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Indian Standard

पावर ट्रांसफार्मर

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(IEC/IEEE 60076-57-129 : 2017 संशोधित)

Power Transformers

Part 57-129 Transformers for HVDC Applications

(IEC/IEEE 60076-57-129 : 2017 MOD)

ICS 29.180

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NATIONAL FOREWORD

This Indian Standard (Part 57-129) which is modified to IEC/IEEE 60076-57-129 : 2017 'Power transformers — Part 57-129: Transformers for HVDC 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.
The text of the IEC standard has been approved as suitable for publication as an Indian Standard without deviations. Certain 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 adopted 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 : 2011 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 : 2013 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
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 60076-10 Power transformers — Part 10: Determination of sound levels	IS 2026 (Part 10) : 2009/ IEC 60076- 10 : 2001 Power transformers Part 10 Determination of sound levels	Identical
IEC 60076-18 Power transformers — Part 18: Measurement of frequency response	IS 2026 (Part 18) : 2018/IEC 60076- 18 : 2012 Power transformers: Part 18 Measurement of frequency response	Identical

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Indian Standard

POWER TRANSFORMERS

PART 57-129 TRANSFORMERS FOR HVDC APPLICATIONS

(IEC/IEEE 60076-57-129 : 2017 MOD)

1 Scope

This part of 60076 International Standard specifies requirements of liquid-immersed three-phase and single-phase converter transformers for use in high voltage direct current (HVDC) power transmission systems including back-to-back applications. It applies to transformers having two, three or multiple windings.

This document does not apply to

– converter transformers for industrial applications (see IEC 61378-1 or IEEE Std C57.18.10);

– converter transformers for traction applications (see IEC 60310).

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 60050-421, *International Electrotechnical Vocabulary – Chapter 421: Power transformers and reactors* (available at http://www.electropedia.org)

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

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

IEC 60076-3:2013, *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 60076-18, *Power transformers – Part 18: Measurement of frequency response*

IEC 60076-10, *Power transformers – Part 10: Determination of sound levels*

IEC 60137, *Insulated bushings for alternating voltages above 1 000 V*

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

IEC 60270, *High voltage test techniques – Partial discharge measurements*

IEC/IEEE 65700-19-03, *Bushings for DC application*

2.2 IEEE references

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

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

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

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

IEEE Std C57.19.00™, *IEEE Standard General Requirements and Test Procedures for Power Apparatus Bushings*

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

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

IEEE Std C57.149™, *IEEE Guide for the Application and Interpretation of Frequency Response Analysis for Oil-Immersed Transformers*

3 Terms, definitions and symbols

For the purposes of this document, the terms and definitions given in IEC 60050-421 and IEC 60076-1 apply to IEC specified transformers for HVDC applications. For IEEE specified transformers for HVDC applications, the terms and definitions given in IEEE Std C57.12.80 apply. For all transformers for HVDC applications, the following apply and take precedence.

NOTE Where the term oil is used in the text, it is understood to be the insulating liquid in the transformer.

ISO, IEC and IEEE 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
- IEEE Standards Dictionary Online: available at http://ieeexplore.ieee.org/xpls/dictionary.jsp

3.1 Terms and definitions

3.1.1
valve side winding
winding connected to the converter

3.1.2
line side winding
winding connected to the AC network

Note 1 to entry: In other standards, valve side can be denoted as DC side and line side can be denoted as AC side.

3.2 Symbols

f_1	rated frequency and also the fundamental frequency
f_h	frequency at harmonic order number h
F_h	loss adjustment factor at harmonic h
f_x	frequency ≥ 150 Hz used to determine the distribution of eddy current losses
F_{SE}	enhancement factor for stray losses in structural parts
F_{WE}	enhancement factor for winding eddy losses
h	harmonic order number
I_{eq}	equivalent sinusoidal r.m.s. current of rated frequency, giving the winding losses, used in temperature rise test
I_h	magnitude of the h^{th} harmonic current in the transformer
I_{LN}	square root of the sum of the square of the fundamental and harmonic currents up to the 49^{th} harmonic for a particular loading condition and associated harmonic current spectra. $I_{LN}=\sqrt{\sum_{h=1}^{49} I_h^2}$ (49 is the highest harmonic to be evaluated). NOTE I_{LN} equals I_r for the nominal load condition but it can also be used for other load conditions (e.g. overload).
I_r	rated current, r.m.s. value of the nominal in-service load current, including harmonics, in the winding under consideration calculated in the same way as I_{LN} above. Used as a basis for the definition of rated impedance.
$I_r^2 R$	ohmic losses at rated current
I_x	load loss test current at frequency f_x
k_h	ratio of the current I_h to the rated current I_r
K_{WE}	windings enhancement loss p.u. at fundamental frequency due to eddy losses
N	number of six-pulse bridges in series from the neutral of the DC line to the rectifier bridge connected to the transformer
P_{1r}	total load losses at fundamental frequency (50 Hz or 60 Hz) and rated current
P_{LLG}	load loss used in determining guaranteed total losses
P_{LLT}	calculated total load loss under service conditions
P_N	total service load loss
P_{NL}	total no-load loss
P_{SE1r}	stray losses in structural parts (excluding windings) at fundamental frequency and rated current
P_{TL}	total loss under service conditions (used for temperature rise test)
P_{WE1r}	eddy losses in windings at fundamental frequency and rated current
P_x	load loss measured at frequency f_x
R	DC resistance of windings including internal leads
S_R	rated power
U_{AC}	AC separate source test voltage for the valve windings (r.m.s. value)
U_{DC}	DC withstand test voltage for the valve windings
U_{dm}	highest DC voltage per valve bridge
U_m	highest system voltage of the line winding
U_{pr}	polarity reversal test voltage (DC voltage) for the valve windings
U_r	rated voltage
U_{vm}	maximum phase-to-phase AC operating voltage of the valve windings of the converter transformer

4 Use of normative references

This document 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 HVDC converter transformers intended for installation in North America where IEEE standards shall be used.

5 General requirements

5.1 General

All the requirements in IEC 60076-1 or IEEE Std C57.12.00 and IEEE Std C57.12.10 are valid unless specific requirements are given in this document. In case of conflicting requirements, this document shall prevail.

5.2 Service conditions

5.2.1 General

Converter transformers in this document shall comply with the service conditions stated in IEC 60076-1 or IEEE Std C57.12.00, except where it is clearly not applicable to converter transformers or when other requirements are specified herein. It is assumed that the transformer operates in an approximately symmetrical three-phase system, unless otherwise stated.

5.2.2 Temperature

If any part of the transformer (for example, the valve bushings) protrudes into the valve hall, the maximum temperature in the valve hall shall be specified in addition to the normal ambient temperature.

NOTE The maximum air temperature in the valve hall is normally between 40 °C and 60 °C depending on the technology used

5.2.3 Load current

The currents flowing through the transformers contain harmonics. Residual DC currents may also flow through the windings. The purchaser shall provide the manufacturer with the harmonic content and the magnitude of the residual DC currents in the enquiry.

The harmonic content should preferably be given by listing a number of typical operating conditions.

5.2.4 AC voltage

The voltage applied to the line side winding shall be approximately sinusoidal (e.g., maximum total harmonic distortion of 5 % with no individual harmonic exceeding 1 %), and the phase voltages supplying a poly-phase transformer shall be approximately equal in magnitude and time displacement.

5.2.5 Direction of power flow

Unless otherwise specified, the transformer shall be designed for both rectifier and inverter operation.

5.3 Unusual service conditions

Conditions other than those described in 5.2 are considered unusual and shall be specified by the purchaser. Special attention on sources of DC current also needs to be considered.

NOTE Sources of DC current could be currents induced by geomagnetic storms and by fundamental frequency currents in DC lines.

5.4 Loading of transformer above rating

Any requirements for loading beyond rated power or at other than rated conditions shall be specified by the purchaser. The loading of HVDC transformers above nameplate rating shall not be made without consultation with the supplier.

NOTE Converter transformers are normally designed for a specific installation and are coordinated with the capabilities of the valves and other DC components. If the station is to be operated above its rated capacity, a detailed thermal study would be needed to determine the capability of all the affected terminal equipment. Detailed information about the transformer design and capabilities at both fundamental and harmonic currents would be part of the study.

6 Rating data

6.1 General

The rating characteristics of the transformer are expressed in steady-state sinusoidal quantities of current and voltages at rated fundamental frequency. The guaranteed losses, impedances and sound level shall correspond to these values. For a general list of rating data see IEC 60076-1 or IEEE Std C57.12.00.

6.2 Rated voltage

The rated voltage is the r.m.s. value of the fundamental component of the phase-to-phase (line-to-line) voltage.

NOTE For single-phase transformers intended to be connected in star to form a three-phase bank or to be connected between the line and the neutral of a three phase system, the rated voltage is indicated as the phase-to-phase voltage, divided by $\sqrt{3}$, for example 400 / $\sqrt{3}$ kV.

6.3 Rated current

The rated current is the square root of the sum of the square of the fundamental and harmonic currents up to the 49th harmonic for the nominal loading condition

$$I_\mathrm{r} = \sqrt{\sum_{h=1}^{49} I_h^2} \tag{1}$$

(49 is the highest harmonic to be evaluated).

6.4 Rated frequency

The rated frequency is the fundamental frequency of either 50 Hz or 60 Hz for which the transformer is designed.

6.5 Rated power

The rated three-phase power is the product of $\sqrt{3}$, the rated voltage and the rated current.

$$S_\mathrm{R} = \sqrt{3} \times U_\mathrm{r} \times I_\mathrm{r} \tag{2}$$

7 Losses

7.1 General

The total losses of a converter transformer shall be the sum of the no-load loss and the load loss at a specific service condition. The guaranteed losses shall be within the tolerances of IEC 60076-1:2011, Table 1 or IEEE Std C57.12.00.

The standard reference temperatures for the losses of converter transformers shall be the ones given in IEC 60076-1 or IEEE Std C57.12.00.

7.2 No-load loss

No-load loss and no-load current are measured in the same way as for conventional AC transformers according to IEC 60076-1 or IEEE Std C57.12.90. This shall be the guaranteed no-load loss.

NOTE The harmonic voltages and DC bias currents have an effect on no-load loss and no-load current. However, in practice the differences due to this effect can be disregarded in comparison to the total losses of the transformer.

7.3 Load loss under rated frequency conditions

The load loss shall be measured in accordance with IEC 60076-1 or IEEE Std C57.12.90.

7.4 Load loss under service conditions

The currents flowing through the windings of converter transformers contain certain harmonics whose magnitudes depend on the parameters of the converter station. The determination of actual load loss in service cannot be deduced from one single load loss measurement. The procedure to determine the load loss in accordance with this document includes two load loss measurements and certain assumptions on loss distribution and a specific calculation scheme (see 9.2).

The determination of actual load loss in service is more complicated due to harmonic effects. The harmonic spectrum for the temperature rise test and the harmonic spectrum to be used for load loss evaluation shall be clearly defined by the purchaser. The spectrum for load loss evaluation may be different from the one specified for temperature rise tests; the latter representing a worst case operating condition.

To determine the losses under service conditions, the following assumptions are made:

– eddy and stray losses are proportional to the square of the current;
– winding eddy losses depend on the frequency with the exponent 2, and stray losses in structural parts depend on the frequency with the exponent 0,8.

Eddy loss and stray loss:

$$\Delta P \propto I^2 \times f^k \qquad (3)$$

where

$$k = \begin{cases} 2 & \text{for winding eddy losses,} \\ 0{,}8 & \text{for stray losses.} \end{cases}$$

Based on a given harmonic spectrum, the total service load loss can be calculated as follows:

$$P_\text{N} = I_\text{LN}^2 R + P_\text{WE1r} \times F_\text{WE} + P_\text{SE1r} \times F_\text{SE} \qquad (4)$$

where

$$I_{\mathrm{LN}}=\sqrt{\sum_{h=1}^{49} I_h^2} \quad \text{(49 is the highest harmonic to be evaluated)} \tag{5}$$

$$F_{\mathrm{WE}}=\sum_{h=1}^{49} k_h^2 \times h^2 \quad \text{and} \tag{6}$$

$$F_{\mathrm{SE}}=\sum_{h=1}^{49} k_h^2 \times h^{0,8} \tag{7}$$

$$\text{with } k_h=\frac{I_h}{I_\mathrm{r}} \text{ and } h=\frac{f_h}{f_1} \tag{8}$$

Alternatively, by agreement between the purchaser and the manufacturer, F_{WE} can be calculated by the method given in Annex F.

