CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

____

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.

   IEEE Standards documents are developed within IEEE Societies and Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board. IEEE develops its standards through a consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of IEEE and serve without compensation. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information contained in its standards. Use of IEEE Standards documents is wholly voluntary. IEEE documents are made available for use subject to important notices and legal disclaimers (see http://standards.ieee.org/IPR/disclaimers.html for more information).

   IEC collaborates closely with IEEE in accordance with conditions determined by agreement between the two organizations.

2) The formal decisions of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees. The formal decisions of IEEE on technical matters, once consensus within IEEE Societies and Standards Coordinating Committees has been reached, is determined by a balanced ballot of materially interested parties who indicate interest in reviewing the proposed standard. Final approval of the IEEE standards document is given by the IEEE Standards Association (IEEE-SA) Standards Board.

3) IEC/IEEE Publications have the form of recommendations for international use and are accepted by IEC National Committees/IEEE Societies in that sense. While all reasonable efforts are made to ensure that the technical content of IEC/IEEE Publications is accurate, IEC or IEEE cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications (including IEC/IEEE Publications) transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC/IEEE Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

5) IEC and IEEE do not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC and IEEE are not responsible for any services carried out by independent certification bodies.

6) All users should ensure that they have the latest edition of this publication.

7) No liability shall attach to IEC or IEEE or their directors, employees, servants or agents including individual experts and members of technical committees and IEC National Committees, or volunteers of IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (IEEE-SA) Standards Board, for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC/IEEE Publication or any other IEC or IEEE Publications.

8) Attention is drawn to the normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

9) Attention is drawn to the possibility that implementation of this IEC/IEEE Publication may require use of material covered by patent rights. By publication of this standard, no position is taken with respect to the existence or validity of any patent rights in connection therewith. IEC or IEEE shall not be held responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patent Claims or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

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

This second edition cancels and replaces the first edition, published in 2011, and constitutes a technical revision. The main changes with respect to the previous edition are as follows:

1)

2)

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

FDIS	Report on voting
XX/XX/FDIS	XX/XX/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.

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 web site 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.

> The National Committees are requested to note that for this publication the stability date is ….
>
> THIS TEXT IS INCLUDED FOR THE INFORMATION OF THE NATIONAL COMMITTEES AND WILL BE DELETED AT THE PUBLICATION STAGE.

[1] A list of IEEE participants can be found at the following URL: (to be provided prior to publication).

INTRODUCTION

If you want to insert an introduction, please refer to the ISO/IEC Directives Part 2:2011, 6.1.4.

1 Scope

This part of IEC 60076 applies to dry-type and liquid-immersed transformers for wind turbine step-up application having a winding with highest voltage for equipment up to and including 72.5 kV. This standard 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 standard comply with the relevant requirements prescribed in the IEC 60076 standards or IEEE C57 standards.

2 Normative references

The following referenced documents are indispensable for the application 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.

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 and other locations where IEEE standards compliance is required by the authority having jurisdiction, where IEEE standards shall be used. If a single reference standard is specified in a particular clause then its use shall be mandatory.

Note: This clause is intended to ensure that the transformer complies with all the relevant requirements of either the IEC or IEEE Standards and does not restrict the customer from special requirements.

IEC Documents

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 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 transformers using high temperature insulating materials

IEC 60721-4-4 **Classification of environmental conditions - Part 4-4: Guidance for the correlation and transformation of the environmental condition classes of IEC 60721-3 to the environmental tests of IEC 60068 - Stationary use at non-weatherprotected locations**

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

IEEE Documents

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

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

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) (Withdrawn)

C57.12.34, IEEE Standard Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers, 5 MVA and Smaller; High Voltage, 34.5 kV Nominal System Voltage and Below; Low Voltage, 15 kV Nominal System Voltage & Below

C57.12.28, IEEE Standard for Pad-Mounted Equipment-Enclosure Integrity

C57.12.29, IEEE Standard for Pad-Mounted Equipment-Enclosure Integrity for Coastal Environments

C57.12.01, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid-Cast and/or Resin-Encapsulated Windings

