IEC/IEEE 60076-57-129

Edition 1.0 2017-11

INTERNATIONAL STANDARD

Power transformers –
Part 57-129: Transformers for HVDC applications

IEC/IEEE 60076-57-129:2017-11(en)

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IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland
Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue
New York, NY 10016-5997
United States of America
stds.ipr@ieee.org
www.ieee.org

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INTERNATIONAL STANDARD

Power transformers –
Part 57-129: Transformers for HVDC applications

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.180

IEEE ISBN 978-1-5044-4257-2
IEC ISBN 978-2-8322-4447-0

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CONTENTS

FOREWORD 6
1 Scope 8
2 Normative references 8
2.1 IEC references 8
2.2 IEEE references 9
3 Terms, definitions and symbols 9
3.1 Terms and definitions 9
3.2 Symbols 10
4 Use of normative references 11
5 General requirements 11
5.1 General 11
5.2 Service conditions 11
5.2.1 General 11
5.2.2 Temperature 11
5.2.3 Load current 11
5.2.4 AC voltage 11
5.2.5 Direction of power flow 11
5.3 Unusual service conditions 12
5.4 Loading of transformer above rating 12
6 Rating data 12
6.1 General 12
6.2 Rated voltage 12
6.3 Rated current 12
6.4 Rated frequency 12
6.5 Rated power 12
7 Losses 13
7.1 General 13
7.2 No-load loss 13
7.3 Load loss under rated frequency conditions 13
7.4 Load loss under service conditions 13
7.5 Determination of hot-spot temperature 14
8 Test requirements 15
8.1 General 15
8.1.1 Routine tests 15
8.1.2 Type tests 15
8.1.3 Special tests 15
8.1.4 Commissioning tests 15
8.2 Test applicability 16
8.2.1 General 16
8.2.2 DC withstand voltage test 16
8.2.3 Polarity reversal test 16
8.2.4 AC applied withstand test for valve side winding(s) 16
8.3 Dielectric test voltage levels 17
8.3.1 Line windings 17
8.3.2 Valve windings 17
8.4 Induced voltage level with partial discharge measurement 18

Documents
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Full document details: IEC/IEEE 60076-57-129-2017

9 Tests 18
9.1 General 18
9.1.1 Applicable tests 18
9.1.2 Test sequence 18
9.1.3 Ambient temperature 18
9.1.4 Assembly 18
9.1.5 Converter transformers for connection to gas-insulated equipment 19
9.2 Load loss and impedance measurements 19
9.2.1 General 19
9.2.2 Calculation procedure 19
9.3 Switching impulse test 20
9.4 Applied switching impulse test on the valve side winding 20
9.5 Lightning impulse tests 20
9.6 DC withstand voltage test 20
9.6.1 Applicability 20
9.6.2 Transformer test temperature 20
9.6.3 Polarity 20
9.6.4 Test procedure 21
9.6.5 Acceptance criteria 21
9.7 Polarity reversal test 21
9.7.1 Applicability 21
9.7.2 Transformer test temperature 21
9.7.3 Test procedure 21
9.7.4 Acceptance criteria 22
9.8 Extended polarity-reversal test 23
9.8.1 Applicability 23
9.8.2 Transformer test temperature 23
9.8.3 Test procedure 23
9.8.4 Acceptance criteria 25
9.9 AC applied voltage test for valve side winding(s) 25
9.9.1 Test procedure 25
9.9.2 Acceptance criteria 25
9.10 AC applied voltage test on line side winding(s) 25
9.11 AC induced voltage test with partial discharge measurement 26
9.11.1 General 26
9.11.2 Acceptance criteria 26
9.12 Induced voltage test including running of oil pumps 26
9.13 Temperature-rise test 26
9.13.1 General 26
9.13.2 Test procedure 27
9.13.3 Tank surface temperature rise measurement 28
9.14 Load current test 28
9.15 Sound level measurement 28
9.16 Insulation power-factor test 29
9.17 Winding insulation resistance test 29
9.18 Core insulation resistance test 29
9.19 Short-circuit test 29
9.20 Frequency Response Analysis (FRA) measurements 29
9.21 Over-excitation test 29
Documents
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10 Dielectric tests on transformers that have been in service 29
11 Sound levels 30
11.1 General 30
11.2 Determination of service sound levels 30
11.3 Guaranteed sound levels 30
12 Bushings 30
12.1 General 30
12.2 Line side winding bushings 31
12.3 Valve side winding bushings 31
13 Tap-changer 31
13.1 General 31
13.2 Current wave shape 31
13.3 Consecutive operation of tap-changers 31
14 High-frequency modelling 31
15 Tolerances 32
15.1 General 32
15.2 Short-circuit impedance tolerances 32
16 Rating plate 32
Annex A (informative) In service overloading of HVDC converter transformers used with current commutated valves (either mercury arc valves or thyristors) 34
A.1 General 34
A.2 Overloading in service 34
A.3 Temperature rise test for demonstrating normal loading condition 36
A.4 Temperature rise test for demonstrating planned overload conditions 36
Annex B (informative) HVDC converter transformers for use with voltage source converters 38
B.1 General 38
B.2 Converter transformer stressed with only fundamental voltage and current 38
B.3 Converter transformers stressed with direct voltage, fundamental voltage and fundamental current 39
B.4 Converter transformer stressed with the valves connected directly to the converter transformer 40
B.5 Summary of stresses 41
Annex C (informative) Design review 42
C.1 General 42
C.2 Topics 42
Annex D (informative) Transformer specification content 44
D.1 General 44
D.2 Data to be provided by the purchaser 44
D.3 Data to be provided by the manufacturer 45
Annex E (informative) Audible sound of converter transformers 47
E.1 General 47
E.2 Technical reference 47
E.3 Current harmonics 47
E.4 Voltage harmonics 47
E.5 DC bias current 48
E.6 Derivation of service sound power levels 48
E.7 Sound level guarantee 48