7.5 Determination of hot-spot temperature

The procedure to determine the hot-spot temperature shall be in accordance with IEC 60076-2 or IEEE Std C57.12.90. Further guidance is provided in IEC 60076-7. It should be noted that the hot-spot temperature rise determined by this procedure may not be the same as the value likely to be obtained in normal service because the extra losses in service due to the harmonic current are mainly concentrated at the ends of the windings whereas those occurring during the test are more evenly distributed throughout the winding. As a result, the hot-spot generated during the test at the equivalent rated frequency current is lower than that developed in normal converter operation. In order to partly compensate for this difference in performance, an enhancement factor for eddy losses will be calculated for the specific harmonic content and added to the temperature rise test current.

NOTE 1 Fibre optic sensors for measuring hot-spot temperature rise in windings are available. Given the uncertainties in determining the hot-spot temperature rise for converter transformers the fibre optic sensors play a more important role than for other transformer types and might be considered more thoroughly.

The hot-spot factor and associated hot-spot temperature under service conditions has to be calculated by the transformer manufacturer, using the harmonic current spectrum or spectra provided by the purchaser. It is the responsibility of the purchaser to ensure that the provided current spectrum or spectra is representative of realistic operating conditions.

NOTE 2 A too conservative harmonic current spectrum will lead to a too pessimistic hot-spot factor. If such hot-spot factor is used in the transformer winding temperature monitoring device, untimely alarms or trips can be experienced even if the real transformer winding temperature is lower than the one calculated by the monitoring equipment.

The manufacturer shall, during the design review, demonstrate how the hot-spot temperature rise, especially considering the effect of the harmonics, has been calculated with reference to a specific converter operating point and specific system conditions. Based on this calculation, the manufacturer shall declare, for each winding of the converter transformers, a hot-spot factor related to service conditions. The manufacturer shall calculate the hot-spot factor that will be experienced during the temperature rise test.

In case of more than one valve winding on one core limb, the location of the hot spot in service may differ from the location during the temperature rise test at rated frequency. For more information see IEC 61378-3.

8 Test requirements

8.1 General

8.1.1 Routine tests

Routine tests according to Table 1 shall be performed on all units.

8.1.2 Type tests

Type tests according to Table 1 shall be performed on one of each type of transformer.

8.1.3 Special tests

Special tests according to Table 1 shall be performed when specified by the purchaser.

8.1.4 Commissioning tests

Commissioning tests, as agreed between purchaser and supplier, shall be performed on site.

Table 1 – Routine, type and special tests

Tests	Routine	Type	Special	Comment
Performance tests				
Winding resistance measurements on all windings on all tap positions	X			
Ratio tests on the rated voltage connection and on all tap positions listed on the nameplate	X			
Polarity and phase relation tests on the rated voltage connection	X			
No-load losses and excitation current	X			
Load loss and impedance measurements on principal and extreme taps	X			See 9.2
Load loss and impedance measurements on all taps			X	See 9.2
Operational tests on all devices	X			
Control (auxiliary) and cooling consumption losses	X			
Zero-sequence impedance voltage			X	
Temperature rise		X		See 9.13
Tank surface temperature rise measurement		X		See 9.13.3
Load current test			X	See 9.14
Dissolved gas in oil analysis	X			
Sound level measurement		X		See 9.15
Short-circuit test			X	See 9.19
Dielectric tests				
Impulse tests				
Full wave	X			See 9.5
Chopped wave	X		X	See 9.5

Tests	Routine	Type	Special	Comment
Switching impulse	X		X	See 9.3
Applied switching impulse on valve side winding	X			See 9.4
DC withstand voltage test	X			See 9.6
Polarity reversal test	X			See 9.7
Extended polarity reversal test			X	See 9.8
AC tests				
Applied voltage on line side winding(s)	X			See 9.10
Applied voltage on valve side winding(s)	X			See 9.9
Induced voltage with partial discharge measurement	X			See 9.11
Induced voltage including running of pumps			X	See 9.12
Insulation power factor test	X			See 9.16
Winding insulation resistance test	X			See 9.17
Core insulation resistance test	X			See 9.18
Low frequency test on auxiliary devices and control and current transformers circuits	X			
Recurrent surge oscillograph (RSO) measurements			X	
Frequency response analysis (FRA) measurements			X	See 9.20
Over-excitation test			X	See 9.21
Mechanical tests				
Lifting and moving devices		X		
Pressure		X		
Leakage	X			

8.2 Test applicability

8.2.1 General

The application of some tests depends on the configuration of the converters. In particular some designs of voltage source converters do not impose DC voltage on the transformers.

8.2.2 DC withstand voltage test

This test does not apply to windings that are not exposed to DC voltage.

8.2.3 Polarity reversal test

This test does not apply to windings that are not exposed to DC voltage or to transformers that are not exposed to voltage polarity reversals during operation.

8.2.4 AC applied withstand test for valve side winding(s)

This test does not apply to windings that are not exposed to DC voltage. In this case the AC withstand voltage test according to IEC 60076-3 or IEEE Std C57.12.00 shall be applied.

8.3 Dielectric test voltage levels

8.3.1 Line windings

The insulation levels for the line terminals, windings and neutrals are defined in IEC 60076-3 or for a Class II transformer in IEEE Std C57.12.00.

8.3.2 Valve windings

8.3.2.1 General

The purchaser shall specify the lightning and switching impulse levels for each terminal to earth and between terminals of the winding(s).

The insulation levels should be coordinated in such a way that there is an adequate margin in excess of the dielectric stresses that appear in actual service.

8.3.2.2 Lightning impulse levels

The lightning impulse level of the valve winding shall be specified for each terminal to earth and between terminals of the winding(s).

NOTE 1 The lightning impulse levels specified between terminals of the winding(s) can be different from that specified for each terminal to ground, depending on system studies.

If the lightning impulse level for an IEC transformer is > 750 kV the chopped wave impulse test is required. Chopped wave tests are required for all IEEE transformers. The chopped wave test voltage shall be 1,1 times the lightning impulse level.

NOTE 2 IEC 60076-3 requires chopped impulse tests to be carried out on windings with Um > 170 kV, which corresponds to an impulse level > 750 kV.

8.3.2.3 Switching impulse levels

The switching impulse level of the valve winding shall be specified for each terminal to earth.

The valve windings are subjected to a transferred switching impulse during the test of the line winding. It is important that the voltage transferred to the valve winding during the line winding switching impulse test is considered in the design of the valve winding and bushings.

NOTE Switching impulse levels and tests are important for the valve side windings even if the voltage levels are lower than would normally be applicable for a switching impulse test on an AC transformer. This is because the switching impulse levels might be very close to the lightning impulse levels for some HVDC transformers for example in back-to-back schemes.

8.3.2.4 DC withstand voltage level

These tests shall be applied to the terminals of the valve winding(s). The test voltage shall be given by

$$U_{\mathrm{DC}} = 1{,}5\ ((N - 0{,}5)\ U_{\mathrm{dm}} + 0{,}7\ U_{\mathrm{vm}}) \qquad (9)$$

Positive polarity shall be used.

8.3.2.5 Polarity-reversal level

These tests shall be applied to the terminals of the valve winding(s).

The test voltage is given by

$$U_{pr} = 1,25\ ((N - 0,5)\ U_{dm} + 0,35\ U_{vm}). \tag{10}$$

8.3.2.6 AC applied withstand level with partial discharge measurement

All terminals of the valve windings shall receive an AC applied voltage withstand test with partial discharge measurement. The test level is given by

$$U_{AC} = \frac{1{,}5\left((N - 0{,}5)U_{dm} + \sqrt{2}U_{vm} / \sqrt{3}\right)}{\sqrt{2}} \text{ (r.m.s. value)} \tag{11}$$

8.4 Induced voltage level with partial discharge measurement

The routine induced voltage test levels shall be chosen as described in IEC 60076-3 or IEEE Std C57.12.00 based on the line winding insulation level.

9 Tests

9.1 General

9.1.1 Applicable tests

Tests listed in Table 1 shall be carried out in accordance with the requirements of IEC 60076-1 or IEEE Std C57.12.00 except for the modifications introduced in Clause 9.

9.1.2 Test sequence

The dielectric tests shall be performed after the load loss test and the temperature rise test (if applicable). The induced voltage test with partial discharge measurements shall be the last dielectric test performed on the converter transformer.

9.1.3 Ambient temperature

All routine dielectric tests should be carried out under the same ambient temperature conditions as the other routine tests under normal indoor laboratory conditions.

Testing at other temperatures may be acceptable but shall be a matter of agreement between purchaser and manufacturer.

NOTE The DC voltage grading along the insulation structure during the DC applied voltage test and the polarity reversal test is temperature dependent and can therefore significantly affect the test outcome.

9.1.4 Assembly

Transformers, including bushings and terminal compartments when necessary to verify air clearances, shall be assembled prior to making dielectric tests, but assembly of items that do not affect dielectric tests, such as radiators and cabinets, is not necessary. Bushings shall, unless otherwise authorized by the end user, be those supplied with the transformer.

9.1.5 Converter transformers for connection to gas-insulated equipment

During dielectric testing of transformers for direct connection to gas-insulated substations, the in-service bushings may be substituted with air-to-oil test bushings. Live-part clearances and locations of the substitute bushings inside the transformer shall be identical, within normal manufacturing tolerances, to those of the in-service bushings. When the required internal clearances, or external air clearances, or both, cannot be achieved, suitable arrangements are required as determined by the manufacturer and end user in advance of the design of the transformer.

9.2 Load loss and impedance measurements

9.2.1 General

The load loss and impedance measurement shall be made with currents of sinusoidal shape. In order to establish the loss under service conditions, two measurements are required. One measurement shall be made at rated frequency and the second one at a frequency not less than 150 Hz. Based on these measurements a calculation shall be made

– to establish the distribution of additional stray losses inside and outside the windings;

– to determine the load loss during service.

The method of loss and impedance measurements shall be as specified in IEC 60076-1 or IEEE Std C57.12.90. The current magnitude at rated frequency shall be equal to rated current and that at elevated frequency between 10 % and 50 % of the rated current. The measurements with the two frequencies make it possible to separate the stray losses into two components, one related to the stray losses in the windings and one related to stray losses in the structural parts.

For the routine test, the measurements shall be performed at the principal, maximum and minimum taps.

As a special test, additional load loss and impedance measurements at all taps shall be made at reduced current. The test current shall be chosen so that the winding temperature does not rise during the measurement so much that it significantly affects the winding resistance. Generally a value of 20 % to 30 % of the rated current is used.

For three-winding transformers, the measurement shall be performed with both valve windings in parallel. The guaranteed losses are based on this measurement. In addition, two extra loss and impedance measurements with only current through one valve winding at a time with fundamental frequency, shall be performed.

NOTE The proportionality between the individual loss components can be assumed to be constant for current harmonics in the winding current above 10 % of the rated current.

9.2.2 Calculation procedure

The load losses obtained from measurements with the two different frequencies, f_1 and f_x, and the corresponding currents, I_r and I_x, are denoted P_{1r} and P_x giving

$$P_{1r} = RI_r^2 + P_{WE1r} + P_{SE1r} \qquad (12)$$

$$P_x = RI_x^2 + \left(\frac{I_x}{I_r}\right)^2 \left(\frac{f_x}{f_1}\right)^2 P_{WE1r} + \left(\frac{I_x}{I_r}\right)^2 \left(\frac{f_x}{f_1}\right)^{0,8} P_{SE1r} \qquad (13)$$

Formulae (12) and (13) permit the evaluation of the two eddy loss components, P_{WE1r} and P_{SE1r}.

Using the calculation rules in Clause 7, the actual service load loss can be determined.

Total in-service losses = no-load loss + calculated service load loss

9.3 Switching impulse test

When a switching impulse test is specified for the line-side winding, it shall be made according to IEC 60076-3 or IEEE Std C57.12.90, at the specified level for the crest value. The valve windings shall be designed to withstand the induced voltage resulting from the line side switching impulse test. The tap position used for this test shall be chosen to bring the test voltage for the valve winding as close as possible to its specified switching impulse level.

9.4 Applied switching impulse test on the valve side winding

When switching impulses are applied on a valve-side winding, the ends of the winding under test shall be connected together and the switching impulse shall be applied between the winding and earth. Terminals of winding(s) not being tested shall be earthed.

