TECHNICAL REPORT

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First edition
2002-07

Wind turbine generator systems –

Part 24: Lightning protection

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINE GENERATOR SYSTEMS –

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FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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Technical reports do not necessarily have to be reviewed until the data they provide are considered to be no longer valid or useful by the maintenance team.

IEC 61400-24, which is a technical report, has been prepared by IEC technical committee 88: Wind turbine systems.

The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
88/128/CDV	88/142/RVC

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 3.

This document, which is purely informative, is not to be regarded as an International Standard.

The committee has decided that the contents of this publication will remain unchanged until 2007. At this date, the publication will be either

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

INTRODUCTION

During the last few years damage to wind turbines due to lightning strokes has been recognized as an increasing problem. The increasing number and height of installed turbines have resulted in an incidence of lightning damage greater than anticipated with repair costs beyond acceptable levels. The influence of lightning faults on operational reliability becomes a concern as the capacity of individual wind turbines increases and turbines move offshore. This is particularly the case when several large wind turbines are operated together in wind farm installations since the potential loss of multiple large production units due to one lightning flash is unacceptable.

Unlike other electrical installations, such as overhead lines, substations and power plants, where protective conductors can be arranged around or above the installation in question, wind turbines pose a different lightning protection problem due to their physical size and nature. Wind turbines typically have two or three blades with a diameter up to 100 m or more rotating 100 m above the ground. In addition, there is extensive use of insulating composite materials, such as glass fibre reinforced plastic, as load-carrying parts. The lightning protection system has to be fully integrated into the different parts of the wind turbines to ensure that all parts likely to be lightning attachment points are able to withstand the impact of the lightning and that the lightning current may be conducted safely from the attachment points to the ground without unacceptable damage or disturbances to the systems.

To that end this report was developed to inform designers, purchasers, operators, certification agencies and installers of wind turbines on the state-of-the-art of lightning protection of wind turbines.

WIND TURBINE GENERATOR SYSTEMS –

Part 24: Lightning protection

1 Scope

During the last few years, all major wind turbine manufacturers have made dedicated efforts towards developing adequate lightning protection systems, and the first experiences with these new designs are beginning to be seen. It is therefore reasonable at this time to consider and prepare for a standardization effort that will give both manufacturers and operators a common framework for appropriate lightning protection of wind turbines.

On the above background the following elements of work have formed the scope of a new working group with the specific aim of preparing a technical report on the subject prior to considering development of a full standard:

- identify the generic problems involved in lightning protection of wind turbines;
- collect and systematize existing experience with both older and new designs of wind turbines;
- describe appropriate methods for evaluating the risk of lightning damage to wind turbines, thereby making reliable cost-benefit evaluations of lightning protection efforts possible;
- describe and outline appropriate methods for lightning protection of wind turbine components, considering the special nature of wind turbines and the extensive use of composite materials;
- compile a technical report outlining problems and solutions as seen today. The working group should identify and quantify areas where further research and proper standardization efforts are needed.

This technical report is structured as follows:

- clause 3 gives the background on the current understanding on lightning phenomenology and its impact on wind turbines;
- clause 4 presents the lightning damage experience as extracted from the various national wind turbine databases;
- clause 5 describes risk evaluation;
- clauses 6 through 10 discuss appropriate methods for protection against lightning damage;
- clause 11 identifies areas for further research.

2 Definitions

For the purposes of this technical report, the following definitions apply.

2.1
accepted lightning flash frequency (N_c)
maximum accepted average annual frequency of lightning flashes which can cause damage to the structure

2.2
air-termination system
part of the external LPS which is intended to intercept lightning flashes

2.3
bonding conductor
conductor interconnecting separate installation parts to equalize potentials between them

2.4
bonding bar
bar on which metal installations, electric power and telecommunication lines, and other cables can be bonded to an LPS

2.5
dangerous sparking
unacceptable electrical discharges caused by lightning currents in the structure to be protected

2.6
direct lightning flash frequency to a structure (N_d)
expected average annual number of direct lightning flashes to the structure

2.7
down-conductor system
part of an external LPS which is intended to conduct lightning current from the air-termination system to the earth-termination system

2.8
downward flash
lightning flash initiated by a downward leader from cloud to earth. A downward flash consists of a first short stroke, which can be followed by subsequent short strokes and may include a long stroke

2.9
earth electrode
part or a group of parts of the earth-termination system which provides direct electrical contact with and disperses the lightning current to the earth

2.10
earth-termination system
part of an external LPS which is intended to conduct and disperse the lightning current to the earth

2.11
effective height (h)
effective height of a wind turbine is the highest point the blades reach, i.e. hub height plus rotor radius

2.12
efficiency of LPS (E)
ratio of the average annual number of direct lightning flashes which cannot cause damage to the structure to the direct lightning flash number to the structure. E can be expressed as the product of the interception efficiency (E_i) and sizing efficiency (E_s) expressing the probability with which the LPS protects the structure against direct lightning flashes

2.13
equivalent collection area (A_e)
equivalent collection area of a structure is defined as an area of ground surface which has the same annual frequency of direct lightning flashes as the structure

2.14
external lightning protection system
consists of an air-termination system, a down conduction system and an earth termination system

2.15
flash charge (Q_{flash})
time integral of the lightning current for the entire lightning flash duration

2.16
foundation earth electrode
reinforcement steel of foundation or additional conductor embedded in the concrete foundation of a structure and used as an earth electrode

2.17
frequency of damage by direct lightning flashes
average number of direct lighting flashes to the structure

2.18
ground flash density (N_g)
average annual ground flash density is the number of lightning flashes per square kilometre per year, concerning the region where the structure is located

2.19
interception efficiency (E_i)
probability with which the air-termination system of an LPS intercepts a lightning stroke

2.20
internal lightning protection system
all measures additional to those mentioned under external lightning protection system including the equipotential bonding, the compliance of the safety distance and the reduction of the electromagnetic effects of lightning current within the structure to be protected

2.21
lightning protection system (LPS)
the complete system used to protect a structure and its contents against the effects of lightning. Commonly it consists of both external and internal lightning protection systems

2.22
lightning current (i)
current flowing at the point of strike

2.23
"natural" components of LPS
component installed not specifically for lightning protection which can be used in addition to the LPS or in some cases could provide the function of one or more parts of the LPS

2.24
peak value (I)
maximum value of the lightning current

2.25
lightning equipotential bonding
bonding of separated conducting installation parts by means of direct conductors or SPD, involved into an internal LPS, to reduce potential differences between these parts caused by lightning current

2.26
lightning stroke
single discharge in a lightning flash to earth

2.27
lightning flash to earth
electric discharge of atmospheric origin between cloud and earth consisting of one or more strokes

2.28
lightning protection zone (LPZ)
zones where lightning electromagnetic environments are to be defined and controlled

2.29
long stroke
stroke with duration time T_{long} (time from the 10 % value on the front to the 10 % value on the tail) of the current typically more than 2 ms and less than 1 s (cf. IEC 61024-1)

2.30
metal installations
extended metal items in the structure to be protected which may form a path for the lightning current, such as the nacelle bed plate, the tower, ladders, elevator rails and wires and interconnected reinforcing steel

2.31
multiple strokes
lightning flash consisting in average of 3-4 strokes, with typical time interval between them of about 50 ms

2.32
point of strike
point where a lightning stroke contacts the earth, a structure or a lightning protection system

2.33
protection level
number denoting the classification of an LPS according to its efficiency

2.34
risk of damage
probable annual loss (human and goods) in a structure due to lightning

2.35
safety distance
minimum distance between two conductive parts within the structure to be protected between which no dangerous sparking can occur

2.36
short stroke
stroke with time to half value T_2 of the impulse current typically less than 2 ms (cf. IEC 61024-1)

2.37
sizing efficiency (E_s)
probability that the intercepted lightning stroke does not cause damage to the structure to be protected

2.38
specific energy (W/R)
time integral of the square of the lightning current for the flash duration; it represents the energy dissipated by the lightning current in a unit resistance

2.39
surge arrester
device designed to protect electrical apparatus from high transient voltage and to limit the duration and frequently the amplitude of follow-current. The term "surge arrester" includes any external series gap which is essential for the proper functioning of the device as installed for service, regardless of whether or not it is supplied as an integral part of the device

2.40
surge protective device (SPD)
device that is intended to limit transient overvoltages and divert surge currents

2.41
thunderstorm days (T_d)
number of thunderstorm days per year obtained from isoceraunic maps

2.42
upward flash
lightning flash initiated by an upward leader from an earthed structure to cloud. An upward flash consists of a first long stroke with or without multiple superimposed short strokes, which can be followed by subsequent short strokes possible including further long strokes

3 Lightning and wind turbines

3.1 The properties of lightning

A lightning stroke can be regarded as a current source. The maximum recorded value of lightning current produced by a single stroke is in the region of 300 kA. Similarly, the maximum recorded values of charge transfer and specific energy are 400 C and 20 MJ/Ω respectively.

These maximum values occur in only a small percentage of flashes worldwide. The median value of peak lightning current is approximately 30 kA with median values of charge transfer and specific energy of 5,2 C and 55 kJ/Ω, respectively. In addition, the electrical characteristics of a stroke vary with the type of lightning flash and the geographical location.

3.2 Lightning discharge formation and electrical parameters

Lightning strokes are produced following a separation of charge in thunderstorm clouds, a process detailed in a number of publications [1][1] [2] [3]. A lightning stroke is observed when this charge is discharged to the earth or to a neighbouring cloud. This chapter is concerned with the first of these discharges, the transfer of charge between a thundercloud and the earth.

A lightning discharge usually consists of several components. The whole event following the same ionized path is termed **flash** and may last more than 1 s. The individual components of a flash are called **strokes**.

Lightning discharges are one of two basic types, downward or upward initiated. A downward initiated discharge starts at the thundercloud and heads towards the earth. In contrast an upward initiated discharge starts at an exposed location of the earth (for example mountain top) or at the top of a tall earthed structure and heads towards a thundercloud. Commonly,

[1] Numbers in square brackets refer to the Bibliography.

these basic types are referred to as “cloud-to-ground flash” or “downward flash” and “ground-to-cloud flash” or “upward (initiated) flash”, respectively.

Both types of lightning are further sub-divided according to the polarity of the charge removed from the thundercloud. A negative discharge lowers negative charge from the thundercloud to the earth. A positive discharge results in positive charge being transferred from the thundercloud to the earth. The majority of lightning discharges are negative, making up about 90 % of all cloud-to-ground flashes. Positive discharges make up the remaining 10 % of all cloud-to-ground flashes. Normally, the latter exhibits higher electrical parameters.

Each lightning stroke is different due to the natural variations in the thundercloud that produced it. For example, it is not possible to predict that the next lightning stroke to a particular structure will have a peak current of a given value. What can be said is that the structure has a given probability of being struck by a lightning stroke exceeding a certain value.

Probability distributions of the electrical parameters that are used to describe a lightning stroke have been produced using direct measurements of actual strokes to tall towers [33] [34]. Further information is now becoming available worldwide from regional and national lightning location systems. These can record the location of a lightning stroke and estimate the peak current.

The probability distributions that describe the electrical parameters of a lightning stroke are different for each type of lightning (upward/downward and positive/negative). The appropriate probability distributions are described below along with the typical wave shape of each type of discharge. The probability level given indicates the probability of the specified electrical parameter exceeding the tabulated value during a lightning stroke. Empirical methods to estimate the probability of the electrical parameters exceeding a specific value exist [4].

3.3 Cloud-to-ground flashes

A cloud-to-ground flash (downward initiated discharge) is initially formed by a **preliminary breakdown** within the cloud. The physics of this process are not fully understood at this time. The parts of the discharge process taking place below cloud level are much better known.

3.3.1 Negative cloud-to-ground flashes

In the case of a negative flash, a **stepped leader** descends from the cloud towards the ground in steps of several tens of meters with a pause time between the individual steps of approximately 50 µs. The steps have short duration (typical 1 µs) impulse currents of more than 1 kA. The leader channel contains, when fully developed, a total charge of about 10 C, or more. The channel diameter is in the range of up to a few tens of metres. The total duration of the stepped leader process is a few tens of milliseconds. The faint leader channel is not visible to the naked eye.

The end of the leader, the leader tip, is at a potential in excess of 10 MV with respect to the earth. As the leader tip approaches the earth this high potential raises the electric field strength at the surface of the earth. When the electric field at ground level exceeds the breakdown value of air “answering” (upward moving) leaders are emitted from the earth or from structures on the ground. These upward moving leaders are commonly termed **connecting leaders**. Connecting leaders play an important role in determining the attachment point of a lightning flash to an object.

When the descending stepped leader meets the upward moving connecting leader a continuous path from cloud to ground is established. The charge deposited in the leader channel, is then discharged to ground by a current wave propagating up the ionized channel at about one third the speed of light. This process is termed the **first return stroke**. The first return stroke may have a peak value of up to a few hundred kilo amperes and a duration of a few hundred microseconds. The process of downward propagating lightning attachment is illustrated in figure 1.

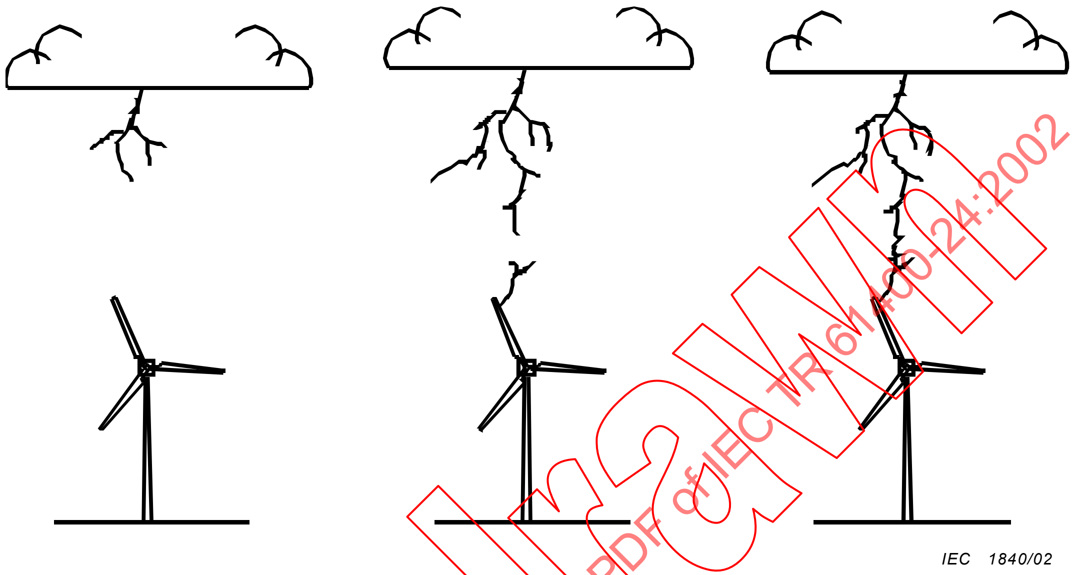


Figure 1 – Processes involved in the formation of a cloud-to-ground flash [4]

After a certain time interval, further leader/return stroke sequences may follow the path taken by the first return stroke. The (dart) leader preceding these **subsequent return strokes** is usually not stepped and much faster (duration of a few milliseconds). The pause time between successive return strokes in a flash is in the order of 10 ms to a few hundred milliseconds. On average, a lightning flash contains 3 to 4 return strokes (including the first one). The return strokes constitute the visible part of the lightning flash.

Following one or more of the return strokes a **continuing current** may flow through the still ionized channel. Continuing currents are quite different compared to the short duration, high amplitude currents of return strokes: the average current amplitude is in the range of a few hundred amperes, while the duration may be as long as several hundred milliseconds. Continuing currents transfer high quantities of charge directly from the cloud to ground. About one-half of all cloud-to-ground flashes contain a continuing current component.

Figure 2 shows a typical profile of the lightning current in a negative cloud-to-ground flash. Following the contact of the stepped leader and the connecting leader, there is a first return stroke resulting (at ground) in a high amplitude impulse current lasting for a few hundred microseconds. The current peak value is in the range of a few kA to 100 kA, the median value being about 30 kA (table 1). Following the first return strokes, subsequent return stroke(s) and continuing current(s) may occur. Although subsequent return strokes generally have a lower current peak value and a shorter duration than first return strokes, they generally have a higher rate of rise of current. Negative cloud-to-ground discharges may be composed of various combinations of the different current components mentioned above, as demonstrated in figure 3.

