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Power transformers –
Part 16: Transformers for wind turbine applications

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POWER TRANSFORMERS –

Part 16: Transformers for wind turbine applications

FOREWORD

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International Standard IEC/IEEE 60076-16 has been prepared by IEC technical committee 14: Power transformers, in cooperation with Performance Characteristics Subcommittee of the IEEE Power and Energy Society [1], under the IEC/IEEE Dual Logo Agreement between IEC and IEEE.

This second edition of IEC/IEEE 60076-16 cancels and replaces IEC 60076-16:2011, and constitutes a technical revision.

The main changes with respect to the previous edition are as follows:

1) relationship between transformer rated power and the output current from the associated generator is introduced;
2) thermal correction of the effective cooling medium has been introduced;
3) testing regime has been strengthened to ensure transformers are suitable for the harsh electrical environment to which they are subjected.

This publication is published as an IEC/IEEE Dual Logo standard.

The text of this standard is based on the following IEC documents:

FDIS	Report on voting
14/959/FDIS	14/965/RVD

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

A list of all parts in the IEC/IEEE 60076 series, published under the general title *Power transformers*, can be found on the IEC website.

1 A list of IEEE participants can be found at the following URL: https://standards.ieee.org/project/60076-16.html

The IEC Technical Committee and IEEE Technical Committee have decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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- withdrawn,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

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~~INTRODUCTION~~

~~This part of IEC 60076 is intended to specify the additional requirements for the transformers for installation in wind turbine applications.~~

~~Wind turbines use generator step-up transformers to connect the turbines to a network. These transformers can be installed in the nacelle or in the tower or outside close to the wind turbine.~~

~~This standard covers transformers for wind turbine applications or wind farms where the constraints on transformers exceed the requirement of the present IEC 60076 series. The constraints are not often known or recognized by the transformer manufacturers, wind turbine manufacturers and operators and as a result the level of reliability of these transformers can be lower than those used for conventional applications.~~

~~The transformers for wind turbine applications are not included in the present list of IEC 60076 standard series.~~

~~The purpose of this standard is help to obtain the same level of reliability as transformers for more common applications.~~

~~This standard deals particularly with the effects of repeated high frequency transient over-voltages, electrical, environmental, thermal, loading, installation and maintenance conditions that are specific for wind turbines or wind farms.~~

~~On site measurements, investigations and observations in wind turbines have detected risks for some different kind of installations:~~

- ~~repeated high frequency transient over or under voltages in the range of kHz;~~
- ~~over and under frequency due to turbine control;~~
- ~~values of over voltage;~~
- ~~over voltage or under voltage coming from LV side;~~
- ~~high level of transient over voltages due to switching;~~
- ~~presence of partial discharge around the transformer;~~
- ~~harmonic contents current and voltage;~~
- ~~overloading under ambient conditions;~~
- ~~fast transient overload;~~
- ~~clearances not in compliance with the minimum prescribed;~~
- ~~installation conditions and connections;~~
- ~~restricted conditions of cooling;~~
- ~~water droplets;~~
- ~~humidity levels that exceed the maximum permissible values;~~
- ~~salt and dust pollution and extreme climatic conditions;~~
- ~~high levels of vibration;~~
- ~~mechanical stresses.~~

~~Therefore it is necessary to take into account in the design of the transformer the constraints of this application, or to define some protective devices to protect the transformer. Additional or improved routine, type or special tests for these transformers have to be specified to be in compliance with the constraints on the network.~~

POWER TRANSFORMERS –

Part 16: Transformers for wind turbine applications

1 Scope

This part of IEC 60076 applies to dry-type and liquid-immersed transformers for ~~rated power 100 kVA up to 10 000 kVA for~~ wind turbine step-up applications having a winding with highest voltage for equipment up to and including ~~36~~ 72,5 kV ~~and at least one winding operating at a voltage greater than 1,1 kV~~. This document applies to the transformer used to connect the wind turbine generator to the wind farm power collection system or adjacent distribution network and not the transformer used to connect several wind turbines to a distribution or transmission network.

Transformers covered by this document comply with the relevant requirements prescribed in the IEC 60076 standards or IEEE C57 standards.

2 Normative references

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

2.1 IEC references

IEC 60076-1~~:2011~~, *Power transformers – Part 1: General*

IEC 60076-2~~:2011~~, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

IEC 60076-3~~:2000~~, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-5~~:2006~~, *Power transformers – Part 5: Ability to withstand short circuit*

IEC 60076-7~~:2005~~, *Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers*

~~IEC 60076-8:1997, *Power transformers – Application guide*~~

IEC 60076-11~~:2004~~, *Power transformers – Part 11: Dry-type transformers*

IEC 60076-12~~:2008~~, *Power transformers – Part 12: Loading guide for dry-type power transformers*

~~IEC 60076-13:2006, *Power transformers – Part 13: Self-protected liquid-filled transformers*~~

IEC 60076-14, *Power transformers – Part 14: Liquid-immersed power transformers using high-temperature insulating materials*

~~IEC 61100, *Classification of insulating liquids according to fire-point and net calorific value*~~

IEC 61378-1~~:2011~~, *Converter transformers – Part 1: Transformers for industrial applications*

~~IEC 61378-3:2006, *Converter transformers – Part 3: Application guide*~~

~~IEC 61400-1:2005, *Wind turbines – Part 1: Design requirements*~~

2.2 IEEE references

IEEE Std C57.12.00™, *IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*

IEEE Std C57.12.01™, *IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers*

IEEE Std C57.12.80™, *IEEE Standard Terminology for Power and Distribution Transformers*

IEEE Std C57.91™, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators*

IEEE Std C57.96™, *IEEE Guide for Loading Dry-Type Distribution and Power Transformers*

IEEE Std C57.110™, *IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents*

IEEE Std C57.154™, *IEEE Standard for the Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures*

ANSI C84.1, *Electric Power Systems and Equipment – Voltage Ratings (60 Hz)*

2.3 ISO references

ISO 12944 (all parts), *Paints and varnishes – Corrosion protection of steel structures by protective paint systems*

ISO 12944-4, *Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 4: Types of surface and surface preparation*

2.4 CENELEC references

EN 50588-1:2015, *Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV – Part 1: General requirements*

3 Terms and definitions

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

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

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

3.1
wind turbine transformer
generator step up transformer connecting the wind turbine to the power collection ~~network~~ system of the wind farm or the adjacent distribution network for single turbine installations

3.2
tower
~~part of the~~ supporting structure of the wind turbine on top of which the nacelle with generator and other equipment~~s are~~ is located

3.3
nacelle
housing that contains the drive-train and other elements on top of a horizontal-axis wind turbine tower

[SOURCE: IEC 60050-415:1999, 415-01-07]

3.4
effective cooling medium
ambient air, either internal or external to the tower or nacelle, or cooling water that comes into contact with the cooling surface of the transformer

3.5
compartmentalized type transformer
transformer with integral enclosure comprised of multiple independent compartments, usually with separate entrances into the HV and LV termination compartments

3.6
sealed transformer
transformer which is so constructed that the external atmosphere is not intended to gain access to the interior

3.7
routine sample test
test which is usually defined as a type test or special test but carried out as an additional routine test on a random sample of transformers

4 Use of normative references

This standard can be used with either the IEC or IEEE normative references but the references shall not be mixed. The purchaser shall include in the enquiry and order which normative references are to be used. If the choice of normative references is not specified, then IEC standards shall be used except for wind turbine transformers intended for installation in North America where IEEE standards shall be used.

5 Rating

The transformer rating specified by the purchaser shall take into account the maximum current delivered to the transformer by the associated wind turbine generator system irrespective of the operating voltage and power factor.

6 Service conditions

6.1 Normal service conditions

6.1.1 General

~~Unless otherwise stated in this standard, the service conditions in IEC 60076-11 and IEC 60076-1 apply.~~

The normal service conditions detailed in IEC 60076-1 or IEEE Std C57.12.00 for liquid-immersed transformers or the normal service conditions in IEC 60076-11 or IEEE Std C57.12.01 for dry-type transformers shall apply unless otherwise stated in this document or specified by the purchaser.

~~4.2 Altitude~~

~~IEC 60076 series applies.~~

6.1.2 Temperature of external cooling ~~air~~ medium

~~The installation of transformers inside an enclosure without active cooling systems increases the transformer temperature.~~

~~The purchaser shall specify the maximum cooling air temperatures if they are different from those stated in IEC 60076-2.~~

~~The transformer shall be designed according to real ambient temperatures and installation real conditions as described by the purchaser at enquiry stage.~~

~~Clause A.1 provides considerations for transformers installed in a naturally ventilated area like at the rear of the nacelle or in a separate enclosure installed outside the tower and equipped with air inlet and outlet.~~

~~In case of transformer installed in the tower or in an enclosure where natural ventilation is not provided the formula in A.1 is not applicable. For transformers operating under these conditions, the effects of air inlet and outlet, cooling conditions, efficiency of air cooling and ventilation shall be considered.~~

~~The purchaser shall prescribe the air ambient temperature and air flow inside the tower at the enquiry stage. If no temperature or air flow is specified, an internal ambient temperature inside the tower of 10 K higher than external temperature shall be assumed and not limited air circulation around the transformers.~~

~~The effect of external direct solar radiation is not taken into account at the design stage. This can increase the temperature of transformers parts and therefore information should be given by purchaser at enquiry time.~~

If the transformer is installed external to the tower or nacelle, the normal conditions specified in IEC 60076-1 or IEEE Std C57.12.00 for liquid-immersed transformers and IEC 60076-11 or IEEE Std C57.12.01 for dry-type transformers shall apply, unless otherwise specified. If the transformer is installed within the tower or nacelle then particular conditions apply as shown in 6.2.

6.2 Particular service conditions for transformers installed in a tower or nacelle

6.2.1 General

Where the transformer is installed in a tower or nacelle then higher temperatures of the cooling medium local to the transformer may be expected.

6.2.2 Temperature rise correction

Based on the ambient conditions of the installation, the purchaser shall specify the yearly average and maximum temperature of the effective cooling medium (e.g. air or water). If the yearly average or maximum temperature of the cooling medium exceeds the relevant value in the respective standard, the difference between the values and the "normal service conditions" values shall be subtracted from the temperature rise limits specified in IEC 60076-2, IEC 60076-11 or IEEE Std C57.12.00 as follows:

$$K_{max} = T_{max\ ecm} - T_{max\ std}$$

$$K_{av} = T_{av\ ecm} - T_{av\ std}$$

where

K_{max} is the temperature correction for the maximum ambient temperature;

K_{av} is the temperature correction for the yearly average ambient temperature;

$T_{max\ ecm}$ is the maximum temperature of the effective cooling medium;

$T_{max\ std}$ is the maximum ambient temperature of the effective cooling medium according to the relevant standard;

$T_{av\ ecm}$ is the average temperature of the effective cooling medium;

$T_{av\ std}$ is the yearly average ambient temperature of the effective cooling medium according to the relevant standard.

K_{av} can be used in determining the temperature rise limit of average winding and winding hot-spot temperatures in all transformers. In liquid-immersed transformers K_{max} can be used in determining the temperature rise limit for the top liquid temperature.

If the only available information is the maximum ambient temperature, the increase of the yearly average ambient temperature can be assumed to be the same as the increase of the maximum ambient temperature, making K_{av} and K_{max} equal.

For example, for a transformer using insulation material of thermal class 105 (regular kraft paper immersed in mineral oil) installed in an environment where the average temperature is 32 °C and the maximum ambient temperature is 48 °C, the corrected temperature rise limits based on IEC 60076-2 would be:

$$K_{av} = (32 - 20) = 12\ \text{K}$$

$$\Delta\theta_w = 65 - K_{av} = 65 - 12 = 53\ \text{K}$$

$$\Delta\theta_h = 78 - K_{av} = 78 - 12 = 66\ \text{K}$$

For liquid-immersed transformers K_{max} can be applied:

$$K_{max} = (48 - 40) = 8\ \text{K}$$

$$\Delta\theta_o = 60 - K_{max} = 60 - 8 = 52\ \text{K}$$

Another example, for a transformer using thermally upgraded insulation material (thermally upgraded kraft paper immersed in mineral oil) with similar conditions to the previous example, the corrected temperature rise limits based on IEEE Std C57.12.00 would be:

$$K_{av} = (32 - 30) = 2\ \text{K}$$

$$\Delta\theta_w = 65 - K_{av} = 65 - 2 = 63\ \text{K}$$

$$\Delta\theta_h = 80 - K_{av} = 80 - 2 = 78\ \text{K}$$

For liquid-immersed transformers K_{max} can be applied:

$$K_{max} = (48 - 40) = 8\ \text{K}$$

$$\Delta\theta_o = 65 - K_{max} = 65 - 8 = 57\ \text{K}$$

where,

$\Delta\theta_w$ is the average winding temperature rise;

$\Delta\theta_h$ is the winding hot-spot temperature rise;

$\Delta\theta_o$ is the top liquid temperature rise.