C47.12.80, IEEE Standard Terminology for Power and Distribution Transformers

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

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

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

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

IEEE 1584/NFPA 70E. IEEE Guide for Performing Arc Flash Hazard Calculations

ANSI C84.1, Electric Power Systems and Equipment - Voltage Ratings (60 Hertz)

ISO Documents

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

CENELEC Documents

CENELEC EN 50464-4 Three-phase oil-immersed distribution transformers 50 Hz, from 50 kVA to 2500 kVA with highest voltage for equipment not exceeding 36 kV - Part 4: Requirements and tests concerning pressurised corrugated tanks

3 Terms and definitions

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

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
the 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 (HAWT) tower [IEV 415-01-07]

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

3.5
compartmentalised type transformers

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

3.6
incident energy

The thermal energy at a typical working distance of 45.7 cm (18 in) from an arc fault, measured in cal/cm^2, which is a function of system voltage, available short circuit current, arc current and the time required for circuit protective devices to open.

3.7
sealed transformer
A transformer which is so constructed that the external atmosphere is not intended to gain access to the interior

4 Rating

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

5 Service conditions

5.1 Normal Service conditions

5.1.1 General

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

5.1.2 Temperature of external cooling medium

If the transformer is installed external to the tower or nacelle the normal conditions specified in the appropriate IEC or IEEE Standard referenced in clause 2 shall apply, unless otherwise specified. If the transformer is installed within the tower or nacelle then particular conditions apply as shown in clause 6.2.

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

5.2.1 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.

5.2.2 Temperature rise correction

Based on the ambient conditions of the installation the purchaser shall specify the average and maximum temperature of the effective cooling medium (air). The difference between the values and the “normal service conditions” values should be subtracted from the temperature rise limits of the respective standard as follows:

$$K_{max} = T_{\max\ ecm} - T_{\max\ std} \quad (1)$$

$$K_{av} = (T_{av\ ecm} - T_{av\ std}) \quad (2)$$

where,

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

K_{av} is the temperature ~~corredtion~~ correction factor for the 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

The K_{max} should be used in determining the temperature rise limit for the top liquid temperature, while K_{av} should be used in determining the temperature rise limit of average winding and winding hot-spot temperatures.

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

For the transformers installed in a tower or nacelle, special care shall be taken when considering 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 2.5% of its rated power (kVA).

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

$$K_{av} = (3\cancel{0}2 - 20) = 12\ \cancel{K}C$$

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

$$\Delta\theta_{\boldsymbol{w}} = 65 - K_{av} = 65 - 12 = \mathbf{53}\ \boldsymbol{\cancel{K}C}$$

$$\Delta\theta_{\boldsymbol{h}} = 78 - K_{av} = 78 - 12 = \mathbf{66}\ \boldsymbol{\cancel{K}C}$$

$$\boldsymbol{\Delta\theta_o = 60 - K_{max} = 60 - 8 = 52\ \cancel{K}C}$$

Another example, for a transformer using thermally upgraded insulation material (thermally upgraded kraft paper immersed in mineral oil) installed in an ambient where the average temperature is 30°C and the maximum ambient is 40°C, the temperature rise limits according IEC 60076-2 would be:

$$K_{av} = (30 - 28) = 2\ C$$

$$K_{max} = (40 - 32) = 8\ C$$

$$\Delta\theta_{\boldsymbol{w}} = 65 - K_{av} = 65 - 2 = \mathbf{63}\ \boldsymbol{C}$$

$$\Delta\theta_{\boldsymbol{h}} = 80 - K_{av} = 80 - 2 = 78\ \boldsymbol{C}$$

$$\boldsymbol{\Delta\theta_o = 65 - K_{max} = 65 - 8 = 57\ C}$$

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.

The effect of external direct solar radiation should be taken into account by the purchaser when calculating the temperature of the effective cooling medium. As per IEC 60721-4-4, the effect of the directly solar irradiation up to 1120W/m^2, if not considered for the thermal loading calculation, can be represented by an increase of 15°C of the temperature applied for a dry heat test, which would represent the internal temperature of a chamber without air renovation.