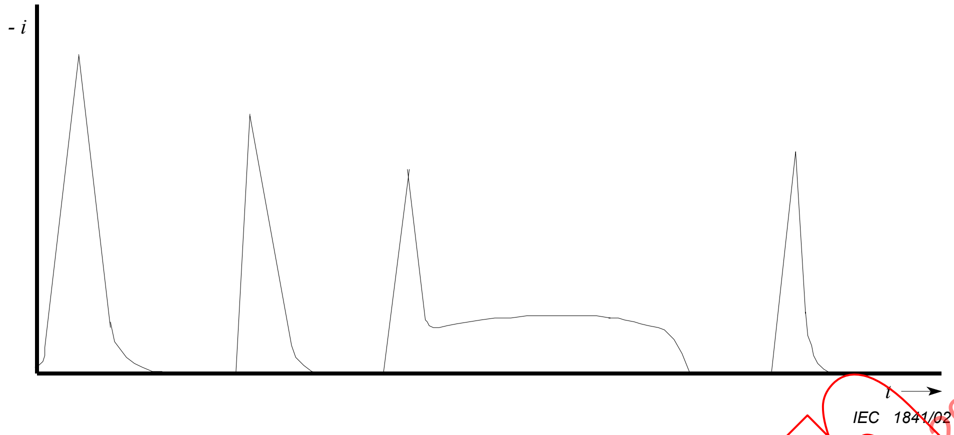


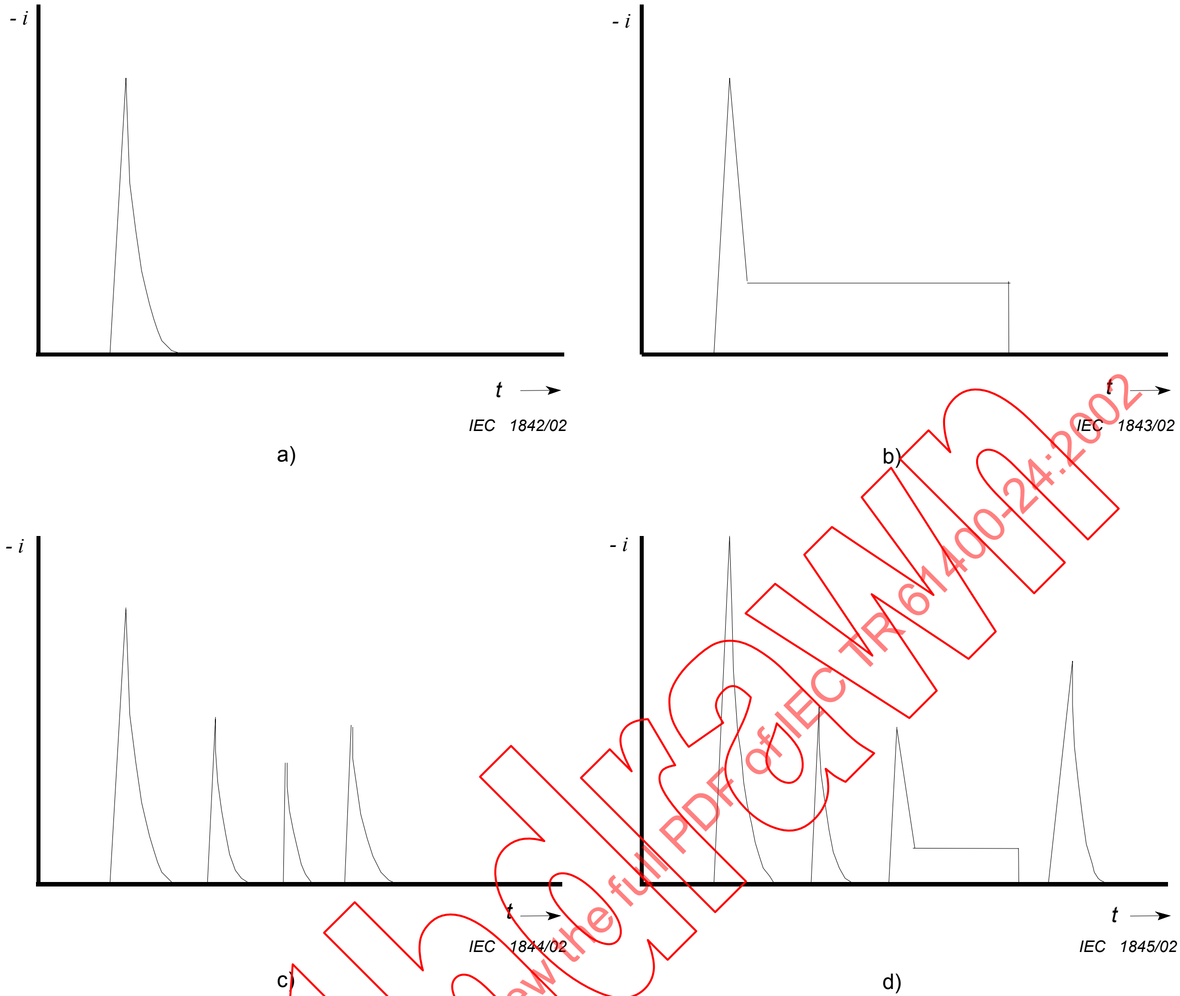
Figure 2 – Typical profile of a negative cloud-to-ground flash (not to scale)

Table 1 – Cloud-to-ground lightning current parameters

Parameter		Stroke type	Probability level		
			95 %	50 %	5 %
Peak current	kA	1st negative	14	30	90
		Subsequent negative	4,6	12	30
		Positive	4,6	35	250
Total charge [a]	C	1st negative	1,1	5,2	24
		Subsequent negative	0,2	1,4	11
		Positive	20	80	350
Specific energy [b]	kJ/Ω	1st negative	6,0	55	550
		Subsequent negative	0,55	6,0	52
		Positive	25	650	15000
Maximum ***di/dt***	kA/µs	1st negative	9,1	24	65
		Subsequent negative	10	40	162
		Positive	0,2	2,4	32

[a] $Q = \int i(t)dt$

[b] $E = \int i^2(t)dt$



a) First return stroke only.
b) First return stroke with continuing current.
c) First return stroke with subsequent return stroke(s).
d) First return stroke with subsequent return stroke(s) and continuing current

Figure 3 – Typical profiles of negative cloud-to-ground flashes (not to scale)

3.3.2 Positive cloud-to-ground flashes

In contrast to negative flashes, positive cloud-to-ground flashes are initiated by a continuously downward propagating leader which does not show distinct steps. The connecting leader and return stroke phases are similar to the processes described in 3.3.1. A positive cloud-to-ground flash usually consists of only one return stroke which may be followed by a continuing current.

Positive cloud-to-ground flashes are of great importance for practical lightning protection because the current peak value, total charge transfer, and specific energy can be much larger compared to the negative flash. The return stroke tends to have a lower rate of current rise in comparison to a negative first return stroke. A typical current profile for a positive cloud-to-ground flash is shown in figure 4. Typical electrical parameters are summarized together with the parameters of negative discharges in table 1 [33] [34].

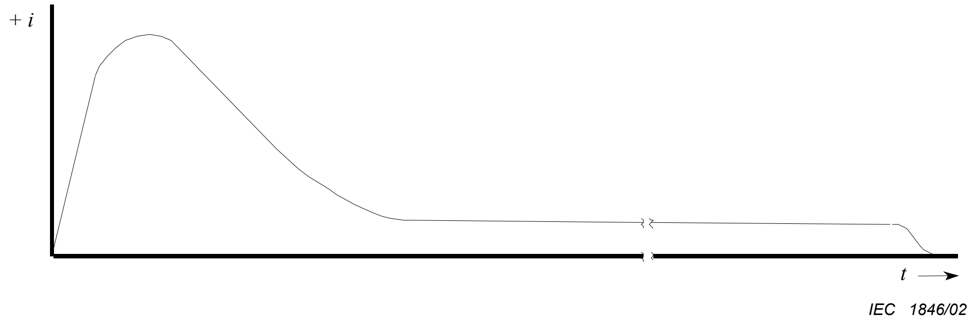


Figure 4 – Typical profile of a positive cloud-to-ground flash

3.4 Upward initiated flashes

The charge in the thundercloud causes an elevation of the electric field on the surface of the earth, but usually not sufficient to launch an upward moving leader. However, the electric field may be significantly enhanced at mountains, objects placed on high ground, or at tall structures like towers or wind turbines. At such locations the electric field strength may become large enough to initiate an upward moving leader from ground towards the thundercloud. Structures with heights in excess of 100 m above the surrounding terrain (like modern wind turbines) are particularly exposed to upward initiated flashes.

An upward initiated flash starts with a continuing current phase. On the continuing current impulse currents can be superimposed (figure 5). The continuing current phase may be followed by **subsequent return stroke(s)** along the same channel. These return strokes are quite similar to the subsequent return strokes of cloud-to-ground flashes (see 3.3). Upward initiated discharges do not contain a component analogous to the first return stroke of cloud-to-ground discharges. The location where an upward lightning stroke attaches to a structure is simply the same point where the upward leader is formed.

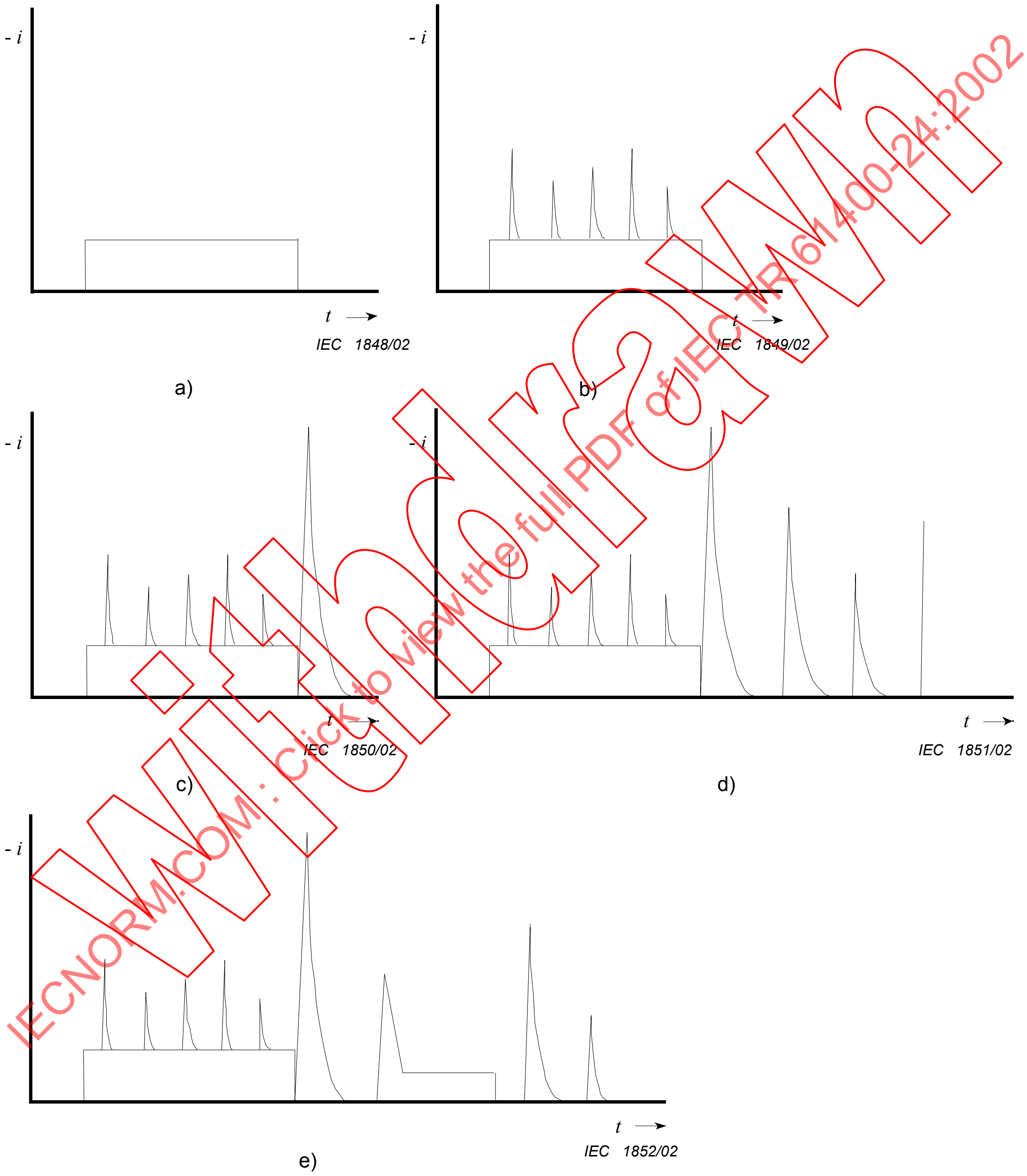
Figure 5 – Typical profile of a negative upward-initiated flash

Measurements of upward initiated discharge parameters are made on tall objects that are prone to this type of stroke. One example is the CN tower in Toronto, Canada that receives at least 50 such flashes per year [5]. Work reported in [6] and [7] has also detailed the form and current parameters of upward flashes at the Peissenberg telecommunication tower in Bavaria, Germany. The following information on current parameters relates to upward negative flashes since, although observed, upward initiated positive flashes are rare.

Although the current peak values of about 10 kA are relatively low, the charge transfer associated with the initial continuing current can be as high as 300 C as shown in table 2 [6]. Upward initiated discharges, too, may be composed of various combinations of the different current components mentioned above, as demonstrated in figure 6.

Table 2 – Upward initiated lightning current parameters

Parameter		Maximum value
Total charge transfer	C	300
Total duration	s	0,5 - 1,0
Peak current	kA	20
Average rate of rise superimposed impulse currents	kA/µs	20
Number of superimposed impulse currents		50



a) (Initial) continuing current only.
b) Initial continuing current with superimposed impulses.
c-d) Initial continuing current with superimposed impulses and subsequent return stroke(s).
e) Initial continuing current with superimposed impulses plus subsequent return stroke(s) with continuing current.

Figure 6 – Different profiles of negative upward initiated flashes (not to scale)

3.5 Lightning protection of wind turbines – the generic problem

Lightning protection of modern wind turbines presents problems that are not normally seen with other structures. These problems are a result of the following:

– wind turbines are tall structures of up to more than 150 m in height;
– wind turbines are frequently placed at locations very exposed to lightning strokes;
– the most exposed wind turbine components such as blades and nacelle cover are often made of composite materials incapable of sustaining direct lightning stroke or of conducting lightning current;
– the blades and nacelle are rotating;
– the lightning current has to be conducted through the wind turbine structure to the ground, whereby significant parts of the lightning current will pass through or near to practically all wind turbine components;
– wind turbines in wind farms are electrically interconnected and often placed at locations with poor earthing conditions.

Tall structures are known to influence the lightning attachment process itself. For structures exceeding 60 m in height, side flashes do occur, where a few per cent of the lightning flashes strike the side of the structure instead of striking at the top. Such side flashes are a cause for concern in connection with wind turbines, since even protected blades struck on the sides may be severely damaged. Furthermore, the fraction of upward initiated lightning flashes increases with height and becomes significant for structures of about 100 m in height [8].

Wind turbines are frequently located in high wind areas, such as coastal areas, on hills or on mountain ridges. Such locations often have relatively high lightning occurrences. As wind turbines are also preferably placed high above the surrounding area and away from other high objects, they become more attractive to lightning. Another issue with wind turbines placed on hills and mountain ridges is earthing. The ground conductivity at such locations is often relatively poor.

Blades for large modern wind turbines are usually made of composite materials, such as glass fibre reinforced plastic or wood laminate. Lightning striking unprotected blades manufactured of these materials invariably causes severe damage since these materials are poor conductors of lightning current. Therefore, lightning protection of such blades is essential. Some nacelle covers are made of glass fibre reinforced plastic, and these should also be protected against direct lightning strokes.

The fact that wind turbines are rotating machines poses special problems. There is a risk of lightning flashes attaching at more than one point on rotating blades and even on more than one blade. This is because lightning flashes consist of several discrete current pulses, within a period of up to 1 s. This is sufficient time to expose more than one blade (for example a 3-bladed wind turbine rotating at 20 rpm moves the blades at 120°/s). When lightning strikes the blades, the current passes through the entire wind turbine structure to the ground. This includes pitch bearings, hub and main shaft bearings, gears, generator bearings, bedplate, yaw bearing and tower. Lightning current passing through gears and bearings may cause damage, particularly when there is a lubrication layer between rollers and raceways or between gear teeth.

Lightning protection techniques for electrical systems are readily available and described in the IEC 61024 series and the IEC 61312 series. Special consideration must be paid to account for the fact that a lightning current passing through the wind turbine will be in closer proximity to electrical systems, as compared to electrical installations in buildings. This is also a concern regarding personnel safety since it may not be possible to achieve minimum safety distances set in standards such as IEC 61024-1.

3.6 Existing IEC standards and technical reports dealing with lightning protection

The standards and technical reports listed in table 3 dealing with lightning protection have been issued by the IEC. Also, table 4 lists standards and reports currently under development. None of these directly address lightning protection of wind turbines. However, the principles described can be used for wind turbines and it is strongly recommended to follow the guidelines set out in these standards.

NOTE Table 4 is not up-to-date. Please consult the IEC Website for current documents.

The following discussion summarizes the applicability of these standards and their short-comings with respect to wind turbines.