For the transformers installed in a tower or nacelle, the purchaser shall carefully consider the influence on the temperature of the enclosure, heat generated by other equipment and by the transformer itself, and the cooling system / air renovation system, if applicable. As reference, if no better information is available, the thermal loading of the transformer, in kilowatts, can be estimated as 1,5 % of its rated power (kVA).

The effect of external direct solar radiation should be taken into account by the purchaser when calculating the temperature of the effective cooling medium. Methods for determining the effect are given in IEC 60721-3-4.

6.3 Content of harmonic currents in the transformer

~~At the enquiry stage the purchaser shall specify the magnitude and frequency of all harmonic currents supplied to the transformer. The manufacturer shall take the losses caused by these harmonic currents into account in the transformer design to prevent that the winding and liquid temperature rises exceed the permissible limits.~~

~~The transformer shall be designed to take into account the increased rating required due to the harmonic currents. The temperature rise test shall be carried out with the equivalent rated power due to the harmonics defined in A.2. The result of the test shall be in compliance with temperature limits guaranteed for the transformer and related to the transformer insulation thermal class.~~

The purchaser shall evaluate the magnitude and frequency of the harmonic currents supplied to the transformer.

Where total harmonic content is less than 5 % of rated current no additional information is required.

Where total harmonic content is greater than 5 % the purchaser shall specify the magnitude and frequencies of all harmonic currents supplied to the transformer. The manufacturer shall calculate the additional losses at rated power caused by these currents using the method given in IEC 61378-1 or IEEE Std C57.110 or as agreed between the purchaser and manufacturer.

During the temperature rise test the transformer shall be supplied with an additional current to represent the additional harmonic losses for the purpose of determining the temperature rises.

A method to calculate the impact of the harmonic currents on the design of the transformer is given in ~~A.2~~ IEC 61378-1 or IEEE Std C57.110.

~~4.5 Wave-shape of supply voltage~~

~~Within the prescribed value of U_m a transformer shall be capable of continuous service at full load without damage under conditions of 'overfluxing' where the ratio of voltage over frequency exceeds the corresponding ratio at rated voltage and rated frequency according to IEC 60076-1.~~

~~The wind turbine manufacturer shall state at enquiry stage the maximum ratio between the voltage and the frequency. The transformer manufacturer shall take into account this value in the design of the transformer.~~

~~The purchaser shall specify in the inquiry the magnitude and frequency of any harmonic voltages present in the supply. A method to calculate the impact of the voltage harmonics on the design of the transformer is given in A.3.~~

6.4 Over-excitation

Unless otherwise specified by purchaser, transformers shall be capable of operating continuously above rated voltage or below rated frequency, at maximum rated power (kVA) for any tap, without exceeding the limits of temperature rise when all of the following conditions prevail.

a) When operating under load:

   1) secondary voltage and volts per hertz do not exceed 115 % of rated values and with a minimum frequency of 95 % of rated value;

   2) power factor is 0,8 or higher.

b) When operating under no load, transformers shall be capable of operating continuously above rated voltage or below rated frequency, on any tap, without over-exciting or exceeding limits of observable temperature rise, when neither the voltage nor volts per hertz exceed 120 % of rated values.

6.5 Harmonic distortion of voltage

When supply voltage harmonics are expected to be in excess of 5 % of rated voltage the purchaser shall specify the magnitude and frequency of any harmonic voltages present in the supply. The transformer shall be designed to withstand the specified condition or 5 % of rated voltage, whichever is higher, without damage.

6.6 Transient ~~over and under~~ voltages

~~The risk of failures of a wind turbine transformer is higher due to the fact of repeated transient over and under voltages on each side on transformer.~~

~~Several solutions are available to increase the reliability of the transformer against these fast transient interactions:~~

- ~~to evaluate the insulation level of the transformer and if necessary apply one or more of the following solutions. This can be done by modeling or measuring the system by high frequency resonance analysis. The resonance frequency test is a special test. The test method shall be agreed between manufacturer and purchaser. One method is described in A.4;~~
- ~~to install standard protection technique such as surge arresters (HV, LV), or RC circuit or surge capacitor.~~

~~The choice of the lists 2 or 3 in Table 1 shall be the responsibility of the system engineer based on specific insulation co-ordination (IEC 60071-1 and -2) and risk assessment.~~

~~The list 3 covers transformers with increased ability to withstand repeated transient over voltages and increases the reliability of the transformer.~~

~~Table 1 – Insulation levels~~

~~Highest voltage for equipment~~ U_m ~~(rms) kV~~	~~Rated short duration separated source AC withstand voltage (RMS) kV~~	~~Rated lightning impulse withstand voltage (peak value) in kV~~	
		~~List 2~~	~~List 3~~
~~≤ 1,1~~	~~3~~	~~-~~	~~20~~
~~3,6~~	~~10~~	~~40~~	~~50~~
~~7,2~~	~~20~~	~~60~~	~~75~~
~~12~~	~~28~~	~~75~~	~~95~~
~~17,5~~	~~38~~	~~95~~	~~125~~
~~24~~	~~50~~	~~125~~	~~150~~
~~36~~	~~70~~	~~170~~	~~200~~

~~High frequency steep surges can be generated by switching operation on LV or HV side. These surges are transferred by cables to the terminals of the transformer. Transformers have different values of resonance frequency. See A.4.~~

~~If the high frequency steep surges generated by switching operation on LV and HV side coincide with the internal frequency of the winding, the result of these surges can resonate with the winding internal frequencies and cause higher electric stresses than the dielectric withstand strength of the windings~~

~~NOTE For~~ U_m ~~≤ 1,1 kV a.c. withstand voltage should have higher value as 10 kV.~~

a) Normal impulse protection

Transformer lightning impulse (LI) (see IEC 60076-3) or basic lightning impulse level (BIL) (see IEEE Std C57.12.80) shall be specified. Increased transformer BIL levels by one step should be considered unless system study indicates otherwise.

b) Switching induced overvoltages

Switching transient voltages, produced by vacuum interrupters and/or SF_6 switching devices, have resulted in dielectric failures of some wind turbine transformers. The first and last transformers in a daisy chain are typically the most vulnerable and are most at risk when currents are light and power factor is particularly low. IEEE Std C57.142 addresses this issue in depth and relates the vulnerability to current chops and voltage restrikes by vacuum or SF_6 interrupters. This is a complex phenomenon that is not covered in depth in this document but should be evaluated by a system study. If system study warrants action, mitigation techniques should be employed.

NOTE The above reference to IEEE Std C57.142 is applicable to both IEC and IEEE applications as there is no current IEC standard that covers this issue.

6.7 Humidity and salinity

~~An abnormal level of humidity and salinity can lead to failures of dry type transformers and problems on open type bushings of liquid-immersed transformers or dry type transformers in enclosures.~~

~~The standard pollution levels for open type bushing for liquid-immersed transformers are defined in IEC 60815 series. There are also simulated rain tests defined in IEC 60137.~~

~~According to IEC 60076-11, the relative humidity in the test chamber shall be maintained above 93 % for environmental class E2 transformers. Salinity shall be such as the conductivity of the water in E2 test shall be in the range of 0,5 to1,5 S/m.~~

~~If a dry type transformer shall operate under more severe conditions than corresponding to class E2 without a protective enclosure against humidity and salinity, the capability of the transformer design shall be demonstrated by the test according to class E3 described in 7.4.5 in this standard.~~

~~IEC 61400-1 states that relative humidity up to 95 % shall be taken into account as a normal environmental condition.~~

~~Higher values of humidity and salinity shall be given at enquiry stage.~~

The purchaser shall define the maximum levels of humidity and salinity to which transformers will be exposed.

Levels of humidity and salinity associated with coastal or off-shore applications have led to issues on transformers. These can include:

- salt spray;
- excessive moisture and humidity;
- dripping water;
- condensation.

The effects of these issues will affect different transformer technologies in different ways (e.g. liquid immersed vs dry type).

Some of the areas of possible mitigation include:

a) increased and more comprehensive maintenance cycles;
b) avoidance of air insulated terminals and exposed conductors, for example, by applying bushing covers or elbow connectors;
c) increased creepage distances.

~~4.8 Special electrical and environmental conditions around the transformer~~

~~IEC 60076-3 recommends general minimum clearances between transformer live parts and conductive parts of the wind turbine.~~

~~Any part of the wind turbine made of insulation material becomes conductive when moistened with rain water, salt water or other conductive liquids. Partial discharges in the surroundings of the transformer can decrease the dielectric strength of the air.~~

~~Therefore the clearances between these wind turbine parts and the live parts of the transformer shall not be less than the clearances recommended in IEC 60076-3.~~

~~The transformer manufacturer shall indicate the required minimum clearances on the outline drawing of the transformer and it is the responsibility of the purchaser to follow up that these requirements will be met.~~

6.8 Level of vibration

Vibrations of the structure where the transformer is to be installed shall be taken into account when designing the transformer~~ and special consideration shall be given in the stress transferred to connection terminals~~.

The purchaser shall specify the vibration spectrum at the enquiry stage. The procedure of vibration test, if any, should be agreed at enquiry stage between purchaser and manufacturer.

~~4.10 Provision for unusual service conditions for transformers for wind turbine applications~~

~~Provision for unusual service conditions are indicated in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers.~~

~~4.11 Transportation and storage conditions~~

~~Transportation and storage conditions are indicated in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers.~~

~~Storage conditions shall be included in maintenance and operation manuals and shall be taken into account by the purchaser.~~

6.9 Corrosion protection

Depending on the kind of installation, the purchaser ~~should choose~~ shall specify a protection class defined in ISO 12944 (all parts), IEEE Std C57.12.28, IEEE Std C57.12.29 or otherwise agreed between purchaser and manufacturer. Unless specified otherwise, level C4 (ISO 12944-4) shall be used except for coastal or off-shore installation where level C5-M (ISO 12944-4) or higher may be appropriate.

6.10 Consideration for hermetically sealed transformers

A hermetically sealed transformer shall be designed to withstand without permanent deformation the expected pressures that occur over the specified temperature range during full loading of the transformer (see CENELEC EN 50588-1:2015, 9.4).

6.11 Flammability issues with transformers mounted in the tower or nacelle

For transformers mounted in the tower or nacelle, less-flammable insulating liquids or dry-type construction are recommended. For dry-type transformers specified according to IEC 60076-11, fire class F1 shall be specified as a minimum.

6.12 Thermal cycling of transformer

Wind turbine transformers are exposed to significant thermal cycling leading to mechanical weakening of the tank in liquid-immersed transformers or in damage to the winding coils in cast resin dry-type transformers. Purchasers should consider an increase in the number of cycles required during endurance testing, particularly where forced air cooling is applied.

Thermal endurance testing for liquid-immersed transformers shall be in accordance with EN 50588-1:2015, 9.4.5. Thermal endurance tests for dry-type transformers shall be subject to agreement between the purchaser and the manufacturer. The number of cycles for the thermal endurance test shall not be less than 2 000 cycles.

NOTE Thermal cycling is usually assumed to be related to the level of load, but during constant load at rated power frequent thermal cycles can be experienced when using switched forced air cooling.

7 Electrical characteristics

~~5.1 Rated power~~

~~The rated power shall be in accordance with 5.1 of IEC 60076-1.~~

~~The rated power S_r of the transformer is based on the fundamental frequency of the voltage U_1 and of the current I_1. The rated power of a three phase transformer is therefore:~~

$$S_r = \sqrt{3} \times U_1 \times I_1$$

~~The temperature rise and the cooling requirements of the transformer shall be determined after allowance is made for any increased losses due to harmonics.~~

7.1 Highest voltage for equipment

The highest voltage for equipment shall be ~~chosen~~ specified in accordance with ~~Clause 5 of~~ IEC 60076-3~~:2000~~ and ANSI C84.1.