5.3 Content of harmonic currents in the transformer

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

Where total harmonic content is less than 5% no correction 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 loss at rated power caused by these currents using the method given in IEC 61378-1 or IEEE 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 IEC 61378-1 or IEEE Std. C57.110, IEEE Recommended Practice for Establishing

Liquid-Filled and Dry-Type Power and Distribution Transformer Capability When Supplying Nonsinusoidal Load Currents.

5.4 Over-excitiation

Unless otherwise specified by purchaser, transformers shall be capable of operating continuously above rated voltage or below rated frequency, at maximum rated 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.

5.5 Harmonic distortion of voltage

When supply voltage harmonics are expected to be in excess of 5%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 percent whichever is higher without damage.

A method to calculate the impact of the voltage harmonics on the design of the transformer is given in Annex ~~1~~A.

5.6 Transient voltages

a. Normal impulse protection

Transformer lightning impulse (LI) (see IEC 60076-3) or basic lightning impulse level (BIL) (see IEEE C57.12.80) shall be specified and protected with overvoltage protection. Increased transformer BIL levels should be considered unless system study indicates otherwise.

b. Switching induced overvoltages

Switching transient voltages, produced by vacuum interrupters and/or SF6 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 C57.142 addresses this issue in depth and relates the vulnerability to current chops and voltage restrikes by vacuum or SF6 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.

5.7 Humidity and salinity

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 failures of dry type transformers core/coil assemblies that were exposed to ambient air. Problems have also occurred with open type bushings of liquid-immersed transformers and dry type transformers in enclosures. Salt spray, and excessive moisture or dripping water constitute service conditions for which some transformers designs are not intended and, therefore, may have detrimental effects on transformer life.

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

NOTE—The seriousness of the effects of the conditions listed above varies widely, depending on the design of the dry-type transformer involved. Although such conditions may have little or no effect on sealed or non-ventilated dry-type transformers, they may have serious effects on ventilated dry-type transformers. Purchasers and manufacturers should jointly determine potential impacts, if any, on ventilated dry-type transformers. Ventilated dry-type is defined in IEEE C57.12.80.

5.8 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 mechanical 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.

5.9 Protection from Incident Energy when unit is energised

5.9.1 The safety of personnel performing maintenance and other operational tasks when the transformer is energised, such as oil sampling, checking of gas pressure levels, operation of switches, etc. must be considered in the design of the transformer to minimize exposure to hazardous incident energy. The following list shows some items that may be specified in order to minimize exposure to incident energy:

Load Break Switches can be made accessible without opening doors that give access to live terminals.

Oil conditioning and monitoring equipment (including gauges, Schrader Valve, Sampling Port, etc.) can be made accessible without opening doors that give access to live terminals.

5.9.2 In some countries additional safety measures should be considered in addition to the safety related requirements specified according to IEEE C57.12.~~26~~34, IEEE C57.12.28 and IEEE C57.12.29 and NFPA 70E.

Note: It is safest to perform all maintenance tasks near energized conductors while the transformer is de-energized.

5.10 Corrosion protection

Depending on the kind of installation, the purchaser should choose a protection class defined in ISO 12944, IEEE C57.12.28, IEEE 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.

5.11 Consideration for hermetically sealed transformers

A hermetically sealed transformer must be designed to withstand without permanent deformation the expected pressures that occur over the specified temperature range during full loading of the transformer. (See clause 6.2.1 and CENELEC EN 50464-4).

5.12 **Flammability issues with transformers mounted in the tower or nacelle**

For transformers in such applications, less-flammable insulating liquids or dry-type construction are recommended.

6 Electrical characteristics

6.1 Highest voltage for equipment

The highest voltage for equipment shall be specified in accordance with IEC 60076-3 and ANSI C84.1.

6.2 Tappings (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 may increase size, weight and cost and may decrease reliability and therefore should only be used where specifically required.

6.3 Connection group

Unless otherwise specified by the purchaser, the connection group shall be Dyn11 or HV ~~leading~~ lagging LV by 30 degrees.

