation de l'arrêt d'urgence, il doit être en mesure de maintenir le rotor à l'arrêt pour les conditions de vent définies pendant au moins une heure après son application.

9 Systèmes mécaniques

9.1 Généralités

Pour les besoins du présent document, un système mécanique est tout système qui ne se compose pas seulement de composants structurels statiques ni de composants électriques, mais utilise ou transmet un mouvement relatif par la combinaison d'arbres, de liaisons, de roulements, de parties glissantes, d'engrenages et d'autres dispositifs. À l'intérieur d'une éolienne, ces systèmes peuvent comprendre des éléments de transmission tels que les multiplicateurs de vitesse, les arbres et les raccords, et des organes auxiliaires tels que les freins, les commandes de calage de pale, les entraînements du dispositif d'orientation. Les organes auxiliaires peuvent être entraînés par des moyens électriques, hydrauliques ou pneumatiques.

Tous les systèmes mécaniques dans la transmission et dans le système de commande doivent être conçus conformément aux normes IEC ou ISO lorsqu'elles sont disponibles. Autrement, des normes reconnues doivent être utilisées. Les facteurs de sécurité partielle doivent être cohérents avec la classe de composants 2 de 7.6.1.3, à moins que les systèmes ne fassent partie de la classe de composants 3.

Il faut particulièrement veiller à assurer que les systèmes de refroidissement et de filtration peuvent maintenir les conditions de fonctionnement applicables à travers toute la plage de températures de fonctionnement lorsque les procédures de maintenance spécifiées sont suivies.

La durée de vie restante d'un composant soumis à l'usure dans le système de freinage doit être contrôlée automatiquement et être soumise à un contrôle régulier. L'éolienne doit être immobilisée lorsqu'il y a trop d'usure des matériaux pour des arrêts d'urgence ultérieurs. Tous les dispositifs de freinage doivent être conçus et maintenus pour que le temps de réponse reste dans des niveaux acceptables.

Le calcul des charges doit reposer sur des simulations comprenant à la fois le niveau de freinage moyen et un niveau de freinage minimal qui permet un frottement minimal et une application de pression prévue pour la conception. Si le frein peut glisser au niveau de freinage minimal, lorsque le frein est appliqué, il doit être conçu pour éviter les surchauffes et l'altération des performances du freinage et pour éviter un risque d'incendie.

Pour les exigences en climat froid, voir 14.7.

9.2 Erreurs de montage

Des erreurs susceptibles de survenir lors du montage ou du remontage de certaines pièces sur lesquelles un risque peut se constituer doivent être rendues impossibles par la conception de ces pièces ou, le cas échéant, par des informations données sur les pièces elles-mêmes et/ou les carters. Les mêmes informations doivent être données sur les pièces mobiles et/ou leurs carters pour lesquels le sens du mouvement doit être connu pour éviter un risque. Toute autre information qui peut être nécessaire doit être donnée dans les manuels d'utilisation et de maintenance de l'opérateur.

Lorsqu'un raccordement défectueux peut provoquer des risques, la conception doit rendre impossible la réalisation de raccords incorrects ou, le cas échéant, des précautions doivent être prises, afin d'éviter tout raccordement défectueux au moyen des informations figurant sur les conduites, les tuyaux et/ou les blocs connecteurs.

9.3 Systèmes hydrauliques ou pneumatiques

Lorsque des organes auxiliaires sont alimentés par énergie hydraulique ou pneumatique, les systèmes doivent être conçus, construits et équipés de façon à éviter tous les dangers potentiels associés à ces types d'énergie. Les moyens d'isolation ou de décharge de l'énergie

accumulée doivent être inclus dans des systèmes de ce type. Tous les conduits et/ou tuyaux transportant de l'huile hydraulique ou de l'air comprimé et leurs fixations doivent être conçus de façon à pouvoir résister à des contraintes internes et externes prévisibles ou à en être protégés. Des précautions doivent être prises pour réduire le plus possible le risque de blessures survenant par suite d'une rupture.

9.4 Multiplicateur de vitesse principal

Le multiplicateur de vitesse principal doit être conçu conformément à l'IEC 61400-4.