~~The wind turbine designer shall inform the transformer manufacturer of peak voltages, frequencies and durations of any transient and repeated over voltages (see also Table 1 of this standard).~~

~~Information about insulation coordination is described in IEC 60071-1 and IEC 60071-2.~~

7.2 Tappings (tap-changer)

~~The requirements in Clause 5 of IEC 60076-1:2011 apply.~~

~~The preferred tapping range if any is either:~~

- ~~+5 % to –5 % in steps of 2,5 %,~~

~~or~~

- ~~+5 % to –5 % in steps of 5 %.~~

~~Tapping selection shall be made by means of off-circuit bolted links or an off-circuit tap changer.~~

Unless otherwise specified, no tappings shall be provided.

Where a transformer is provided with tappings on a winding these shall all be full-power tappings. When specified, tappings other than full-power tappings may be provided, and this shall be stated on the nameplate.

NOTE The provision of tappings on a transformer can increase size, weight and cost and can decrease reliability and therefore are only generally used where specifically required.

7.3 Connection group

Unless otherwise specified by the purchaser, ~~transformer connections shall be Dyn with clock hour figure 5 or 11 in accordance with Clause 7 of IEC 60076-1:2011~~ the connection group for a two winding three-phase transformer shall be Dyn11 or LV lagging HV by 330 degrees. Other combinations of windings shall be subject to agreement between the purchaser and the manufacturer.

7.4 Dimensioning of neutral ~~terminal~~ connection

The neutral ~~terminal~~ connection shall be capable of carrying full phase rated current unless otherwise specified by the purchaser.

7.5 Short-circuit impedance

~~For general purpose the impedance voltage shall be in accordance with IEC 60076-5.~~

Commonly recognized minimum values for the short-circuit impedance of transformers at the rated current (principal tapping) are given in Table 1. If lower values are required, the ability of the transformer to withstand short circuit shall be subject to agreement between the manufacturer and the purchaser.

Table 1 – Recommended minimum values of short-circuit impedance for transformers with two separate windings

Short-circuit impedance at rated current	
Rated power kVA	**Minimum short-circuit impedance** %
25 to 630	4,0
631 to 1 250	5,0
1 251 to 2 500	6,0
2 501 to 6 300	7,0
6 301 and above	8,0

For auxiliary windings when the combined impedance voltage of the tertiary winding and the system result in short-circuit current levels for which the transformer cannot feasibly or economically be designed to withstand, the manufacturer and the purchaser shall mutually agree on the maximum allowed over-current. In this case, provision should be made by the purchaser to limit the over-current to the maximum value determined by the manufacturer and shall be stated on the rating plate.

7.6 Insulation levels for high ~~voltage~~ and low voltage windings

The ~~selected~~ insulation level for the high voltage and low voltage windings shall be in accordance with ~~Table 1 of this standard~~ IEC 60076-3 or IEEE Std C57.12.00 and IEEE Std C57.12.01. Insulation levels may be increased as detailed in 6.6.

~~5.8 Temperature rise guaranteed at rated conditions~~

~~The design of the transformer shall be in accordance with the operating conditions (harmonic contents, ambient temperature) stated by the purchaser at the enquiry stage.~~

~~The guaranteed temperature rise shall take into account the additional losses due to harmonics if specified, which increase eddy losses and stray losses in the windings and structural/frame parts.~~

~~If no harmonics are specified at the design stage but the actual real load current in service contains harmonics, the load on the transformer may need to be reduced to prevent the transformer temperature rises exceed the guaranteed limits.~~

~~Examples of calculations of the impact of harmonic currents are given in A.2.~~

7.7 Overload capability

The maximum sustained power output (including reactive power) of the wind turbine shall not be considered an overload condition for the transformer and shall be provided for in the nominal rating. The maximum sustained and peak loading cycle(s) including the worst case power factor shall be defined by the purchaser.

The principles in the appropriate loading guides ~~liquid-immersed transformers in IEC 60076-7 and for dry type transformers in IEC 60076-12~~ shall ~~apply~~ be applied to the defined loading cycle:

- for liquid-immersed transformers, in IEC 60076-7 or IEEE Std C57.91;
- for dry-type transformers, in IEC 60076-12 or IEEE Std C57.96;
- for high temperature liquid-immersed transformers, in IEC 60076-14 or IEEE Std C57.154.

Transformer connections and any switches (e.g. de-energized tap changer) shall be suitably rated to carry peak overloads.

7.8 Inrush current

~~Due to frequent energizing of the transformers during wind farm operation, transformers are frequently exposed to mechanical and thermal effects of inrush currents.~~

~~Frequency of energisation (number of energisation per year) shall be given at enquiry stage. Unless otherwise specified, switching is done on the HV (grid) side. The method of switching and synchronization shall be described in case of generator side energisation.~~

~~System inrush current limitations (maximum value, duration) shall be given at enquiry stage by the purchaser.~~

Unless otherwise specified by the purchaser, the short-circuit apparent power of the system shall be assumed to be in accordance with IEC 60076-5:2006, 3.2.2.4. Any limitations in the peak value of inrush current or the duration of such current shall be specified by the purchaser.

7.9 Frequency of energization

Where the frequency of energization is in excess of 24 events per year, the expected value shall be given by the purchaser.

7.10 Ability to withstand short circuit

Transformers shall ~~fulfill~~ comply with the requirements of IEC 60076-5, IEEE Std C57.12.00 or IEEE Std C57.12.01. ~~If the purchaser requires a test to demonstrate this fulfillment, this test shall be stated in the contract.~~

7.11 Operation with forced cooling

When additional cooling by means of fans or pumps is provided, the nominal rated power ~~rating~~ with and without forced cooling shall be ~~subject to agreement between~~ in accordance with IEC 60076-1 or IEEE Std C57.12.00 for liquid-immersed transformers or with IEC 60076-11 or IEEE Std C57.12.01 for dry-type transformers unless otherwise agreed by the purchaser and the manufacturer.

~~The rating plate shall indicate both the power rating without forced cooling and the maximum power rating with forced cooling.~~

~~NOTE In case of forced cooling, the back-to-back method to carry out the temperature rise test for the transformer is preferred and is subject to agreement between manufacturer and purchaser at enquiry stage. Temperatures measured by the back-to-back tests correspond more closely to those obtained in practice during normal operation.~~

For dry-type transformers forced air cooling should not affect temperature of sensors. Direct air flow on the sensors should be avoided.

Control of the forced cooling equipment for liquid-immersed transformers should be by means of winding temperature monitoring and/or top oil temperature monitoring by either direct methods or simulation.

7.12 Over-temperature protection

Unless otherwise specified, for transformers mounted in the tower or nacelle, the manufacturer shall provide a suitable over-temperature detector that can provide an alarm or trip signal.

8 Rating plate

Rating plate requirements are detailed in IEC 60076-1 or IEEE C57.12.00 for liquid-immersed transformers or in IEC 60076-11 or IEEE C57.12.01 for dry-type transformers.

In addition, the number of this document shall be stated on the nameplate.

9 Tests

9.1 List and classification of tests (routine, type and special tests)

The lists and classification of tests are detailed in IEC 60076-1 or IEEE Std C57.12.00 for liquid-immersed transformers or in IEC 60076-11 or IEEE Std C57.12.01 for dry-type transformers.

~~7.2 Routine tests~~

~~Tests described in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers apply.~~

~~NOTE Impulse test for all transformers type and partial discharge tests for liquid-immersed transformers can be justified on each unit by agreement between purchaser and manufacturer at enquiry stage. See IEC 60076-13 for this kind of test cycle for partial discharge test on liquid-immersed transformers.~~

~~7.3 Type tests~~

~~Tests described in IEC 60076-1 for liquid-immersed transformers and IEC 60076-11 for dry type transformers shall apply.~~

~~Partial discharge for liquid-immersed transformers less 72,5 kV are not defined in IEC 60076-3 and consequently test condition of IEC 60076-13 shall apply.~~

~~NOTE Chopped wave test can be a part of type testing by agreement between purchaser and manufacturer at enquiry stage.~~

~~7.4 Special tests~~

~~7.4.1 General~~

~~Special tests shall be defined at enquiry stage by the purchaser.~~

~~7.4.2 Chopped wave test~~

~~The extension of the lightning impulse test to include impulses chopped on the tail as a special test is recommended after agreement at enquiry stage.~~

~~The peak value of the chopped impulse shall be 110 % of the specified full wave impulse (BIL).~~

~~Clause 14 of IEC 60076-3:2000 shall apply.~~

~~7.4.3 Electrical resonance frequency test~~

~~The method is described in A.4.~~

~~7.4.4 Climatic tests~~

~~IEC 60076-11 shall apply for dry type transformers.~~

~~7.4.5 Environmental test E3~~

~~The transformer shall be placed in a test chamber in which temperature and humidity are kept under control.~~

~~The volume of the chamber shall be at least five times that of the rectangular box circumscribing the transformer. The clearances from any part of the transformer to walls, ceiling and spraying nozzles shall be not less than the smallest phase-to-phase clearance between live parts of the transformer (see IEC 60076-3) and not less than 150 mm according to 26.3.1 of IEC 60076-11:2004.~~

~~The temperature of the air in the test chamber shall be such as to ensure condensation on the transformer.~~

~~The humidity in the chamber shall be maintained above 95 %. This may be achieved by periodically or continuously atomizing a suitable amount of water.~~

~~The conductivity of the water shall be in the range of 3,6 S/m to 4 S/m.~~

~~The position of the mechanical atomizers shall be chosen in such a way that the transformer is not directly sprayed.~~

~~The transformer shall be kept in air having a relative humidity above 95 % for not less than 6 h, without being energized.~~

~~Within 5 min thereafter, the transformer shall be submitted to a test with induced voltage as follows:~~

~~a) transformers with windings intended for connection to a system which are solidly earthed or earthed through a low impedance shall be energised at a voltage of 1,1 times the rated voltage for a period of 15 min;~~

~~b) transformers with windings intended for connection to systems which are isolated or earthed through considerable impedance shall be submitted to a test with induced voltage for 3 successive periods of 5 min. During the test, each high voltage terminal in turn shall be connected to earth and a voltage of 1,1 times the rated voltage shall be applied between the other terminals and earth. The three-phase test can be replaced by single-phase tests with the two non-earthed phase terminals being interconnected.~~

~~Preferably the dielectric test should be performed in test chamber.~~

~~During the voltage application, no flash over shall occur, and visual inspection shall not show any serious tracking.~~

~~If no information in respect of test condition a) or b) is available, test b) should be performed.~~

~~7.4.6 Fire behavior test~~

~~IEC 60076-11 shall apply for dry type transformers.~~

~~Liquids for immersed transformers are described in IEC 61100.~~

9.2 Additional tests for wind turbine transformers

9.2.1 General

Due to the harsh operating environment for wind turbine transformers, a number of tests in addition to the standard tests applied shall be carried out.

9.2.2 Lightning impulse type tests

Transformers shall be subjected to full lightning impulse type testing including chopped wave. Chopped wave tests are not required on transformers specified to IEEE standards where separable high voltage connectors are fitted.

9.2.3 Lightning impulse routine sample tests

A lightning impulse test, comprising full wave tests only, shall be applied to a minimum 10 % sample of the contract chosen on a random basis, unless otherwise agreed between the purchaser and the manufacturer. Chopped wave lightning impulse tests may be applied together with the routine lightning impulse tests where specified by the purchaser.

9.2.4 Partial discharge test for liquid-immersed transformers

Where specified by the purchaser, a partial discharge test in accordance with the method specified in IEC 60076-11 or IEEE Std C57.12.01 shall be carried out. The maximum acceptable level of partial discharge shall be 100 pC.

NOTE 1 The test specified here is in the document for dry-type transformers but for the purposes of this clause is applied to liquid-immersed transformers.

NOTE 2 This test has been specified in accordance with the dry-type routine test method due to the impractical nature of a full partial discharge test to IEC 60076-3 or IEEE Std C57.12.01 being applied to multiple units in production.

9.2.5 Climatic and environmental tests for dry-type transformers

The following additional tests shall be performed when specified by the purchaser at time of enquiry when no relevant test evidence is available:

a) climatic tests for dry-type transformers in accordance with IEC 60076-11;

b) environmental tests for dry-type transformers in accordance with IEC 60076-11.