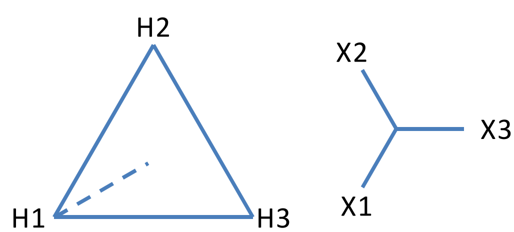

Figure 1 - Phase relation for a Dyn11 connection

6.4 Dimensioning of neutral connection

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

6.5 Short-circuit impedance

Commonly recognised minimum values for the short-circuit impedance of transformers at the rated current (principal tapping) are given in Table 2. 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 1250	5,0
1251 to 2500	6,0
2501 to 6300	7,0
6301 and above	8,0

(A comma in the impedance is the same as a decimal)

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.

6.6 Insulation levels for high and low voltage windings

The insulation level for the high voltage and low voltage windings shall be in accordance with the relevant IEC or IEEE Standard.

6.7 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 for liquid-immersed transformers in IEC 60076-7 or IEEE C57.91, for dry type transformers in IEC 60076-12 or IEEE C57.96 and IEC 60076-14 or IEEE C57.154 for high temperature insulating systems shall be applied to the defined loading cycle. Transformer connections and any switches (e.g. de-energised tap changer) shall be suitably rated to carry peak transient overloads.

6.8 Inrush current

The purchaser shall specify any limitations in the maximum value of inrush current or the duration of such current.

6.9 Frequency of energisation

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

6.10 Ability to withstand short circuit

Transformers shall comply with the requirements of IEC 60076-5, IEEE C57.12.00 or IEEE C57.12.01.

6.11 Operation with forced cooling

When additional cooling by means of fans or pumps is provided, the nominal power rating with and without forced cooling shall be subject to agreement between the purchaser and the manufacturer.

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

6.12 Over-temperature protection

Unless otherwise specified, transformers mounted in the tower or nacelle shall be provided with an over-temperature detector that can provide an alarm or trip signal.

7 **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 standard shall be stated on the nameplate.

8 Tests

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

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

8.2 Additional tests for wind turbine transformers

9.2.1 Lightning impulse type tests

Transformers shall be subjected to full lightning impulse testing including chopped wave as a design test on every new design. Chopped wave tests are not required on transformers with separable high voltage connectors.

9.2.2 Lightning impulse routine 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.

9.2.3 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 C57.12.01 shall be carried out. The maximum acceptable level of partial discharge ~~that requires further investigation~~ shall be ~~150~~ 100 pC. Partial discharge levels above 100 pC shall be investigated.

Note: The test specified here is in the standard for dry-type transformers but for the purposes of this clause is applied to liquid-immersed transformers.

9.2.4 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 type test evidence is available.

a. Climatic tests for dry type transformers in accordance with IEC 60076-11.

b. Environmental tests to category E1 or E2 for dry type transformers in accordance with IEC 60076-11. Alternatively purchasers may select Environmental tests for dry type transformers to classification E3 as detailed in clause 9.2.4.1 of this standard.

9.2.4.1 Environmental test E3

This test procedure includes a condensation test and a humidity penetration test according to IEC 60076-11. The condensation test shall be the same as described under 26.3.1, except for the conductivity of water which shall be in the range of 3,6 S/m to 4,0 S/m.

At the beginning of the humidity penetration test, the transformer shall be in a dry condition. It shall be installed in a de-energised condition and held in the climatic chamber for 144 hours. The temperature of the climatic chamber shall be held at (50 ±3) °C and the relative humidity held at (90 ± 5) %. At the end of this period and ~~and~~ before more than 3 hours in normal ambient conditions at the latest, the transformer shall be subjected to the separate-source AC withstand voltage test and the induced AC withstand voltage test, but at voltages reduced to 80 % of the standardised values.