9.5 Système d'orientation

Le système d'orientation peut se composer de dispositifs pour maintenir une orientation fixe (par exemple freins hydrauliques), de dispositifs pour modifier cette orientation (par exemple moteurs électriques, multiplicateurs de vitesse et pignons) et de dispositifs pour guider la rotation (par exemple un roulement).

Tous les moteurs doivent être conformes aux parties correspondantes de l'Article 10.

Les parties non redondantes du multiplicateur de vitesse (l'orientation à engrenage final, par exemple) doivent être considérées comme appartenant à la classe de composants 2. Si plusieurs entraînements de dispositif d'orientation assurent une redondance suffisante dans le système d'orientation à engrenage, et que le remplacement est aisé, le réducteur de vitesse à engrenages et le pignon de commande final peuvent être considérés comme appartenant à la classe de composants 1.

La sécurité contre les piqures doit être déterminée selon l'ISO 6336-2. Il est admis d'appliquer la courbe de limite supérieure (1) correspondant au facteur de durée Z_{NT} , qui permet de limiter les piqures. Une résistance à la flexion en pied de dent doit être démontrée conformément à l'ISO 6336-3. Les charges de pliage alterné appliquées sur la denture doivent être considérées comme étant conformes à l'ISO 6336-3:2006, Annexe B. Les valeurs minimales de S_F et de S_H sont spécifiées dans le Tableau 4. Ces valeurs doivent être obtenues à l'aide des charges caractéristiques F_k . Ainsi, S_F et S_H incluent le facteur de sécurité partielle pour les conséquences, γ_n , les matériaux, γ_M et les charges, γ_f .

Tableau 4 – Facteurs de sécurité minimale $S_{H,min}$ et $S_{F,min}$ pour le système d'orientation à engrenage

	Classe de composants 1	Classe de composants 2
Durabilité de surface (piqûre)	$S_{H,min} = 1,0$	$S_{H,min} = 1,1$
Résistance à la fatigue par flexion en pied de dent	$S_{F,min} \geq 1,1$	$S_{F,min} = 1,25$
Résistance statique au pliage	$S_{F,min} \geq 1,0$	$S_{F,min} = 1,2$

Toutefois, des facteurs de sécurité inférieurs, S_F et S_H peuvent être appliqués si des surveillances efficaces sont mises en place. Si des facteurs de sécurité inférieurs à 1,0 sont appliqués, le manuel de maintenance doit préciser les intervalles de remplacement anticipé.

9.6 Système de calage

Le système de calage peut se composer de dispositifs pour ajuster l'angle de calage de pale (actionneurs hydrauliques, moteurs électriques, multiplicateurs de vitesse, freins et pignons, par exemple) et de dispositifs pour guider la rotation (un roulement, par exemple).

Tous les moteurs doivent être conformes aux parties correspondantes de l'Article 10. Pour les systèmes de calage avec des entraînements du dispositif de calage/des actionneurs

individuels assurant une redondance suffisante, ceux-ci peuvent être considérés comme appartenant à la classe de composants 2.

Pour la classe de composants 2, les multiplicateurs de vitesse et les engrenages doivent satisfaire aux parties correspondantes de 9.5.

9.7 Freins mécaniques pour fonction de protection

Lorsque des freins mécaniques sont utilisés pour une fonction de protection (voir 7.4.3.3), il s'agit généralement de dispositifs de frottement appliqués par pression de ressort hydraulique ou mécanique. La durée de vie restante d'un composant d'usure (les patins de frottement, par exemple) doit être contrôlée par le système de commande, qui doit mettre l'éolienne en état d'immobilisation lorsqu'il y a trop d'usure des matériaux pour un arrêt d'urgence supplémentaire.

Le calcul des charges doit reposer sur des simulations comprenant une plage appropriée du niveau de freinage. Si le frein peut glisser à l'arrêt au niveau de freinage minimal, chaque fois que le frein doit maintenir l'éolienne dans un état stationnaire, la période de glissement dans un vent turbulent doit être suffisamment courte pour éviter les surchauffes et l'altération des performances du freinage et pour éviter un risque d'incendie.