~~Annex A~~
~~(informative)~~

~~Calculation method and tables~~

~~A.1 Cooling of transformer in a naturally ventilated room~~

~~A.1.1 Assumptions~~

~~The room is cooled by naturally air circulation therefore:~~

Q_{AF} ~~is the heat dissipation by forced air circulation (kW)~~

$$Q_{AF} = 0 \qquad \text{(A.1)}$$

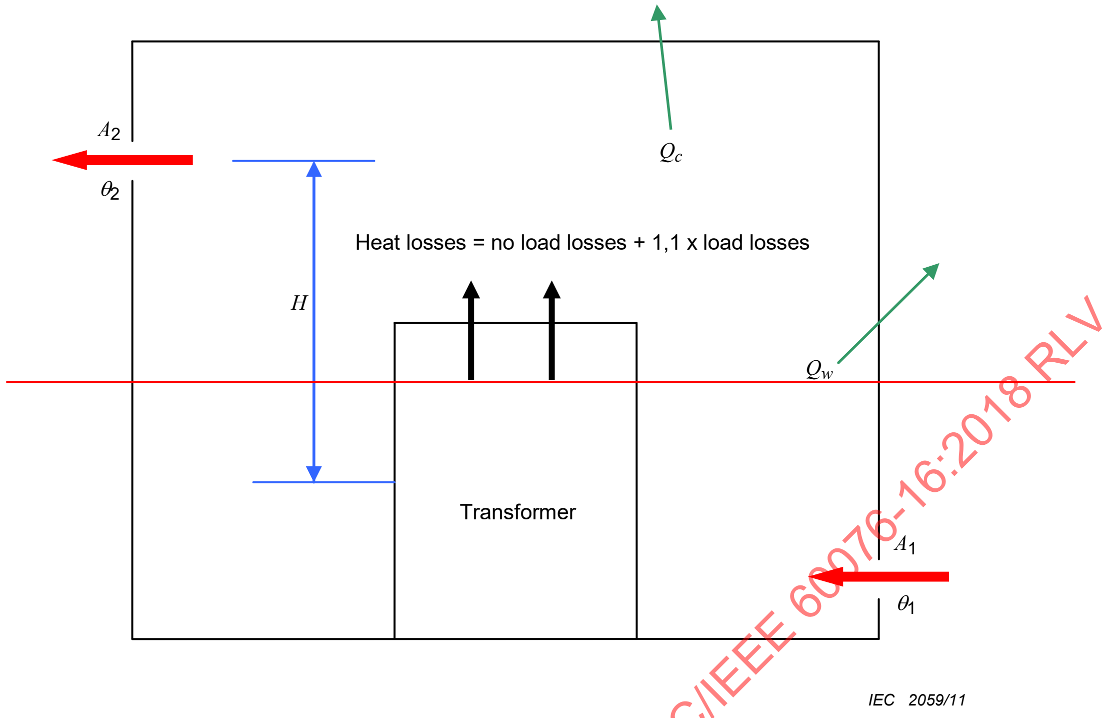
Q_c, Q_w ~~are losses dissipated respectively through ceiling and the walls (kW)~~

$$Q_c = Q_w = 0 \qquad \text{(A.2)}$$

~~In case of harmonics in load current special considerations shall be taken into account according A.2 or the transformer shall to be derated.~~

~~The heat dissipation through ceiling and the walls is generally low. This quantity is depending on the heat transfer coefficients of the materials of the walls and ceiling, the surface area of ceiling and the walls and difference between indoor and outdoor temperatures.~~

~~See following Figure A.1:~~



~~**Key**~~

~~A_1 Air inlet effective cross section (m^2)~~

~~A_2 Air outlet effective cross section (m^2)~~

~~θ_1, θ_2 Air temperatures of inlet and outlet (°C)~~

~~H Difference in height between mid outlet surface and mid height of transformer (m)~~

~~Q_c, Q_w Losses dissipated respectively through ceiling and the walls (kW)~~

~~**Figure A.1 – Heat dissipation in a natural ventilated room**~~

~~**A.1.2 Data for the calculation of ventilation**~~

~~Transformer produces losses that are dissipated in the room. This subclause gives the calculation of these losses.~~

~~$\Delta\theta_a$ is the air temperature rise (K):~~

$$\cancel{\Delta\theta_a = \theta_2 - \theta_1} \text{ ~~approximate value = 15 K~~} \qquad \text{~~(A.3)~~}$$

~~NLL is the transformer no load losses (kW);~~

~~LL are the transformer nominal load losses at reference temperature (kW);~~

~~HL are the transformer heat losses in the room (kW);~~

~~Heat losses = No load losses + 1,1 × Load losses:~~

$$\cancel{HL = NLL + 1{,}1 \times LL} \text{ ~~(kW)~~} \qquad \text{~~(A.4)~~}$$

~~NOTE Value 15 K indicated above is common empirical value from the experience of the manufacturers.~~

~~A.1.3 Output~~

~~Losses produces by the transformers should be dissipated outside the room. This annex allows to give the surface of the air inlet.~~

A_1 ~~is the air inlet effective cross section (m²);~~

A_2 ~~is the air outlet effective cross section (m²);~~

$$A_2 / A_1 > 1{,}1 \text{ (minimum 10 \% more)} \quad \text{(A.5)}$$

Q_{tot} ~~is the heat dissipation in the transformer's room (kW);~~

$$Q_{tot} = Q_{nac} + Q_{wc} + Q_{AF} \text{ (kW)} \quad \text{(A.6)}$$

Q_{nac} ~~is the dissipation by natural air circulation (kW);~~

$$Q_{nac} = 0{,}1 \times A_1 \times \sqrt{H\, \Delta\theta_a^{3}} \text{ (kW)} \quad \text{(A.7)}$$

$\Delta\theta_a$ ~~is the air temperature rise (K);~~

Q_{wc} ~~is the heat dissipation through the walls and ceiling (kW);~~

$$Q_{wc} = Q_w + Q_c = 0 \text{ (see assumption)} \quad \text{(A.8)}$$

Q_{AF} ~~is the heat dissipation by forced air circulation (kW);~~

$Q_{AF} = 0$ ~~(see assumption).~~

~~To assure a good ventilation of the room:~~

$$HL = Q_{nac} + Q_{wc} \text{ (kW)} \quad \text{(A.9)}$$

~~The required air inlet section~~ A_1 ~~is then given by:~~

$$A_1 = \frac{HL}{0{,}1\sqrt{H\ \Delta\theta_a^{3}}} \text{ (m}^2\text{)} \quad \text{(A.10)}$$

~~Calculation of air outlet section~~ A_2 ~~:~~

~~See formula (A.5).~~

~~A.1.4 Numerical application for a 1 000 kVA transformer~~

~~In this example, harmonics are not considered.~~

$$NLL = 2{,}3 \text{ kW}$$

~~LL = 11 kW~~

~~The heat losses HL in the room are:~~

$$\cancel{HL = NLL + 1{,}1 \times LL = 2{,}3 + 1{,}1 \times 11 = 14{,}4\ \text{kW}}$$

~~H = 4,6 m~~

~~Finally it comes:~~

$$\cancel{A_1 = \frac{14{,}4}{0{,}1 \times \sqrt{4{,}6 \times 15^3}} = 1{,}155\ \text{m}^2}$$

~~The effective cross section of the air inlet shall be at least of 1,155 m² to assure a correct cooling of the transformer in its naturally ventilated room.~~

~~Calculation of air outlet section A_2:~~

$$\cancel{A_2\ \text{minimum} = 1{,}1 \times 1{,}155 = 1{,}271\ (\text{m}^2)}$$

~~The effect of transformer installed in a natural ventilated room is increasing temperature rises of the transformer by approximately half of air increased temperature between inlet and outlet (IEC 62271-202).~~

~~A.2 Determination of the power rating of a transformer loaded with non-sinusoidal currents~~

~~A.2.1 Transformer load losses~~

~~The transformer losses are of two types:~~

- ~~direct losses (Ohmic losses) = $I^2 \times R$ (W);~~ ~~(A.10)~~
- ~~additional losses υ are equal to eddy losses + stray losses.~~

~~The stray losses and eddy losses definitions are as in IEC 60076-8 and IEC 61378-1. Two frequencies method for separating stray losses and eddy losses by measurement is stated in IEC 61378-3.~~

~~A.2.2 Eddy losses (e_1)~~

~~Losses due to electromagnetic flux in the winding.~~

~~e_1 are eddy losses per unit for considered winding.~~

~~A.2.3 Load losses (Ll)~~

~~Load losses (Ll) for a considered winding at the reference temperature.~~

$$\cancel{Ll = R \times I^2 \times (1 + e_1)\ (\text{W})} \quad \cancel{(A.11)}$$

~~A.2.4 Stray losses (s_i)~~

~~Losses due to electromagnetic flux in clamps, cover, tank and other metallic parts.~~

~~A.2.5 Total load losses (Tl)~~

~~The transformer total load losses Tl are given by:~~

$$\cancel{Tl = R_1 \times I_1^2 \times (1+e_1) + R_2 \times I_2^2 \times (1+e_2) + S_i \text{ (W)}} \quad \text{(A.12)}$$

~~A.2.6 Harmonics~~

~~The losses of a transformer loaded with non sinusoidal currents depend on the frequency of each harmonic present in the current and its RMS value.~~

~~The total losses of the transformer at rated current change when the current contains harmonic content instead of a simple sinusoidal shape.~~

~~A transformer designed without special care concerning harmonic content of its current must be derated.~~

~~Harmonic components are represented by a periodic wave having a frequency that is an integral multiple of the fundamental frequency.~~

~~Harmonics are designated by their harmonic number or multiple of the fundamental frequency.~~

~~Harmonic with a frequency of 250 Hz is called the 5th harmonic (5 times the fundamental harmonic) with a fundamental frequency of 50 Hz for example.~~

~~Harmonics superimpose themselves on the fundamental wave form, distorting it and changing its magnitude.~~

~~Harmonic currents are generated when a non linear load is connected to the secondary of the transformer (examples: convertors, electronic equipment).~~

~~The problems caused by harmonic currents are: increased losses and overheating in the transformer, eddy losses are of most and stray losses are of the less concern when harmonic currents are present.~~

~~The eddy losses increase with the square of the frequency.~~

~~Due to these physical reasons (increased losses and overheating) the harmonic spectrum must be known before designing or sent to the transformer manufacturer to determine the ability to withstand such harmonics.~~

~~A.2.7 Eddy losses due to harmonic currents~~

~~A.2.7.1 RMS current calculation: I_{rms}~~

~~The root mean square (RMS) of current I_{rms} supplying a non sinusoidal load is:~~

$$\cancel{I_{rms} = \sqrt{\sum_{h=1}^{h=n} I_h^2} \text{ (A)}} \quad \text{(A.13)}$$

~~where~~

~~h is the current harmonic order;~~

~~I_h is the magnitude of the harmonic h (A).~~

~~A.2.7.2 Eddy losses calculation~~

~~The eddy current losses at a particular harmonic are given by:~~

$$P_h = P_f \times r_h^2 \times h^2 \text{ (W)} \qquad \text{(A.14)}$$

~~where~~

~~P_f are the eddy losses at the fundamental frequency f with the RMS of rated current I_r (W);~~

~~P_h are the eddy losses at harmonic h (W);~~

~~r_h is the ratio of the magnitude of the current of harmonic of order h over the fundamental current:~~

$$r_h = \frac{I_h}{I_1} \qquad \text{(A.15)}$$

~~The total eddy losses (P_{EL}) are given by the sum of the eddy losses for each individual harmonics.~~

$$P_{EL} = P_f \sum_{h=1}^{h=n} r_h^2 \times h^2 \text{ (W)} \qquad \text{(A.16)}$$

~~A.2.7.3 Stray losses~~

~~The stray losses at a particular harmonic h vary according to 6.2 of IEC 61378-1:2011 and Annex A.~~

$$SL_{ih} = r_h^{\,2} \times h^{0,8}$$

~~where~~

~~r_h is the ratio of the magnitude of the current of harmonic of order h over the fundamental current.~~

~~Example:~~

~~Harmonic h = 5~~

~~Magnitude = 25,8 %~~

$$SL_{i5} = 0{,}258^2 \times 5^{0,8} = 0{,}241\,2$$

~~A.2.8 Harmonic eddy loss factor: K factor~~

~~The K factor is the ratio between total eddy losses due to all harmonic currents referred to eddy losses at fundamental current I_1.~~

~~The eddy losses increase by K time its sinusoidal value when the transformer is loaded with non sinusoidal currents.~~

$$K \text{ factor} = \frac{P_{EL}}{P_f} \tag{A.17}$$

A.2.9 Transformer total losses Ttl s in service with non sinusoidal current

Ttl s = no load losses (Nll) + total load losses with non sinusoidal current (Lls)

$$Ttl_s = Nll + \left[\left(Ih_1^2 \times R_1 \times I_1^2\right) \times \left(k_1 \times (1+e_1)\right)\right] + \left[\left(Ih_2^2 \times R_2 \times I_2^2\right) \times \left(k_2 \times (1+e_2)\right)\right] + S_i \tag{A.18}$$

A.2.10 Top oil temperature rise with non sinusoidal currents TO_i for liquid-immersed transformers

See IEC 60076-7 for top oil temperature rise calculation:

$$TO_i = TO_{rx} \left(Ttl_s / Ttl \right)^{0,8} \tag{A.19}$$

where

TO_i is the top oil temperature rise with non sinusoidal currents;

TO_r is the top oil temperature rise at rated current.