9.5 Lightning impulse tests

The lightning impulse test procedure shall be as specified in IEC 60076-3 or IEEE Std C57.12.90. The tests on the line windings shall be applied to each line terminal, one at a time.

For the valve winding one of the two tests below applies.

If the same insulation level is specified to earth and across the winding, each end of the winding shall be impulsed with the other solidly earthed. The value of the lightning impulse level is based on system studies and given by the purchaser.

If different insulation levels are specified to earth and across the winding, a test procedure where the non-tested end of the winding is earthed via a suitable resistance may be considered. The resistance is selected to obtain the requested test voltage across the winding at the same time as the requested voltage to earth appears at the impulsed terminal. The test shall be carried out from each end of the winding.

When impulse testing the valve winding of a converter transformer, all other terminals shall be solidly earthed.

Lightning impulse tests on windings that do not have all their terminals brought out through the tank or cover shall be subject to agreement between the purchaser and the supplier.

9.6 DC withstand voltage test

9.6.1 Applicability

This test is not applicable for transformers that are subjected to the extended polarity-reversal test according to Alternative 2 in 9.8.3.

9.6.2 Transformer test temperature

During the DC withstand voltage test the temperature of the oil shall be (20 ± 10) °C.

NOTE If the required temperature is difficult to achieve, for example if tested in a very warm region, then a higher temperature can be accepted by agreement between the purchaser and the manufacturer.

9.6.3 Polarity

Positive polarity shall be used.

9.6.4 Test procedure

Terminals not being tested shall be solidly earthed. Oil pumps shall not be running during this test. No preconditioning of the converter-transformer insulation structure at a lower voltage level is allowed. The voltage shall be brought up to the test level within 1 min and held for 120 min, after which the voltage shall be reduced to zero in 1 min or less.

Partial discharge measurements shall be performed throughout the entire DC withstand voltage test.

NOTE 1 Ultrasonic transducers installed on the converter transformer tank can help to distinguish internal discharges from external discharges during the DC withstand voltage test. Other detection methods can also be helpful.

NOTE 2 After a DC withstand voltage test is completed, the insulation structure retains a considerable electrical charge. This could represent a danger without appropriate precautions and unless adequately discharged subsequent partial discharge measurements could be affected.

9.6.5 Acceptance criteria

The test is considered accepted if there is no disruptive discharge and if the measured partial discharges are within the limits given below.

Partial discharges shall be measured with a method according to IEC 60270.

The results shall be considered acceptable and no further partial discharge tests required when, during the last 30 min of the test, no more than 30 pulses ≥ 2 000 pC are noted with no more than 10 pulses ≥ 2 000 pC in the last 10 min. If this condition is not met, the test may be extended for 30 min.

There may be only one 30 min extension, and the transformer shall be accepted when the number of pulses in such a 30 min period is no more than 30 with no more than 10 pulses in the last 10 min.

If no disruptive discharge occurs the test shall be regarded as non-destructive. A failure to achieve the partial discharge requirements shall not lead to an immediate rejection of the transformer but shall require a consultation between the purchaser and supplier with a view to further investigations and actions.

9.7 Polarity reversal test

9.7.1 Applicability

This test is not applicable for transformers connected to voltage source converters or if they are not subject to polarity reversals in service.

This test is not applicable for transformers that are subjected to the extended polarity-reversal test according to 9.8.

9.7.2 Transformer test temperature

During the polarity-reversal tests the temperature of the oil shall be (20 ± 10) °C.

NOTE If the required temperature is difficult to achieve, for example if tested in a very warm region, then a higher temperature can be accepted by agreement between the purchaser and the manufacturer.

9.7.3 Test procedure

Terminals not being tested shall be solidly earthed. A double reversal test shall be used as shown in Figure 1.

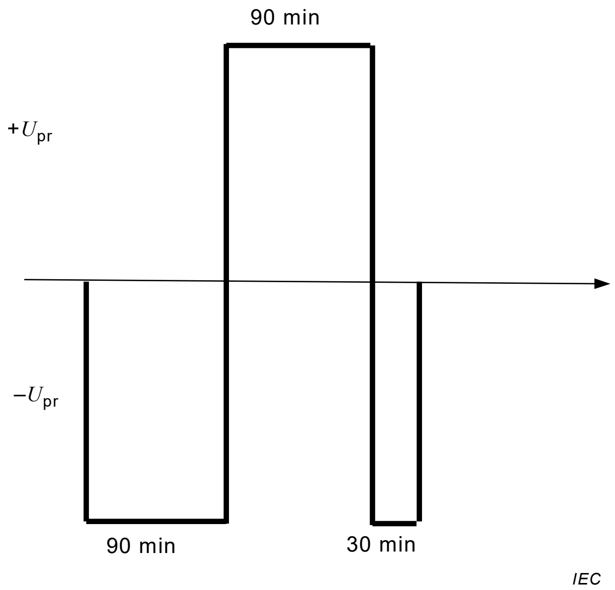


Figure 1 – Double reversal test voltage profile

Oil pumps shall not be running during the test. No preconditioning of the converter-transformer insulation structure by voltage application is allowed. The test shall be made with two reversals. The test sequence shall include 90 min at negative polarity followed by 90 min at positive polarity and finally 30 min at negative polarity. Each reversal of the voltage from one polarity to the other shall be completed within 2 min. Grounding of the DC generator may be needed during the voltage reversal. Grounding during reversal shall be limited to the minimum time required by the test setup. The partial discharge levels shall be monitored during the entire test sequence.

NOTE 1 Ultrasonic transducers installed on the converter transformer tank can help to distinguish internal discharges from external discharges during the polarity reversal test. Other detection methods can also be helpful.

NOTE 2 After a polarity reversal test is completed, the insulation structure retains a considerable electrical charge. This could represent a danger without appropriate precautions and unless adequately discharged subsequent partial discharge measurements could be affected.

9.7.4 Acceptance criteria

The test is considered accepted if there is no disruptive discharge and if the measured partial discharges are within the limits given below.

Partial discharges shall be measured with a method according to IEC 60270. Partial discharges shall be measured throughout the entire polarity-reversal test.

The results shall be considered acceptable when, during the 30 min following the completion of each reversal, no more than 30 pulses ≥ 2 000 pC are noted, with no more than 10 pulses > 2 000 pC occurring in the last 10 min.

The polarity reversal is completed when the voltage has reached 100 % of the test value.

If no disruptive discharge occurs, the test shall be regarded as non-destructive. A failure to achieve the partial discharge requirements shall not lead to an immediate rejection of the transformer but shall require a consultation between the purchaser and supplier with a view to further investigations and actions.

9.8 Extended polarity-reversal test

9.8.1 Applicability

This test is a special test that is recommended when rapid polarity reversals (from one polarity to the other with less than one hour at zero voltage), to reverse the power flow, are part of the normal operation. If ordered, this test should be regarded as a design test.

If an extended polarity-reversal test is selected then the DC bushings that will be mounted on the transformer, which will be subjected to this test, shall be tested with polarity-reversal test with the same duration as for the transformer test.

NOTE 1 Several Cigré working groups have been trying to assess the polarity reversal test. It was originally initiated in A2/B4.28 [16][2] which was pointing to a potential flaw in achieving the highest possible electrical stress in the test. This caused A2/D1.41 [17] to investigate the matter without being able to conclude fully. There are indications that charging times are long with contemporary transformer oil types, but how that translates into a suitable formulation for the polarity reversal test has not been concluded. The number of polarity reversal test failures or field failures in the industry is small and there is no immediate reason to change the polarity reversal test for all HVDC applications. The extended polarity reversal test therefore exists as a standardized test to be applied by the users of the document convinced that it is needed for their application.

This test is not covered by the DC bushing standard IEC/IEEE 65700-19-03:2014. It is important for the transformer manufacturer to establish the capability of the DC bushings.

NOTE 2 It is understood that short duration polarity reversals can occur during fault clearance without an intended reverse power flow. On its own, this would not be a reason to apply this test.

9.8.2 Transformer test temperature

During the extended polarity-reversal tests the temperature of the oil shall be (20 ± 10) °C.

NOTE If the required temperature is difficult to achieve, for example if tested in a very warm region, then a higher temperature can be accepted by agreement between the purchaser and the manufacturer.

9.8.3 Test procedure

There are two alternatives for this test:

- Alternative 1 – The test sequence shall include 6 h at one polarity followed by 6 h at the opposite polarity and finally 30 min at the first polarity. The choice of the first polarity shall be made by the manufacturer unless otherwise specified by the purchaser at the tender stage. Figure 2 shows the test with a negative first polarity. Other test durations may be agreed between the purchaser and the manufacturer.
- Alternative 2 – The test sequence shall include 2 h as the DC withstand test at positive polarity according to 9.6, followed by a reduction to the polarity-reversal test level for 1 h at positive polarity, followed by 6 h at negative polarity and finally 30 min at positive polarity. See Figure 3. Other test durations may be agreed between the purchaser and the manufacturer.

Terminals not being tested shall be solidly earthed.

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

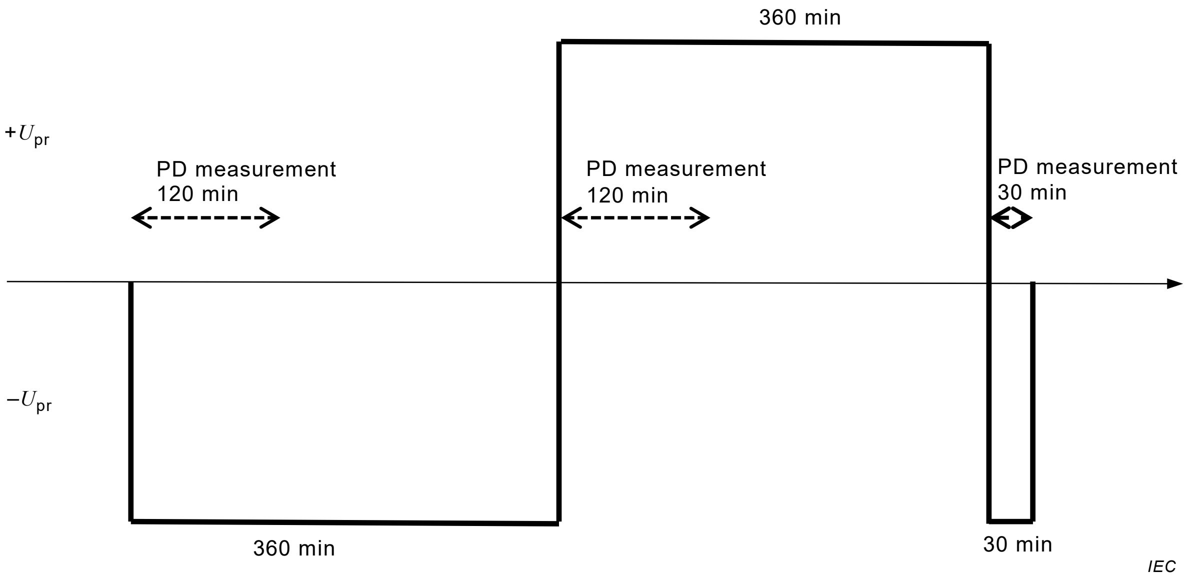


Figure 2 – Extended polarity reversal test alternative 1

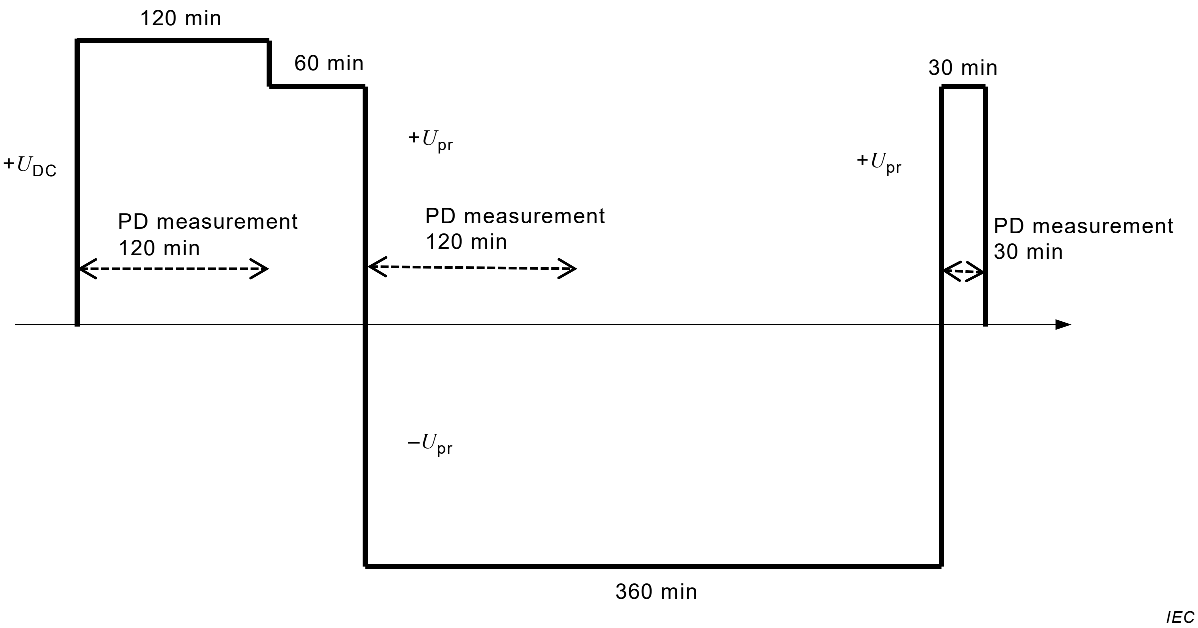


Figure 3 – Extended polarity reversal test alternative 2

Oil pumps shall not be running during the test. No preconditioning of the converter-transformer insulation structure by voltage application is allowed. The test shall be made with two reversals.