9.8 Roulements des éléments roulants

9.8.1 Généralités

La base de l'analyse des caractéristiques assignées des roulements doit être l'ISO 76, ISO 281 et l'ISO/TS 16281. Le calcul doit tenir compte des conditions réelles de fonctionnement et de lubrification, ainsi que de l'environnement du roulement. Un facteur d'ajustement de la durée conforme à l'ISO 281 et à l'ISO/TS 16281 doit être appliqué avec précaution.

Les charges pour la conception doivent refléter les charges déterminées dans les différents cas de charge de 7.4 et les facteurs de sécurité appropriés de 7.6. La conception du roulement doit prendre en considération la quantité attendue de rotations au cours de sa durée de vie et le fait que les rotations sont continues ou discontinues.

9.8.2 Roulements de l'arbre principal

La durée de vie assignée de référence modifiée L_{10mr} (probabilité de survie de 90 %) des roulements de l'arbre principal doit satisfaire ou dépasser la durée de vie prévue à la conception spécifiée de l'éolienne.

9.8.3 Roulements du générateur

La durée de vie assignée de référence modifiée L_{10mr} (probabilité de survie de 90 %) des roulements du générateur doit satisfaire ou dépasser la durée de vie prévue à la conception spécifiée de l'éolienne.

Les roulements du générateur qui peuvent être remplacés dans l'éolienne sans outil particulier peuvent être spécifiés pour une durée de vie prévue à la conception plus courte.

9.8.4 Roulements de calage et d'orientation

Pour les roulements de calage et d'orientation, le rapport de la charge statique de base sur la charge pour la conception doit être d'au moins 1,0, conformément à l'ISO 76. La distribution des charges due à la flexibilité des parties connectées doit être soigneusement prise en considération.

Les roulements utilisés dans les systèmes de calage et d'orientation sont exposés à un mouvement oscillatoire discontinu. Par conséquent, les effets potentiels d'une lubrification insuffisante due à un petit mouvement doivent être pris en considération.

10 Système électrique

10.1 Généralités

Le système électrique d'une installation d'éolienne comporte tous les équipements électriques installés dans chaque éolienne, y compris les bornes de l'éolienne, et est appelé ci-après « système électrique de l'éolienne ».

L'Article 10 inclut les composants électriques spécifiques aux conceptions d'éoliennes dont les caractéristiques et fonctionnalités ne sont pas particulièrement traitées dans d'autres normes relatives au système et au composant. L'Article 10 traite également des composants d'éoliennes communs, mais ne se veut pas exhaustif. Les composants spécifiques sont régis par la conception de l'éolienne, ces composants et assemblages doivent être évalués pour les emplacements d'installations électriques, mécaniques et environnementales et l'application (voir 10.2).

Le système de collecte de puissance n'est pas couvert par le présent document.

10.2 Exigences générales pour le système électrique

La conception du système électrique doit garantir une dangerosité minimale pour les personnes et les animaux domestiques ou d'élevage ainsi qu'un minimum de dégâts potentiels sur l'éolienne et le système électrique externe au cours du fonctionnement et de la maintenance dans toutes les conditions électriques et environnementales normales et extrêmes (voir 6.4.2 et 6.4.3) pour la zone spécifique de fonctionnement du matériel, y compris les effets supplémentaires liés à l'ensemble de l'éolienne et à ses caractéristiques assignées environnementales. Les composants et sous-assemblages électriques doivent être classés en fonction de leurs conditions électriques et de l'environnement de fonctionnement.

Il convient que l'équipement électrique soit conçu pour assurer la protection contre d'éventuels arcs électriques en s'appuyant sur des normes nationales ou internationales reconnues et sur des méthodologies d'appréciation du risque.

Pour les exigences en climat froid, voir 14.8.

Sauf spécification contraire indiquée dans le présent document, la conception du système électrique d'une éolienne doit satisfaire aux exigences de l'IEC 60204-1. Pour les matériels dont les tensions nominales des circuits d'entrée et/ou de sortie sont supérieures à 1 000 V en courant alternatif ou à 1 500 V en courant continu, les exigences applicables de l'IEC 60204-11 doivent s'appliquer. Le fabricant doit stipuler la ou les normes de conception utilisées. La conception du système électrique doit tenir compte de la nature fluctuante de la production d'électricité à partir des éoliennes.