Documents
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Annex F (informative) Determination of transformer service load loss at rated non-sinusoidal converter current from measurements with rated transformer current of fundamental frequency 49
F.1 General 49
F.2 Alternative method for calculation of the winding eddy loss enhancement factor 50
Bibliography 52

Figure 1 – Double reversal test voltage profile 22
Figure 2 – Extended polarity reversal test alternative 1 24
Figure 3 – Extended polarity reversal test alternative 2 24
Figure A.1 – Example of an overload diagram 36
Figure B.1 – Configuration with no additional stresses on the converter transformer 39
Figure B.2 – Configuration with multi-level VSC HVDC converter station applied in a monopolar scheme with DC overhead line transmission 40
Figure B.3 – Configuration with VSC valves connected directly to the converter transformer 41
Figure F.1 – Cross-section of a winding strand 51

Table 1 – Routine, type and special tests 15
Table A.1 – Example of an overload table 35

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POWER TRANSFORMERS –

Part 57-129: Transformers for HVDC applications

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International Standard IEC/IEEE 60076-57-129 has been prepared by IEC technical committee 14: Power transformers, in cooperation with the Transformers Committee of the IEEE Power & Energy Society[1], under the IEC/IEEE Dual Logo Agreement.

This publication cancels and replaces the first edition of IEC 61378-2 published in 2001 and IEEE Std C57.129™ published in 2007.

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

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

FDIS	Report on voting
14/904/FDIS	14/907/RVD

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

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

A list of parts of the 60076 International Standard, published under the general title *Power transformers*, can be found on the IEC website.

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

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
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A bilingual version of this publication may be issued at a later date.

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POWER TRANSFORMERS –

Part 57-129: Transformers for HVDC applications

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*

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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.

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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 hth harmonic current in the transformer

I_{LN} square root of the sum of the square of the fundamental and harmonic currents up to the 49th 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

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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.

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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 √3 , for example 400 / √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

$$I_r = \sqrt{\sum_{h=1}^{49} I_h^2} \tag{1}$$

(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.

$$S_R = \sqrt{3} \times U_r \times I_r \tag{2}$$

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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:

$$\Delta P \propto I^2 \times f^k \tag{3}$$

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:

$$P_{\mathrm{N}} = I_{\mathrm{LN}}^2 R + P_{\mathrm{WE1r}} \times F_{\mathrm{WE}} + P_{\mathrm{SE1r}} \times F_{\mathrm{SE}} \tag{4}$$

where

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

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

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

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

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.

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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

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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.

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