Each reversal of the voltage from one polarity to the other shall be completed within 2 min. Grounding of the DC generator may be needed during the voltage reversal. Grounding during reversal shall be limited to the minimum time required by the test setup. The partial discharge levels shall be monitored during the entire test sequence.

NOTE 1 Ultrasonic transducers installed on the converter transformer tank can help to distinguish internal discharges from external discharges during the polarity reversal test. Other detection methods can also be helpful.

NOTE 2 After a polarity reversal test is completed, the insulation structure retains a considerable electrical charge. This could represent a danger without appropriate precautions and unless adequately discharged subsequent partial discharge measurements could be affected.

9.8.4 Acceptance criteria

The test is considered accepted if there is no disruptive discharge and if the measured partial discharges are within the limits given below.

Partial discharges shall be measured with a method according to IEC 60270. Partial discharges shall be measured throughout the entire test.

No more than 30 pulses of partial discharge with magnitude equal to or greater than 2 000 pC are recorded during any sliding 30 min window for up to 2 h following the completion of each polarity reversal.

The polarity reversal is completed when the voltage has reached 100 % of the test value.

In the case of Alternative 2, the acceptance criteria according to 9.6.5 is valid for the DC withstand part of this test.

If no disruptive discharge occurs, the test shall be regarded as non-destructive. A failure to achieve the partial discharge requirements shall not lead to an immediate rejection of the transformer but shall require a consultation between the purchaser and supplier with a view to further investigations and actions.

9.9 AC applied voltage test for valve side winding(s)

9.9.1 Test procedure

The test shall be made at rated frequency. The voltage shall be applied on each winding with its available terminals connected together. All non-tested terminals shall be earthed.

The partial discharge measurement shall be made according to the applicable parts of IEC 60076-3:2013, Annex A, with measuring equipment as specified in IEC 60270 or IEEE Std C57.113.

The duration of the test shall be 1 h.

NOTE Ultrasonic transducers installed on the converter transformer tank can help to distinguish internal discharges from external discharges during the AC applied voltage test. Other detection methods can also be helpful.

9.9.2 Acceptance criteria

The test is successful if all the following criteria are fulfilled:

a) no collapse of the test voltage occurs;
b) none of the PD levels recorded during the one hour period exceed 250 pC;
c) the PD levels measured during the one hour period do not exhibit any rising trend and no sudden sustained increase in the levels occur during the last 20 min of the test;
d) the measured PD levels during the one hour period do not increase by more than 50 pC.

IEC 60076-3:2013, Annex A or IEEE Std C57.12.90 suggests actions to be taken following an unsuccessful test.

NOTE The acceptance criteria of 250 pC is reduced from 500 pC (in both IEC 61378-2 and in IEEE Std C57.129). The new level is the same as in IEC 60076-3.

9.10 AC applied voltage test on line side winding(s)

Converter transformers receive an applied voltage test on the line side winding(s) as described in IEC 60076-3 or IEEE Std C57.12.00 and IEEE Std C57.12.90.

9.11 AC induced voltage test with partial discharge measurement

9.11.1 General

AC induced voltage tests with partial discharge measurement shall be performed in accordance with IEC 60076-3 or IEEE Std C57.12.00 and IEEE Std C57.12.90 excluding the limits for partial discharge which is given below. The test levels shall be based on the voltage levels of the line side winding.

Attention shall be given to individual and random high-level discharge pulses detected by acoustic emissions during the induced test. If the number of high-level discharge pulses exceeds one per minute at a level greater than 2 000 pC, the transformer should be subjected to a pre-conditioning period, described in the following note. In addition to the partial discharge requirement, the results shall be considered acceptable and no further induced test required when the partial discharge level is less than 250 pC and the rate of high-level discharge pulses (> 2 000 pC) is less than or equal to one pulse per minute. In other cases the induced test shall be repeated.

NOTE DC charges can give rise to random, high-level (> 1 000 pC) discharge pulses associated with acoustic detection during the induced test. Earthing of the windings for a long period (24 h) might not be sufficient to remove these residual DC charges in the transformer insulation due to the DC testing. Energizing the transformer at about 1,1 × U_r (line winding) and at rated frequency (50/60 Hz) or other frequency decided by the manufacturer, for at least 1 h prior to the induced tests can help remove any remaining DC charges.

9.11.2 Acceptance criteria

The test is successful if all the following criteria are fulfilled:

a) no collapse of the test voltage occurs;
b) none of the PD levels recorded during the one hour period exceed 250 pC;
c) the PD levels measured during the one hour period do not exhibit any rising trend and no sudden sustained increase in the levels occur during the last 20 min of the test;
d) the measured PD levels during the one hour period do not increase by more than 50 pC;
e) the PD level measured at a voltage level of (1,2 × U_r)/√3 after the one hour period does not exceed 100 pC.

NOTE The acceptance criteria of 250 pC is reduced from 500 pC (in both IEC 61378-2 and in IEEE Std C57.129). The new level is the same as in IEC 60076-3.

9.12 Induced voltage test including running of oil pumps

An additional induced test shall be performed with the oil pumps running, if required by the purchaser, for a cooling system that utilizes pumps for oil directed cooling (OD).

Unless otherwise specified, the test shall be performed in the same way and with the same acceptance criteria as for the normal induced test, according to 9.11, but without the enhanced test level.

If agreed between the manufacturer and the purchaser, this test can replace the induced test in 9.11, but in that case, the test shall include the enhanced test level.

9.13 Temperature-rise test

9.13.1 General

IEC 60076-2 or IEEE Std C57.12.90 shall be used for determining the temperature-rise characteristics.

For converter transformers, the effects of harmonic currents shall be considered in determining (by calculation and by test) the operating temperature of the oil and the windings and other structural metallic parts.

The purpose of the test is

– to establish the top-oil temperature rise;
– to establish the winding temperature rise.

9.13.2 Test procedure

The test procedure for oil-immersed transformers according to IEC 60076-2 or IEEE Std C57.12.90 shall be modified as described below.

The top-oil temperature rise shall be determined in steady-state conditions with dissipation of the total service losses as calculated in 7.4.

When the top-oil temperature rise has been established, the test shall continue with a sinusoidal test current of 50/60 Hz equivalent to the load losses under rated service conditions. This condition shall be maintained for 1 h in the windings, during which measurements of oil and cooling medium temperatures shall be made. At the end of the test, the temperature rise of the windings shall be determined.

The equivalent test current shall be equal to

$$I_{\text{eq}} = I_{\text{r}} \left(\frac{I_{\text{LN}}^2 \times R + F_{\text{WE}} \times P_{\text{WE1r}} + F_{\text{SE}} \times P_{\text{SE1r}}}{I_{\text{r}}^2 \times R + P_{\text{WE1r}} + P_{\text{SE1r}}} \right)^{0,5} \tag{14}$$

where

$$F_{\text{WE}} = \sum_{h=1}^{49} k_h^2 \times h^2 \tag{15}$$

and

$$F_{\text{SE}} = \sum_{h=1}^{49} k_h^2 \times h^{0,8} \tag{16}$$

Values for I_{eq} shall be established for each valve winding.

Unless otherwise specified, the temperature rise test is conducted with the transformer connected on the maximum current tapping.

The temperature rise test shall be performed with the current in each winding equal to I_{eq} for that winding with a tolerance of ± 10 %. The measured temperature rises shall be corrected for the difference between I_{eq} and the test current.

For three winding transformers, the measurement of the temperature rise of the two valve windings may be made at the same time unless the current through one of the windings differs from I_{eq} for that winding by more than 10 % in which case an extra measurement shall be performed with the current through that winding adjusted to meet the 10 % tolerance. For the additional measurement the other valve winding may be open circuited. I_{eq} for the line winding shall be chosen so the temperature rise is representative of the highest temperature of the parallel parts of the line winding. Unless otherwise agreed, the I_{eq} for the line winding shall be the value of the highest I_{eq} of the valve windings transferred to the line winding with the turns ratio and corrected for the actual transformer topology (e.g. considering parallel windings).

NOTE 1 Generally, a three-winding transformer has two valve windings with the same rated power, each feeding one converter bridge. The three-phase connection is normally star-star and star-delta. Normally, all windings are tested in the same time frame with both valve windings short circuited and with voltage supplied at the line side windings.

NOTE 2 Even with the harmonics corrections above, it is possible that the temperature rise test does not produce the same hot-spot rise as in normal service since the extra losses due to harmonic currents are mainly concentrated at the extreme ends of the windings, while the correction factor applied during the test will generate extra losses uniformly along the winding. As a result, the hot spot generated during the test can be less than that developed in normal converter operation.

9.13.3 Tank surface temperature rise measurement

The tank surface temperature rise over ambient temperature shall be measured and recorded. The method shall be agreed between the manufacturer and the purchaser.

The measurement is made during the temperature rise test of the converter transformer. Measurement of the tank surface temperatures shall be done during the 1 h equivalent current (I_{eq}) period when average winding temperature rise is established. The measurement of the tank temperature shall commence not less than 30 min after I_{eq} is applied.

9.14 Load current test

In order to verify the current-carrying capability of the transformer, a load-current test shall be carried out at a current that gives the total service loss as calculated in 7.4 unless a higher current is specified. The duration of the test shall be not less than 12 h; a longer test duration may be specified by the purchaser. A chromatographic analysis of dissolved gas in the oil shall be used in order to detect possible overheating and possible abnormal temperatures. When a temperature-rise test is performed, the load-current test shall be omitted.

9.15 Sound level measurement

The procedure to determine the sound power level of HVDC converter transformers shall be in accordance with IEC 60076-10 or IEEE Std C57.12.90 (i.e. at sinusoidal excitation).

In order to estimate the total sound power level of an HVDC converter transformer in service, it is required to measure the sound power level of the sound contributing components individually:

- sound power level at no-load excitation;
- sound power level due to load current;
- sound power level of the cooling device.

If for thermal reasons the cooling device cannot be switched off when performing the measurement with load current then a logarithmical subtraction of the cooling device sound power level has to be applied in order to calculate the sound power level due to load current.

The sound level measurement at no-load excitation shall be with rated voltage applied to the line side terminals.

The sound level measurement with load current shall be at rated current I_r at fundamental frequency and principal tap unless otherwise specified.

NOTE The quantity I_r is applicable for this test because the measured sound level at I_r forms the basis for the calculation of the load sound power level of the transformer in service which is determined by simply adding the sound power increase level due to the current harmonics to the measured sound power level.

Reported sound level figures shall all be given as A-weighted sound power levels.

Additionally, the estimated sound power level(s) for the service condition(s) set out in Clause 11 allowing for the specified harmonic voltage/current and DC bias shall be calculated and reported.

9.16 Insulation power-factor test

Insulation power factor (tan δ) procedures for tests are described in IEEE Std C57.12.90. The voltage should not be above 10 kV.

9.17 Winding insulation resistance test

Insulation resistance tests shall be made on converter transformers to determine the insulation resistance from individual windings to ground or between individual windings.

Tests shall be performed as described in IEEE Std C57.12.90. The oil temperature during the test shall be recorded.