10.3 Conditions d'environnement internes

Les conditions d'environnement internes à l'éolienne sont susceptibles d'être différentes des conditions d'environnement externes.

Les conditions d'environnement doivent être déterminées pour les emplacements dans lesquels se trouvent les principaux composants et sous-assemblages de l'éolienne et doivent être réalisées conformément à l'IEC 60721 (toutes les parties). En principe, les emplacements à l'étude incluent, entre autres, le moyeu, les sections de mât, la nacelle, la base du mât, la fondation du mât.

Les conditions d'environnement internes dépendent des systèmes de régulation climatique spécifiques et de la pollution prévisible de l'environnement inclus dans la conception d'éolienne spécifique. Le chauffage, le refroidissement et la ventilation active doivent être pris en considération.

Le fabricant doit spécifier les conditions de service suivantes pour le fonctionnement, le stockage et le transport de chaque sous-assemblage et composant principal de l'éolienne. Dans la mesure du possible, les classifications de l'IEC 60721 (toutes les parties) doivent être utilisées:

- température du liquide de refroidissement (min./max.);
- température ambiante (min./max.);
- humidité (min./max.);
- degré de pollution;
- vibrations;
- catégorie de surtension (OVC – *overvoltage category*);
- altitude pour les considérations thermiques, si assignée pour le fonctionnement au-dessus de 1 000 m;
- altitude pour les considérations de coordination d'isolement, si assignée pour le fonctionnement au-dessus de 2 000 m;

Ces déterminations de condition d'environnement sont la base de la coordination de l'isolement définie en 10.3.

L'IEC 60664-1 et l'IEC 60664-3 pour le matériel dont la tension assignée atteint 1 000 V en courant alternatif et l'IEC 60071-1 et l'IEC 60071-2 pour le matériel dont la tension assignée est supérieure à 1 000 V en courant alternatif doivent être utilisées pour évaluer les exigences de coordination de l'isolement du matériel d'éolienne spécifique, sauf spécification contraire selon les exigences de composant spécifiques indiquées dans le présent document. Cette évaluation de la coordination de l'isolement doit porter sur la catégorie de surtension, le degré de pollution et les conditions d'environnement du matériel électrique dans l'éolienne.

Les conditions d'environnement minimales dans l'éolienne doivent correspondre au degré de pollution 3. Les zones spécifiques faisant l'objet d'une pollution conductrice (poussière du balai de bague collectrice et poussière de freinage, par exemple) doivent correspondre au degré de pollution 4.

Le degré de pollution peut être réduit dans certaines zones du matériel par encapsulation, à l'aide d'un revêtement enrobant, etc. Le degré de pollution dans l'ensemble du matériel peut également être réduit à l'aide d'enveloppes assurant la protection conformément à l'IEC 60529. Il peut s'agir de contrôler et de réduire le degré de pollution au niveau de la ligne de fuite par des fonctions de conception ou la prise en considération des caractéristiques de fonctionnement du composant ou du matériel.

Le degré de pollution 2 peut être atteint en réduisant les possibilités d'accumulation de débris (ventilation filtrée) et de condensation ou d'humidité élevée aux emplacements de ligne de fuite. L'application continue de chaleur, au moyen de l'utilisation d'éléments thermiques, ou l'alimentation continue du matériel en cours d'utilisation peut permettre de contrôler la condensation. L'alimentation continue est considérée comme existante lorsque le matériel fonctionne sans interruption tous les jours 24 h/24 h ou lorsque qu'il fonctionne avec des interruptions dont la durée ne permet pas le refroidissement jusqu'au point de condensation.

Le degré de pollution 1 peut être atteint par enrobage, par moulage du matériel ou du circuit ou en le plaçant dans une enveloppe IP 67.

La catégorie de surtension IV doit être appliquée pour déterminer les espacements de distance d'isolement dans les emplacements généraux à l'intérieur d'une éolienne. Les parafoudres qui permettent de protéger les circuits de commande et de protection et les autres circuits assurant la sécurité de fonctionnement de l'éolienne doivent inclure des circuits de signalisation et de surveillance ou d'autres moyens automatiques pour indiquer la défaillance d'un parafoudre. Une protection contre les surtensions peut être utilisée pour passer en local à une catégorie de surtension inférieure à IV pour les matériels ou circuits spécifiques.