Bibliography

1. IEEE Documents

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

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

C57.12.34, IEEE Standard Requirements for Pad-Mounted, Compartmental-Type, Self-Cooled, Three-Phase Distribution Transformers, 5 MVA and Smaller; High Voltage, 34.5 kV Nominal System Voltage and Below; Low Voltage, 15 kV Nominal System Voltage & Below

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

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

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

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

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

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

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

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

C57.106, IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment

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

C57.111, IEEE Guide for Acceptance of silicone Insulating Fluid and Its Maintenance in Transformers

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

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

C57.120, IEEE Loss Evaluation Guide for Power Transformers and Reactors

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

C57.123, IEEE Guide for Transformer Loss Measurement

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

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

C57.131, IEEE Standard Requirements for Tap Changers

C57.147 IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers

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

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

C57.106 IEEE Guide for Acceptance and Maintenance of Insulating Oil in Equipment

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

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

C57.147 IEEE Guide for Acceptance and Maintenance of Natural Ester Fluids in Transformers

IEC Documents

IEC 60076-8: Power transformers – Application guide

IEC 60076-13: Power transformers – Part 13: Self-protected liquid-filled transformers

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

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

IEC 61039 General classification of insulating liquids

IEC 60050: IEV 415-01-07, International Electrotechnical Vocabulary

6. Gas Pressure Calculations for Sealed Transformers under Varying Load Conditions, T. V. Oommen, IEEE Power Engineering Review, volume PER-3, Issue 5, dated 1983

7. 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

Annex A
(Informative)

Annex A Calculation of Losses for Nonsinusoidal Loads

A.1 Definitions for Calculations

F_{HL}	Harmonic loss factor for winding eddy currents
$F_{HL\text{-}STR}$	Harmonic loss factor for other stray losses
H	Harmonic order
h_{max}	Highest significant harmonic number (h_{max} = 39)
I	RMS load current (A)
I_1	RMS fundamental load current (A)
I_h	RMS current at harmonic “h” (A)
I_{max}	Maximum permissible rms nonsinusoidal load current (A)
I_R	RMS fundamental current under rated frequency and rated load conditions (A)
$I_{1\text{-}R}$	High-voltage (HV) rms fundamental line current under rated frequency and rated load conditions (A)
$I_{2\text{-}R}$	LV rms fundamental line current under rated frequency and rated load conditions (A)
I_T	RMS test current (A)
$I_{1\text{-}T}$	HV rms test current (A)
$I_{2\text{-}T}$	LV rms test current (A)
P_{EC}	Winding eddy-current loss (ECL) (W)
$P_{EC\text{-}R}$	Winding ECL under rated conditions (W)
$P_{EC\text{-}O}$	Winding ECLs at the measured current and the power frequency (W)
P	I^2R loss portion of the load loss (W)
P_{DC}	Total calculated ~~I^2R~~ I^2R losses at ambient temperature (W)
$P_{2\text{-}DC}$	LV calculated ~~I^2R~~ I^2R losses at ambient temperature (W)
P_{AC}	Measured impedance losses at ambient temperature (W)
P_{LL}	Load loss (W)
$P_{LL\text{-}R}$	Load loss under rated conditions (W)
P_{NL}	No load loss (W)
P_{OSL}	Other stray loss (W)
$P_{OSL\text{-}R}$	Other stray loss under rated conditions (W)
$P_{TSL\text{-}R}$	Total stray loss under rated conditions (W) R Direct current (DC) resistance (ohm)
R_1	DC resistance measured between two HV terminals (ohm)
R_2	DC resistance measured between two LV terminals (ohm)
θ_g	Hottest-spot conductor rise over top-oil temperature (°C)
$\theta_{g\text{-}R}$	Hottest-spot conductor rise over top-oil temperature under rated conditions (°C)
θ_{g1}	Hottest-spot HV conductor rise over top-oil temperature (°C)
$\theta_{g1\text{-}R}$	Hottest-spot HV conductor rise over top-oil temperature under rated conditions (°C)
θ_{TO}	Top-oil rise over ambient temperature (°C)
$\theta_{TO\text{-}R}$	Top-oil rise over ambient temperature under rated conditions (°C)
(pu)	This symbol modifier may be added to the listed symbols to represent a per-unit value of that quantity. Current quantities are referred to the rated rms load current I_R, and loss quantities are referred to the rated load ~~I^2R~~ I^2R loss density, e.g., I_h (pu) and $P_{EC\text{-}R}$ (pu)

A.2 Load Loss Equation

$$P_{LL} = P + P_{EC} + P_{OSL}\ (W) \qquad (\sim\sim 10\sim\sim A.1)$$

There are additional effects of harmonics on eddy currents P_{EC} and other stray currents P_{OSL}; harmonic load currents are frequently accompanied by a DC component. The DC component will marginally increase the core loss but will also increase the magnetizing current which will increase the audible noise level. Higher DC load current components may adversely affect the performance of the trans~~-~~former capability.