9.18 Core insulation resistance test

The insulation resistance between the core and ground shall be measured after complete assembly of the transformer at a level of at least 500 V DC for a duration of 1 min.

9.19 Short-circuit test

Tests shall be performed as described in IEC 60076-5 or IEEE Std C57.12.90.

9.20 Frequency Response Analysis (FRA) measurements

Tests shall be performed as described in IEC 60076-18 or IEEE Std C57.149.

9.21 Over-excitation test

The over-excitation test is a special test that shall be performed when specifically required by the purchaser.

Two oil samples shall be taken before the test and a DGA analysis shall be performed on both samples.

The transformer shall be energized in no-load condition at 110 % of its nominal voltage at the principal tap, for a duration of 8 h unless otherwise agreed between the purchaser and the manufacturer.

No-load losses and excitation current shall be measured at the beginning and at the end of the test. The values measured at the end of the test shall not be higher by more than 5 % than those measured at the beginning of the test.

Two-oil samples shall be taken after the test and a DGA analysis shall be performed on both samples. The acceptance limits for the increase of the dissolved gas-in-oil shall be agreed between the purchaser and the manufacturer.

10 Dielectric tests on transformers that have been in service

Dielectric tests may be warranted on transformers that have been in service and refurbished or repaired.

Field dielectric tests may also be warranted on the basis of detection of combustible gas or other circumstances. However, periodic dielectric tests are not recommended because of the severe stress imposed on the insulation.

The test methods and appropriate test levels shall be in accordance with the provisions of IEC 60076-3 or IEEE Std C57.12.90 specific to the circumstance and should be carried out in consultation with the manufacturer.

11 Sound levels

11.1 General

Depending on the converter scheme and its control settings, three factors contribute if present to the sound level increase of converter transformers while in service. Such factors shall be clearly distinguished and treated independently.

1) current harmonics;
2) DC bias currents;
3) voltage harmonics (normally not considered due to the minor influence).

11.2 Determination of service sound levels

Due to the unavailability of power supply equipment of sufficient power for distorted voltage/current wave shapes in factory test laboratories, it is not possible to perform as in service sound level measurements at the transformer manufacturer's facility. It is therefore standard practice to determine the sound power level at no-load excitation and the sound power level due to load current according to IEC 60076-10 or IEEE Std C57.12.90 at standard sinusoidal quantities (both without sound contribution of the cooling device). The service sound power levels of the HVDC converter transformer are then derived separately for both conditions by adding the relevant sound increase level as estimated, based on the provided harmonic voltage/current spectra and the given DC bias current, if any. Both derived components will finally be combined with the sound power level of the cooling device to receive an estimate for the total sound power level of the converter transformer as in service. For detailed information and background to sound levels of converter transformers, see Annex E.

Estimates for the sound increase levels shall be provided by the manufacturer in the quotation and in the transformer test report. The harmonic voltage/current spectra and the DC bias current, as applicable, shall be specified by the purchaser in order for the manufacturer to derive and provide the estimates.

Sound increase levels are typically provided as A-weighted total sound levels (i.e. comprising all frequency bands) but can – if required – also be provided as A-weighted sound levels in 1/3 octave bands.

11.3 Guaranteed sound levels

Sound levels for HVDC converter transformers are specified/guaranteed as sound power levels, typically A-weighted total sound power levels (i.e. comprising all frequency bands) but can – if required – also be specified/guaranteed as A-weighted sound power levels in 1/3 octave bands.

If required by the purchaser, the transformer manufacturer shall guarantee the sound power levels at no-load excitation, due to load current – both at sinusoidal excitation at the magnitudes as mentioned in 9.14 or as specified – and of the cooling device.

12 Bushings

12.1 General

The current harmonic spectra shall be considered in the design of the bushings.

The purchaser should provide the current harmonic spectra for the bushings. Otherwise the same current harmonic spectra as for the windings shall be used.

12.2 Line side winding bushings

The bushings shall be designed and tested according to IEC 60137 or IEEE Std C57.19.00.

12.3 Valve side winding bushings

The bushings shall be designed and tested according to IEC/IEEE 65700-19-03.

The polarity reversal test is not required on the bushing if it is intended for a transformer which is not going to be tested for polarity reversal.

NOTE DC bushings in general have more insulation than AC bushings. In addition, the oil immersed portion at higher voltages (generally over 200 kV) is designed such that they form an integral part of the insulation structure of the transformer. As such, they are not interchangeable with other DC bushings with similar ratings, and only those bushings specifically designed and tested with the particular insulation structure can be expected to work as replacements.

13 Tap-changer

13.1 General

When an on-load tap-changer (OLTC) is provided, it shall be in accordance with IEC 60214-1 or IEEE Std C57.131.

13.2 Current wave shape

The rate of change of currents in the tap-changer is higher in service on transformers with delta-connected valve windings compared to the corresponding sinusoidal current at fundamental frequency. The purchaser shall specify di/dt for the actual current wave shape.

NOTE Additional information can be found in IEC 60214-2.

Due to the high frequency of operation, the mechanical and electrical aspects of on-load tap-changers should be reviewed thoroughly to ensure a robust design. Normally some de-rating (higher current rating versus actual current) should be considered due to di/dt, wear, linkages, and the sheer number of operations. On-line filtering of the tap-changer oil may be considered in case of a very high number of operations (30 000 per year).

13.3 Consecutive operation of tap-changers

Unless otherwise specified, the tap-changers shall be capable of continuous uninterrupted tapping from the principal tap to the maximum positive tap and back to the principal tap without exceeding the temperature limits of the transition resistor and other parts of the tap-changer.

To enable a proper thermal dimensioning, the maximum top oil temperature, the maximum load currents and step voltages in each tap position during the required operation sequence shall be given by the purchaser to the OLTC manufacturer.

14 High-frequency modelling

If requested by the purchaser, the manufacturer shall provide a high-frequency model of the transformer. If required, this model shall be verified through low-voltage measurements.

15 Tolerances

15.1 General

The tolerances shall be in accordance with IEC 60076-1:2011, Table 1 or IEEE Std C57.12.00, with the exceptions given in 15.2.

15.2 Short-circuit impedance tolerances

Unless otherwise specified by the purchaser, the measured impedance shall not deviate from the value specified by the purchaser by more than ±5 % at the principal tap. The tolerances for each tap ($+\delta e_k$ and $-\delta e_k$) are shown in Formulae (17) and (18).

$$+\delta e_k = 5\% + \frac{|1 - \text{tapping factor}|}{3} \times 100\% \tag{17}$$

$$-\delta e_k = -5\% \tag{18}$$

The definition of tapping factor (corresponding to a given tapping) is the ratio U_x/U_r:

where

U_r is the rated voltage of the winding;

U_x is the voltage that would be developed at no-load at the terminals of the winding, at the tapping concerned, by applying rated voltage to an untapped winding.

If the purchaser provides maximum and minimum impedances across the tapping range then these are limits without tolerances.

Unless otherwise specified by the purchaser, the impedance at the principal tap and the variation of impedance over the tapping range for transformers of duplicate or similar design for the purpose of identical application in service, or interchangeability, shall not exceed ±3 % of the mean test values.

16 Rating plate

The rating plate shall be in accordance with IEC 60076-1 or IEEE Std C57.12.00 with the following modifications.

The rating plate shall contain the words “Converter Transformer.” In addition, the full-wave LI or BIL, in kilovolts, of line terminals shall be designated as below:

- Line side winding — LI or BIL
- Line side winding neutral — LI or BIL
- Valve side windings to ground — LI or BIL
- Valve side windings between terminals to ground) — LI[BT] or BIL[BT] (only if different from winding
- Valve side windings U_{DC}
- Valve side windings U_{pr}
- Valve side windings U_{AC}

An example would be:

Line side	U_m 245 / SI 750 / LI 950 / LIC 1 045 / AC 395 kV
Line side neutral	U_m 52 / LI 250 / AC 95 kV
Valve side Y	LI 1 300 / LI[BT] 1 050 / SI 1050 / U_{DC} 724 / U_{pr} 509 / U_{AC} 535 kV
Valve side D	LI 750 / SI 650 / U_{DC} 376 / U_{pr} 229 / U_{AC} 390 kV

Annex A
(informative)

In service overloading of HVDC converter transformers used with current commutated valves (either mercury arc valves or thyristors)

A.1 General

The converter transformer loading conditions are different than those of an AC transformer. The main differences result from the pulse-shaped current waveform, leading to high content of harmonics in the load current. High frequency currents and related magnetic flux introduce additional eddy losses in the conductors and core, as well as in the constructional parts of the transformer.

The converter transformer should be designed based on the actual harmonic current spectra for each overload case, given by the purchaser.

The distribution of eddy losses in the windings for a converter transformer subjected to a high content of harmonics is more non-uniform than in an AC transformer due to the high frequency components of the eddy losses. Therefore, for transformers designed for DC converter operation, the temperature gradient between the hot-spot temperature rise and the winding average temperature rise may be higher, and the location of the hot spot(s) will be in different parts of the winding when compared to the location in transformers under normal AC operating conditions. The direct consequence of this fact is a failure to generate the hottest spot temperature by simulating the converter operation with an equivalent power frequency sinusoidal current of increased magnitude. Such a current of increased magnitude will result in correct value of the average temperature rise of the winding, but the hottest spot will have a lower temperature than under operational conditions. On the other hand, during the oil temperature rise test the current is increased, in order to include the core loss in the total loss being dissipated. Therefore, the windings may be overloaded to some extent during the standard temperature rise test, depending on the proportion of the core loss and the harmonic content of the current.

Depending on the design of both the converter transformer and the converter station, the load distribution between valve and line windings may be different and may depend on the load. This has to be considered if necessary.

Based on valve winding configuration, all necessary information to calculate harmonic losses shall be specified and includes amplitude of harmonic currents, vector sum of harmonic currents, wave shape, and phase angle of harmonic currents.

A.2 Overloading in service

The loading beyond nameplate power rating can result from the following:

– planned overloads;
– emergency overloads;
– failure of equipment (auxiliary equipment of the unit, or the converter station).

All types of loading beyond nameplate can result in significant reduction of the insulation life, ultimately leading to an increased risk of the transformer's failure. Other harmful effects resulting from overloading include evolution of free gas from insulation, mechanical stresses in the active part and construction (thermal expansion and reduced mechanical strength), leaking gaskets (tank and bushings), wear of the tap-changer contacts, aging of auxiliary equipment, and excessive oil expansion. Accelerated aging of the active part of the converter transformer is especially critical since the hottest spot temperature may increase beyond the thermal limits for cellulose and combined with high electrical stress will give rise to dielectric failure. Therefore, the user should address, in the technical specification, the various possible loading conditions of the transformer, especially if planned overloading conditions such as an overload profile during low ambient temperature or limited duration overload capability are required.

It is usual that the converter transformer is designed to have a power rating compatible with the overload capacity of the whole converter station.

The overload specification shall contain the following data for each overload case if necessary:

- ambient temperature;
- overload factor [p.u.];
- duration of overload;
- preload [p.u.];
- number of cooler circuits in service (if applicable);
- permissible over-temperatures for oil, winding, and hot spot;
- spectrum of harmonics for pre-overload and overload;
- tap-changer position.

The data should be given in form of tables and/or diagrams as shown in Table A.1 and Figure A.1.