Table 3 – Standards and technical reports issued by IEC (Mid 2001)

Publication No.	Title
IEC 61024-1 Ed. 1.0	*Protection of structures against lightning – Part 1: General principles*
IEC 61024-1-1 Ed. 1.0	*Protection of structures against lightning – Part 1: General principles – Section 1: Guide A: Selection of protection levels for lightning protection systems*
IEC 61024-1-2 Ed. 1.0	*Protection of structures against lightning – Part 1-2: General principles – Guide B – Design, installation, maintenance and inspection of lightning protection systems*
IEC 61312-1 Ed. 1.0	*Protection against lightning electromagnetic impulse – Part 1: General principles*
IEC/TS 61312-2 Ed. 1.0	*Protection against lightning electromagnetic impulse (LEMP) – Part 2: Shielding of structures, bonding inside structures and earthing*
IEC/TS 61312-3 Ed. 1.0	*Protection against lightning electromagnetic impulse – Part 3: Requirements of surge protective devices (SPDs)*
IEC/TS 61312-4 Ed. 1.0	*Protection against lightning electromagnetic impulse – Part 4: Protection of equipment in existing structures*
IEC/TR2 61662 Ed. 1.0	*Assessment of the risk of damage due to lightning*
IEC/TR2 61662-am1 Ed. 1.0	*Assessment of the risk of damage due to lightning. Amendment No. 1*
IEC 61663-1 Ed. 1.0	*Lightning protection – Telecommunication lines – Part 1: Fibre optic installations*
IEC 61663-1 Corr. 1	Corrigendum 1
IEC 61663-2 Ed. 1	*Lightning protection – Telecommunication lines – Part 2: Lines using metallic conductors*

IEC 61024-1 details the basic principles and definitions for lightning protection of common structures up to 60 m high. It provides information for the design, installation, inspection and maintenance of effective systems for protection of the structures, as well as for people, installations and contents in or on them. As the height of modern wind turbines frequently exceeds 60 m, they fall outside the scope of the standard. However, structures exceeding 60 m in height will be dealt with in IEC 61024-1, second edition (see table 4). In general, the standard does not address the following subjects that may be relevant for wind turbines: electrical distribution systems and generating systems, telecommunication systems, vehicles and offshore installations.

IEC 61024-1-1 presents methods for evaluating the risk of lightning striking common structures and methods for selecting a protection level that will reduce the risk for people to an acceptable level. IEC 61024-1-2 is a guide on how to design lightning protection systems for common structures.

IEC 61312-1 gives a basis for protection of electrical and electronic systems against the adverse effect of electromagnetic pulses produced by lightning current as well as direct conduction of parts of the lightning current itself. This standard does not address vehicles and off-shore installations.

More details concerning protection of electrical and electronic systems against lightning electromagnetic pulses by shielding, bonding, surge protective devices (SPDs) and earthing, as well as application issues are described in technical specifications IEC 61312-2, IEC 61312-3, IEC 61312-4 and IEC 61312-5 (see table 4).

The technical report IEC 61662 presents detailed methods for evaluating the risk of damage due to lightning strokes. It supplements IEC 61024-1-1 by including reliability issues and economic considerations.

IEC 61663-1 and 61663-2 deal with the lightning protection of telecommunication systems.

Finally, technical report IEC 61819 (see table 4), gives the basic parameters to be used in laboratory environments to simulate the effects of lightning on components of lightning protection systems including SPDs. The report may be of particular interest when testing lightning protection components, such as blade protection systems.

Table 4 – IEC TC 81 work in progress (Mid 2001)

NOTE Table 4 is not up-to-date. Please consult the IEC Website for current documents.

Publication No.	Title
IEC 61024-1 Ed. 2.0	*Lightning protection of structures – Part 1: Protection against physical damages and life hazards by means of LPS, ADIS.*
IEC 61312-3-am1 TS Ed. 1.0	*Amendment to IEC 61312-3: Coordination of SPD within existing structures, ACDV.*
IEC 61662 Ed. 2.0	*Management risk due to lightning, ACDV*
IEC 61819 TR Ed. 1.0	*Test parameters simulating the effects of lightning protection system (L.P.S.) components, APUB.*

4 Damage statistics

4.1 Data on wind turbine lightning damage

Wind turbine databases are maintained in several European countries and cover more than 4000 wind turbines. The raw data is usually taken in the form of monthly reports from turbine owners and operators on either a voluntary basis or as a requirement in country specific subsidy programmes. Government-based, or subsidized, organizations assemble summaries of these statistics monthly or annually. Lightning caused fault or damage statistics compiled from these databases are presented here to help identify the risks involved. This is to assist wind turbine manufacturers and owners when assessing and specifying lightning protection systems.

4.2 Damage statistics

4.2.1 Damage event frequency

Damage events are registered in the databases as turbine faults caused, in the judgement of the reporting person, directly or indirectly by lightning. A summary of these faults is shown in table 5 for Germany, Denmark and Sweden. The lightning caused faults vary from 3,9 to 8 events per 100 turbine years. Restated, in Northern Europe one would expect that 4 to 8 turbines of every 100 would be damaged by lightning in a given year.

Table 5 – Lightning damage frequency

Country	Period	Turbines in database	Capacity MW	Turbine years	Lightning faults	Faults per 100 turbine years
Germany	1991-1998	1498	352	9204	738	8,0
Denmark	1990-1998	2839	698	22000	851	3,9
Sweden	1992-1998	428	178	1487	86	5,8

These summary numbers are, of course, subject to a great deal of variables including local thunderstorm activity, turbine overall height, turbine protection (stroke events to well protected turbines would not show up in database if no damage is associated with it) and the local terrain.

The local terrain and regional risk effects for Germany are shown in table 6.

Table 6 – Regional effect on lightning damage (Germany)

Site category	Turbines number	Capacity MW	Turbine years	Lightning faults	Faults per 100 turbine years	Direct strokes %	Indirect strokes [a] %
Coastal	616	178	4018	223	5,6	33,6 %	65,9 %
Northern lowlands	519	88	3213	239	7,4	23,4 %	76,6 %
Low mountains	363	86	1973	277	14,0	30,3 %	69,3 %
Total	1498	352	9204	739	8,0	29,1 %	70,6 %

[a] Damage caused by indirect strokes implies damage caused by a lightning stroke not hitting the structure directly.

Clearly, the wind turbines installed in the low mountain areas have a higher risk of lightning damage (14 faults per 100 unit years) compared to the wind turbines installed in coastal areas (for further details please refer to 4.4).

4.2.2 Component specific damage

Separating out the damage events by component can help provide inputs to the risk assessment process (see clause 5).

Figure 7 shows the relationship in a bar chart for several categories from the German data, and figure 8 displays the results of the Danish database using the same analysis. It is interesting to note that although the categories are not identical, 40 % to 50 % of all reported events attributable to lightning cause damage to the control system.

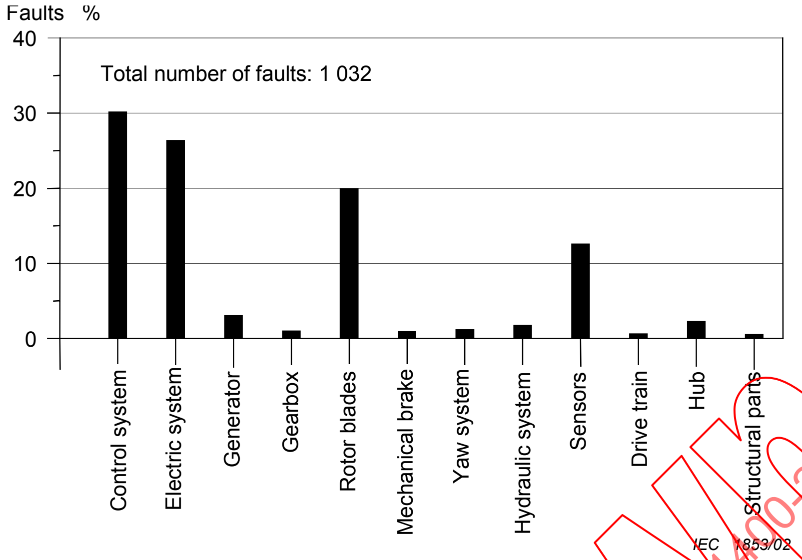


Figure 7 – Faults by component (Germany)

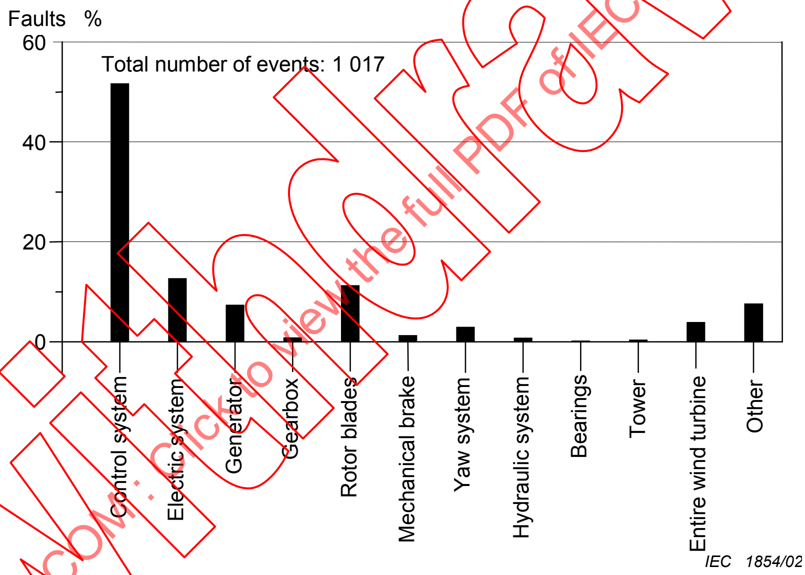


Figure 8 – Faults by component (Denmark)

A summary of the Swedish database is shown in table 7. The Swedish data indicate that 43 % of all events impact the control system, and 5,8 lightning damage events occur per 100 turbine years. It should be noted that damage to blades is 47 % more likely in this database if the turbine is configured with tip brakes.

Table 7 – Lightning fault summary (Sweden)

Type	Unit years	Lightning faults	Faults per 100 unit years	System faults per 100 unit years			
				Blade	Control	Power	Other
Tip brake	586	43	7,3	0,7	3,1	2,4	1,2
No tip brake	901	43	4,8	0,3	2,2	1,3	0,9
Total	1487	86	5,8	0,4	2,6	1,7	1,0

4.2.3 Turbine size and age issues

It is useful to assess the distribution of component damage as a function of wind turbine size. As has been pointed out, recent turbines are both larger (height and rated power) and more effectively protected against lightning damage. For the sake of comparison, turbines above 450 kW were considered to be of recent construction. These turbines should reflect some implementation of lightning protection. Figures 9 (Germany) and 10 (Denmark) show the distribution of component damage for new and old constructions using this 450 kW delimiter.

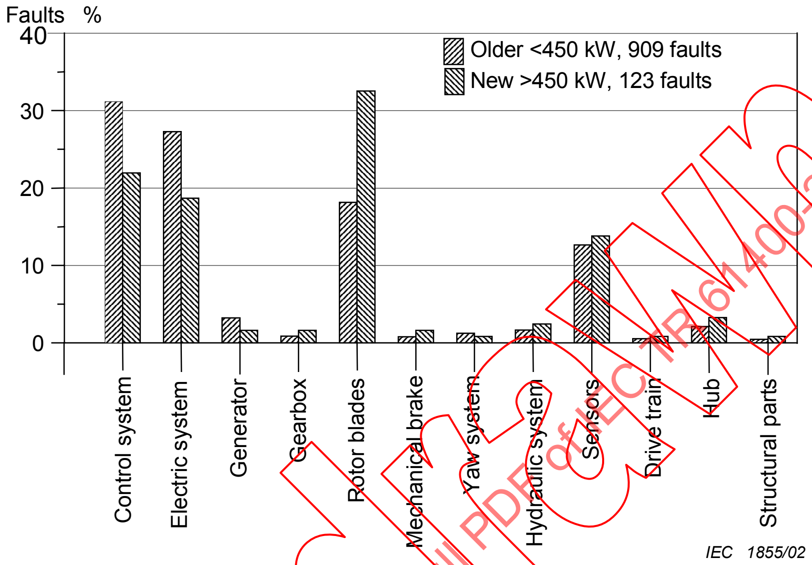


Figure 9 – Faults by component (Germany)

It is interesting to note that the damage pattern is different for newer turbines as compared to older turbines. With older turbines the most common damage was to the control system, while damage to the blades is the most common type with newer turbines. This is encouraging as it suggests that the lightning protection of control systems has improved in recent years.

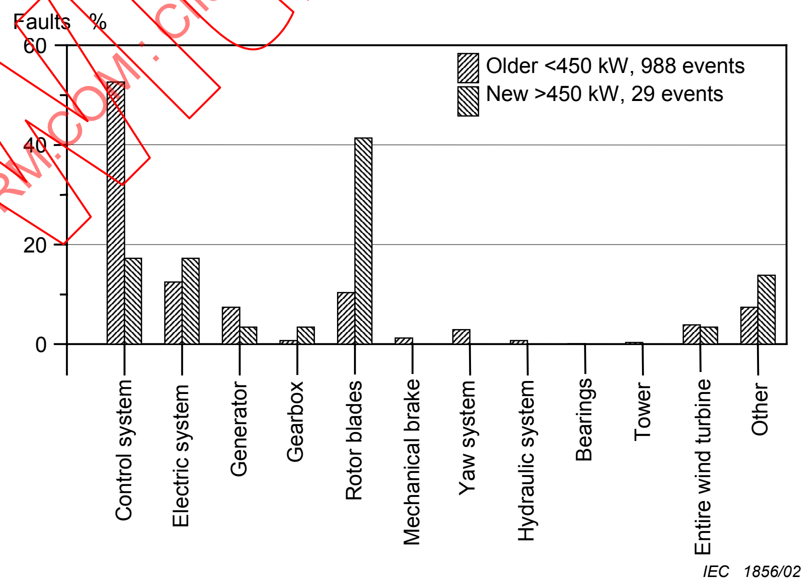


Figure 10 – Faults by component (Denmark)

4.2.4 Damage repair cost

The average repair cost (in DEM) of lightning fault events per component is shown in figure 11 from the German database. This includes the reported cost of replacement or repair, including labour, parts and crane costs, etc. By far, blade damage is the most expensive type to repair and, as one would expect, the larger turbines are more expensive to repair for most types of damage.

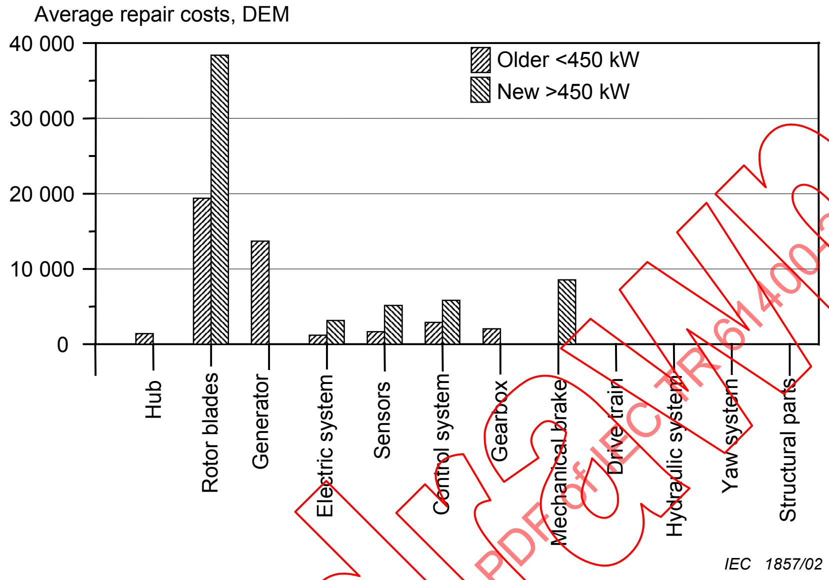


Figure 11 – Repair costs by component and size (Germany)

4.2.5 Impact on energy production

A turbine damaged by a lightning stroke has some downtime associated with the diagnosis of damage and the subsequent repair. Lost energy resulting from this downtime is lost income to the turbine owner. Figure 12 displays the average downtime attributable to such faults, also separated by component for the German data. Generator and blade damage result in large downtimes, probably due to component lead times and shipping. Surprisingly, control system repairs also lead to large downtimes.