A.3 Transformer per Unit Loss Equations

Since the greatest concern about a transformer operating under harmonic load conditions will be for overheating of the windings, it is convenient to consider loss density in the windings on a per-unit basis (base current is rated current, and base loss density is the ~~I^2R~~ I^2R loss density at rated current). Therefore, Equation ~~10~~A.1 applied to rated load conditions can be rewritten on a per-unit basis as follows:

$$P_{LL-R} = 1 + P_{EC-R}(pu) + P_{OSL-R}(pu)\ \ pu$$

(~~10~~A.2)

Given the ECL under rated conditions for a transformer winding or portion of a winding, (P_{EC-R}), the ECL due to any defined nonsinusoidal load current can be expressed as

$$P_{EC} = P_{EC-R} \sum_{h=1}^{h=h_{max}} \left(\frac{I_h}{I_R}\right)^2 h^2 (W)$$

(~~10~~A.3)

The ~~I^2R~~ I^2R loss at rated load is 1 per unit (by definition). For nonsinusoidal load currents, the equation for the rms current in per-unit form (base current is rated current) will be

$$I(pu) = \sqrt{\sum_{h=1}^{h=h_{max}} I_h(pu)^2}\ \ pu$$

(~~10~~A.4)

Equation ~~10~~A.3 can also be written in per-unit form (base current is rated current, and base loss density is the ~~I^2R~~ I^2R loss density at rated current)

$$P_{EC}(pu) = P_{EC-R}(pu) \sum_{h=1}^{k=h_{max}} \left(\frac{I_h}{I_R}\right)^2 h^2\ pu$$

(~~10~~A.5)

A.4 Transformer Losses at Measured Currents

Equations ~~10~~A.2 through ~~10~~A.5 assume that the measured application currents are taken at the rated cur- rents of the transformer. Since this is seldom encountered in the field, a new term is needed to describe the winding eddy losses at the measured current and the power frequency, P_{EC-O}. Three assumptions in addition to the basic premises of the transformer capability equivalent are necessary to clarify the use of this term:

1. The eddy losses are approximately proportional to the square of the frequency. This assumption will cause any subsequent equations to be accurate for small conductors and low harmonics, with errors on the high side, for a combination of larger conductors and higher harmonics.

2. The eddy losses are a function of the current in the conductors. Any equation for loss can then be expressed in terms of the rms load current, *I*.
3. Superposition of eddy losses will apply, which will permit the direct addition of eddy losses due to the various harmonics.

Equations ~~10~~A.3 and ~~10~~A.5 may now be written more generally in the following equation:

$$P_{EC} = P_{EC-O} \sum_{h=1}^{k=h_{max}} \left(\frac{I_h}{I}\right)^2 h^2 (W)$$

(~~10~~A.6)

By removing the rms current *I* from the summation, the equation becomes

$$P_{EC} = P_{EC-O} \frac{\sum_{h=1}^{k=h_{max}} I_h^2 h^2}{I^2} (W)$$

(~~10~~A.7)

The rms value of the nonsinusoidal load current is then calculated as

$$I(pu) = \sqrt{\sum_{h=1}^{k=h_{max}} I_h^2 (A)}$$

(~~10~~A.8)

The rms current value *I* may be expressed by its harmonic components:

$$P_{EC} = P_{EC-O} \frac{\sum_{h=1}^{k=h_{max}} I_h^2 h^2}{\sum_{h=1}^{k=h_{max}} I_h^2} (W)$$

(~~10~~A.9)