Table A.1 – Example of an overload table

Case	Duration	Overload factor (p.u.) power	Redundant cooling	Ambient temperature (°C)	$I_{v\text{-star}}$ (A)	I_{dc} (A)	Harmonic spectrum no.
Rated	Cont.	1	Off (hot spot 105 °C)	40	3 009	2 457	1
1	Cont.	1,1	On (hot spot 105 °C)	40	3 318	2 710	2
2	2 h	1,2	On (hot spot 120 °C)	40	3 630	2 964	3
3	2 h	1,25	On (hot spot 120 °C)	33	3 786	3 092	3
4	≤ 10 s	1,5	On or off	40	4 581	3 741	3

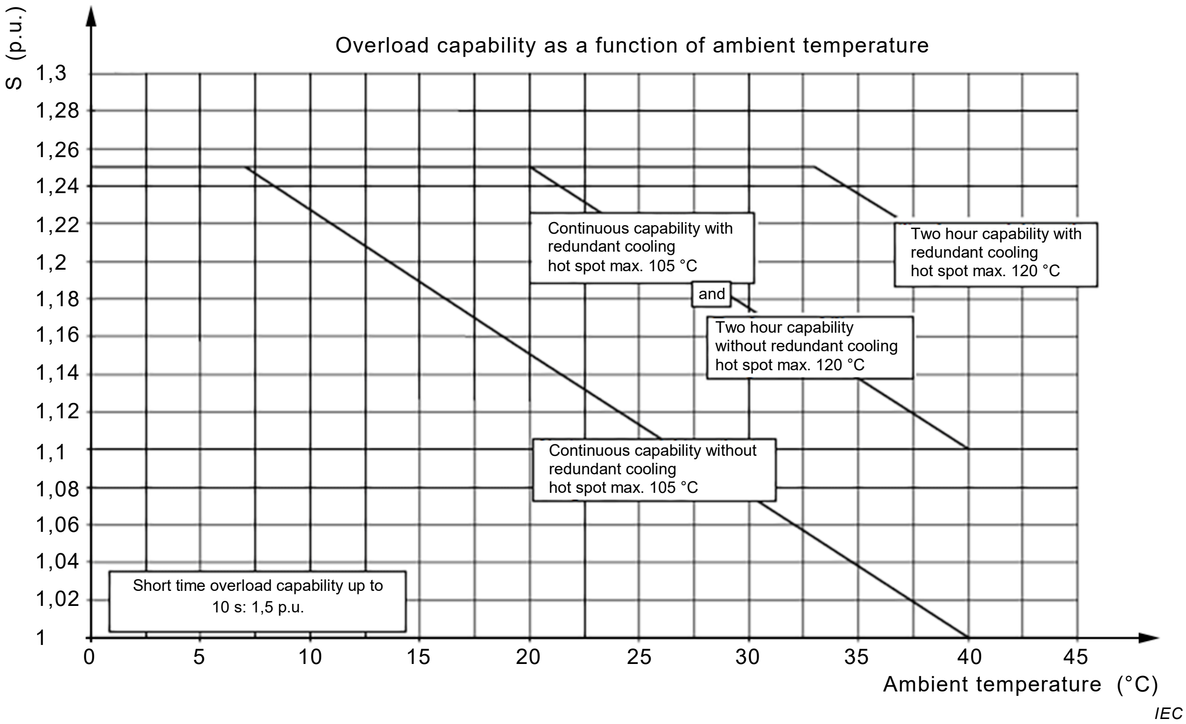


Figure A.1 – Example of an overload diagram

It shall be pointed out that overload conditions have an important impact on the transformer design and aging and should therefore be handled carefully by both user and transformer manufacturer.

Exact specifications of overload conditions allow the user to estimate the risk caused by such service conditions and enable the manufacturer to allow for such conditions. Such risk estimations can be done by using mathematical models as described in “Risk assessment using transformer loss of life data”.

A.3 Temperature rise test for demonstrating normal loading condition

The temperature rise test of the converter transformer, when performed in accordance with 9.13, is to test the rated loading of the unit, because

a) the magnitude of the power frequency current is increased to simulate the presence of harmonics, i.e. to get the same amount of load losses,
b) the current is further increased to include the no-load loss (core loss).

The transformer designer takes the above parameters into account while designing the windings. Any requirements for overload exceeding these limits shall be clearly specified by the user in the technical specification.

A.4 Temperature rise test for demonstrating planned overload conditions

When a planned overload condition such as a low temperature overload capability or an emergency overload profile is specified, it may be required to perform additional heat run tests(s) at the specified overload rating(s). If such a demonstration is required, it should be clearly stated in the enquiry. Moreover, acceptance criteria regarding maximum hot-spot rise, mean winding rise, and top oil rise during overload condition(s) shall be clearly defined.

NOTE It is recognized that a heat run test performed at load levels exceeding the rated power of the transformer will cause a certain aging on the transformer insulation.

Short-duration overloads of less than 10 min do not normally need to be verified by an overload heat run test.

When the overload rating is continuous (e.g. permanent overload rating below a certain ambient temperature), the overload temperature rise test should be performed with the same testing method as described in 9.13 and it is normally performed immediately after the standardized heat run test for rated conditions. The harmonic content shall be simulated in the same way. A different harmonic profile during overload operation than during rated conditions may be specified.

Otherwise, when the overload rating has a specific maximum duration limit, the test sequence should be modified accordingly and agreed upon by the user and manufacturer.

Unless otherwise specified, all cooling equipment, including redundancy, if provided, shall be in operation during the overload heat run test.

It should be emphasized that during overload, not only all of the current carrying components will be subjected to the increased temperature rise but also all constructional parts will experience much higher stray flux than at rated normal operating conditions. The stray flux increase can lead to localized saturation of the metallic parts resulting in severe overheating. Parts that may be affected by such increase flux are tank steel, bushing turrets, tank shielding, core clamps, tie plates or rods, core laminations, etc.

Due to the fact that there is no harmonic current at the overload test, such test is not fully relevant regarding hot-spot phenomena for both inside the windings and in other structural parts of the transformer. The harmonics can also cause different hot-spot locations.

Before starting the overload heat run test, it is recommended to install a thermocouple on the tank area that has been observed to be the hottest during the normal heat run test.

The hot-spot, oil, and/or winding thermometers shall be calibrated before performing the overload test.

Thermocouples should also be installed within the transformer tank for measuring the metallic part temperatures not in contact with insulation material such as core clamps, tie plates or tie rods, tank shields. Their locations should be agreed upon by the user and the manufacturer.

The problematic of performing, for example, a low temperature overload test in a normal ambient temperature condition is that the temperature rises will normally exceed the allowable limits applicable to the standardized temperature rise test. Such deviation can be acceptable provided that the temperature limits do not exceed those contained in IEC 60076-7 or IEEE Std C57.91.

If, for the specified overload condition and actual ambient air temperature within the test bay, the temperature limits in Table A.1 are exceeded, then it is allowable to reduce the overload current in such a way that these limits are not exceeded.

During the overload heat run test, the metallic parts of the transformer tank shall be monitored by means of an infrared camera technique.

The overload temperature rise test is considered successful if the following criteria are met:

– temperature limits in Table A.1 are not typically exceeded;
– no oil is discharged.
– gassing limits agreed to by the manufacturer and purchaser are not exceeded. Additional information can be found in IEC 60076-2 or IEEE Std C57.130.

Annex B
(informative)

HVDC converter transformers for use with voltage source converters

B.1 General

Recently, new HVDC converter schemes using voltage source converter (VSC) technologies have been put into operation. The principle of operation of such converter technology is quite different from the usual technologies using current commutated valves (either mercury arc valves or thyristors). Moreover, different power electronic technologies (GTOs, IGBTs, etc.) may be used in the design of voltage source DC converters.

The operating stresses that are applied to the converter transformers feeding a voltage source HVDC converter are also quite different from the stresses imposed on converter transformers using current commutated HVDC valves.

Different technologies regarding topologies and switching strategies may be used for voltage source DC converters.

In a two- or three-level topology the valves act like controllable switches connecting the stiff DC voltage to the line side, see Figure B.1.

An alternative technology is that the valves are divided into modules, each module with its own DC capacitor. In this case each module acts like a two-level controllable voltage source, see Figure B.2. This is defined as a multi-level VSC.

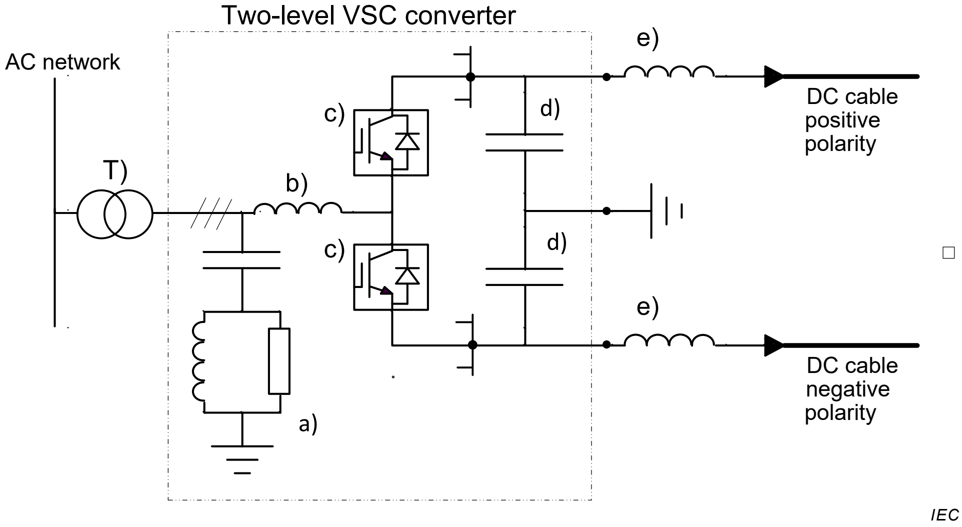
The transformer can also be connected directly to the converter valves, Figure B.3 shows an example of that.

The converters can also be in a symmetric or in an asymmetric configuration. In a symmetric configuration there is no DC voltage at the transformer windings but in an asymmetric configuration there is. Figure B.1 and Figure B.3 show two examples with symmetric configurations and Figure B.2 shows one example with asymmetric configuration.

B.2 Converter transformer stressed with only fundamental voltage and current

In the configuration outlined in Figure B.1, the transformer operates with lower stresses than the transformer for a line commutated converter. Among the differences, the main characteristics are as follows:

– no DC bias voltage applied to the valve winding(s);
– no harmonic current, unless the harmonic filters are not located in between the valve winding(s) of the converter transformer and the DC converter;
– voltage wave shape applied to the valve winding is sinusoidal.



Key

a) AC filter

b) Converter reactor

c) Converter valve

d) DC capacitor

e) Smoothing reactor

T) Transformer

Figure B.1 – Configuration with no additional stresses on the converter transformer

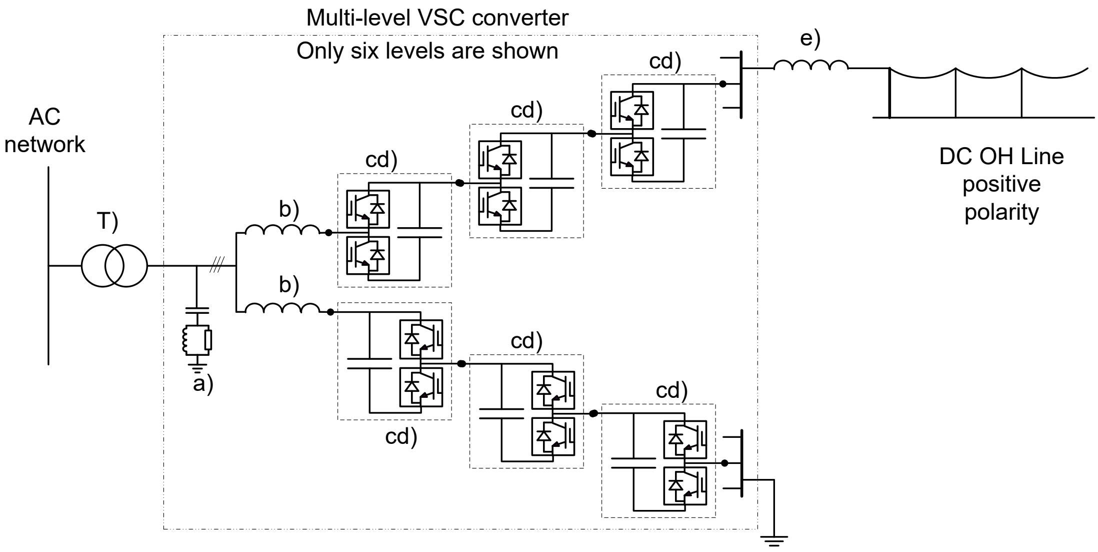
As a consequence of the differences outlined above Figure B.1, converter transformers feeding an HVDC voltage source converter, with a configuration in accordance with Figure B.1, are similar to normal AC substation power transformers and should be specified and tested according to IEC 60076-1 and IEC 60076-3 or IEEE Std C57.12.00 and IEEE Std C57.12.90. No special test needs to be performed to demonstrate the transformer performance in a converter application.

B.3 Converter transformers stressed with direct voltage, fundamental voltage and fundamental current

In the configuration outlined in Figure B.2, the transformer operates with lower stresses than the transformer for a line commutated converter. Among the differences, the main characteristics are as follows:

– no or very low levels of harmonic currents.

The voltage wave shape applied to the valve winding is sinusoidal in addition to a DC bias voltage. The DC bias voltage is half of the DC pole voltage.