A.2.11 De-rating of the transformer

De-rating of the transformer shall be approximately as follows:

SrE = permissible loading for the transformer:

$$SrE = Sr \times \left(Ttl / Ttl_s \right)^{0,5} \tag{A.20}$$

Sr is the nominal load of the transformer (kVA).

The derating factor of transformer is $(Ttl / Ttl_s)^{0,5}$.

A.2.12 Calculation examples of harmonic effects for liquid-immersed and dry type transformers

A.2.12.1 Equivalent currents due to harmonic contents

This example is for design purpose and to demonstrate the influence of the transformer design especially regarding the importance of quantity of the eddy losses. Eddy losses are depending on the design of the windings (dimension, raw material, impedance).

The magnitude of the harmonic is given according to IEC 61378 series to enhancement factors.

Two examples are given in the following Tables A.1 and A.2. Table A.1 is for a liquid-immersed transformer and Table A.2 is for a dry type transformer.

In the first table: RMS current is increased by 3,82 % above fundamental current, resulting in eddy losses increased by a K factor of 3,808 and stray losses by a factor of 1,308.

In the second table: RMS current is increased by 4,6 % above fundamental current, resulting in eddy losses increased by a K factor of 5,96 and stray losses by a factor of 1,41.

~~A.2.12.2 Example for a liquid-immersed transformer~~

~~A.2.12.2.1 Calculation of the permissible loading for the transformer~~

~~Table A.1 – Impact of harmonics content on liquid-immersed transformer losses~~

Harmonic order (h)	Magnitude (%)	I_h/I_1	$(I_h/I_1)^2$ enhancement factor	Eddy losses enhancement factor	Stray losses enhancement factor
1	100	1	1	1,000	1,000 0
5	25,8	0,258	0,066 56	1,664	0,241 2
7	8,3	0,083	0,006 89	0,338	0,032 7
11	5,2	0,052	0,002 70	0,327	0,018 4
13	3,3	0,033	0,001 09	0,184	0,008 5
17	1,5	0,015	0,000 23	0,065	0,002 2
19	1,4	0,014	0,000 20	0,071	0,002 1
23	0,9	0,009	0,000 08	0,043	0,001 0
25	0,8	0,008	0,000 06	0,040	0,000 8
29	0,7	0,007	0,000 05	0,041	0,000 7
31	0,6	0,006	0,000 04	0,035	0,000 6
		Σ	1,077 9	3,808	1,308
	RMS current	1,038 2			-
	THD	27,91 %	THD is the total harmonic distortion rate (%)		

~~THD according to IEC60076-1:2011,3.13.2~~

$$I_r^2 = \sqrt{\sum_{h=1}^{h=n} I_h^{\,2}}$$

$$I_r^2 = 1{,}077\ 9$$

$$K \quad \text{factor} = \frac{P_{\mathrm{EL}}}{P_{\mathrm{f}}} = 3{,}808$$

~~This calculation below is done with the coefficient calculated in Table A.1.~~

~~Rated power = 1 000 kVA~~

~~No load losses = 1 100 W~~

~~Load losses at 75 °C = 10 456 W~~

~~Frequency = 50 Hz~~

~~Rated top oil temperature rise = 60 K~~

~~Mean winding temperature rise = 65 K~~

~~Low voltage winding~~

~~Calculated losses at fundamental current~~

~~I^2R losses at 75 °C = 4 000 W~~

~~Eddy losses (4 %) = 160 W~~

~~Total losses at 75 °C = 4 000 + 160 = 4 160 W~~

~~LV winding gradient = 18 K~~

~~Stray losses = 320 W~~

~~Calculated losses in service with non sinusoidal currents~~

~~I^2R losses = 4 000 × (1,038 2)^2 = 4 312 W~~

~~Eddy losses = 160 × 3,808 = 609 W~~

~~Total LV winding losses = 4 312 + 609 = 4 921 W~~

~~Calculated LV winding gradient = 18 × (4 921/4 160)$^{0,5 \times 1,6}$ = 20,6 K~~

~~Total in service stray losses = 320 × 1,308 = 419 W~~

~~High voltage winding~~

~~Calculated losses at fundamental current~~

~~I^2R losses at 75 °C = 5 300 W~~

~~Eddy losses (12 %) = 636 W~~

~~Total losses at 75 °C = 5 300 + 636 = 5 936 W~~

~~HV winding gradient = 17 K~~

~~Stray losses = 40 W~~

~~Calculated losses in service with non sinusoidal currents~~

~~I^2R losses = 5 300 × (1,038 2)^2 = 5 710 W~~

~~Eddy losses = 636 × 3,808 = 2 421 W~~

~~Total HV winding losses = 5 710 + 2 421 = 8 131 W~~

~~Calculated HV winding gradient = 17 × (8 131/5 936)$^{0,5 \times 1,6}$ = 21,9 K~~

~~Total in service stray losses = 40 × 1,308 = 52 W~~

~~Transformer total losses (Ttl) at fundamental current~~

~~Ttl = no load losses (NLl) + total load losses (Ll)~~

~~Ttl = 1 100 + 4 000 + 160 + 320 + 5 300 + 636 + 40 = 11 556 W~~

~~Transformer Total losses Ttl s in service with non sinusoidal current~~

~~Ttl s = 1 100 + 4 312 + 609 + 419 + 5 710 + 2 421 + 52 = 14 623 W~~

~~pu increased top oil temperature rise with non sinusoidal currents~~

~~$TOi\,/\,Tor$ = $(14\,623/11\,556)^{0,8}$ = 1,21 (+21 %)~~

~~Derating of the transformer shall be approximately:~~

~~Permissible loading for the transformer = Rated power × $(11\,556/14\,623)^{0,5}$~~

~~Permissible loading for the transformer = Rated power × 0,89~~

~~Derating of the transformer shall be approximately 11 %.~~

~~A.2.12.2.2 Conclusion~~

~~The 1 000 kVA transformer taken as an example is not appropriate for the service described and~~

- ~~transformer shall be designed with reduced winding temperatures and top oil temperature rises,~~

~~or~~

- ~~purchaser has to select a transformer with a higher rated power (e.g. 1 000/0,89 kVA),~~

~~or~~

- ~~the transformer rated power is not adequate for such load profile and the user shall reduce transformer loading by a factor of 0,89.~~

~~NOTE In the case where the (ohmic and eddy) losses are known in both LV and HV windings, then the specific losses of the considered winding should be considered for an accuracy value of derating based on winding hot spot.~~

~~A.2.12.3 Example for a dry type transformer~~

~~A.2.12.3.1 Calculation of the permissible loading of the transformer~~

~~Table A.2 – Impact of harmonics content on dry type transformers losses~~

~~Harmonic order (h)~~	~~Magnitude (%)~~	~~I_h/I_1~~	~~$(I_h/I_1)^2$ enhancement factor~~	~~Eddy losses enhancement factor~~	~~Stray losses enhancement factor~~
~~1~~	~~100~~	~~1~~	~~1~~	~~1,000~~	~~1,000 0~~
~~5~~	~~26,2~~	~~0,262~~	~~0,068 64~~	~~1,716~~	~~0,248 8~~
~~7~~	~~11,0~~	~~0,110~~	~~0,012 10~~	~~0,593~~	~~0,057 4~~
~~11~~	~~8,1~~	~~0,081~~	~~0,006 56~~	~~0,794~~	~~0,044 7~~
~~13~~	~~5,8~~	~~0,058~~	~~0,003 36~~	~~0,569~~	~~0,026 2~~
~~17~~	~~4,2~~	~~0,042~~	~~0,001 76~~	~~0,510~~	~~0,017 0~~
~~19~~	~~2,6~~	~~0,026~~	~~0,000 68~~	~~0,244~~	~~0,007 1~~
~~23~~	~~1,9~~	~~0,019~~	~~0,000 36~~	~~0,191~~	~~0,004 4~~
~~25~~	~~1,6~~	~~0,016~~	~~0,000 26~~	~~0,160~~	~~0,003 4~~
~~29~~	~~1,2~~	~~0,012~~	~~0,000 14~~	~~0,121~~	~~0,002 1~~
~~31~~	~~0,8~~	~~0,008~~	~~0,000 06~~	~~0,062~~	~~0,001 0~~
		Σ	~~1,093 9~~	~~5,960~~	~~1,412~~
	~~RMS current~~	~~1,046~~			-
	~~THD~~	~~30,65 %~~	~~THD is the total harmonic distortion rate (%)~~		

~~THD according to IEC 60076-1:2011, 3.13.2~~

~~Calculation of the equivalent current~~

$$I_r^2 = \sqrt{\sum_{h=1}^{h=n} I_h^{\,2}}$$

$$I_r^2 = 1{,}093\ 9$$

~~K factor =~~ $\frac{P_{\mathrm{EL}}}{P_{\mathrm{f}}}$ ~~= 5,960~~

~~Rated power = 1 000 kVA~~

~~No load losses = 2 300 W~~

~~Load losses at 120 °C = 11 000 W~~

~~Frequency = 50 Hz~~

~~Mean winding temperature rise = 100 K~~

~~*Low voltage winding*~~

~~Calculated losses at fundamental current~~

~~I^2R losses at 120 °C = 4 100 W~~

~~Eddy losses (2,9 %) = 120 W~~

~~Total losses at 120 °C = 4 100+120 = 4 220 W~~

~~LV winding gradient = 100 K~~

~~Stray losses = 320 W~~

~~Calculated losses in service with non sinusoidal currents~~

~~I^2R losses = 4 100 × (1,046)^2 = 4 485 W~~

~~Eddy losses = 120 × 5,959 = 715 W~~

~~Total LV winding losses = 4 485 + 715 = 5 200 W~~

~~Calculated LV winding gradient = 100 × (5 200 / 4 220)$^{0,5 \times 1,6}$ = 118,1 K~~

~~Total in service stray losses = 320 × 1,412 = 452 W~~

~~*High voltage winding*~~

~~Calculated losses at fundamental current~~

~~I^2R losses at 120 °C= 6 000 W~~

~~Eddy losses (7,5 %) = 450 W~~

~~Total losses at 120 °C = 6 000 + 450 = 6 450 W~~

~~HV winding gradient = 100 K~~

~~Calculated losses in service with non sinusoidal currents~~

~~I^2R losses = 6 000 × (1,046)^2 = 6 563 W~~

~~Eddy losses = 450 × 5,959 = 2 682 W~~

~~Total HV winding losses = 6 563 + 2 682 = 9 245 W~~

~~Calculated HV winding gradient = 100 × (9 245/6 450)$^{0,5 \times 1,6}$ = 133,4 K~~

~~Transformer total losses (Ttl) at fundamental current~~

~~Ttl = no load losses (Nll) + total load losses (Ll)~~

~~Ttl = 2 300 + 4 100 + 123 + 320 + 6 000 + 450 = 13 293 W~~

~~Transformer total losses Ttl s in service with non sinusoidal currents~~

~~Ttl_s = 2 300 + 4 485 + 715 + 452 + 6 563 + 2 682 = 17 197 W~~

~~Derating of transformer shall be approximately:~~

~~Permissible loading for the transformer = Rated power × (13 293 /17 197)^{0,5}~~