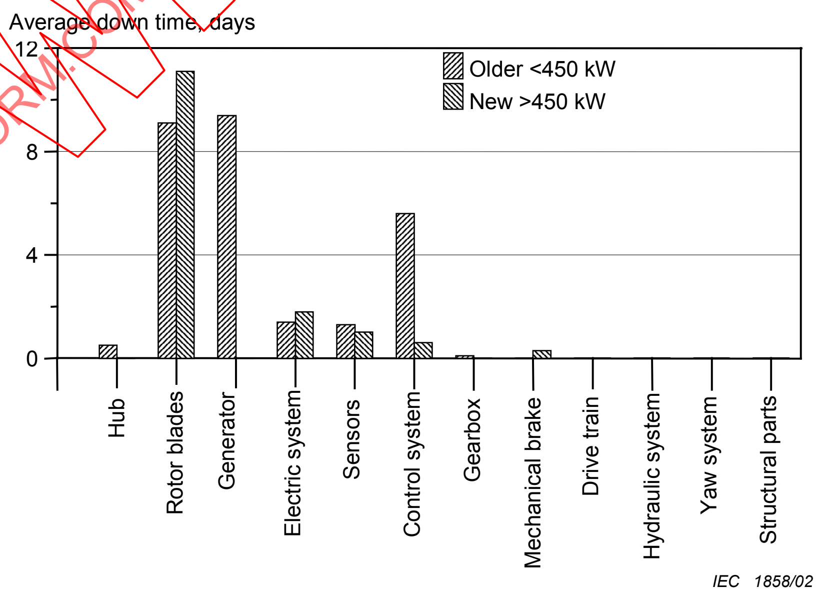


Figure 12 – Average down time by component and size (Germany)

It is interesting to compare the lost production and availability from lightning damage to those resulting from other faults. Such a comparison is shown in table 8 for the Danish database for the years 1992-1997. Undoubtedly, lightning faults have a larger impact than the average fault.

Table 8 – Energy and availability loss compared to other faults

Faults	**Number of incidents**	**Average wind turbine downtime** h	**Average lost energy** kWh
	DK	**DK**	**DK**
All faults	10 192	91	2 249
Lightning faults	461	110	3 200
Difference from average fault	–	+20,8 %	+42,3 %

4.2.6 Seasonal fault distribution

As is discussed elsewhere in this report, lightning behaves stochastically. Lightning activity and lightning incidences to ground vary in a seasonal and annual manner. Figure 13 shows wind turbine lightning fault incidence tracking the annual number of thunderstorm days in Denmark.

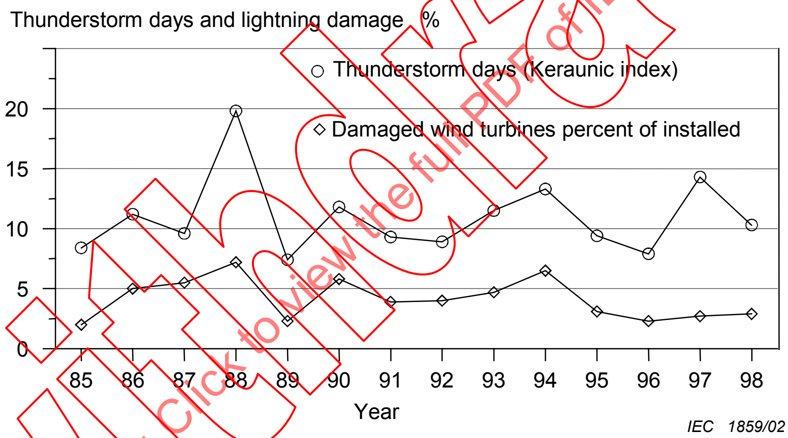


Figure 13 – Annual variation in lightning activity and damage (Denmark)

Figures 14 and 15 show information from the Danish and German databases that display this variability throughout the year. Note that in both countries winter thunderstorms cause a relatively high number of lightning faults even though the thunderstorm frequency is much lower than in the summer months.

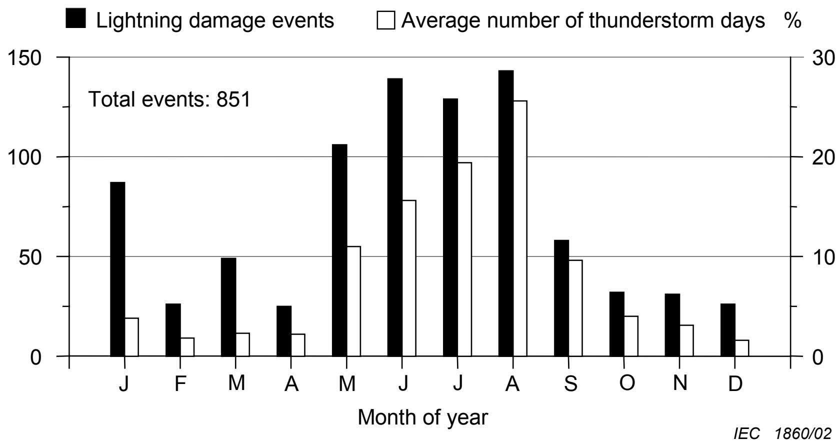


Figure 14 – Faults caused by lightning (Denmark 1990-1998)

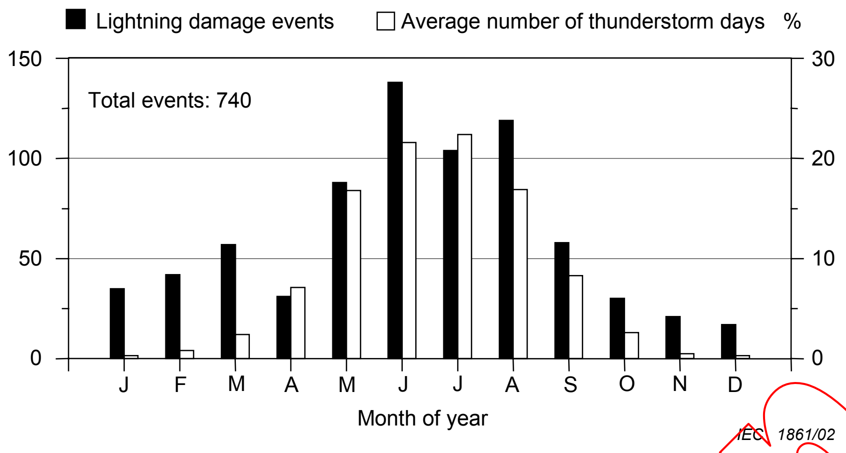


Figure 15 – Lightning damage events (Germany 1991-1998)

4.3 Database merits and weaknesses

There are wind turbine operation and maintenance databases available for significant numbers of units in Sweden, Denmark, and Germany. These databases have some merits and problems associated with their use in interpreting lightning damage data.

4.3.1 General

The results of analysis from the three databases can be different due to the following factors:

– different turbine heights;
– different levels of wind turbine lightning protection (turbine or site specific);
– susceptibility of local distribution system to conduct surges (overhead lines);
– variations in local lightning incidence levels or topography;
– variations in reporting practice and reporting reliability.

One lightning flash may cause multiple faults. How these are included in the data processing and how the operator chose to report the damage can be quite variable. Also, the nature of these databases is that only a problem or fault is reported (if the wind turbine did not automatically restart). As a result, direct strokes or indirect surges to a well-protected turbine go unreported. Use of these databases to quantify the level of risk would therefore have a tendency towards underestimation – especially in the case of recently installed (better protected) units.

4.3.2 Denmark

A rather thorough operations and maintenance database is available for about 2/3 of the 5000 turbines installed in Denmark which is maintained by:

Energi og Miljoedata
Niels Jernes Vej 10
DK 9220 Aalborg, Denmark

This is frequently reported on in Windstat's magazine.

4.3.3 Germany

The data concerning lightning events in Germany are taken from the "250 MW-Wind" Programme and the accompanying Scientific Measurement and Evaluation Programme (WMEP) operated by

Institut für Solare Energieversorgungstechnik e. V. (ISET)
Königstor 59
D-34119 Kassel, Germany

All wind turbine operators funded under this programme are obliged to deliver to ISET maintenance and repair reports for a minimum time period of 10 years. These reports have to be filled out in the case of turbine faults, including the assumed causes such as lightning strokes. Due to the obligation of the operators to participate in the WMEP to receive funding and the permanent data checks within the ongoing programme, the relatively high reliability of these data should be mentioned.

4.3.4 Sweden

Swedish turbine owners must submit monthly maintenance and production reports. This Swedish database is maintained by:

SwedPower AB, Vindstatistik
P.O. Box 527
S-162 16 Stockholm, Sweden

4.4 Conclusions and recommendations

4.4.1 Conclusions

The presented data above emphasizes the need for improved wind turbine protection.

The reported data shows that

– four to eight lightning faults have been experienced per 100 turbine years for Northern European countries;
– wind turbines placed in low mountain areas in Germany have shown up to 14 lightning faults per 100 turbine years;
– 7 % to 10 % of all lightning faults have involved blade damage;
– 43 % to 51 % of lightning faults have involved control system damage;
– 20 % to 32 % of lightning faults have involved damage to the power system;
– lightning faults have been responsible for 40 % more lost energy and 20 % more downtime compared to the average fault;
– although blade damage has been shown to be the most expensive type of damage, by far the most common was damage to the control system.

However, it should be noted that there are caveats which should be stated with the data. The following are examples:

– variations in local stroke frequency can be large even within a given country or region;
– lightning events (direct or indirect) to well-protected turbines do not show up in the database if they do not cause a fault;
– the differences in turbine heights, protection levels, and local topography impact these statistics;
– variations in reporting practices influence these statistics.

4.4.2 Database improvements

To improve the understanding of the impact of various damage mechanisms it would be useful to include more cost information in the wind turbine owner reports. This is not always feasible but recommended where possible.

A suggested lightning damage questionnaire is found in annex A. Use of this is recommended to provide consistent reporting between each country's maintenance database.

5 Evaluation of the risk of lightning damage to a wind turbine

5.1 Introduction

The design of any lightning protection system should take into account the risk of lightning striking and/or damaging the structure in question. The risk of lightning striking any structure is a function of structure height, the local topography and the local level of lightning activity. Lightning damage can take the form of the hazard posed to humans from step/touch voltages or explosions and fires caused by a lightning flash. Lightning damage can also be physical damage to the structure or its contents. Information about local lightning conditions should be collected whenever possible (for example at high latitudes where winter lightning may pose a special threat).

The goal of any lightning protection system is to reduce this damage to a tolerable level. The tolerable level is based on an acceptable risk if human safety is involved. If human safety need not be considered, or if the risk of damage is below the acceptable risk to humans, then any analysis is purely economic. This is done by assessing the cost of the lightning protection system against the cost of the damage it will prevent.

The standard IEC 61024-1-1 and the technical report IEC 61662 both include some information relating to the evaluation of the lightning risk to a structure. The information contained within these publications is summarized below and used to illustrate some important issues specific to wind turbine risks. The analysis is, however, a limited one and should not be used as a worked example. The full standard or technical report should be referred to.

5.2 Assessing the lightning flash frequency to a wind turbine

The first stage in any lightning risk analysis is the estimation of the frequency of lightning flashes. IEC 61024-1-1 gives guidance on how the lightning flash frequency can be estimated. When assessing the lightning flash frequency to a structure, the collection of data detailing the local ground flash density (N_g) is necessary. National organizations may be able to provide this information. If the ground flash density is not available, it may be estimated using the following relationship:

$$N_g = 0{,}04 \times T_d^{1{,}25} \qquad (1)$$

where

N_g is the annual average ground flash density per km^2;

T_d is the number of thunder storm days per year obtained from isoceraunic maps (typically available from national meteorological organizations).

The average annual frequency of direct lightning flashes to the structure can be assessed from

$$N_d = N_g \times A_d \times C_d \times 10^{-6} \qquad (2)$$

where

N_d is the annual average number of direct lightning strikes to the structure;

N_g is the annual average ground flash density;

A_d is the equivalent collection area of direct lightning strikes to the structure;

C_d is the environmental factor. Appropriate values are C_d = 1 for wind turbines on flat land and C_d = 2 for wind turbines on a hill or a knoll.

The equivalent collection area of a structure is defined as an area of ground surface which has the same annual frequency of direct lightning flashes as the structure. For isolated structures the equivalent collection area is the area enclosed with a border line obtained from the intersection between the ground surface and a straight line with a 1:3 slope which passes from the upper parts of the structure (touching it there) and rotating around it.

It is recommended that all wind turbines are modelled as a tall mast with a height equal to the hub height plus one rotor radius. This is true for wind turbines with any types of blades including blades made solely from non-conductive material such as glass reinforced plastic.

Figure 16 shows the equivalent collection area produced by a wind turbine placed on flat ground. Clearly this is a circle with a radius of three times the turbine height.

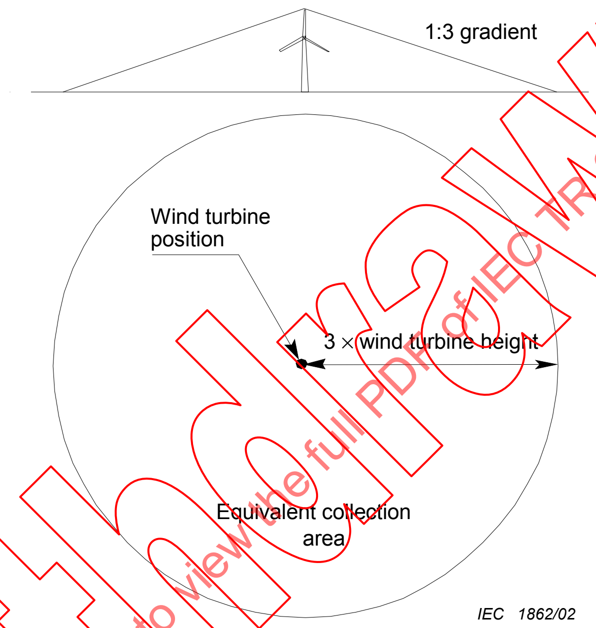


Figure 16 – Equivalent collection area of the wind turbine

The following equation can therefore be used when estimating the annual number of lightning flashes to a wind turbine placed on flat ground.

$$N_d = N_g \times 9\pi h^2 \times 10^{-6} \qquad (3)$$

where

h is the effective height of the wind turbine in metres.

IEC 61024-1-1 provides guidance when the turbine is in complex terrain or in proximity to other structures.

5.3 Use of IEC 61024-1-1

Once an estimate of the lightning flash frequency to a structure has been arrived at, a suitable lightning protection system must be selected. A failure of the lightning protection system results in what is known as a critical event. If a failure of the lightning protection system may result in the loss of human life, the permitted annual number of critical events may be set by a national or local statutory or regulatory authority. When any losses due to lightning will be purely economic, the permitted annual number of critical events may be set by the owner of the structure.

The permitted number of critical events generally varies according to the usage of the structure, the location, the construction and the average number of people within or near it at any given time.

IEC 61024-1-1 states that the number of permitted annual critical events (N_c) must be greater than or equal to the product of the annual average number of direct lightning strikes to the structure (N_d) and one minus the lightning protection system efficiency (1 – E).

$$N_c \geq N_d \times (1 - E) \quad (4)$$

where

E is the lightning protection system efficiency;

N_d is the number of annual average number of direct lightning strikes to the structure;

N_c is the permitted annual number of critical events.

The lightning protection system efficiency is a product of two individual efficiencies, the interception efficiency (ability to intercept a flash) and the sizing efficiency (ability to conduct the flash current). This concept is taken up in IEC 61024-1. The minimum lightning protection system efficiency can be defined using the following equation.

$$E \geq 1 - \frac{N_c}{N_d} \quad (5)$$

NOTE In the new revision of 61024-1 E is defined as:

$$E \geq 1 - R_a / R_d \quad (6)$$

where

R_d is the risk of damage;

R_a is the tolerable risk of damage.

IEC 61024-1 defines four lightning protection system levels, level I through level IV. These have the efficiencies shown below in table 9.

Table 9 – Lightning protection system levels

Protection levels	Interception efficiency E_i	Sizing efficiency E_s	Efficiency $E = E_i \times E_s$
I	0,99	0,99	0,98
II	0,97	0,98	0,95
III	0,91	0,97	0,90
IV	0,84	0,97	0,80

Physically, the more efficient lightning protection system will have larger conductor diameters and larger earthing systems (to improve the sizing efficiency) and will be designed with an increased quantity and/or reduced spacing of lightning interception points (to improve the interception efficiency). The current, specific energy, rate of current rise and charge transfer levels needed to obtain the various lightning protection system sizing efficiencies are shown in table 10.

Table 10 – Maximum values of lightning parameters corresponding to protection levels

Protection level	Peak current kA	Specific energy kJΩ⁻¹	Average rate of current rise kA/µs	Total charge transfer C
I	200	10 000	200	300
II	150	5 600	150	225
III	100	2 500	100	150
IV				

A level I lightning protection system must, for example, be able to carry a peak current of 200 kA without damage.

Example

Take a wind turbine with a hub height of 60 m and a rotor diameter of 60 m. It is situated in an area of flat ground with a ground flash density of 0,2 flashes per square kilometre per year. The permitted annual number of critical events is 1 in 100 000 (a level used in the United Kingdom). As the wind turbine will not contain personnel for more than 1 % of the year, the permitted number of critical events can be modified to be 1 in 1 000 (1 in 100 000 multiplied by 1 %). The estimated lightning flash frequency must first be found.

$$N_d = N_g \times 9\pi h^2 \times 10^{-6}$$
$$N_d = 0{,}2 \times 9\pi(90)^2 \times 10^{-6} \quad (7)$$
$$N_d = 0{,}046 \ year^{-1}$$

The lightning protection system (LPS) efficiency must be such that no more than 1 in 1 000 critical events per year occur. The required LPS efficiency can therefore be found.

$$E \geq 1 - \frac{N_c}{N_d}$$
$$E \geq (1 - \frac{10^{-3}}{0{,}046}) \times 100 \ \% \quad (8)$$
$$E \geq 97{,}8 \ \%$$

In this location, a LPS efficiency of 97,8 % is required so a level I lightning protection system would have to be installed.