Key

a) AC filter (if applicable)

b) Converter reactor

cd) Power modules including DC capacitance

e) Smoothing reactor

T) Transformer

The figure is simplified, for example, a 20-level VSC converter requires 20 power modules.

Figure B.2 – Configuration with multi-level VSC HVDC converter station applied in a monopolar scheme with DC overhead line transmission

As a consequence of the DC bias voltage the transformers for VSC asymmetric configurations should be specified according to this document.

B.4 Converter transformer stressed with the valves connected directly to the converter transformer

In the configuration outlined in Figure B.3, the converter transformer is exposed to more harmonic stress than the converter transformers of a line commutated converter. Some of the stresses are as follows:

– no DC bias voltage applied to the valve winding(s).

The voltage wave shape will be based on PWM, several commutations per period. This, plus the use of GTO- or IGBT-based valves, may result in the winding insulation being exposed to repetitive fast transient overvoltage and the associated potential voltage aging effects on the insulation system.

The voltage wave shape that may appear on valve winding is close to a square wave shape and this may generate an increased flux density and minor hysteresis loops in the magnetic core. If this is the case, care should be taken in the design of the magnetic circuit to cope with the special voltage wave shape applied to the valve winding.

The converter transformer is loaded with current harmonics as is the converter transformer for a line commutated converter. However, the spectra can have a higher content of higher harmonics than that for a line commutated converter.

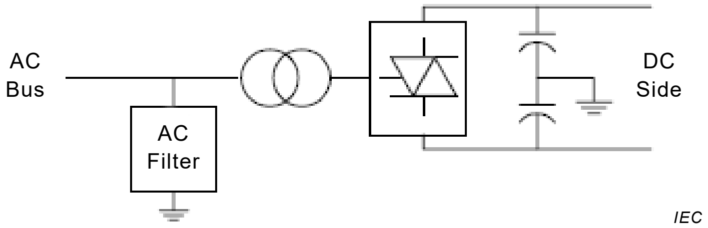


Figure B.3 – Configuration with VSC valves connected directly to the converter transformer

In this configuration all considerations regarding current harmonic current loading of line commutated HVDC converter transformer are applicable to VSC HVDC converter transformers. In addition, the consequences due to the voltage harmonics have to be evaluated and considered in the design, rating and testing of VSC converter transformers.

It should be noted that operational losses of converter transformers used in conjunction with such VSC HVDC schemes may be higher than tested losses.

B.5 Summary of stresses

As the stress and service conditions for the transformer depend on the configuration of and operation strategy for the voltage source converters, abnormal service conditions have to be fully defined and specified by the purchaser. Furthermore, the reactive power exchange of a voltage source can be varied within a large range independent of the active power. Therefore, care should be taken by the purchaser to specify the following parameters:

- operation range for active and reactive power versus combination of AC voltage and tap changer position;
- valve side voltage time domain waveform plus the harmonic content;
- time domain waveform plus the harmonic content for the transformer current;
- any other unusual service condition in relation to the transformer standard to be applied.

Annex C
(informative)

Design review

C.1 General

Testing may not address all issues important to converter transformer performance. Considering the complexity of converter transformer design, design review is an important factor that should be considered regarding impact on satisfactory in service performance.

C.2 Topics

A sample of topics that could be included in the design review process is as follows.

a) *Gaskets and gasket tightening.* A properly designed gasket tightening system will allow the gasket material to reach its “normal” life of 15 to 20 years without premature failure. The system should include proper gasket compression, gasket stops, O’ring groves, machined surfaces, etc. Aging tests should be designed to demonstrate that the life of the gasket material is 25 to 35 years. With an increased focus on the environment (ISO 14001) most utilities are focusing on stopping leaks. The manufacturer should demonstrate how he has addressed the above issues.

b) *Replacement bushings.* Sufficient information as to bushing dimensions/parameters should be provided at time of contract by the manufacturers; this is especially important if replacement bushings should be no longer available from the original converter transformer supplier.

c) *Bolt tightening torques.* Tightening torques for all bolts should be provided. Proper sizing of bolts is important to allow appropriate bolt tightening torques. The manufacturer should provide information on the preceding issue and any other issues relating to bolt tightening torques.

d) *Model studies.* The design review process should include the result of engineering studies, including the transient modeling of dielectric tests such as polarity reversal.

e) *Bushings.* Mounting of the bushing should be reviewed regarding reliability, for example, side mounted bushings. Careful review should be given to using non-ANSI DC bushings on converter transformers designed/tested in accordance with this document. Are there compatibility issues? These and other bushing mounting issues should be addressed by the manufacturer.

f) *Electrical connections.* The manufacturing process requires a large number of electrical connections for easy manufacturing, which become a potential source of failure in the field. Many of these connections are buried and thus are inaccessible. Some considerations are: crimped connections shall have a monitoring hole or other means to ensure that it is fully inserted prior to and after crimping; the person doing the brazed connections shall be pre-qualified by doing a braze on an identical connection(s) (if the person has not done one in the last six months); the connection(s) shall be cut apart or x-rayed or other means used to ensure the braze is done properly; bolted connections shall use bolts/bolting system (typical range of bolt sizes are M8 to M12) to provide sustained clamping force over the service life of the transformer (including a 50 % redundancy over that required by code); spring-type connections shall have I00 % redundancy; connections where there is no oil flow (such as draw lead/draw rod bushings) should consider a guideline of 1,55 A/mm^2 (1 000 A/in^2). As a “rule of thumb,” a bolt should be mechanically loaded to an elastic elongation that is greater than the thermal dimensional changes in the connected materials over the full range of temperature variation. (The larger the bolt, the greater the tightening torque that shall be used. High torque is difficult to achieve for internal bolted connections). In general, the manufacturer should address all electrical connection issues.

g) The hot spot in a converter transformer has a number of unique aspects. Experience has shown that it is difficult to determine it adequately by test in the factory. Aspects such as AC harmonic fluxes, large amounts of DC insulation (cocoon), and tradeoffs between AC and DC electrical stresses make it extremely difficult to determine accurately the hot-spot temperature. However, typically, the overcurrent used for the temperature rise test will result in slightly higher losses in the top disc compared to those produced in service (including harmonics), and thus the temperature at the top of the winding will be representative. This assumes the estimated total losses are correct. It should be noted that harmonic currents have a higher impact on the eddy losses in the middle of the winding than at the ends. It is also not possible to estimate the hot-spot temperature using a factor of 1,3 or 1,5 times the gradient over top oil temperature; hot-spot temperature may be higher. Factors to consider are, but not limited to, as follows.

   i) Additional insulation at the ends of the windings may cause reduced cooling.

   ii) Possible restricted oil flows as a result of the DC insulation “cocoon.”

   iii) The “cocoon” insulation may influence the oil flow independent of how the losses are generated.

   iv) Possible increased losses due to electrical fluxes crossing the ends to the windings radially instead of axially and is a function of yoke distance.

   v) “Harmonic fluxes” tend to have higher impact at the middle of the windings.

   vi) In a converter transformer, the total content of current harmonics in the windings shall be considered, even the six-pulse harmonics. (The six-pulse harmonics may be cancelled as seen from the outside of a twelve-pulse converter transformer, but not inside the transformer windings.) The impact of harmonic flux is a function of converter transformer design. During the design review, the manufacturer shall demonstrate how the hot-spot temperature rise, as determined during the temperature rise test, is related to hot-spot temperature in operation, especially considering the effect of harmonics.

CIGRĖ has published a report [2] on conducting design reviews for power transformers that can be referenced.

Annex D
(informative)

Transformer specification content

D.1 General

Annex D is intended to provide a checklist for the specification of HVDC converter transformers. It also contains an indication of the data to be provided at tender stage to enable converter system design and following tests.

Detailed information and background can be found in [1].

D.2 Data to be provided by the purchaser

The data below should be provided by the purchaser. The manufacturer needs it as input to the transformer design.

System data

- AC system voltages, nominal and extreme (maximum and minimum) steady state voltages. Temporary over and under voltages should also be given together with the respective duration.
- AC system frequencies, nominal and extreme (maximum and minimum) steady state frequencies. Temporary over and under frequencies should also be given together with the respective duration.
- AC system short circuit power.
- AC system grounding conditions, for example directly grounded.
- Current wave form. This is normally achieved by the current spectrum (fundamental frequency plus harmonics).
- DC system voltage, nominal and maximum steady state.

Environmental data

- Ambient temperature levels
- Site altitude above sea level
- Pollution aspects
- Maximum wind loading
- Seismic requirements

Performance requirements

- Number of phases per unit
- Rated power
- Operation range for active and reactive power versus combination of AC voltage and tap changer position
- Any overload requirements according to Annex A
- Rated voltage for each winding
- No-load rated voltage
- Rated frequency

- Winding connections and vector relationship
- Maximum voltage for each winding
- Tap-changer range and tap-changer step
- Short circuit impedance including impedance tolerances
- Cooling class and requirements
- Temperature rise limits for windings and oil
- Full wave lightning impulse withstand level for each winding
- Full wave lightning impulse withstand level for the line side neutral terminal
- Chopped wave lightning impulse withstand level for each winding
- Induced switching impulse withstand levels for the line side winding, if required
- Applied switching impulse withstand levels for each valve side winding, if required
- Induced AC voltage test level for the line side winding, if higher than the standard level
- Applied AC voltage test level for the line side neutral terminal, if higher than the standard level
- DC withstand voltage test level, or N, U_{dm} and U_{vm}, for each valve winding
- Polarity reversal test level, or N, U_{dm} and U_{vm}, for each valve winding
- Applied AC voltage test level, or N, U_{dm} and U_{vm}, for each valve winding
- Further test requirements, if any, for example special tests
- Parameters for guaranteed losses, including fundamental frequency and harmonic currents, voltages, tap-changer positions and ambient temperature
- Loss capitalization rates
- Sound level limits for transformer and coolers
- Transport limitations
- Requirements on bushings, tap-changers, current transformers, coolers, control cabinets and instrumentation
- Information about auxiliary power supply
- Any specific requirements for time limits and methods regarding replacement of the transformers or components

D.3 Data to be provided by the manufacturer

The data below should be provided by the manufacturer. The system designer (often the purchaser) needs it for further system studies.

<u>Performance data provided at tender stage [designed and guaranteed values]</u>

- No-load losses
- Load losses
- Auxiliary losses, for example cooling equipment losses
- Short circuit impedance, rated and related to tap-changer positions
- Zero sequence impedance
- Sound levels, transformer and coolers

Performance data provided following tests [measured values]

- No-load losses
- Load losses
- Auxiliary losses, for example cooling equipment losses
- Short circuit impedance, rated and related to tap-changer positions
- Zero sequence impedance
- Winding turns ratio for each tap-changer position
- Temperature rise, oil, average winding and hot spot
- Sound levels, transformer and coolers

Supplementary data normally provided at tender stage

- Information about core, including core material, number of limbs, flux density saturation curve and voltage/time limits
- Information about windings, including conductor material, arrangement, winding types and insulation details
- Circuit parameters, including winding capacitances, bushing capacitances, impedance/frequency characteristics, AC resistance/frequency characteristics
- Information about bushings, tap-changers, coolers
- Transport data, including dimensions and weight

Annex E
(informative)

Audible sound of converter transformers

E.1 General

HVDC transformers are subjected to terminal voltages and winding currents which due to the converter operation deviate more or less from the sinusoidal wave shape. The characteristic and the degree of the distortion, i.e. the harmonic voltage/current content, depend on the applied HVDC converter scheme and its control. The harmonic voltage/current content has always an increasing impact to the sound level developed by the converter transformer in comparison with equivalent conditions on entirely sinusoidal quantities.

Moderate uncompensated DC bias currents in valve windings caused by converter switching un-symmetries contribute – if present – additionally to the sound level increase of converter transformers in service.

The total sound level increase of converter transformers can be anywhere between negligible and extreme, practically between < 2 dB(A) and 30 dB(A), depending on the harmonic voltage/current content and on the DC bias control quality.

As the sound level increase of converter transformers can be significant, it is inevitable to consider this effect carefully for any HVDC project from planning to commission.

E.2 Technical reference

IEC 60076-10-1, *Power transformers – Part 10-1: Determination of sound levels – Application guide*

E.3 Current harmonics

Current harmonics in windings contribute to the transformer load sound level and their impact usually forms the most significant part of the overall sound increase level for a converter transformer. In order to calculate the sound increase level, the relevant current spectrum in magnitude and phase shall be specified by the purchaser or by the manufacturer of the converter and provided to the transformer manufacturer. Where phase angles are not available, a statistical approach will be applied for the calculation. Detailed information of the theory and engineering practice of the sound level produced by harmonic currents in windings is given in IEC 60076-10-1:2016, 4.2.5 and Annex A.