~~Permissible loading for the transformer = Rated power × 0,88~~

~~Derating of transformer shall be approximately 12 %.~~

~~A.2.12.3.2 Conclusion~~

~~The 1 000 kVA transformer taken as example is not appropriate for the service described and~~

- ~~transformer shall be designed with reduced winding temperatures,~~

~~or~~

- ~~purchaser has to select a transformer with a higher rated power (eg 1 000/0,88 kVA),~~

~~or~~

- ~~the transformer rated power is not adequate for such load profile and the user shall reduce transformer loading by a factor of 0,88.~~

~~A.3 Effects of voltage harmonics~~

~~The effect of this voltage distortion leads to an increasing of:~~

- ~~magnetic flux density;~~
- ~~no load losses;~~
- ~~no load current;~~
- ~~noise level;~~
- ~~magnetic core temperature;~~

~~Bh: Flux density corresponding to harmonic h (T)~~
~~Bn: Flux density at nominal voltage (T)~~
~~Vh: Voltage harmonic components (V)~~
~~V1: Rated voltage. (V)~~

~~Table A.3 – Example of voltage harmonic order~~

~~Harmonic order (*h*)~~	~~Magnitude (%)~~	~~Vh/V1~~	~~(Vh/V1)²~~	~~Bh/Bn~~	~~(Bh/Bn)²~~
~~1~~	~~100~~	~~1~~	~~1~~	~~1~~	~~1~~
~~2~~	~~4~~	~~0,04~~	~~0,001 6~~	~~0,02~~	~~0,000 4~~
~~3~~	~~16~~	~~0,16~~	~~0,025 6~~	~~0,053 333~~	~~0,002 844 44~~
~~4~~	~~6~~	~~0,06~~	~~0,003 6~~	~~0,015~~	~~0,000 225~~
~~5~~	~~20~~	~~0,2~~	~~0,04~~	~~0,04~~	~~0,001 6~~
~~6~~	~~2~~	~~0,02~~	~~0,000 4~~	~~0,003 333~~	~~$1,1111 \times 10^{-5}$~~
~~7~~	~~11~~	~~0,11~~	~~0,012 1~~	~~0,015 714~~	~~0,000 246 94~~
~~8~~	~~2~~	~~0,02~~	~~0,000 4~~	~~0,002 5~~	~~0,000 006 25~~
~~9~~	~~5,8~~	~~0,058~~	~~0,003 36~~	~~0,006 444~~	~~$4,1531 \times 10^{-5}$~~
~~10~~	~~4,2~~	~~0,042~~	~~0,001 76~~	~~0,004 2~~	~~0,000 017 64~~
~~11~~	~~2,6~~	~~0,026~~	~~0,000 68~~	~~0,002 364~~	~~$5,5868 \times 10^{-6}$~~
~~13~~	~~1,9~~	~~0,019~~	~~0,000 36~~	~~0,001 462~~	~~$2,1361 \times 10^{-6}$~~
~~15~~	~~1,6~~	~~0,016~~	~~0,000 26~~	~~0,001 067~~	~~$1,1378 \times 10^{-6}$~~
~~29~~	~~1,2~~	~~0,012~~	~~0,000 14~~	~~0,000 414~~	~~$1,7122 \times 10^{-7}$~~
~~31~~	~~0,8~~	~~0,008~~	~~0,000 06~~	~~0,000 258~~	~~$6,6597 \times 10^{-8}$~~
		~~Σ~~	~~1,090 3~~		~~1,005 402 014~~

~~**RMS voltage**~~	~~**1,044**~~
~~**THD (voltage)**~~	~~**30,05 %**~~
~~**RMS flux density**~~	~~**1,003**~~
~~**THD (flux density)**~~	~~**7,35 %**~~

~~THD according to IEC60076-1:2011, 3.13.2.~~

~~RMS voltage is the square root of the sum of (Vh/V1)².~~

~~RMS flux density is the square root of the sum of (Bh/Bn)².~~

~~The consequences of this high voltage distortion (THD <5 % is considered being practically sinusoidal) are not high as flux density is much less distorted than voltage.~~

~~Magnetic flux density is time integral of voltage and thus each harmonic flux density component is inversely relative to the harmonic order. The increase in RMS flux value is close to zero, therefore no correction is needed for the measured no load losses in regard to voltage harmonics.~~

~~The following parameters are also related to the design of the transformer under non sinusoidal voltage:~~

- ~~no load current (especially under presence of DC component);~~
- ~~noise level, (especially under presence of DC and second harmonics);~~
- ~~magnetic core temperature (especially under presence of DC and second harmonics).~~

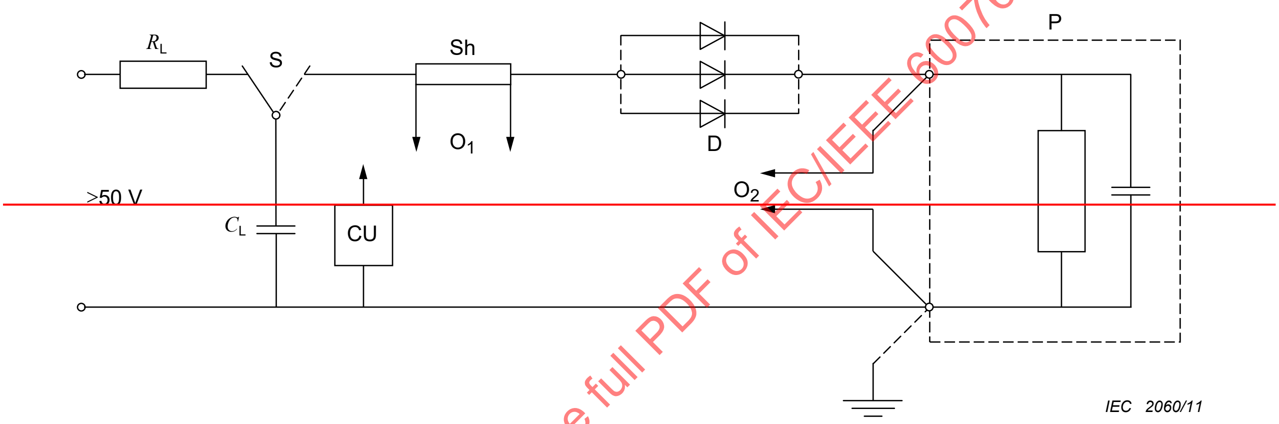
~~NOTE The harmonic frequency flux density components increase only eddy current part no load losses. With grain oriented core materials this part is approximately 50 % of total no load losses. The second part, hysteresis losses part, also approximately 50 % is influenced only by an increase in hysteresis loop area and peak flux density reached, which both in practical cases are not influenced.~~

~~A.4 Electrical resonance frequency measurement~~

~~A.4.1 Method of measurement~~

~~In order to determine the resonance natural frequency of a winding of a transformer, in a frequency range between 50 Hz and some 100 kHz, the measurement using the principle by capacitor current injection will be used. This method is also described in Annex F of IEC 62271-100:2008. During the measurement the other windings shall be short circuited.~~

~~The general diagram of current injection device, given by IEC 62271-100 is given in Figure A.2 below.~~



~~**Key**~~

~~R_L Charging resistor~~

~~S Switching relais~~

~~C_L Source capacitance~~

~~Sh Current measuring shunt~~

~~O_1 Cathode-ray oscillograph, trace 1 recording magnitude and linearity of the current and checking the diode operation~~

~~O_2 Cathode-ray oscillograph, trace 2 recording the response of the circuit~~

~~D Parallel connection of up to 100 fast silicon switching diodes~~

~~P Circuit the prospective TRV of which is to be measured~~

~~CU Control unit to provide the sequence of operation~~

~~**Figure A.2 – Schematic diagram of power frequency current injection apparatus**~~

~~NOTE Other method like frequency sweep with respective continuous impedance measurements can be used. During the measurement other windings of transformer shall be short circuited.~~

~~A.4.2 Measurement of the resonance frequency of a transformer winding~~

~~The principle consists in discharging a capacitor in the winding of the transformer and to analyse the visual winding voltage response.~~

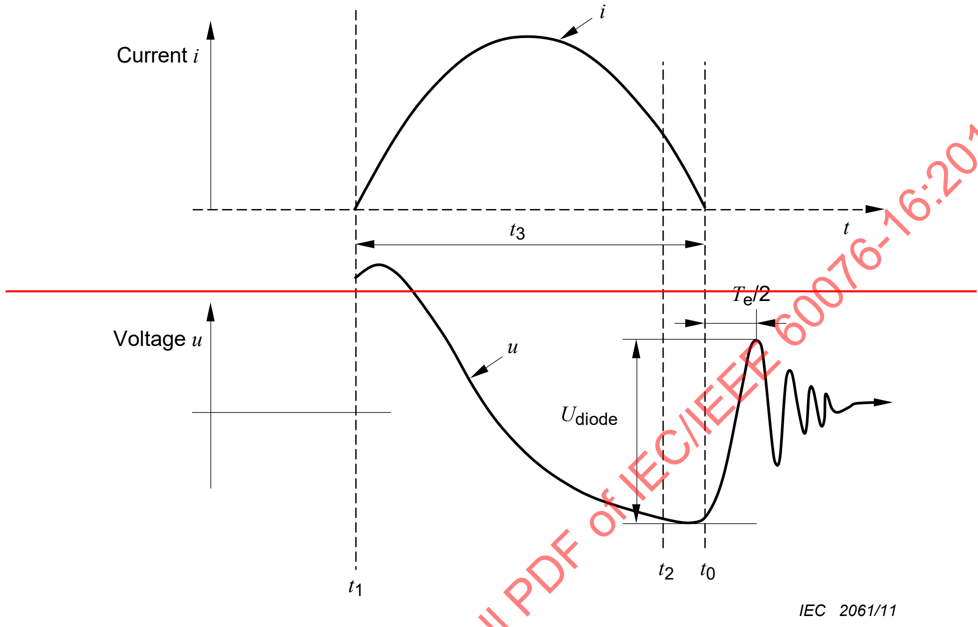
~~The capacitance discharge is followed by a dumped oscillation, as no energy is feeded.~~

~~The frequency of this oscillation is the frequency of resonance of the transformer.~~

~~he following Figure A.3 shows the waveforms of current i and voltage u after the time where the current passes through 0 after switching the switching relay S.~~

~~The transient recovery voltage (TRV) is starting and the dumped oscillation is illustrated.~~

~~The first half cycle Te/2 of the TRV gives the frequency of resonance of the switched winding of the transformer.~~



~~**Key**~~

~~t_0 Time where current passes trough zero (beginning of the TRV oscillation)~~

~~t_1 Instant of switching of relays S~~

~~t_2 Tripping of the cathode-ray oscillograph~~

~~t_3 Duration of current through diode D~~

~~u Voltage curve across the terminals of the circuit P~~

~~i Waveform of the injected current~~

~~U_{diode} Maximum voltage stressing of the diodes~~

~~$T_e/2$ Duration of half cycle of TRV~~

~~**Figure A.3 – Switched transformer winding voltage responses with capacitor injection**~~

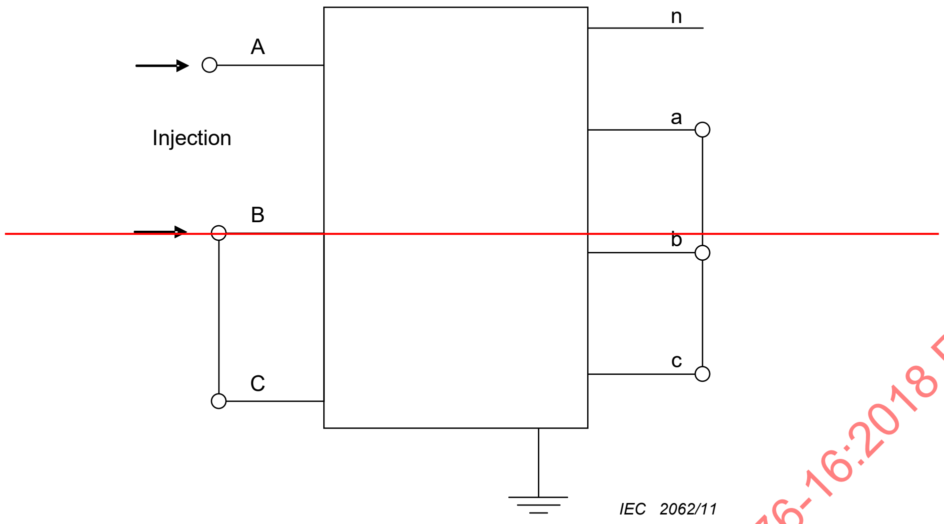
~~A.4.3 Practical aspects of the injection measurement method~~