A.5 Harmonic Loss Factor for Winding Eddy Currents

It is convenient to assign a single number which may be used to determine the capabilities of a trans- former in supplying power to a load. F_{HL} is a proportionality factor applied to the winding eddy losses, which represents the effective rms heating as a result of the harmonic load current. F_{HL} is the ratio of the total ECLs due to the harmonics, (P_{EC}), to the ECLs at the power frequency, as if no harmonic currents existed, (P_{EC-O}). This defining equation form is

$$F_{HL} = \frac{P_{EC}}{P_{EC-O}} \frac{\sum_{h=1}^{k=h_{max}} I_h^2 h^2}{\sum_{h=1}^{k=h_{max}} I_h^2}$$

(~~10~~A.10)

Equation ~~10~~A.10 permits F_{HL} to be calculated in terms of the actual rms values of the harmonic currents. Various measuring devices permit calculations to be made in terms of the harmonics normalized to the total rms current or to the first or fundamental harmonic. Equation ~~10~~A.10 may be adapted to these situations by dividing the numerator and denominator by either I_1, the fundamental harmonic current, or by *I*, the total rms current. These terms may now be applied to Equation ~~10~~A.10 term by term, resulting in Equations ~~10~~A.11 and ~~10~~A.12:

$$F_{HL} = \frac{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^2}{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I_1}\right]^2}$$

(~~10~~A.11)

The quantity may be directly read on a meter, not needing the computation procedure:

$$F_{HL} = \frac{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I}\right]^2 h^2}{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I}\right]^2}$$

(~~10~~A.12)

In either case, F_{HL} remains the same value since it is a function of the harmonic current distribution and is independent of the relative magnitude. Two examples may be used to clarify these definitions. In both examples, a nonsinusoidal load current of 1804 A rms will be used as the rated current, which is representative of a 2000 kW WTG operating at approximately 95% capacity. The load may be described by the harmonic distribution, normalized to the rms load current of 1804 A (see Table ~~10~~A.1)

The calculations are tabulated in Table ~~10~~A.2.

The summation of the third column, $(I_h/I)^2$, is equal to 1.000 and represents the rated rms load on a per- unit basis. The harmonic loss factor for this harmonic distribution is

$$F_H = \frac{2.750375}{1.000} = 2.750375$$

(~~10~~A.13a)

This same loading example may also be described in terms of the harmonic currents, normalized to the harmonic current of the fundamental frequency, as found in Table ~~10~~A.3.

Note that the values of the harmonic current, I_h, are the same in both examples, but the normalized values are different since these values are normalized to the harmonic current of the fundamental frequency. The calculation is tabulated as shown in Table ~~10~~A.4.

Whether the individual harmonic currents are normalized to the rms load current I, or to the fundamental load current I_1, the value of harmonic loss factor is the same:

$$F_H = \frac{2.750375}{1.000} \approx \frac{2.831007}{1.045816} = 2.750375$$

(~~10~~A.13b)

Table A.1 - Harmonic Current Distribution, Normalized to the Example RMS Load Current of 1804 A

h	I_h	$\frac{I_h}{I}$
1	1764	0.978
5	308.5	0.171039
7	194.4	0.10778
11	79.39	0.044016
13	50.52	0.028009
17	27.06	0.015003
19	17.68	0.009802
23	11.29	0.006259
25	10.04	0.005566
29	8.78	0.004868
31	5.73	0.003177

Table A.2 - Example 1: Harmonic Loss Factor Calculation for Harmonic Distribution of Table A.1

h	$\frac{I_h}{I}$	$\left(\frac{I_h}{I}\right)^2$	h^2	$\left(\frac{I_h}{I}\right)^2 h^2$
1	0.978	0.956484	1	0.956484
5	0.171	0.029241	25	0.731025
7	0.108	0.011664	49	0.571536
11	0.044	0.001936	121	0.234256
13	0.028	0.000784	169	0.132496
17	0.015	0.000225	289	0.065025
19	0.0098	9.6E–05	361	0.03467
23	0.0054	2.92E–05	529	0.015426
25	0.003	0.000009	625	0.005625
29	0.0017	2.89E–06	841	0.00243
33	0.00093	8.65E–07	1089	0.000942
35	0.00052	2.7E–07	1225	0.000331
39	0.00029	8.41E–08	1521	0.000128
∑	-----	1.000	-----	2.750375