5.4 Use of IEC 61662

While IEC 61024-1-1 allows the assessment of the level of lightning protection system to be provided for a particular object, a more rigorous analysis of lightning protection system requirements for a structure can be performed using the technical report IEC 61662.

IEC 61662 allows the assessment of the risk of both direct and indirect (magnetically coupled, transferred overvoltages, etc.) lightning damage in terms of safety or cost. In a similar manner to IEC 61024-1-1, a risk is calculated for a structure and compared with an acceptable risk level. If the calculated risk level exceeds the acceptable risk level, the lightning protection system on the structure must be improved. This is especially the case when there is a risk to human life.

The maximum cost of a lightning protection system can also be justified in terms of comparing the annual cost of installation with the annual cost of lightning damage that it prevents. This type of analysis can be performed if the risk to human life is zero or has been shown to be below the acceptable risk.

For the purposes of a wind turbine, the standard can be used as follows. Direct lightning damage, occurring when lightning strikes the wind turbine, takes one or more of a number of forms

- injury/loss of human life due to excessive step or touch voltages, debris, explosion and fire;
- fire/explosions following sparking of internal metallic parts;
- overvoltage damage to electronics contained within the wind turbine;
- damage to the blades[2].

Direct lightning damage is always proportional to the lightning stroke frequency that the structure in question will receive. In contrast, indirect damage occurs when lightning strikes a nearby object or the ground. It results from

- fire/explosion caused by the sparking of incoming services;
- overvoltage damage due to the rise in potential of incoming services;
- fire/explosions and overvoltage damage due to the rise in potential of items within the wind turbine due to coupled magnetic fields.

The indirect damage frequency varies according to the number of nearby lightning strokes and the number of lightning strokes affecting the incoming services.

If the total frequency of lightning damage is higher than the acceptable level, measures such as the installation of a better lightning protection system must be taken. Once the frequency of lightning damage causing human losses has been reduced below the acceptable frequency, a cost centred analysis can be carried out. The annual cost of any lightning protection system, c_{am}, should not exceed the annual cost of lightning damage (the frequency of lightning damage multiplied by its cost). This is expressed in the equation below.

$$c_{am} < F_{total} \times c_{losses} \quad (9)$$

where

F_{total} is the annual frequency of damage;

c_{losses} is the average cost per lightning damage event.

The annual cost of the turbine lightning protection system can be found using equation 10 as given in IEC 61662. This equation relates the total cost of the turbine lightning protection system, c_{pm} (during the lifetime of the turbine) with the annual cost using amortization (a), interest (i) and maintenance (m) rates. Substituting this into equation 9 leads to equation 11 that states the maximum amount of money that can economically be spent on the turbine lightning protection system.

$$c_{am} = c_{pm}(a + i + m) \quad (10)$$

$$c_{pm} < \frac{F_{total} \times c_{losses}}{(a + i + m)} \quad (11)$$

2 This type of damage has been added into the calculation but is not an inherent feature in the technical report IEC 61662. A method of modifying the standard to account for this is described.

where

c_{pm} is the total cost of the turbine lightning protection system;

a is the amortization rate;

i is the interest rate;

m is the maintenance rate.

This method of calculation does not involve the use of a defined level of acceptable risk but relies purely on an economic analysis.

As the cost of damage to the blades will be different to the cost of damage to the control system, it is suggested that the cost of protection measures be analyzed once for the blade lightning protection system and once for the control system. In both cases, the annual frequency of lightning damage will be different as will the expected cost of any losses. An example of such an analysis is given below.

5.5 Analysis of blade lightning protection system costs

Take the wind turbine detailed previously with a hub height of 60 m and a rotor diameter of 60 m. The estimated annual lightning flash frequency was 0,046 flashes per year. Assume that all of the lightning flashes that the turbine receives attach to the blades. For a turbine with unprotected blades we can assume that each lightning flash will cause damage to the blades severe enough to require blade replacement.

If we could incrementally install a lightning protection system, each 1 % of efficiency would result in a reduction in the amount of lightning damage by

$$N_p = N_d \times 0,01$$
$$N_p = 0,046 \times 0,01 = 0,000\ 46\ \text{year}^{-1} \qquad (12)$$

where

N_p is an estimate of the annual number of blade faults that will be prevented with 1 % efficiency of the blade lightning protection system.

Every 1 % of lightning protection system efficiency increase will result in a reduction in the annual amount of lightning damage. There is a cost-saving associated with this reduction:

$$c_{saved} = N_p \times c_{damage} \qquad (13)$$

where

c_{saved} is the cost-saving resulting from a decrease in the annual frequency of lightning damage;

c_{damage} is the cost associated with the replacement of a blade following a lightning stroke.

The cost of blade damage can be represented as a percentage of the turbine cost. If each blade is 5 % of the turbine cost, then the equation above can be re-written as:

$$c_{saved} = N_p \times c_{damage}$$
$$c_{saved} = 0,00046 \times 0,05 \times c_{turbine} \qquad (14)$$
$$c_{saved} = 0,023 \times c_{turbine} \times 10^{-3}$$

where $c_{turbine}$ is the cost of the wind turbine.

It is only economic to install a blade lightning protection system if the annual cost of the system over the turbine lifetime is less than the cost-saving that results from the installation. From the equations described earlier, it can be said:

$$c_{\text{pm}} < \frac{c_{\text{saved}}}{(a+i+m)} \tag{15}$$

Take the case where a = 4 %, i = 8 % and m = 1 %. Using the previously derived expression for c_{saved}:

$$c_{\text{pm}} < \frac{0{,}023 \times c_{\text{turbine}} \times 10^{-3}}{(a+i+m)}$$
$$c_{\text{pm}} < 0{,}18 \times c_{\text{turbine}} \times 10^{-3} \tag{16}$$

An expression giving the maximum cost of 1 % efficiency of the blade lightning protection system as a function of the turbine cost has now been produced. The equation can, however, be simplified further:

$$\frac{c_{\text{pm}}}{c_{\text{turbine}}} < 0{,}18 \times 10^{-3}$$
$$\frac{c_{\text{pm}}}{c_{\text{turbine}}} < 0{,}018\ \% \tag{17}$$

This equation shows that for the turbine detailed, the maximum cost of 1 % of blade lightning protection system efficiency is 0,018 % of the total turbine cost. We could, therefore, say that the installation of a level II (95 % efficient) blade lightning protection system could cost up to 1,7 % (95 % × 0,018 = 1,7 %) of the total turbine cost in an area with a relatively low annual ground flash density of 0,2 flashes per km^2.

5.6 Analysis of lightning protection costs for wind turbine control systems

Unlike lightning damage to wind turbine blades, damage to control systems comes from a number of direct and indirect sources. Coupled with the more distributed and diverse nature of wind turbine control systems, this makes an analysis of the lightning protection costs for wind turbine control systems more difficult to perform.

Take as an example, the turbine previously discussed. The turbine will receive 0,046 direct lightning strokes annually. The number of indirect strokes that will affect the wind turbine are, however, much greater. The turbine is situated in an area with a soil resistivity of 250 Ωm. Power cables and a metallic SCADA system cable run from the turbine to a substation sited 1 km away.

IEC 61662 states that these services will be affected by a number of lightning strokes to ground. The average annual number of lightning strokes affecting the incoming services, N_{k}, can be assessed as follows:

$$N_{\text{k}} = N_{\text{g}} \times A_{\text{k}} \times 10 \tag{18}$$

where

A_{k} is the area of influence of the service in km^2, this includes the effective collection area of the service itself and the effective collection area of any adjacent structure connected to the service under consideration.

The procedure for assessing A_k is given in IEC 61662. In the example given, the power cable would have an area of influence of 0,05 km^2 while the data cable would have an area of influence of 1 km^2. The total number of lightning strokes affecting these incoming services is therefore 0,01 and 0,2 per year for the power and data cable respectively. In comparison to estimated annual lightning flash frequency of 0,046 per year, it is clear that the data cable will suffer by lightning flashes approximately four times that of the wind turbine itself. If a fibre-optic cable with no metallic shield is used, the number of lightning strokes affecting the data cable would have been reduced to zero.

Further damage mechanisms concerned with magnetic field coupling are given in IEC 61662 (amendment 1). The result is that damage to wind turbine control systems can occur with a greater frequency in comparison to blade damage.

The earlier analysis concerning blade damage showed that the cost of a lightning protection system was proportional to the frequency and cost of damage. For wind turbine control systems, the frequency of damage will be increased in comparison to blade damage but the cost of such damage will fall. The effect on the maximum amount that can be economically spent on 1 % of lightning protection system efficiency for the turbine control systems would depend on the exact configuration of the wind turbine, something that is beyond the scope of this report.

6 Lightning protection of wind turbine blades

6.1 Blade structure

Modern wind turbine blades are large hollow structures manufactured of composite materials, such as glass reinforced plastic (GRP), wood, wood laminate and carbon reinforced plastic (CRP). CRP is typically used for reinforcement of the blade structure or for special components such as the tip shaft for blades with tip brakes (tip-stall braking mechanism). Some parts and discrete components such as mounting flanges, balancing weights, hinges, bearings, wires, electrical wiring, springs and fixtures are made of metal. At some point in time hopes were high that lightning would not strike blades made of non-conducting material only, but practical experiences have clearly demonstrated that this is not the case. Lightning does in fact strike blades without any metallic components, and whenever a lightning arc is formed inside the blade damage is severe.

The two sides or surface skins of a blade are normally manufactured as separate sheets of glass fibre or other composite materials glued together along the leading and trailing edges and to an internal load-carrying structure also made of glass fibre. Inside the blade, there are large air filled cavities formed by the surface skin and the internal structure and stretching the entire length of the blade.

There are several types of blades depending on the control and braking mechanism employed. Four main types are shown in figure 17.

Type A blades use a flap (aileron) in the outer part of the leading edge for braking. On type A blades, lightning attachment points are often found on the steel flap hinges, and severe damage is often seen since the cross-section of the steel wires used for operating the flap is usually insufficient for conducting the lightning current.

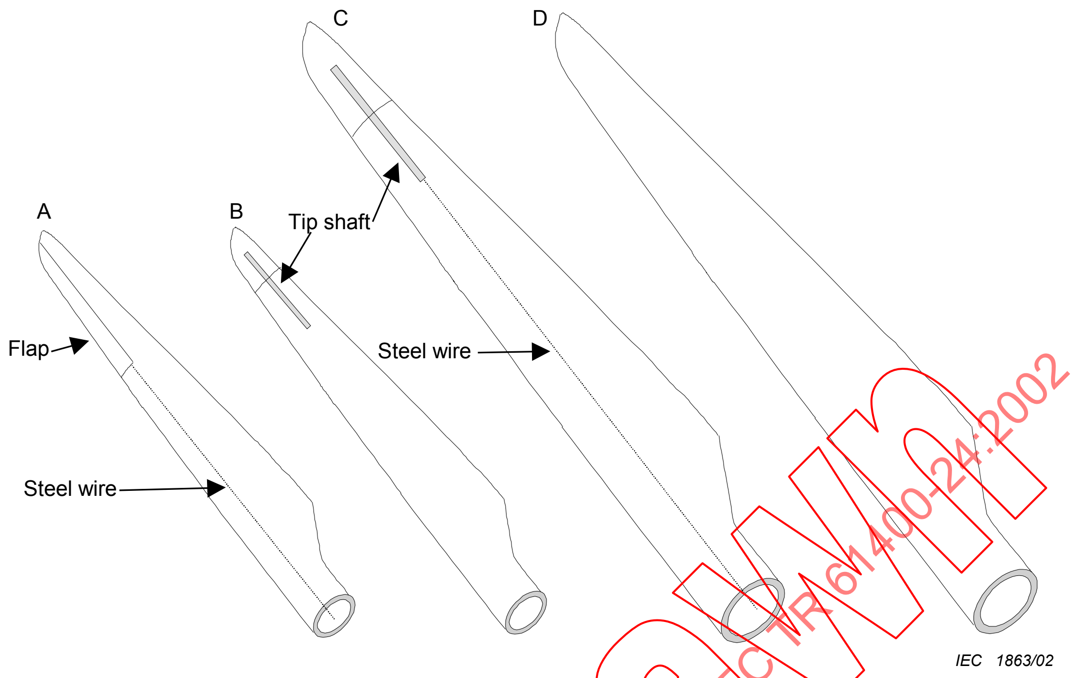


Figure 17 – Types of wind turbine blades

Type B blades use a tip brake which is retained by a spring and released at excessive rotational speed by centrifugal force. With type B blades, lightning attachment points are predominantly seen within a few tens of centimetres from the outermost tip, or on the sides of the tip at the position of the outermost end of the tip shaft. From the attachment point, a lightning arc is formed inside the tip section to the outermost end of the tip shaft, and from the other end of the shaft an arc is formed inside the main blade down to the steel mounting flange at the blade root. Such internal arcs invariably cause catastrophic destruction to the blade. Blades of type A and B were commonly used with older wind turbines as large as 100 kW.

Type C is a modern blade with a tip brake controlled by a steel wire. With type C blades lightning attachment points are predominantly found within a few tens of centimetres from the outermost tip of the blade, or on the sides of the tip at the position of the outermost end of the tip shaft. With type C as with type B, a lightning arc formed inside the tip section between the attachment point and the outermost end of the shaft causes severe damage. On type C blades, damage to the main blade is mostly seen when the steel wire has been unable to carry the lightning current. Steel wires used for this purpose are of a minimum diameter of 10 mm or 12 mm for 17 m long blades. Such wires are capable of conducting most lightning currents, and thereby protecting the main blade from damage (See 6.5 for further discussion of the sizing of materials).

Type D is a blade constructed entirely from non-conducting materials. As with the other types of blades, lightning attachment points are mostly found close to the tip. Compared to the other types of blades, attachment points can also be found randomly distributed at other positions along the length of the blade.

Lightning strokes to non-conducting blades may at least partly be explained by the fact that pollution and water make such blades more conductive over time. High voltage laboratory experiments have shown that arc attachments occur to a non-conducting blade sprayed with saline water practically as if the blade were metallic [9]. Another part of the explanation is that the blades are simply in the way of lightning striking the wind turbine. In addition, it is known that discharges develop along a surface more easily than through air. In any case, practical experience shows that severe lightning damage to non-conducting blades (type D) is quite common.

6.2 Blade damage mechanism

Typical types of damage at the lightning attachment points are delamination and incineration of the surface composite material, and heating or melting of metallic components serving as the attachment point.

The most severe damage to wind turbine blades is caused, however, when lightning forms arcs inside the blade. The arcs may form in the air filled cavities inside the blade or along the internal surfaces. Another type of damage is seen when the lightning current or part of it is conducted in or between layers of composite materials, presumably because such layers hold some moisture. The pressure shock wave caused by such internal arcs may literally explode the blade, ripping the blade surface skins apart along the edges and from the internal carrying spar. All grades of damage are seen ranging from surface cracking to complete disintegration of the blade. In some cases, pressure waves have propagated from the blade struck by lightning through the hub and into the other blades causing pressure damage to them.

Internal arcs often form between the lightning attachment point at the tip of the blade and some conducting component internal to the blade. With type C, the damage is often limited to the tip section, whereas the main blade is unharmed. Damage to type C main blades has normally been seen when an arc has formed inside the main blade. Typically, this has happened in cases where the steel wire controlling the tip brake was of insufficient cross-section to conduct the lightning current from the tip shaft to the hub. With type A blades, the main blade is destroyed.

The phenomenon responsible for the severe structural damage to wind turbine blades is therefore the formation of a pressure shock wave around an arc of lightning inside the blade. Minor damage may occur when a lightning arc is formed on the outside surface or when the lightning current is conducted by metallic components with insufficient cross-section.

6.3 Lightning protection for wind turbine blades

6.3.1 Generic problem

The generic problem of lightning protection of wind turbine blades is to conduct the lightning current safely from the attachment point to the hub, in such a way that the formation of a lightning arc inside the blade is avoided. This can be achieved by diverting the lightning current from the attachment point along the surface to the blade root, using metallic conductors either fixed to the blade surface or inside the blade. Another method is to add conducting material to the blade surface material itself, thus making the blade sufficiently conducting to carry the lightning current safely to the blade root. Variations of both these methods are used with wind turbine blades (see figure 18).