~~A.4.3.1 Injection test figures~~

~~This measurement is carried out in single phase supply for three phase transformers.~~

~~Below is described a scheme to measure phase A.~~

~~In case of injection between A and B (then B and C connected together) with LV phases (a, b, c) short circuited and LV neutral not connected, the following way of injection given in Figure A.4 will be used:~~



~~**Key**~~

~~A,B,C High voltage terminals~~

~~a,b,c Low voltage terminals~~

~~n Is neutral terminal~~

~~**Figure A.4 – HV Injection test figure**~~

~~With the 3 LV phases short circuited, 3 different ways of HV injection should be considered:~~

- ~~HV phases B and C connected together and LV neutral connected to the ground of transformer. This case shall be used when the LV neutral is earthed during operation and gives the value of phase A.~~
- ~~HV phases B and C connected together and connected to ground and LV neutral connected to the ground of transformer. This case is valid to see the difference in case of high voltage system ground fault and gives the value of phase A.~~
- ~~HV phases B and C connected together and LV neutral not connected. This case shall be used when the LV neutral is not earthed during operation. Figure A.4 shows this kind of measurement configuration and gives the value of phase A.~~

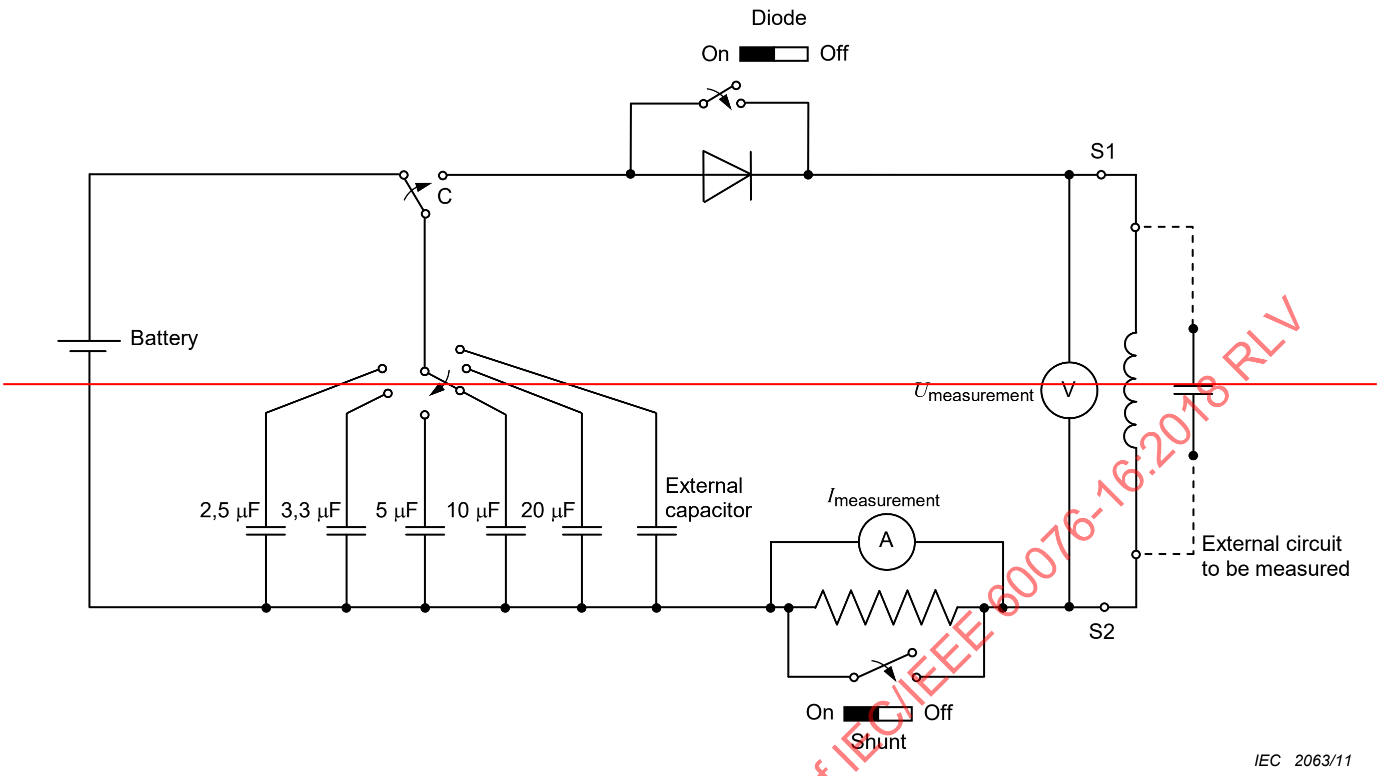
~~For measurement of the other phases, rotation of the same sequences should be applied.~~

~~**A.4.3.2 Example of measurement system**~~

~~Figure A.5 is showing a practical measurement system with devices such as:~~

– ~~battery supply, capacitors, driving diode, winding of transformer to be measured at the bushings;~~

– ~~S1 and S2, current and voltage measuring and waveform visualisation devices;~~



~~**Figure A.5 – Example of measurement device**~~

~~The recommendations are as follows:~~

- ~~contact C with no bounces required;~~
- ~~some diodes with reduced recovery time may be used and mounted in parallel;~~
- ~~supply of the voltage visualisation device (oscilloscope) by battery or with an insulation transformer.~~

~~A.5 Table of symbols~~

~~Symbol~~	~~Meaning~~	~~Units~~
θ_1	~~Air inlet temperature~~	~~°C~~
θ_2	~~Air outlet temperature~~	~~°C~~
$\Delta\theta_a$	~~Air temperature rise between outlet and inlet~~	~~K~~
υ	~~Additional losses~~	~~W~~
A_1	~~Air inlet effective cross section~~	~~m²~~
A_2	~~Air outlet effective cross section~~	~~m²~~
~~AF~~	~~Air forced cooling~~	~~-~~
~~Bh~~	~~Flux density corresponding to harmonic *h*~~	~~T~~
~~Bn~~	~~Flux density at nominal voltage~~	~~T~~
~~E2 , E3~~	~~Environmental classes~~	~~-~~
e_i	~~Eddy losses per unit for considered winding~~	~~-~~

~~Symbol~~	~~Meaning~~	~~Units~~
~~f~~	~~Frequency~~	~~Hz~~
~~h~~	~~Current harmonic order~~	~~-~~
H	~~Difference in height between mid outlet surface and mid height of the transformer~~	~~m~~
HL	~~Heat losses of transformer~~	~~kW~~
~~HV~~	~~High voltage~~	~~kV~~
~~I~~	~~Load current circulating in the considered winding (see A.2)~~	~~A~~
~~I_{rms}~~	~~RMS current~~	~~A~~
~~I_1~~	~~Fundamental current~~	~~A~~
Ih	~~Magnitude of the harmonic h current~~	~~A~~
~~I_r~~	~~Rated current~~	~~A~~
~~K factor~~	~~Ratio between total eddy losses due to all harmonic currents referred to eddy losses at fundamental current~~	~~-~~
~~LL~~	~~Transformer nominal load losses at reference temperature~~	~~kW~~
Ll	~~Load losses for a considered winding at reference temperature~~	~~W~~
Lls	~~Transformer total load losses with non sinusoidal current~~	~~W~~
~~LV~~	~~Low voltage~~	~~V~~
NLL	~~Transformer no-load losses~~	~~kW~~
P_{EL}	~~Total eddy losses for each individual harmonics~~	~~W~~
P_f	~~Eddy losses at fundamental frequency with rated current~~	~~W~~
Ph	~~Eddy losses at harmonic h~~	~~W~~
Q_{AF}	~~Heat dissipation by forced air circulation~~	~~kW~~
Q_c, Q_w	~~Losses dissipated respectively through ceiling and the walls~~	~~kW~~
Q_{nac}	~~Dissipation power by natural air circulation~~	~~kW~~
Q_{tot}	~~Heat dissipation power in the transformer's room~~	~~kW~~
Q_{wc}	~~Heat dissipation through the walls and ceiling~~	~~kW~~
R, R_1, R_2	~~Winding resistance~~	~~Ω~~
~~rh~~	~~Ratio of magnitude of current harmonic h over fundamental current~~	~~-~~
~~S_i~~	~~Stray losses~~	~~W~~
~~SL_{ih}~~	~~Stray losses for harmonic of order h referred to stray losses at fundamental current I_1~~	~~-~~
~~Sr~~	~~Nominal load of the transformer~~	~~kVA~~
~~SrE~~	~~Permissible loading for the transformer~~	~~kVA~~
~~THD~~	~~Total harmonic distortion rate~~	~~%~~
Tl	~~Transformer total load losses~~	~~W~~
~~TOi~~	~~Top oil temperature rise with non sinusoidal currents~~	~~K~~
~~Tor~~	~~Top oil temperature rise with rated current~~	~~K~~
Ttl	~~Transformer total losses at fundamental current~~	~~W~~

~~Symbol~~	~~Meaning~~	~~Units~~
$Ttls$	~~Transformer total losses in service with non sinusoidal current~~	~~W~~
U_m	~~Highest voltage for equipment~~	~~kV~~
~~V1~~	~~Rated voltage~~	~~kV~~
~~Vh~~	~~Voltage harmonic at order *n* expressed per unit~~	~~V~~

Annex A
(informative)

Effects of voltage harmonics

A.1 Design and specification considerations

Special consideration needs to focus on the effects of a rapid ramp-up of power due to a rapid increase of current during a quick change of wind speed to which the blade pitch motors are slow to react. IEC 60076-14:2013, Annex B refers to bubbling effect that can be caused by rapid ramp-up effect and needs to be considered. Additionally, consideration should be given to the following:

- harmonic current filtering;
- harmonic impact on the neutral;
- power factor correction equipment;
- electrostatic shielding;
- harmonic spectrum analysis;
- winding design to mitigate heat attributed to eddy currents;
- losses when performing temperature rise calculations;
- switching transients.

Further consideration needs to be given for power flow reversal, heat rise during LVRT, and harmonic loading due to power factor control equipment.

NOTE IEEE Std C57.12.00 requires these transformers to be considered to be a hybrid transformer which is a Class 1 compartmentalized type power transformer with step-up capabilities and never energized from the LV terminals.

A.2 Effects of voltage harmonics

The effect of this voltage distortion leads to an increasing of:

- magnetic flux density;
- no load losses;
- no load current;
- noise level;
- magnetic core temperature;

The following example of the voltage harmonic order in Table A.1 highlights this issue.

Bh:	Flux density corresponding to harmonic h	(T)
Bn:	Flux density at nominal voltage	(T)
Vh:	Voltage harmonic components	(V)
V1:	Rated voltage.	(V)

Table A.1 – Example of voltage harmonic order

Harmonic order (h)	**Magnitude (%)**	**Vh/V1**	**(Vh/V1)^2**	**Bh/Bn**	**(Bh/Bn)^2**
1	100	1	1	1	1
2	4	0,04	0,001 6	0,02	0,000 4
3	16	0,16	0,025 6	0,053 333	0,002 844 44
4	6	0,06	0,003 6	0,015	0,000 225
5	20	0,2	0,04	0,04	0,001 6
6	2	0,02	0,000 4	0,003 333	$1,111\ 1 \times 10^{-5}$
7	11	0,11	0,012 1	0,015 714	0,000 246 94
8	2	0,02	0,000 4	0,002 5	0,000 006 25
9	5,8	0,058	0,003 36	0,006 444	$4,153\ 1 \times 10^{-5}$
10	4,2	0,042	0,001 76	0,004 2	0,000 017 64
11	2,6	0,026	0,000 68	0,002 364	$5,586\ 8 \times 10^{-6}$
13	1,9	0,019	0,000 36	0,001 462	$2,136\ 1 \times 10^{-6}$
15	1,6	0,016	0,000 26	0,001 067	$1,137\ 8 \times 10^{-6}$
29	1,2	0,012	0,000 14	0,000 414	$1,712\ 2 \times 10^{-7}$
31	0,8	0,008	0,000 06	0,000 258	$6,659\ 7 \times 10^{-8}$
		Σ	1,090 3		1,005 402 014

RMS voltage	**1,044**
THD (voltage)	**30,05 %**
RMS flux density	**1,003**
THD (flux density)	**7,35 %**

Total harmonic distortion (THD).