Les coups de foudre directs ou à proximité peuvent induire des conditions de surtension élevée dans les systèmes électriques externes et les systèmes électriques de l'éolienne, y compris les circuits du matériel dans le moyeu, la nacelle et le mât. Les parafoudres, s'ils sont utilisés, doivent être installés à proximité immédiate du matériel à protéger.

10.4 Dispositifs de protection

Un système électrique d'éolienne doit, en plus des exigences de l'IEC 60364 (toutes les parties), être équipé de dispositifs adaptés qui assurent la protection contre le dysfonctionnement soit à l'intérieur de l'éolienne, du matériel, des sous-assemblages et des composants ou par suite d'un dysfonctionnement du système électrique externe, qui peut mener à une condition ou un état d'insécurité. Ces fonctions de dispositif de protection incluent les protections contre les courts-circuits, les surintensités, les défauts à la terre, les échauffements et les défauts d'arc.

10.5 Déconnexion des sources d'alimentation

Un ou plusieurs dispositifs de déconnexion verrouillables doivent être prévus pour déconnecter le matériel de chaque source d'alimentation électrique dont la tension est dangereuse ou dépasse les valeurs d'énergie dangereuse ou à partir de laquelle une tension ou énergie dangereuse est déduite. Les niveaux de tension et d'énergie dangereuses sont définis dans l'IEC 60204-1 et l'IEC 60204-11.

L'arrêt d'urgence n'est pas destiné à fournir une fonction de déconnexion de routine à cet effet.

Les appareils de connexion à semiconducteur sans contact de déconnexion à entrefer supplémentaire ne permettent pas de satisfaire aux exigences de 10.4.

Lorsque le système d'éclairage ou d'autres systèmes électriques sont nécessaires pour la sécurité au cours de la maintenance, des circuits auxiliaires doivent être fournis avec leurs propres dispositifs de déconnexion, de sorte que ces circuits puissent rester alimentés tandis que tous les autres circuits sont privés d'alimentation.

Les circuits et matériels assignés à plus de 1 000 V en courant alternatif ou 1 500 V en courant continu doivent satisfaire à l'Article 5 de l'IEC 60204-11:2000.

10.6 Système de mise à la terre

Une éolienne doit être équipée d'un système local de prise de terre afin de satisfaire aux exigences de l'IEC 60364 (toutes les parties) (pour le fonctionnement correct de l'installation électrique) et de l'IEC 62305-3 (pour la protection contre la foudre).²⁸ La plage des conditions de sol, pour laquelle le système de prise de terre est adéquat, doit être indiquée dans les documents de conception avec des recommandations, si d'autres conditions de sol sont observées.

²⁸ Des considérations supplémentaires sont incluses dans l'IEC 61400-24:2010, Article 9.

Le choix et l'installation de l'équipement du dispositif de mise à la terre (prises de terre, conducteurs de terre, bornes principales de terre et barres) doivent être effectués conformément à l'IEC 60364-5-54.

Des dispositions doivent être prises dans tout système électrique fonctionnant au-dessus de 1 000 V en courant alternatif ou 1 500 V en courant continu pour la mise à la terre au cours de la maintenance conformément à l'IEC 60204-11.

10.7 Protection contre la foudre

Le système de protection contre la foudre d'une éolienne doit être conçu conformément à l'IEC 61400-24. Une approche fondée sur le risque doit être appliquée lors de la conception du système de protection eu égard au risque de dommages et à la sécurité des personnes.

La conception doit prendre en considération la protection des zones suivantes:

- pales du rotor;
- moyeu/hélice;
- nacelle;
- mât.

Il peut également être nécessaire de connecter et/ou d'intégrer des composants de système supplémentaires (des transformateurs et appareillages externes hors du domaine d'application du présent document, par exemple) dans le système de protection contre la foudre.

La protection des systèmes électriques de l'éolienne doit suivre une approche fondée sur la protection contre la foudre (voir l'IEC 62305-4), la conception combinant liaisons équipotentielle, blindages et parafoudres.

Les exigences de conception du système de protection contre la foudre sont fournies dans l'IEC 61400-24.

