भारतीय मानक

Indian Standard

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IEEE/IEC 60076-16 : 2018

पॉवर ट्रांसफार्मर

भाग 16 विंड टरबाईन अनुप्रयोगों हेतु ट्रांसफार्मर

(पहला पुनरीक्षण)

Power Transformers

Part 16 Transformers for Wind Turbine Applications

(First Revision)

ICS 29.180

भारतीय मानक ब्यूरो
BUREAU OF INDIAN STANDARDS
मानक भवन, 9 बहादुर शाह ज़फर मार्ग, नई दिल्ली - 110002
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI - 110002
www.bis.gov.in www.standardsbis.in

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NATIONAL FOREWORD

This Indian Standard (Part 16) (First Revision) which is identical to IEEE/IEC 60076-16 : 2018 'Power transformers — Part 16: Transformers for wind turbine applications' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Transformers Sectional Committee and approval of the Electrotechnical Division Council.

This revision has been undertaken to align with the latest version of IEC 60076-16 : 2018. The main changes with respect to the previous edition are as follows:

a) Relationship between transformer rated power and the output current from the associated generator is introduced;

b) Thermal correction of the effective cooling medium has been introduced; and

c) Testing regime has been strengthened to ensure transformers are suitable for the harsh electrical environment to which they are subjected.

The text of IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain terminologies and conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appears referring to this standard, they should be read as 'Indian Standard'; and

b) Comma (,) has been used as a decimal marker, while in Indian Standards the current practice is to use a point (.) as the decimal marker.

In this standard, reference appears to International Standards for which Indian Standards also exists. The corresponding Indian Standards, which are to be substituted, are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60076-1 Power transformers — Part 1: General	IS 2026 (Part 1) : 2011 Power transformers: Part 1 General (*second revision*)	Technically Equivalent
IEC 60076-2 Power transformers — Part 2: Temperature rise for liquid-immersed transformers	IS 2026 (Part 2) : 2010 Power transformers: Part 2 Temperature-rise (*first revision*)	Technically Equivalent
IEC 60076-3 Power transformers — Part 3: Insulation levels, dielectric tests and external clearances in air	IS 2026 (Part 3) : 2018/IEC 60076-3 : 2013 Power transformers: Part 3 Insulation levels, dielectric tests and external clearances in air (*fourth revision*)	Identical

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Indian Standard

POWER TRANSFORMERS
PART 16 TRANSFORMERS FOR WIND TURBINE APPLICATIONS

(First Revision)

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.

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:

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

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

where

K_{max}	is the temperature correction for the maximum ambient temperature;
K_{av}	is the temperature correction for the yearly average ambient temperature;
$T_{\text{max ecm}}$	is the maximum temperature of the effective cooling medium;
$T_{\text{max std}}$	is the maximum ambient temperature of the effective cooling medium according to the relevant standard;
$T_{\text{av ecm}}$	is the average temperature of the effective cooling medium;
$T_{\text{av std}}$	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:

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

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

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

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

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

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

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

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 IEC 61378-1 or IEEE Std C57.110.

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 voltages

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

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.

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.

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.

6.9 Corrosion protection

Depending on the kind of installation, the purchaser 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

7.1 Highest voltage for equipment

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

7.2 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 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, 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 connection

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

7.5 Short-circuit impedance

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 and low voltage windings

The insulation level for the high voltage and low voltage windings shall be in accordance with 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.

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 shall 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

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

7.11 Operation with forced cooling

When additional cooling by means of fans or pumps is provided, the nominal rated power with and without forced cooling shall be 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.

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.

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)

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.

Bibliography

IEC references

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

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

IEC 60214-1, *Tap-changers – Part 1: Performance requirements and test methods*

IEC 60214-2, *Tap-changers – Part 2: Application guide*

IEC 60721-3-4, *Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 4: Stationary use at non-weather protected locations*

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*

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[2] Withdrawn.

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*

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

(*Continued from second cover*)

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60076-5 Power transformers — Part 5: Ability to withstand short circuit	IS 2026 (Part 5) : 2011 Power transformers: Part 5 Ability to withstand short circuit (*first revision*)	Technically Equivalent
IEC 60076-7 Power transformers — Part 7: Loading guide for mineral- oil-immersed power transformers	IS 2026 (Part 7) : 2009/IEC 60076-7 : 2005 Power transformers: Part 7 Loading guide for oil-immersed power transformers	Identical
IEC 60076-11 Power transformers — Part 11: Dry-type transformers	IS 2026 (Part 11) : 2021/ IEC 60076-11 : 2018 Power transformers: Part 11 Dry-type transformers	Identical
IEC 60076-12 Power transformers — Part 12: Loading guide for dry-type power transformers	IS 2026 (Part 12) : 2018/IEC 60076-12 : 2008 Power transformers: Part 12 Loading guide for dry-type power transformers	Identical
IEC 60076-14 Power transformers — Part 14: Liquid-immersed power transformers using high-temperature insulating materials	IS 2026 (Part 14) : 2018/ IEC 60076-14 : 2013 Power transformers: Part 14 Liquid-immersed power transformers using high-temperature insulation materials	Identical

The Committee has reviewed the provisions of the following international standards referred in this adopted standard and decided that they are acceptable for use in conjunction with this standard.

International Standard	*Title*
IEC 61378-1	Converter transformers — Part 1: Transformers for industrial applications

For the purpose of deciding whether a particular requirement of this standard is complied with the final value, observed or calculated expressing the result of a test or analysis shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding of numerical values (*second revision*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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This Indian Standard has been developed from Doc No.: ETD 16 (20725).

Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected

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