In specific cases it is possible to derive the load sound level of the converter transformer for the provided current spectrum from individual sound level measurements at different harmonic frequencies. For this procedure a set of harmonic test currents has to be derived from the provided current spectrum. Detailed information on this method is provided in IEC 60076-10-1:2016, 4.2.5.2. The application of this method has limits and clearly requires an agreement between purchaser and manufacturer mainly because the harmonic supply equipment is not necessarily available.

E.4 Voltage harmonics

Voltage harmonics on winding terminals contribute physically to the transformer core induction and impact therewith the transformer no-load sound level. As the core induction is however derived from the voltage by integration, the induction harmonics decrease inversely with the harmonic order and do therefore distort the core induction wave shape usually only insignificantly.

As moreover the AC network terminal of the converter transformer is operated with a constant voltage and limits for the harmonic distortion have to be maintained on this terminal, the sinusoidal voltage wave shape will be preserved to a high degree by the system/filter set up.

The sound increase level of the transformer no-load sound level due to voltage harmonics is in consequence usually of only minor impact and in most cases not considered.

E.5 DC bias current

Uncompensated DC bias currents in valve windings due to for example switching un-symmetries of the converters have an increasing impact to the transformer no-load sound level because this results in so called ‘half-cycle’ core saturation. The physical background and consequences are explained in detail in IEC 60076-10-1:2016, 4.2.1 including a general figure for the sound increase level which has to be taken into account for this effect. It is important to recognize that due to the complexity of the subject an exact sound increase level for a provided DC bias current figure can usually not be derived and the transformer manufacturer’s best estimate as per internal studies and background information shall therefore be accepted.

E.6 Derivation of service sound power levels

Voltage harmonics and DC bias current both affect core magnetization and therefore the sound level at no-load excitation. The sound increase levels for both effects have to be combined (added) logarithmically before adding the result algebraically to the determined no-load sound power level at sinusoidal excitation in order to receive an estimate for the no-load sound power level of the transformer in service.

The sound increase level due to current harmonics contributes to the load sound power level and shall be added algebraically to the determined sound power level due to load current at sinusoidal current loading in order to receive an estimate for the load sound power level of the transformer in service.

The sound level of the cooling device shall be determined separately and combined logarithmically with the two sound level components derived before in order to receive an estimate for the total service sound power level of the converter transformer.

E.7 Sound level guarantee

The specification and guarantee of sound levels for HVDC converter transformers shall all be in terms of sound power and not sound pressure or sound intensity. This is, because frequently performed sound propagation studies for HVDC substations require sound power levels as input quantity for the installed substation equipment. Information on sound level considerations and propagation for HVDC substations is provided in IEC TS 61973. It is however not the transformer manufacturer’s responsibility to perform any audible noise studies for HVDC substations as for instance the estimation of the sound pressure level at the substation fence due to the emitted sound power of the converter transformer.

The service sound power level of converter transformers shall neither be specified nor guaranteed because HVDC system parameters and not the transformer design dictate the sound level increase of the transformers in service.

Annex F
(informative)

Determination of transformer service load loss at rated non-sinusoidal converter current from measurements with rated transformer current of fundamental frequency

F.1 General

Using the notations given in the list of symbols in IEC 61378-1:2011, 6.3 the following relations can be written for the winding loss.

$$\begin{aligned} P_{W1} &= R_W \times I_1^2 \times \left(1 + K_{WE} \times 1^x\right) \\ P_{W2} &= R_W \times I_2^2 \times \left(1 + K_{WE} \times 2^x\right) \\ P_{Wh} &= R_W \times I_h^2 \times \left(1 + K_{WE} \times h^x\right) \\ \hline P_W &= R_W \times I_L^2 + R_W \times K_{WE} \times \sum_1^n I_h^2 \times h^x \end{aligned} \tag{F.1}$$

Consequently

$$\frac{P_W - R_W \times I_L^2}{P_{W1} - R_W \times I_1^2} = \sum_1^n \left(\frac{I_h}{I_1}\right)^2 \times h^x \tag{F.2}$$

With x = 2 for windings, the enhancement factor is equal to

$$F_{WE} = \sum_1^n \left(\frac{I_h}{I_1}\right)^2 \times h^2 \tag{F.3}$$

In high-current busbar connection systems, the loss will follow the same basic rule as for windings, but the exponent, x, is lower. With x = 0,8, the enhancement factor for connections is equal to

$$\frac{P_C - R_C \times I_L^2}{P_{C1} - R_C \times I_1^2} = \sum_1^n \left(\frac{I_h}{I_1}\right)^2 \times h^{0,8} = F_{CE} \tag{F.4}$$

Based on other studies, the enhancement factor for the stray loss in structural parts is taken as equal to that of busbar systems.

$$F_{SE} = \frac{P_{SE}}{P_{SE1}} = F_{CE} \tag{F.5}$$

NOTE Subclause 9.1.2 (Losses and frequency) of IEC 61378-3: 2006, contains the explanation of the choice of x = 2 for windings and x = 0,8 for high current busbar and structural parts.

Further conventions of loss calculations:

a) the winding loss P_{W1} is taken as the sum of the measured $I_1^2 \times R_W$ loss and the calculated eddy loss P_{WE1}.

$$P_{W1} = \left(I_1^2 \times R_W\right) + P_{WE1} \tag{F.6}$$

b) the sum of the eddy losses P_{CE1} from connections and the stray loss P_{SE1} in structural parts is equal to the measured total loss P_1 minus the winding loss P_{W1} according to a) and minus the measured $I_1^2 \times R_C$ loss of the connections.

$$P_{CE1} + P_{SE1} = P_1 - \left(P_{W1} + \left(I_1^2 \times R_C\right)\right) \tag{F.7}$$

Total loss with distorted current:

$$P_N = I_{LN}^2 \times \left(R_W + R_C\right) + \left(F_{WE} \times P_{WE1}\right) + F_{CE} \times \left(P_{CE1} + P_{SE1}\right) \tag{F.8}$$

All loss components in the above calculations are adjusted to the reference temperature (see IEC 60076-1:2011, 11.1.1 and IEC 60076-11:2004, Clause 12).

The respective components in Formulae (F.1) to (F.8) shall be the sum of the values calculated for each winding separately.

The calculated eddy losses P_{WE1} in the windings together with the measured $I_1^2 \times R_W$ loss give an accurate value for the total winding loss P_{W1}.

The sum of stray loss from connections and structural parts P_{CE1} + P_{SE1} can be derived with reasonable accuracy as the difference between the total measured loss P_1 minus the winding loss P_{W1} and minus the measured quantity $I_1^2 \times R_C$ of the DC loss of the connections.

F.2 Alternative method for calculation of the winding eddy loss enhancement factor

A more accurate estimate of the eddy loss enhancement factor for windings, F_{WE} described in Clause A.1, can be made if the winding eddy loss components from axial and radial stray flux, P_{WEax1} and P_{WErad1} respectively, are known. These may be calculated at fundamental frequency using a finite element method of field analysis.

Since the distribution of the harmonic stray flux is the same as that of the flux at fundamental frequency in conventional windings consisting of individual strands, the following relationships may be derived (see Figure F.1).

Relation between strand dimensions and penetration depths:

$$X_{ah} = t \times \left(\frac{\mu_r \times \mu_0 \times \omega_1 \times h}{2 \times \rho} \right)^{0,5}$$

$$X_{rh} = s \times \left(\frac{\mu_r \times \mu_0 \times \omega_1 \times h}{2 \times \rho} \right)^{0,5}$$

where

ω_1 is the pulse of fundamental frequency;

h is the harmonic order;

μ_0 is the permeability of the vacuum;

μ_r is the relative permeability (copper μ_r = 1).

ρ is the density in kg/m^3.

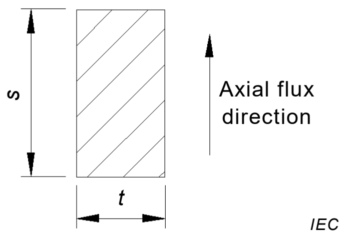


Figure F.1 – Cross-section of a winding strand

The additional resistance, R_{ADh}, at frequency of order, $h \times \omega_1$, may be defined as

$$R_{ADh} = R_h - R_W \quad \text{(F.9)}$$

where

R_h is the winding resistance at frequency, $h \times \omega_1$.

The increase of additional resistance R_{ADh} in relation to R_{AD1} fundamental frequency, is the same for all winding strands, regardless of the specific eddy loss of each strand and may be expressed as follows:

$$\frac{R_{ADh}}{R_{AD1}} = \frac{\Psi(X_h)}{\Psi(X_1)} \quad \text{(F.10)}$$

where

$$\Psi(X_h) = 2X_h \times \frac{\sin hX_h - \sin X_h}{\cos hX_h + \cos X_h}. \quad \text{(F.11)}$$

Hence the expression for the winding enhancement factor F_{WE} may be expressed as:

$$F_{WE} = \frac{P_{WEax1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times \frac{\Psi(X_{ah})}{\Psi(X_1)} + \frac{P_{WErad1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times \frac{\Psi(X_{rh})}{\Psi(X_1)} \quad \text{(F.12)}$$

For foil windings the winding enhancement factor may be taken as:

$$F_{WE} = \frac{P_{WEax_1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^2 + \frac{P_{WErad1}}{P_{WE1}} \times \sum_1^n \left(\frac{I_h}{I_1} \right)^2 \times h^{0,5} \quad \text{(F.13)}$$

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NATIONAL ANNEX G

(*National Foreword*)

G-1 BIS CERTIFICATION MARKING

The product(s) conforming to the requirements of this standard may be certified as per the conformity assessment schemes under the provisions of the *Bureau of Indian Standards Act*, 2016 and the Rules and Regulations framed thereunder, and the product(s) may be marked with the Standard Mark.

G-2 The reference ambient temperature for Indian conditions is given below:

a) Maximum ambient air temperature	50 °C
b) Maximum daily average ambient air temperature	40 °C
c) Maximum yearly weighted average ambient temperature ambient air temperature	32 °C *Min*

1) In case of outdoor transformers	–25 °C
2) In the case of transformers where both the transformer are intended for installation indoors	–5 °C and cooler

(*Continued from second cover*)

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60137 Insulated bushings for alternating voltages above 1 000 V	IS/IEC 60137 : 2017 Insulated bushings for alternating voltages above 1 000 V	Identical
IEC 60214-1 Tap-changers —Part 1: Performance requirements and test methods	IS 8468 (Part 1) : 2018/IEC 60214-1 : 2014 Tap–changers: Part 1 Performance requirements and test methods (*first revision*)	Identical
IEC 60270 High voltage test techniques — Partial discharge measurements	IS/IEC 60270 : 2000 High-voltage test techniques — Partial discharge measurements	Identical
IEC/IEEE 65700-19-03 Bushings for d.c. application	IS/IEC/IEEE 65700-19-03 : 2014 Bushing for d.c. application	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 60050-421	International electrotechnical vocabulary — Chapter 421: Power transformers and reactors
IEEE Std C57.12.00	IEEE standard for general requirements for liquid-immersed distribution, power, and regulating transformers
IEEE Std C57.12.10	IEEE standard requirements for liquid-immersed power transformers
IEEE Std C57.12.80	IEEE standard terminology for power and distribution transformers
IEEE Std C57.12.90	IEEE standard test code for liquid-immersed distribution, power, and regulating transformers
IEEE Std C57.19.00	IEEE standard general requirements and test procedures for power apparatus bushings
IEEE Std C57.113	IEEE recommended practice for partial discharge measurement in liquid-filled power transformers and shunt reactors
IEEE Std C57.131	IEEE standard requirements for tap changers
IEEE Std C57.149	IEEE guide for the application and interpretation of frequency response analysis for oil-immersed transformers

The reference ambient temperature for Indian conditions have been specified in National Annex G given at the end of this standard.

Only English language text has been retained while adopting it in this Indian Standard, and as such the page numbers given here are not the same as in the International Standard.

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, shall be rounded off in accordance with IS 2 : 2022 'Rules for rounding off 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.

This Indian Standard has been developed from Doc No.: ETD 16 (19305).

Amendments Issued Since Publication

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