Root mean square (RMS) voltage is the square root of the sum of (Vh/V1)^2.

RMS flux density is the square root of the sum of (Bh/Bn)^2.

The consequences of this high voltage distortion (THD < 5 % is considered to be practically sinusoidal) are not considered significant as flux density is distorted much less than voltage.

Magnetic flux density is time integral of voltage and thus each harmonic flux density component is inversely proportional to the harmonic order. The increase in RMS flux value is close to zero, therefore no correction is needed for the measured no load losses in regard to voltage harmonics.

The following parameters are also related to the design of the transformer under non-sinusoidal voltage:

- no load current (especially under presence of DC component);
- noise level (especially under presence of DC and second harmonics);
- magnetic core temperature (especially under presence of DC and second harmonics).

NOTE The harmonic frequency flux density components are increased mainly by eddy current no load losses. With grain oriented core materials, this accounts for approximately 50 % of total no load losses. Hysteresis losses also accounts for approximately 50 % of total no load losses and is influenced by an increase in hysteresis loop area and frequency. In practical cases this influence is negligible.

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IEC 61039, *Classification of insulating liquids*

IEC 61378-3, *Converter transformers – Part 3: Application guide*

IEC 61400-1, *Wind turbines – Part 1: Design requirements*

IEEE references

IEEE Std 1584™, *IEEE Guide for Performing Arc Flash Hazard Calculations*

NFPA 70E, *Standard for Electrical Safety in the Workplace*

IEEE Std C57.12.10™, *IEEE Standard Requirements for Liquid-Immersed Power Transformers*

IEEE Std C57.12.26™, *IEEE Standard for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers for Use with Separable Insulated High-Voltage Connectors (34 500 GrdY/19 920 Volts and Below, 2500 kVA and Smaller)* [2]

IEEE Std C57.12.28™, *IEEE Standard for Pad-Mounted Equipment – Enclosure Integrity*

IEEE Std C57.12.29™, *IEEE Standard for Pad-Mounted Equipment – Enclosure Integrity for Coastal Environments*

IEEE Std C57.12.34™, *IEEE Standard Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers, 10 MVA and Smaller; High Voltage, 34.5 kV Nominal System Voltage and Below; Low Voltage, 15 kV Nominal System Voltage and Below*

IEEE Std C57.12.51™, *IEEE Standard for Ventilated Dry-Type Power Transformers, 501 kVA and Larger, Three-Phase, with High-Voltage 601 V to 34 500 V; Low-Voltage 208Y/120 V to 4160 V – General Requirements*

IEEE Std C57.12.52™, *IEEE Standard for Sealed Dry-Type Power Transformers, 501 kVA and Higher, Three-Phase, with High-Voltage 601 to 34500 Volts, Low-Voltage 208Y/120 to 4160 Volts – General Requirements*

ANSI C57.12.55™, *American National Standard for Transformers – Used in Unit Installations, Including Unit Substations – Conformance Standard*

IEEE Std C57.12.59™, *IEEE Guide for Dry-Type Transformer Through-Fault Current Duration*

IEEE Std C57.12.91™, *IEEE Standard Test Code for Dry-Type Distribution and Power Transformers*

IEEE Std C57.12.90™, *IEEE Standard Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers*

IEEE Std C57.18.10™, *IEEE Standard Practices and Requirements for Semiconductor Power Rectifier Transformers*

IEEE Std C57.94™, *IEEE Recommended Practice for Installation, Application, Operation, and Maintenance of Dry-Type General Purpose Distribution and Power Transformers*

IEEE Std C57.104™, *IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers*

IEEE Std C57.105™, *IEEE Guide for Application of Transformer Connections in Three-Phase Distribution Systems*

IEEE Std C57.106™, *IEEE Guide for Acceptance and Maintenance of Insulating Mineral Oil in Electrical Equipment*

IEEE Std C57.109™, *IEEE Guide for Liquid-Immersed Transformers Through-Fault-Current Duration*

IEEE Std C57.111™, *IEEE Guide for Acceptance of Silicone Insulating Fluid and Its Maintenance in Transformers*

[2] Withdrawn.

IEEE Std C57.113™, *IEEE Recommended Practice for Partial Discharge Measurement in Liquid-Filled Power Transformers and Shunt Reactors*

IEEE Std C57.116™, *IEEE Guide for Transformers Directly Connected to Generators*

IEEE Std C57.120™, *IEEE Guide for Loss Evaluation of Distribution and Power Transformers and Reactors*

IEEE Std C57.121™, *IEEE Guide for Acceptance and Maintenance of Less-Flammable Hydrocarbon Fluid in Transformers*

IEEE Std C57.123™, *IEEE Guide for Transformer Loss Measurement*

IEEE Std C57.124™, *IEEE Recommended Practice for the Detection of Partial Discharge and the Measurement of Apparent Charge in Dry-Type Transformers*

IEEE Std C57.127™, *IEEE Guide for the Detection and Location of Acoustic Emissions from Partial Discharges in Oil-Immersed Power Transformers and Reactors*

IEEE Std C57.131™, *IEEE Standard Requirements for Tap Changers*

IEEE Std C57.142™, *IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by Transformers, Switching Device, and System Interaction*

IEEE Std C57.147™, *IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers*

IEEE Std C57.152™, *IEEE Guide for Diagnostic Field Testing of Fluid-Filled Power Transformers, Regulators, and Reactors*

Gas Pressure Calculations for Sealed Transformers under Varying Load Conditions

T.V. Oommen, IEEE Power Engineering Review, volume PER-3, Issue 5, dated 1983

Calculation of Mechanical Stresses in Hermetically Sealed Transformers

D Herfati et al. CIRED International Conference on Electricity Distribution, Vienna, 21-24 May 2007, Paper 309

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Power transformers –
Part 16: Transformers for wind turbine applications

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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POWER TRANSFORMERS –

Part 16: Transformers for wind turbine applications

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of 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, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). 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.

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International Standard IEC/IEEE 60076-16 has been prepared by IEC technical committee 14: Power transformers, in cooperation with Performance Characteristics Subcommittee of the IEEE Power and Energy Society [1], under the IEC/IEEE Dual Logo Agreement between IEC and IEEE.

This second edition of IEC/IEEE 60076-16 cancels and replaces IEC 60076-16:2011, and constitutes a technical revision.

The main changes with respect to the previous edition are as follows:

1) relationship between transformer rated power and the output current from the associated generator is introduced;
2) thermal correction of the effective cooling medium has been introduced;
3) testing regime has been strengthened to ensure transformers are suitable for the harsh electrical environment to which they are subjected.

This publication is published as an IEC/IEEE Dual Logo standard.

The text of this standard is based on the following IEC documents:

FDIS	Report on voting
14/959/FDIS	14/965/RVD

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

A list of all parts in the IEC/IEEE 60076 series, published under the general title *Power transformers*, can be found on the IEC website.

The IEC Technical Committee and IEEE Technical Committee have decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

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

A bilingual version of this publication may be issued at a later date.

1 A list of IEEE participants can be found at the following URL: https://standards.ieee.org/project/60076-16.html

POWER TRANSFORMERS –

Part 16: Transformers for wind turbine applications

1 Scope

This part of IEC 60076 applies to dry-type and liquid-immersed transformers for wind turbine step-up applications having a winding with highest voltage for equipment up to and including 72,5 kV. This document applies to the transformer used to connect the wind turbine generator to the wind farm power collection system or adjacent distribution network and not the transformer used to connect several wind turbines to a distribution or transmission network.

Transformers covered by this document comply with the relevant requirements prescribed in the IEC 60076 standards or IEEE C57 standards.

2 Normative references

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

2.1 IEC references

IEC 60076-1, *Power transformers – Part 1: General*

IEC 60076-2, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

IEC 60076-3, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-5, *Power transformers – Part 5: Ability to withstand short circuit*

IEC 60076-7, *Power transformers – Part 7: Loading guide for mineral-oil-immersed power transformers*

IEC 60076-11, *Power transformers – Part 11: Dry-type transformers*

IEC 60076-12, *Power transformers – Part 12: Loading guide for dry-type power transformers*

IEC 60076-14, *Power transformers – Part 14: Liquid-immersed power transformers using high-temperature insulating materials*

IEC 61378-1, *Converter transformers – Part 1: Transformers for industrial applications*

2.2 IEEE references

IEEE Std C57.12.00™, *IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*

IEEE Std C57.12.01™, *IEEE Standard for General Requirements for Dry-Type Distribution and Power Transformers*

IEEE Std C57.12.80™, *IEEE Standard Terminology for Power and Distribution Transformers*

IEEE Std C57.91™, *IEEE Guide for Loading Mineral-Oil-Immersed Transformers and Step-Voltage Regulators*

IEEE Std C57.96™, *IEEE Guide for Loading Dry-Type Distribution and Power Transformers*

IEEE Std C57.110™, *IEEE Recommended Practice for Establishing Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents*

IEEE Std C57.154™, *IEEE Standard for the Design, Testing, and Application of Liquid-Immersed Distribution, Power, and Regulating Transformers Using High-Temperature Insulation Systems and Operating at Elevated Temperatures*

ANSI C84.1, *Electric Power Systems and Equipment – Voltage Ratings (60 Hz)*

2.3 ISO references

ISO 12944 (all parts), *Paints and varnishes – Corrosion protection of steel structures by protective paint systems*

ISO 12944-4, *Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 4: Types of surface and surface preparation*

2.4 CENELEC references

EN 50588-1:2015, *Medium power transformers 50 Hz, with highest voltage for equipment not exceeding 36 kV – Part 1: General requirements*

3 Terms and definitions

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

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

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

3.1
wind turbine transformer
generator step up transformer connecting the wind turbine to the power collection system of the wind farm or the adjacent distribution network for single turbine installations

3.2
tower
supporting structure of the wind turbine on top of which the nacelle with generator and other equipment is located

3.3
nacelle
housing that contains the drive-train and other elements on top of a horizontal-axis wind turbine tower

[SOURCE: IEC 60050-415:1999, 415-01-07]

3.4
effective cooling medium
ambient air, either internal or external to the tower or nacelle, or cooling water that comes into contact with the cooling surface of the transformer

3.5
compartmentalized type transformer
transformer with integral enclosure comprised of multiple independent compartments, usually with separate entrances into the HV and LV termination compartments

3.6
sealed transformer
transformer which is so constructed that the external atmosphere is not intended to gain access to the interior

3.7
routine sample test
test which is usually defined as a type test or special test but carried out as an additional routine test on a random sample of transformers

4 Use of normative references

This standard can be used with either the IEC or IEEE normative references but the references shall not be mixed. The purchaser shall include in the enquiry and order which normative references are to be used. If the choice of normative references is not specified, then IEC standards shall be used except for wind turbine transformers intended for installation in North America where IEEE standards shall be used.

5 Rating

The transformer rating specified by the purchaser shall take into account the maximum current delivered to the transformer by the associated wind turbine generator system irrespective of the operating voltage and power factor.

6 Service conditions

6.1 Normal service conditions

6.1.1 General

The normal service conditions detailed in IEC 60076-1 or IEEE Std C57.12.00 for liquid-immersed transformers or the normal service conditions in IEC 60076-11 or IEEE Std C57.12.01 for dry-type transformers shall apply unless otherwise stated in this document or specified by the purchaser.

6.1.2 Temperature of external cooling medium

If the transformer is installed external to the tower or nacelle, the normal conditions specified in IEC 60076-1 or IEEE Std C57.12.00 for liquid-immersed transformers and IEC 60076-11 or IEEE Std C57.12.01 for dry-type transformers shall apply, unless otherwise specified. If the transformer is installed within the tower or nacelle then particular conditions apply as shown in 6.2.