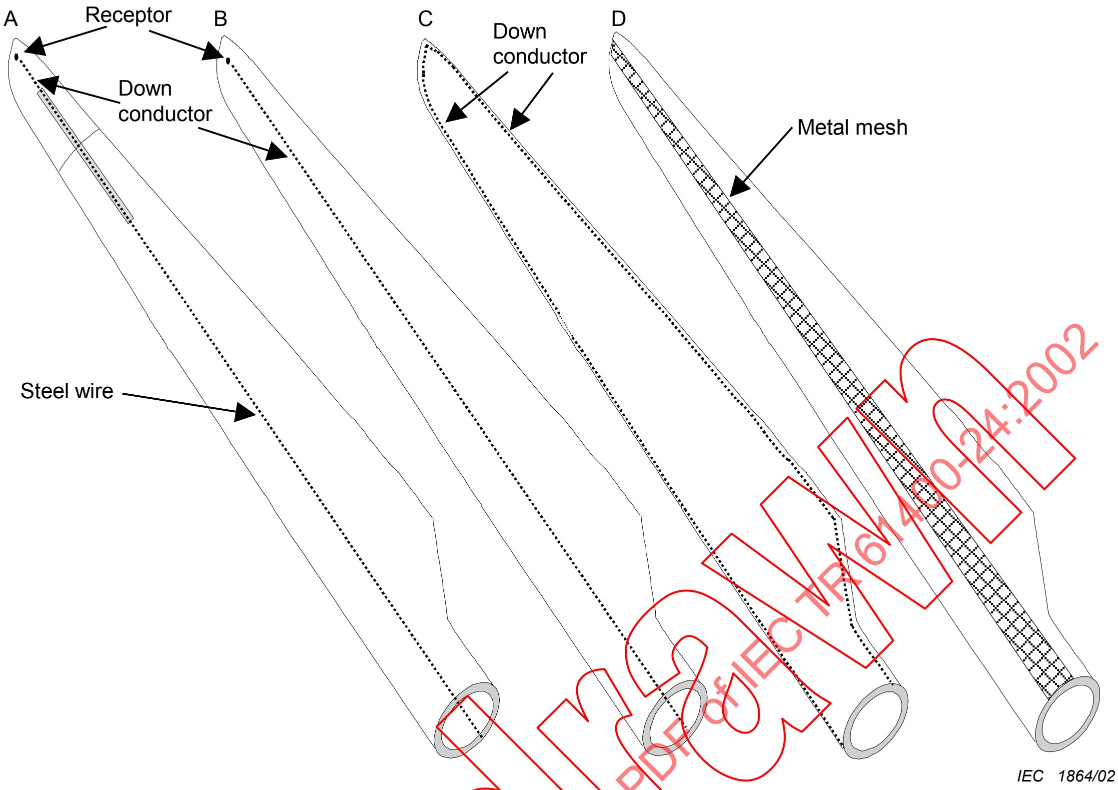


Figure 18 – Lightning protection for large modern wind turbine blades

6.3.2 Lightning air termination systems on the blade surface or embedded in the surface

Metallic conductors on the blade surface serving as an air termination system or a down conductor system must have sufficient cross-section to be able to withstand a direct lightning stroke and conduct the full lightning current. In addition, certain dimensions are needed in order to achieve reliable fixing to the blade surface. The minimum cross-section for aluminium is 50 mm^2 and achieving reliable fixing of such conductors may be problematic. Furthermore, conductors mounted on the blade surface may compromise the aerodynamics of the blade or generate undesirable noise [10] [11].

For lightning conductors embedded in the blade, wires or braids of either aluminium or copper are used. In the literature, several protection systems are described where a metallic conductor connected to the blade root is placed either on the blade surface along the trailing edge of the blade or embedded in the trailing edge. Some blade constructions have metallic conductors placed along both the leading and the trailing edge (type C). In addition, some have metallic diverters placed on the surface around the blade at several positions along the blade, each of these being connected to conductors placed along the blade edges [11] [12] [13] [14] [15].

6.3.3 Adhesive metallic tapes and segmented diverter strips

Adhesive aluminium tape placed on the blade surface has been used in several investigations. However, such tapes tended to peel off within a few months [12] [16]. Provided that the problem of keeping the tape on the blade can be solved, it is possible that metallic tapes can be an interesting protection method, especially for existing unprotected blades. It should, however, be noted [10] that large pressure waves are associated with guiding the flash close to the blade surface. This may lead to structural damage.

Some promising experiments with segmented diverter strips have been performed recently [17] [18]. Such segmented strips are used on aircraft radomes because they do not interfere with the radar signal. However, no application of segmented diverter strips on wind turbine blades has been reported.

It is possible that metallic tape and segmented diverter strips can be used as one-shot protection requiring replacement after a lightning stroke.

6.3.4 Internal down conductor systems

A solution to the problems with conductors placed on the blade surface is to have the lightning conductors placed inside the blade. Metallic fixtures for the conductor penetrate the blade surface and serve as discrete lightning receptors. Such protection systems are used on aircraft [10].

The lightning protection system used on many blades currently in manufacture have such discrete lightning receptors placed at the blade tip (types A and B). From the receptors at the tip, an internal down conductor system leads the lightning current to the blade root. For blades with tip brakes, the steel wire controlling the tip is used as a down conductor (type A). If the blade is without tip brake, then a copper wire placed along the internal spar is used as a down conductor (type B).

Within the last few years several thousands of blades with this lightning protection system (types A and B) have been produced. Early experiences with this lightning protection system for blades as long as 20 m are very promising [19]. However, experience with longer blades is insufficient at the time of publication.

6.3.5 Conducting surface materials

An alternative to a lightning air termination system placed on the blade surface, is to make the surface itself conducting. In the aircraft industry, lightning protection of glass and carbon fibre composite material for wings and surfaces exposed to lightning is achieved by adding conducting material to the outer layers, thereby reducing damage to a small area at the attachment point. The conducting material may be metal sprayed onto the surface, metal coated fibres in the outer layers of the composite material, metal wire woven into the outer layers of the composite material, or meshes of metal placed just beneath the surface [10] [15] [21] and [20]. Lightning protection of wind turbine blades have been made with metal mesh placed along the sides of the blades just under the gel coat (figure D). Sometimes the extreme tip of the blade is either made of metal or covered with a metal sheet [12] [13] [14] [15] [22] and [23].

6.4 Interception efficiency

The interception efficiency is an issue with the lightning protection methods using discrete air-termination systems placed on the blade surface. Solid conductors and segmented diverters on the surface and discrete receptors penetrating the surface must be placed in such a way that the likelihood of lightning attaching to the unprotected part of the surface is reduced to an acceptable level.

The spacing of discrete receptors giving an interception efficiency equal to that of solid conductors would in theory be the spacing where the flashover voltage along the blade surface is smaller than the breakdown voltage of the blade skin. In practice, both the breakdown voltage of the blade skin and the surface flashover voltage will be difficult to establish as variations due to different composite material as well as influence of ageing, cracks, humidity and pollution must be expected. Furthermore, the interception efficiency of segmented diverters and of discrete receptors will be influenced by the presence of conducting materials inside the blade [10]. For instance, on aircraft radomes solid conductors are placed on the surface with spacing ranging from 30 cm to 60 cm, however, the interception efficiency is not 100 %, as occasional puncture of protected aircraft radomes occur.

Conductors placed on the inside of the radome are for mechanical reasons fixed every 15 cm with fasteners protruding to the outside and serving as receptors [10].

For blades up to 20 m long, it appears that receptors at the tip of the blade are adequate. It may be necessary for longer blades to have more than one receptor to obtain the desired interception efficiency. Documentation of practical experiences and further research into the problem of designing adequate air-termination systems for wind turbine blades longer than 20 m is needed.

6.5 Sizing of materials

The materials used for lightning protection of wind turbine blades shall be able to withstand the electric, thermal and electrodynamic stresses imposed by the lightning current. Minimum dimensions for materials used for air termination and down conduction are listed in table 11 (see also IEC 61024-1).

Table 11 – Minimum dimensions of lightning protection system materials

Material	Air termination mm^2	Down conductor mm^2
Copper	35	16
Aluminium	70	25
Steel	50	50

Further, dimensions which take into account electrical and electrodynamic effects and predictable accidental stresses are under consideration by IEC TC 81, as shown in table 12 (see also IEC 61024-1).

Table 12 – Proposed minimum dimensions for lightning protection system materials

Material	Configuration	Minimum cross-sectional area mm^2
Copper	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round for air termination rods	200
Aluminium	Solid tape	70
	Solid round	50
	Stranded	50
Aluminium alloy	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round for air termination rods	200
Hot dip galvanized steel	Solid tape	50
	Solid round	50
	Stranded	50
	Solid round for air termination rods	200
Stainless steel	Solid tape	60
	Solid round	78
	Stranded	70
	Solid round for air termination rods	200

Components under load such as the steel wires for tip brakes may have to be even more solid, as the mechanical strength is reduced if heated to high temperatures. There are a few experiences with steel wires for tip brake control that have broken or melted due to lightning currents even for wires of up to 10 mm diameter (cross-sectional area 78 mm^2). The temperature rise of conductors carrying lightning current can be evaluated as shown in equation 19 (see also IEC 61819). The constructor must consider the temperature rise of all components subjected to all or parts of the lightning current and secure that such components have sufficient strength to fulfil its function immediately after a lightning stroke. Equation 19 may be used to calculate the temperature rise:

$$\theta - \theta_0 = \frac{1}{\alpha} \times \left\{ \exp\left[\frac{(W/R \times \alpha \times \rho_0}{q^2 \times \lambda \times c_w} \right] - 1 \right\} \qquad (19)$$

where

$\theta - \theta_0$ is the temperature rise of the conductors (K);

α is the temperature coefficient of the resistance (1/K);

W/R is the specific energy of the current impulse (J/Ω);

ρ_0 is the specific ohmic resistance of the conductor at ambient temperature (Ωm);

q is the cross-sectional area of the conductor (m^2);

γ is the material density (kg/m^3);

c_w is the thermal capacity (J/kgK).

Table 13 shows the inputs to this equation for common materials and table 14 shows temperature rises for different conductors. It should be noted that in the case of pre-loaded wires the temperature rise does not have to reach the melting point to cause failure.

Table 13 – Physical characteristics of typical materials used in lightning protection systems

Quantity		Material			
		Copper	Aluminium	Mild Steel	Stainless steel [a]
ρ_0	Ωm	$17{,}8 \times 10^{-9}$	29×10^{-9}	120×10^{-9}	$0{,}7 \times 10^{-6}$
α	1/K	$3{,}92 \times 10^{-3}$	$4{,}0 \times 10^{-3}$	$6{,}5 \times 10^{-3}$	$0{,}8 \times 10^{-3}$
γ	kg/m^3	8 920	2 700	7 700	8 000
θ_s (melting point)	°C	1 080	658	1 530	1 500
c_s	J/kg	209×10^3	397×10^3	272×10^3	–
c_w	J/kgK	385	908	469	500

[a] Austenitic non magnetic

Table 14 – Temperature rise [K] for different conductors as a function of *W/R*

Cross-section mm^2	Material											
	Aluminium			Steel			Copper			Stainless steel		
	W/R MJ/Ω			*W/R* MJ/Ω			*W/R* MJ/Ω			*W/R* MJ/Ω		
	2,5	**5,6**	**10**	**2,5**	**5,6**	**10**	**2,5**	**5,6**	**10**	**2,5**	**5,6**	**10**
4	–	–	–	–	–	–	–	–	–	–	–	–
10	564	–	–	–	–	–	169	542	–	–	–	–
16	146	454	–	1120	–	–	56	143	309	–	–	–
25	52	132	283	211	913	–	22	51	98	940	–	–
50	12	28	52	37	96	211	5	12	22	190	460	940
100	3	7	12	9	20	37	1	3	5	45	100	190

6.6 Blade to hub connection

At the root of the blade, the down conduction system is usually either terminated to the blade mounting flange or to the hub.

If the blade is pitch regulated (type D), the lightning current is either allowed to pass uncontrolled through the pitch bearing or some kind of bonding across the bearing is provided such as a sliding contact or a flexible bonding cable with enough slack to allow for the pitch motion. The flexible bonding across the bearing can be combined with the innermost part of the down conductor from the blade.

In blades with tip brake (type C), the hydraulic system, which actuates the control wire, must be protected. Standard hydraulic cylinders that are normally used can be damaged by flashovers from the rod to the cylinder housing. Usually, the hydraulic cylinder is protected by diverting the lightning via a flexible bonding strap with sufficient slack to allow for the motion. Another approach with a sliding air gap construction has been described [24].

Care must be taken to reduce the slack in such bonding straps, since the inductive voltage drop across the slack may become very high, thus resulting in inefficient protection of the cylinder [24].

6.7 Carbon reinforced plastic (CRP)

Carbon reinforced plastic (CRP) is widely used for tip shafts and, in some cases, for re-inforcement of the blades. The use of CRP is expected to increase as blades get bigger.

The conductivity of CRP materials depends very much on the orientation of the fibres. Although carbon fibres are electrically conducting, CRP materials, where layers of carbon fibres are fixed in a matrix, have a conductivity about 1 000 times lower than aluminium [25] and [21]. Therefore, the resistive heating of CRP conducting current is very high, and gases develop in the material as the matrix evaporates at about 200 °C. The pressure from evaporating gases can cause rupture and delamination of the layers. The CRP may even incinerate, in particular at the lightning attachment point [21].

In aircraft where CRP is used, it is considered mandatory that lightning protection is provided for CRP components that may be struck by lightning or may conduct lightning current [10].

Cases are known where CRP tip shafts for wind turbine blades have been damaged by lightning. Some laboratory experiments have also demonstrated problems with CRP shafts conducting lightning current [24]. Laboratory tests of blades with CRP skin have shown surface delamination and incineration at the lightning attachment point [9] and [26].

CRP should be considered as a conductor and hence proper bonding between CRP and other conducting components must be made. CRP components of large dimensions may be able to conduct lightning current without being damaged. Further research is needed since there is not sufficient information available about the lightning **current-carrying** capability of CRP materials in general, and particularly, not of the specific CRP materials and configurations used in wind turbine blades.

6.8 Wiring inside blades

Wiring for sensors placed on or inside blades must be protected by appropriate equipotential bonding to the down conduction system. Wiring should either be shielded cables or placed in metal tubes. The shielded cable or metal tube should be placed as close as possible to the down conductor and bonded to it.

7 Protection of bearings and gearbox

7.1 Damage to bearings due to AC and DC currents

Electric currents are known to cause damage to bearings. Most experience of this originates from machinery in which AC or DC currents pass through bearings which form a path in an electrical circuit. Such currents cause damage over time even at current densities lower than 2 A/mm^2. At a current density of 1,4 A/mm^2, bearings are damaged within a few thousand hours and even at 0,7 A/mm^2, damage is to be expected. The lower limit, at which only a small risk of damage remains, is about 0,1 A/mm^2 [27]. Other relatively well-known sources of damage are welding currents and recurring electrostatic discharge currents passing through bearings to ground.

7.2 Damage to bearings due to lightning currents

Clearly, lightning currents have a much shorter duration compared to the above-mentioned AC and DC currents. Arcing between bearing raceways and rolling elements can dissipate energy enough to cause severe pitting.

Practical experience with lightning damage to wind turbine bearings is scarce since wind turbine bearings are not normally checked after lightning strikes. Also, it is difficult to establish the chain of evidence as it may take years before the ensuing damage has developed. Furthermore, such delayed damage to bearing rolling elements and raceways is not easily attributed as caused by lightning, because the pitting and molten material originating from the lightning current arc is eroded as more and more material from the rollers and raceways is milled inside the bearing. Most of such cases of delayed damage are probably never identified as being caused by lightning.

There have been cases, however, where lightning appears to have been the cause of damage to bearings. In particular, two or possibly three instances of damage to the offshore wind turbines should be mentioned since they have drawn considerable attention – not least because of the high repair costs. In those cases, the wind turbines in question were hit by lightning causing damage to the blades, and after some time severe damage to the large main bearings developed. Such major component repairs are costly and even more so for wind turbines located offshore.

Recently, four wind turbines in a wind farm in Denmark were struck by lightning. The owner, a power utility, decided to dismantle a 90 kW wind turbine struck by lightning to check the bearings. This wind turbine clearly had not been running after the time of the lightning stroke since one blade was completely destroyed and lay on the ground. Pitting and abrasion damage of up to 3 mm were found on about a dozen of the 46 rollers, and a corresponding number of similar marks were found on the raceways of the front main bearing. The bearing manufacturer subsequently estimated that such damage would result in a reduction of the remaining bearing lifetime by a factor of 3.

7.3 Laboratory investigations

Few investigations of the damaging effect of lightning current on bearings have been made. In one investigation [28], it was found that lightning current caused abrasions at the points of formation of arcs between rollers and raceways. Damage to a bearing was found to occur at current densities above a threshold of approximately 4 kA/mm^2. The damage threshold increased with increasing mechanical load on the bearing. Bearings with low mechanical loads had discrete pitting and abrasions, but those with higher loads exhibited damage in the form of a flute shape along the contact zone between rollers and raceway. At higher current values the characteristic shapes remained the same, but, the amount of molten material and the damaged area increased. Apart from the current density and the load, it was found that the amount of damage was reduced when the bearings were lubricated.