10.8 Câbles électriques

Les câbles électriques doivent être assignés pour les applications électriques, d'inflammabilité, mécaniques et environnementales dans lesquelles ils sont utilisés et doivent être installés de la manière pour laquelle ils sont assignés. Lorsqu'il est probable que des rongeurs ou d'autres animaux endommagent les câbles, des câbles ou conduits blindés doivent être utilisés.

- Les câbles doivent être protégés ou assignés pour atténuer le risque éventuel d'incendie en cas de défaut.
- Les câbles de commande doivent être séparés et/ou protégés des câbles d'alimentation, sauf si les défaillances d'isolement sont spécifiquement traitées dans l'analyse des pannes.
- Les serre-câbles, supports et détendeurs doivent être adaptés au type de câble de manière à éviter d'endommager l'isolation du câble.
- Les câbles doivent être protégés ou placés judicieusement afin de ne pas être endommagés par abrasion et usure.

10.9 Autoexcitation

Tout système électrique qui peut à lui seul autoexciter une éolienne doit être déconnecté et rester déconnecté en toute sécurité en cas de perte du raccordement au réseau.

Si une batterie de condensateurs est montée en parallèle avec une génératrice asynchrone (c'est-à-dire pour la correction du facteur de puissance), un commutateur approprié est exigé pour déconnecter la batterie de condensateurs lorsqu'il existe une perte de puissance du réseau, afin d'éviter toute autoexcitation de la génératrice. Par ailleurs, si des condensateurs sont montés, ce dispositif doit être suffisant pour démontrer que les condensateurs ne peuvent pas provoquer d'autoexcitation.

10.10 Protection contre l'impulsion électromagnétique générée par la foudre

La protection contre les surtensions doit être conçue conformément aux exigences de l'IEC 62305-4.

Les limites de la protection doivent être conçues de sorte que toute impulsion électromagnétique générée par la foudre transmise aux équipements électriques ne dépasse pas les limites fixées par les niveaux d'isolation des équipements.

10.11 Qualité de puissance

Les procédures de l'IEC 61400-21 peuvent être utilisées pour démontrer la satisfaction aux exigences de l'opérateur du réseau de distribution publique ou de transmission.

10.12 Compatibilité électromagnétique

Pour assurer l'immunité aux perturbations rayonnées et conduites, tous les composants électriques installés dans l'éolienne doivent satisfaire aux exigences des normes de produit correspondantes et doivent au moins satisfaire aux exigences les plus importantes de l'IEC 61000-6-2 ou aux exigences définies lors de l'évaluation de la sécurité fonctionnelle du système de commande (Article 8).

10.13 Systèmes électroniques de conversion de puissance et matériel

Le convertisseur doit être évalué pour l'environnement dans lequel il est installé (voir le Tableau 18 de l'IEC 62477-1:2012). L'intérieur de l'éolienne n'est pas considéré comme un espace conditionné. Si le convertisseur est installé dans un espace conditionné, il doit être évalué pour cet environnement. Le degré de pollution doit être choisi en fonction de la pénétration d'eau due à l'humidité et à la condensation en raison de durées prolongées d'absence d'alimentation. Les conditions de service environnementales définies dans l'IEC 62477-1 peuvent être modifiées afin d'adapter l'application finale spécifique à l'intérieur de l'éolienne.

L'IEC 61800-4 doit être appliquée pour les convertisseurs fonctionnant au-dessus de 1 000 V en courant alternatif ou de 1 500 V en courant continu.

Les commandes et la protection du convertisseur doivent en outre satisfaire aux exigences applicables de l'Article 8.

10.14 Boucle de torsion/d'égouttement

L'aptitude à l'emploi du câblage faisant l'objet de déplacement, de flexion ou de torsion pendant le fonctionnement de l'éolienne doit être examinée dans les conditions d'utilisation et la durée de vie assignée de l'application.

Si le fonctionnement de l'éolienne peut engendrer une torsion des câbles souples, comme les câbles de raccordement entre les parties tournantes (nacelle) et les parties de la structure fixe (mât ou fondations), les conditions d'utilisation opérationnelles ne doivent pas endommager les conducteurs ou leur isolation. L'évaluation doit porter sur la durée de vie en service et sur les conditions de fonctionnement électriques et environnementales du sous-assemblage.