Table A.3 - Example 1: Harmonic Currents of Table A.2, Normalized to the Harmonic Current of the Fundamental Frequency

h	I_h	$\frac{I_h}{I}$
1	1764.	0.978
5	308.5	0.1710
7	194.9	0.1081
11	79.39	0.0440
13	50.52	0.0280
17	27.06	0.0150
19	17.68	0.0098
23	9.82	0.0054
25	5.46	0.0030
29	3.03	0.0017
33	1.68	0.00093
35	0.94	0.00052
39	0.52	0.00029

A.6 Harmonic Loss Factor for Other Stray Losses

Although the heating due to other stray losses is generally not a consideration for dry-type transformers, it can have a substantial effect on liquid-filled transformers. A relationship similar to the harmonic loss factor for winding eddy losses exists for these other stray losses in a transformer and may be developed in a similar manner. However, the losses due to bus bar connections, structural parts, tank, etc., are proportional to the square of the load current and the harmonic frequency to the 0.8 power. This may be expressed in a form similar to Equation ~~10~~A.14:

Table A.4 - Example 2: Harmonic Loss Factor Calculation for Harmonic Distribution of Table A.1

h	I_h	$\left(\frac{I_h}{I}\right)^2$ ~~$\frac{I_h}{I}$~~	h^2	$\left(\frac{I_h}{I}\right)^2 h^2$
1	1.000	1	1	1
5	0.175	0.030625	25	0.765625
7	0.110	0.0121	49	0.5929
11	0.045	0.002025	121	0.245025
13	0.029	0.000841	169	0.142129
17	0.009	0.000081	289	0.023409
19	0.0100	0.0001	361	0.0361
23	0.0055	3.03E–05	529	0.016002
25	0.0031	9.61E–06	625	0.006006
29	0.0017	2.89E–06	841	0.00243
33	0.00093	8.65E–07	1089	0.000942
35	0.00051	2.6E–07	1225	0.000319
39	0.00028	7.84E–08	1521	0.000119
Σ	—	1.045816	—	2.831007

$$P_{OSL} = P_{OSL-R} \sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I_g}\right]^2 h^{0.8}$$

(~~10~~A.14)

The equations corresponding to the harmonic loss factor, normalized to the fundamental current and normalized to the rms current, respectively, are

$$F_{HL-STR} = \frac{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I_1}\right]^2 h^{0.8}}{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I_1}\right]^2}$$

(~~10~~A.15)

$$F_{HL-STR} = \frac{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I}\right]^2 h^{0.8}}{\sum_{h=1}^{k=h_{max}} \left[\frac{I_h}{I}\right]^2}$$

(~~10~~A.16)

Using the harmonic distribution from the last example, the calculation is tabulated for the normalized fundamental current base as shown in Table ~~10~~A.5:

$$F_{HL-STR} = \frac{1.191107}{1.045816} = 1.138926$$

(~~10~~A.17)

Table A.5 - Example 2: Harmonic Currents of Table A.4, Normalized to the Harmonic Current of the Fundamental Frequency

h	I_h	$\left(\frac{I_h}{I}\right)^2$ ~~$\frac{I_h}{I}$~~	$h^{\cancel{2}0.8}$	$\left(\frac{I_h}{I}\right)^2 h^{\cancel{2}0.8}$
1	1.000	1	1	1
5	0.175	0.030625	3.623898	0.110982
7	0.110	0.0121	4.743276	0.057394
11	0.045	0.002025	6.809483	0.013789
13	0.029	0.000841	7.783137	0.006546
17	0.009	0.000081	9.646264	0.000781
19	0.0100	0.0001	10.54394	0.001054
23	0.0055	3.03E–05	12.2852	0.000372
25	0.0031	9.61E–06	13.13264	0.000126
29	0.0017	2.89E–06	14.7883	4.27E–05
33	0.00093	8.65E–07	16.39877	1.42E–05
35	0.00051	2.6E–07	17.18915	4.47E–06
39	0.00028	7.84E–08	18.74354	1.47E–06
Σ	—	1.045816	—	1.191107

A.7 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 which the blade pitch motors are slow to react. 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.

These transformers must be considered a hybrid transformer which is a Class 1 power transformer with step-up capabilities, which is compartmentalized, and never energized from the LV terminals.