Another set of results have been produced by other researchers who applied lightning currents to pitch bearings and generator bearings [24]. They made identical tests to a rotating and a stationary generator bearing, and they only observed damage on the rotating bearing. The cause of damage is the arcing between rolling elements and raceways at the breakdown points through the insulating hydrodynamic lubrication layer present in the rotating bearing.

It is evident that further investigations into the damage mechanisms of bearings is required. Investigation of the lightning current distribution from the wind turbine hub to the tower have shown that 80 % of the applied lightning current pulse passed through the outermost main shaft bearing. The other 20 % was distributed through the second main shaft bearing, the gearbox and the generator [29].

7.4 Lightning damage to gearbox

Except for the above-mentioned investigation [29] which documented that part of the lightning current which will enter the gearbox, there is no solid evidence available about damage to gears due to lightning.

There have been cases where gears and shaft bearings have been damaged in connection with lightning striking the wind turbine blades. However, so far, it has not been established if such damage is a secondary effect of main bearing lightning damage [30]. In some cases, pitting has been found in dismantled gearboxes, but again it has been difficult to establish a solid chain of evidence.

7.5 Lightning protection of bearings and gearbox elements

It is possible that large heavily loaded bearings and stationary bearings may be able to conduct the lightning current without significant damage. Therefore, lightning protection of the slow moving pitch bearings and yaw bearings may not be needed. In any case, it is recommended that an alternative current path be provided across bearings at risk with a flexible conductor, a sliding contact or similar arrangement.

As far as the main shaft bearings, gearbox and generator bearings are concerned, it is difficult to combine the need for lubrication to reduce friction with the good metallic contact needed to conduct lightning currents. Attempts at reducing the fraction of lightning currents passing through the main shaft bearings by providing alternative current paths with sliding contacts, brushes and spark gaps, are being made by most manufacturers. Large bearing structures have very low impedances, whereas sliding contacts, brushes or spark gaps with their connections to local ground have higher impedances. Therefore, such measures cannot divert all of the lightning current away from the bearings [30].

Some manufacturers use diversion components, such as carbon brushes, designed for much lower current levels. This may result in arcing across or through the component when subjected to lightning current. Furthermore, wear of brushes may require frequent replacement, and with carbon brushes there may be a problem with carbon dust [12].

In order to reduce the lightning current through bearings, the lightning current must be diverted via a low impedance path, and the impedance of the bearing structure must be increased by incorporating a resistive or insulating layer somewhere in the current path through the bearing [30] and [31]. Figure 19 shows how such an alternative current path can be established at the front end of the low speed shaft, while at the same time introducing insulating layers in all the current paths through the bearings, the gearbox and the high speed shaft to the nacelle bedplate (local ground plane). Many manufacturers make use of a flexible coupling inserted in the high speed shaft, which may also provide the needed insulation and thereby protect the generator from lightning currents entering into the generator shaft [32].

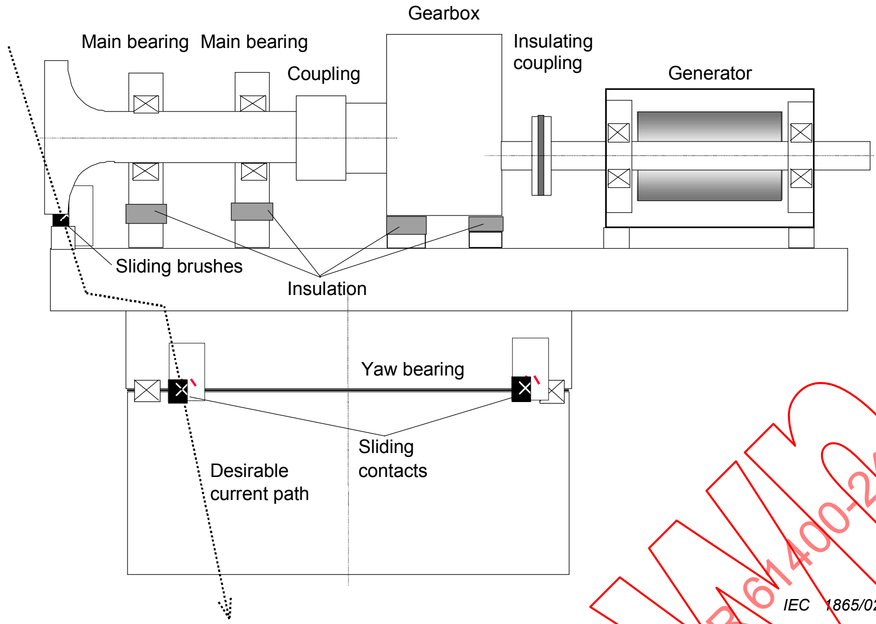


Figure 19 – Alternative current path to reduce lightning current

Consideration has to be paid to the large voltages that may develop between the insulated drive train and the nacelle bedplate during a lightning flash or an electric fault since this can be hazardous to personnel present in the nacelle. Electrical equipment on the drive train must be protected against these overvoltages.

8 Protection of electrical and control system

8.1 Introduction

In this chapter, the basic electrical system of a wind turbine is described. Also, a methodology is presented to define zones of protection to facilitate the choice and sizing of an appropriate protection methodology for the electrical components. Finally, methods for shielding, bonding and surge protection are described.

8.2 Configuration of electrical equipment

8.2.1 Electrical system

Irrespective of the choice of generator, control principles, voltage levels and physical arrangement of the electrical equipment, similarities are found in all wind turbine electrical systems. Four different equipment sections can be identified. Starting from the generator and progressing toward the incoming cables, the sections are:

– generator section,

– low voltage switchgear and power conditioning section,

– transformer section, and

– medium voltage switchgear section.

Depending on the size of the wind turbine, the last two sections may be common to a group of wind turbines. For turbines with a rated power of 250 kW and above, it is customary for each wind turbine to have its own transformer. Figure 20 describes the latter situation.

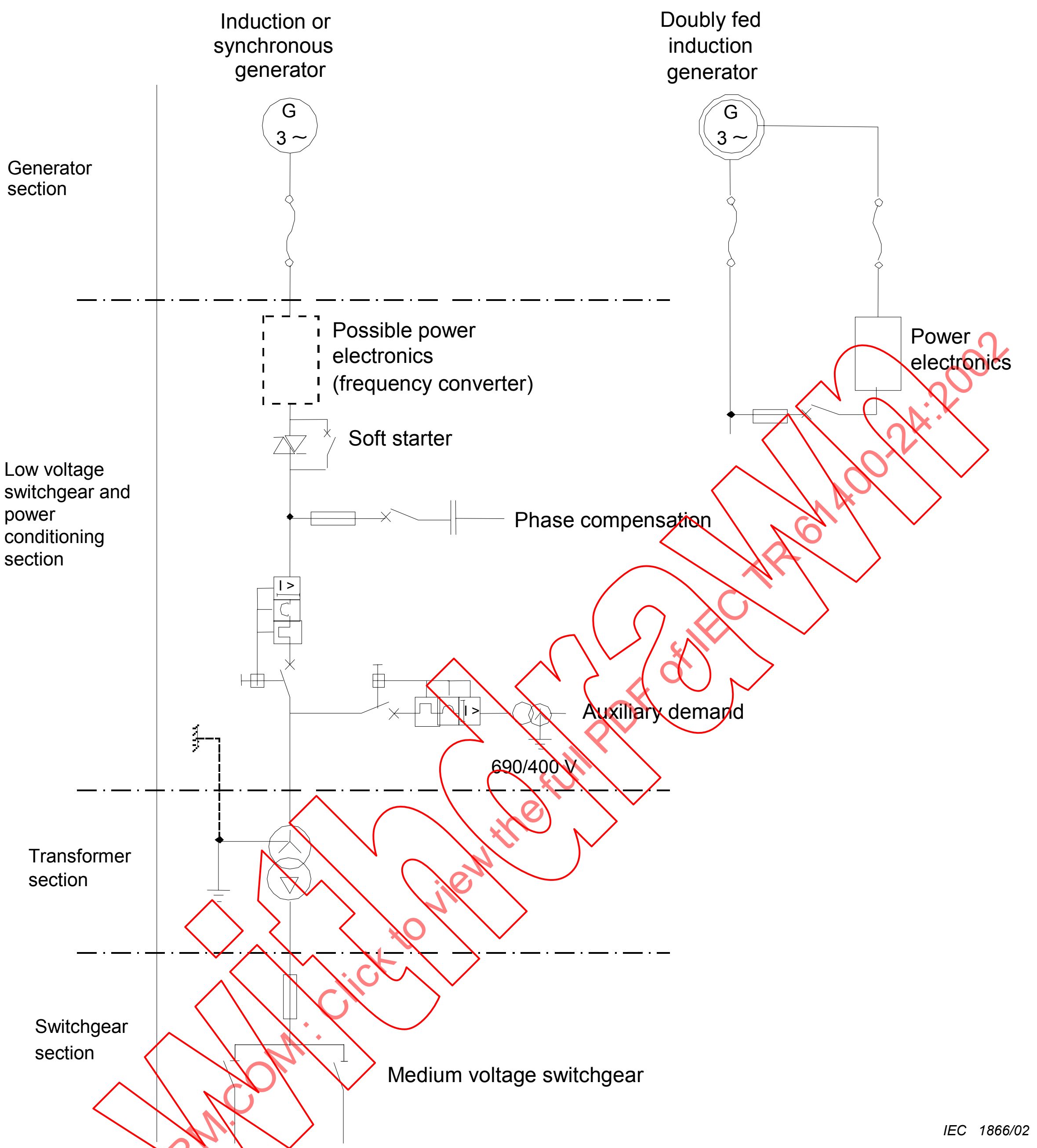


Figure 20 – Principle configuration of electrical equipment in a grid-connected wind turbine

The medium voltage switchgear in the switchgear section serves two purposes:

– to route the cables from one wind turbine to the next and to provide a disconnect facility so that sections of the cable grid, typically radial connections, can be isolated and earthed when service or repair are needed;

– to protect the wind turbine by breaking the supply from the grid to the wind turbine if faults occur in the transformer or power system of the wind turbine. This is accomplished using medium voltage fuses or circuit-breakers. This section is always situated at ground level, either in an external transformer housing or inside the tower, if the transformer is placed inside the wind turbine.

The transformer in the transformer section raises the voltage from the generator voltage, typically low voltage (i.e. below 1 kV), to the medium voltage level (i.e. below 36 kV) used in the power collection system in the wind farm. The star point on the low voltage side of the transformer is connected to the earthing system of the installation and to the central earthing busbar of the wind turbine. The transformer is placed either in an external transformer housing, together with the medium voltage switchgear, in the bottom of the tower or in the nacelle. The transformer is typically oil insulated if placed in an external housing, and with dry-type insulation if placed inside the wind turbine.

The low voltage switchgear and power conditioning section fulfils a number of functions. The following is a description of a typical arrangement, which is not representative of all wind turbines. They provide an outlet to an auxiliary transformer stepping the voltage down from the generator level to the standard level used in industrial installations (400/230 V or 190/110 V depending on local standards). Pumps, control systems, outlets and lighting are supplied from this transformer. A moulded case circuit-breaker (MCCB) with short circuit and thermal overload tripping connects to the primary power circuits. The capacitor banks for reactive power compensation are connected immediately after the MCCB, either through fuses or through smaller MCCBs. The capacitors are switched by contactors. Depending on the type of turbine, variable speed or not, power electronics – typically in the form of a frequency converter (variable speed) or a thyristor soft starter (fixed speed induction generator) – are inserted directly before the generator. The physical location of this section follows the location of the transformer.

The generator is found in the nacelle. In some cases, variable speed is obtained by using a doubly fed induction generator where the wound rotor is also connected to the main power circuit. This and the necessary rotor power electronics are illustrated in the upper right part of figure 20.

8.2.2 Control system

The control system forms an extended cable system in the nacelle, tower and rotor (see figure 21). Power to the control system cubicles is supplied from the auxiliary transformer via automatic fuses in the auxiliary power supply panel. This is converted to an appropriate voltage level for the supply of the microprocessors, sensors, transducers and similar equipment which form the control system. The major part of the control system is located in the bottom of the tower or in the nacelle. In many cases, a decentralized system is placed in the hub, controlling and supervising the blade movement.

Communication lines are required between the various control system components whether they are in the tower base, the nacelle or the hub. These internal links are often fibre optic cables. If they contain no metallic wire they protect the equipment at both ends from overvoltages induced by lightning currents.

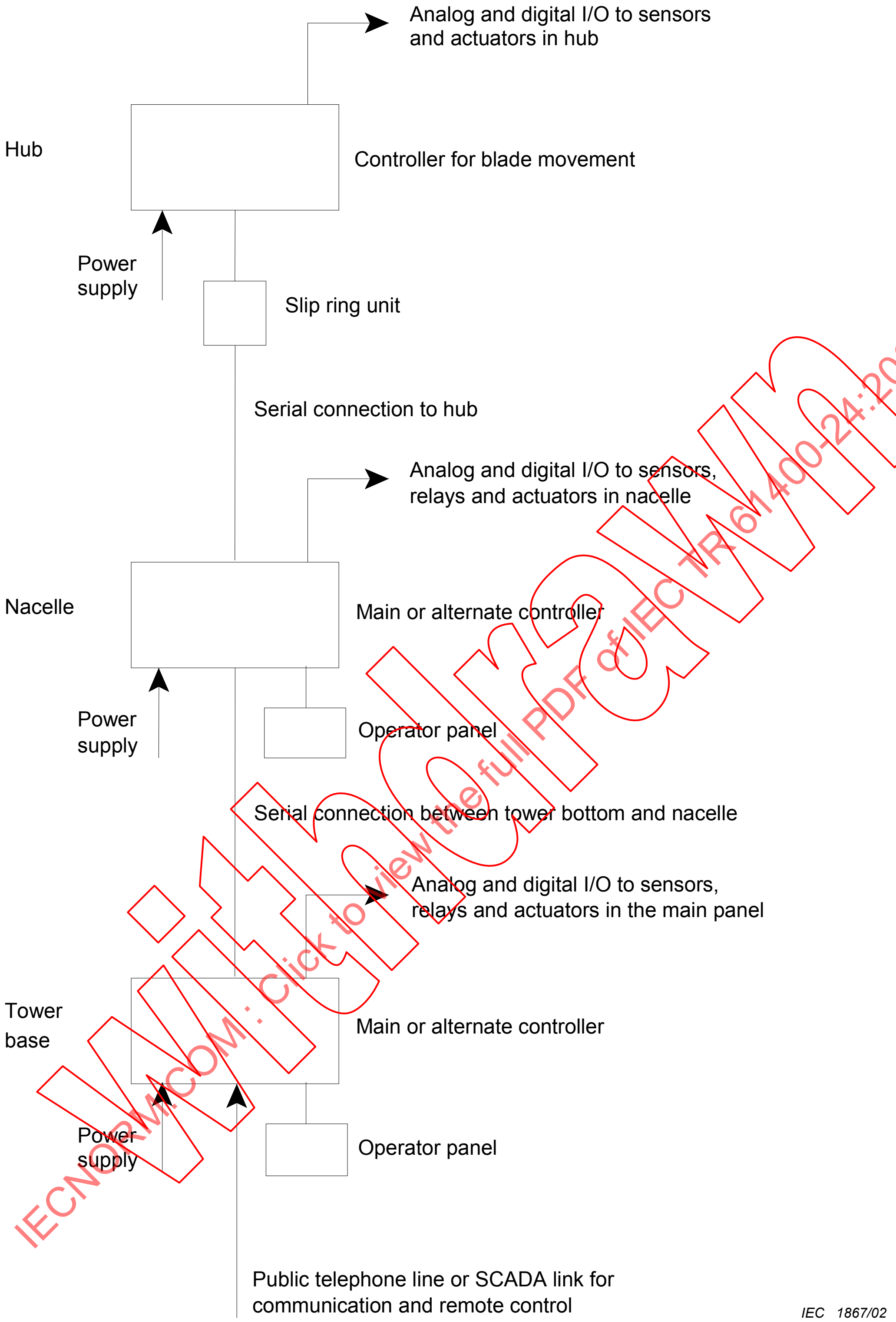


Figure 21 – Principle control system configuration

Remote control and supervision is usually by modem and telephone cables or supervisory control and data acquisition link (SCADA link). If not properly protected by overvoltage suppressors, this line can be the source of a major part of the faults in the control system caused by lightning flashes not directly hitting the wind turbine. It should be noted that as the control system operates at substantially lower voltages than the power system, it is much more vulnerable to lightning damage.

8.3 Lightning protection zones

A wind turbine can be divided into physical areas which roughly define the nature of the influence of a lightning flash to components in that zone. The division of the wind turbine into lightning protection zones is a tool for ensuring systematic and sufficient protection of all components of the wind turbine. These lightning protection zones (LPZ) are defined depending on whether or not direct lightning attachment is possible and the magnitude of the lightning current and associated electromagnetic field expected in that zone (see table 15). Lightning protection methods are then applied to ensure that components, for example machinery or control systems, can withstand the electromagnetic field and lightning current that might enter the zone in which the components are placed. For instance, protection against overvoltages is only necessary for cables passing from one zone into a zone with a lower protection level, whereas internal connections within the zone may be unprotected. This approach is detailed further in IEC 61312, and it is discussed below.

Table 15 – Lightning protection zones

LPZ 0_A	Direct lightning attachment, full lightning current, unattenuated electromagnetic field
LPZ 0_B	No lightning attachment, full lightning current, unattenuated electromagnetic field
LPZ 1	No lightning attachment, reduced lightning current, attenuated electromagnetic field
LPZ 2	Further reduced lightning current, further attenuated electromagnetic field

NOTE Lightning protection zones with higher numbers may be defined for further reduction of lightning influences.

8.3.1 Zone 0

The boundary between LPZ 0_A and LPZ 0_B is determined by means of the rolling sphere model as shown in figure 22 (see also IEC 61024-1). The areas marked in grey are LPZ 0_B where a lightning flash cannot attach, and the rest of the surface of the wind turbine is LPZ 0_A. Locations against which the sphere cannot roll are protected against direct stroke attachment. As can be seen, lightning flashes may attach to most of the surface of the wind turbine – such areas are consequently LPZ 0_A. By means of air-terminations (for example lightning rods) placed at the rear edge of the nacelle cover, a zone LPZ 0_B may be created at the top of the nacelle whereby meteorological instruments can be protected against direct lightning attachment. At the foot of the wind turbine there is also a zone LPZ 0_B where a transformer cubicle, if any, will be protected against direct lightning.

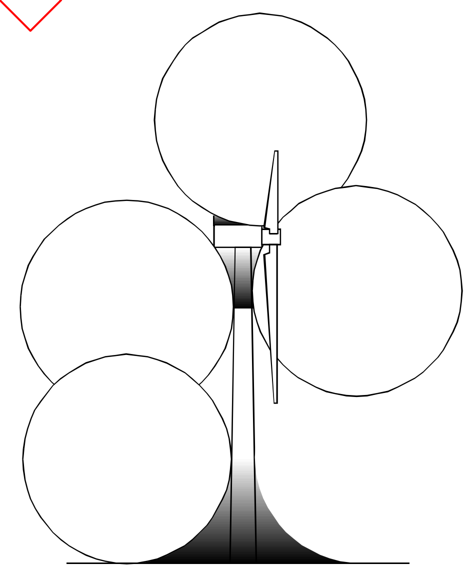


Figure 22 – Rolling sphere model

8.3.2 Other zones

The boundary between LPZ 0_A or LPZ 0_B and LPZ 1 can be made at the tower or at the top cover of the nacelle if there is a metal cover (or sufficient metal content) to protect components beneath with a Faraday cage. In the case of GRP nacelle covers, it is recommended that a metal frame or strapping be integrated into the nacelle cover to, as a minimum, define the area within as Zone 0_B to protect nacelle components from direct strokes (see figure 23). This should, of course, be bonded thoroughly to the bedplate. Ideally, a mesh of metal in a GRP cover should be integrated into this frame to define the nacelle as LPZ 1. It is recommended that such a mesh has a maximum grid size equal to half the distance to the nearest component at risk.

Figure 23 also shows how the interior of the wind turbine may be divided into protection zones LPZ 1 and LPZ 2. The nacelle (with enough metal in the cover), the tower, and the transformer cubicle are protection zone LPZ 1. The devices inside metal cabinets in LPZ 1 areas are in protection zone LPZ 2. For instance, controls inside a cabinet inside a metal tower are in LPZ 2, but in a metal cabinet outside the tower it is LPZ 1.

Very sensitive equipment may be placed within a still more protected zone LPZ 3 in another level of metal cabinets. It is the sensitivity of the components in a given zone (i.e. withstand limits) that defines the level to which the lightning influences (such as current, voltage and electromagnetic field) must be reduced to in that zone. Therefore, no specific values of current, voltage and electromagnetic field in each zone are recommended in IEC 61312.

8.3.3 Zone boundaries

At each zone boundary, it must be ensured that cables and wires crossing the boundary do not conduct large parts of the lightning current or voltage transients into the protection zone with the higher number. This is accomplished by means of proper bonding and shielding practices and overvoltage protection of cables and wires at the zone boundary. The goal is to reduce current and voltage to a level tolerable for the equipment placed in the protection zone with the higher number.

The amount of necessary components for protection against overvoltages can and should be reduced by means of appropriate division into zones, appropriate positioning of cables, use of shielded cables (see 8.5.2), and use of optical fibres for transmission of signals and data. Surge protective devices (SPD) may be relatively expensive and bulky, and this fact alone indicates that the use should be limited. In addition, such devices may fail due to the influences to which they are exposed and due to degradation.

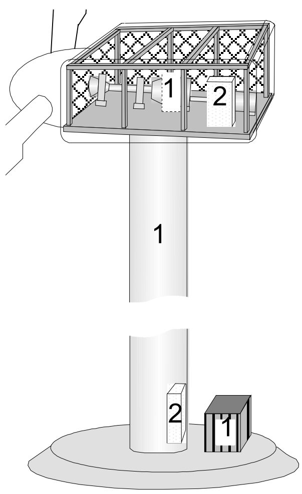


Figure 23 – Example of the division of the interior of a wind turbine into protection zones

8.3.4 Zone protection requirements

To avoid the occurrence of damage or unacceptable failure, it should be ensured that within a given zone no components are exposed to parts of the lightning current, voltage differences, or electromagnetic fields above their withstand levels. Example requirements for the various zones are given in table 16.

Table 16 – Examples of component requirements in given zones

Zone	Lightning protection requirements
LPZ 0_A	Components in this zone must be able to tolerate direct attachment of lightning flashes with currents corresponding to the chosen lightning protection level, tolerate the unattenuated electromagnetic field from the lightning current, and conduct the full lightning current.
LPZ 0_B	As in LPZ 0_A except that the components do not have to tolerate direct lightning attachment.
LPZ I	The electromagnetic field from the lightning current is attenuated 25 dB to 50 dB, and conductor bound currents and voltages are limited by means of SPDs to, for example 3 kA (8/20 µs) and 6 kV (1,2/50 µs), respectively.
LPZ 2	The electromagnetic field is further attenuated by means of metal cabinets, and conductor bound currents and voltages are further limited by means of SPDs.

8.4 Surge coupling mechanisms

Lightning currents can induce transients into circuits through various coupling mechanisms. These can readily cause voltages high enough to damage power supplies, PC boards, sensor and other electrical and electronic devices. The following is a description of the three most common coupling mechanisms.

8.4.1 Conduction

Lightning current will find its way to earth through all available conductors and will be distributed according to their impedances. For conductive coupling into a circuit there has to be an entry and an exit for the current. Due to the very high potentials involved, these can be flashover arcs across insulation or small air gaps. Conductive coupling can be minimized by providing preferential, low impedance paths for the lightning current. Proper insulation levels and good bonding techniques can prevent flashovers.

8.4.2 Capacitive coupling

High frequency signals with steep voltage rises, like lightning, are readily transferred through capacitive coupling. The voltage rise is associated with an electric field, and conductors in that field can develop a potential proportional to the rate of change of the electric field and inversely proportional to its distance from the source.

Capacitive coupling between one component and another can be reduced by

– shielding (a complete metal enclosure, braided wire sheath or wire mesh screen);
– increasing the distance between the interacting components (for example move the wires close to a ground plane, use grounded metallic conduit, wire ways or race trays), and
– reducing the exposed surface.

8.4.3 Magnetic coupling

The steep current rise associated with a lightning stroke causes magnetic fields with a large rate of change. This can be the source of damaging voltages induced into loops of conductors in that field. Although avoidable, this is a major cause of lightning damage in a wind turbine electrical system.

As shown in figure 24, the surge current flowing in the conductor (bold line down the middle) generates flux lines linking all of the circuits shown. In the first circuit (see figure 24a), the loop area is very large, and the enclosed flux is significant enough to create a destructive differential mode potential. Using a twisted-pair cable, the exposed loop area can be minimized thereby safely reducing, or even eliminating, the induced surge.

In the second circuit (see figure 24b), although the wire is twisted, the loop area formed is large and both ends are grounded. As a result, a common mode surge could be introduced into the circuit. This can be resolved by removing the ground at one side. This should be done with caution, however, as the induced voltage may exceed the flashover voltage. If the induced voltage can exceed the flashover voltage, an SPD can be used for protection. Common mode noise may be dampened by winding several turns of the twisted wire around a toroidal core to choke the common mode noise, as shown in figure 24b.

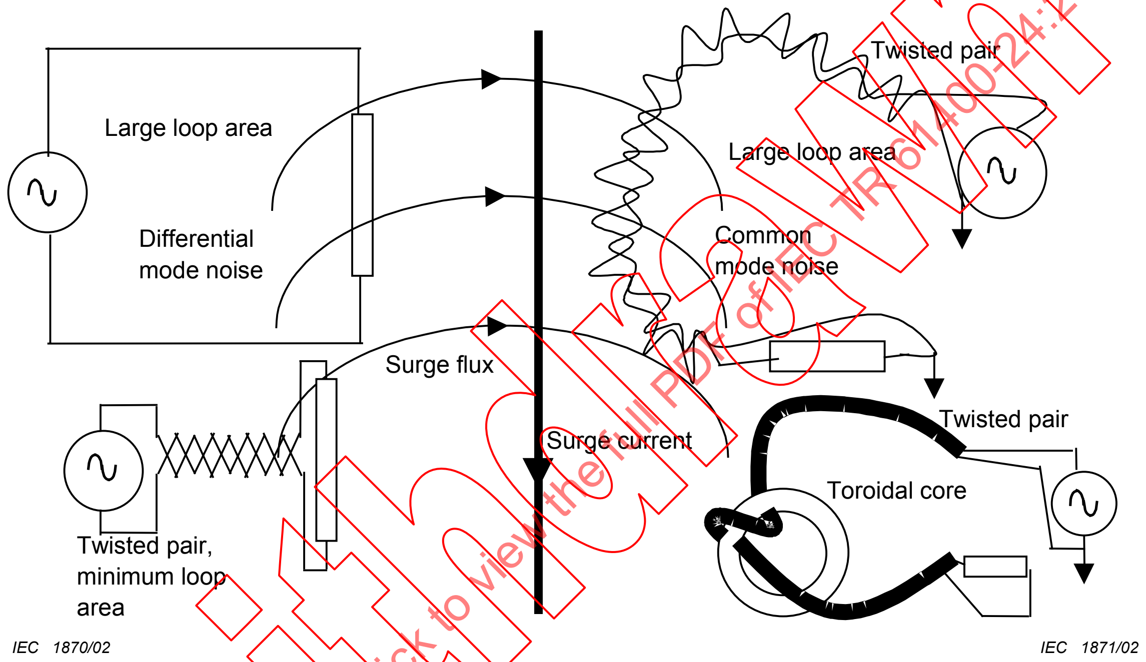


Figure 24a **Figure 24b**

Figure 24 – Differential and common mode coupling

Suggestions to reduce magnetic coupling:

– high-frequency magnetic fields can be reduced significantly with a metal enclosure (race ways, pipes, shields, metal box). The magnetic disturbance is deflected and dissipated as eddy currents in a metal cover;

– avoid forming large-loop areas that are susceptible to flux linkage – keep conductors close to metal components such as gearboxes and generators;

– twisted cables can reduce magnetic coupling because the area enclosed is very small and the signal induced in the wire pairs should cancel at differential inputs.

8.5 Bonding and shielding

Bonding within a wind turbine is required to establish equipotential bonds between parts of the wind turbine. These equipotential bonds provide protection against touch and step voltages during a lightning stroke. Equipment bonds play an important role in defining the probability of damage to electrical and electronic systems.

Shielding is the means by which electromagnetic field levels are attenuated. The reduction of electromagnetic fields can substantially reduce levels on voltages induced into circuits.

Much of the damage currently experienced in wind turbine control systems can be prevented by effective bonding and shielding. Some considerations for the bonding and shielding needed in a wind turbine are discussed below. It is strongly recommended to consult IEC 61024-1 and IEC 61312 which give detailed guidance on the need for bonding and shielding in structures.

8.5.1 Bonding

Due to the transient nature of the lightning current, the peak voltage drop along a conductor can be approximated as

$$V = L\frac{di}{dt} \qquad (20)$$

where

L is the inductance of the conductor;

di/dt is the maximum rate of change of lightning current.

The inductance of a conductor can normally be considered to be in the order of 1µH/m and the maximum di/dt can vary from 0,2 to 200 kA/µs depending on the lightning stroke and the level of current sharing between individual conductors. The voltage drop along a bonding strap can therefore be up to 200 kV/m.

Consider the system shown in figure 25 with two control cabinets located on different metallic planes inside a wind turbine nacelle. A lightning current flows into the upper plane and is transferred to the lower plane via a bond strap. When a lightning current flows through the bond strap, the potential of cabinet 1 is raised with respect to cabinet 2. The possible result of this change in potential would be damage to components located in cabinet 1 or 2. The situation can be improved by good bonding practice.

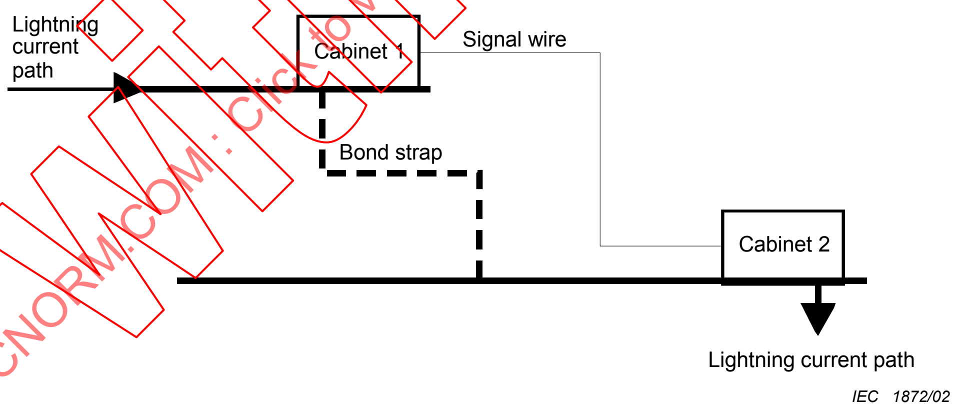


Figure 25 – Two control cabinets located on different metallic planes inside a nacelle

The use of multiple bond straps and minimizing the bond strap length will result in the lowest possible voltage difference between the two metal planes.

Bonding within a wind turbine should therefore use multiple conductors that are:

- capable of carrying the predicted fraction of lightning current to pass through the path in question;
- as short and straight as possible.

Wiring can also be protected by routing wires in conduits/raceways or by using shielded cable as discussed in 8.5.2.

8.5.2 Shielding

When lightning currents flow through a wind turbine large magnetic fields are produced. If these changing magnetic fields pass through a loop they will induce voltages within that loop. The magnitude of the voltage is proportional to the rate of change of the magnetic field and the area of the loop in question. The constructor must consider the magnitude of induced voltages and make sure that such voltages do no exceed the withstand level of the cabling and attached equipment.

The diagram below shows a loop of wire running next to a current-carrying conductor. The voltage drop across the impedance Z will be proportional to the rate of change of the magnetic field (see figure 26).

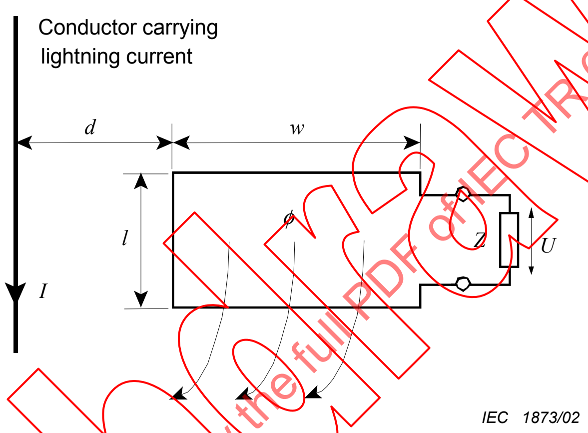


Figure 26 – Magnetic coupling mechanism

This can be expressed in the following formulae:

$$U = \frac{d\phi}{dt} \tag{21}$$

where

ϕ is flux linkage in Wb;

U is the voltage induced in the loop in V

It can be shown that the total flux passing through the loop is:

$$\phi = \frac{\mu_0 lI}{2\pi}\left[\ln\left(\frac{d+w}{d}\right)\right] \tag{22}$$

Therefore, the voltage induced in the loop is:

$$U = \frac{\mu_0}{2\pi} \times l \times \ln\left(\frac{d+w}{d}\right) \times \frac{di}{dt} = M \times \frac{di}{dt} \tag{23}$$

where

μ_0 is the permittivity of air and the other dimensions are as given on the diagram;

M is described in the mutual inductance between the loop and the current-carrying conductor.