BS EN 60076-3:2013

BSI Standards Publication

Power transformers

Part 3: Insulation levels, dielectric tests and external clearances in air

bsi.

...making excellence a habit.™

National foreword

This British Standard is the UK implementation of EN 60076-3:2013. It is identical to IEC 60076-3:2013. It supersedes BS EN 60076-3:2001, which will be withdrawn on 4 September 2016.

The UK participation in its preparation was entrusted to Technical Committee PEL/14, Power transformers.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

Published by BSI Standards Limited 2013

ISBN 978 0 580 72472 5
ICS 29.180

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 31 December 2013.

Amendments/corrigenda issued since publication

Date	Text affected

EUROPEAN STANDARD

NORME EUROPÉENNE

EUROPÄISCHE NORM

EN 60076-3

November 2013

ICS 29.180

Supersedes EN 60076-3:2001

English version

Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air (IEC 60076-3:2013)

Transformateurs de puissance -
Partie 3: Niveaux d'isolement, essais diélectriques et distances d'isolement dans l'air
(CEI 60076-3:2013)

Leistungstransformatoren -
Teil 3: Isolationspegel, Spannungsprüfungen und äußere Abstände in Luft
(IEC 60076-3:2013)

This European Standard was approved by CENELEC on 2013-09-04. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Avenue Marnix 17, B - 1000 Brussels

Ref. No. EN 60076-3:2013 E

Foreword

The text of document 14/745/FDIS, future edition 3 of IEC 60076-3, prepared by IEC/TC 14 "Power transformers" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60076-3:2013.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2014-06-04
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2016-09-04

This document supersedes EN 60076-3:2001.

EN 60076-3:2013 includes the following significant technical changes with respect to EN 60073-3:2001:

– Three categories of transformer are clearly identified together with the relevant test requirements, these are summarised in Table 1.
– Switching impulse levels are defined for all U_m>72,5kV.
– The procedure for Induced voltage tests with PD has been revised to ensure adequate phase to phase test voltages.
– The AC withstand test has been redefined (LTAC instead of ACSD).
– Induced voltage tests are now based on U_r rather than U_m.
– New requirements for impulse waveshape (k factor) have been introduced.
– Tables of test levels have been merged and aligned with IEC 60071-1:2010.
– Additional test levels have been introduced for U_m > 800kV.
– A new Annex E has been introduced, which sets out the principles used in assigning the tests, test levels and clearances in air.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC [and/or CEN] shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 60076-3:2013 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60071-2	NOTE Harmonized as EN 60071-2.
IEC 60076-4	NOTE Harmonized as EN 60076-4.
IEC 60214-1	NOTE Harmonized as EN 60214-1.
IEC 61083-1	NOTE Harmonized as EN 61083-1.
IEC 61083-2	NOTE Harmonized as EN 61083-2.
IEC 62271-1	NOTE Harmonized as EN 62271-1.

Annex ZA
(normative)
Normative references to international publications with their corresponding European publications

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-421		International electrotechnical vocabulary (IEV) - Chapter 421: Power transformers and reactors	-	-
IEC 60060-1		High-voltage test techniques – Part 1: General definitions and test requirements	EN 60060-1	
IEC 60060-2		High-voltage test techniques - Part 2: Measuring systems	EN 60060-2	
IEC 60071-1		Insulation co-ordination - Part 1: Definitions, principles and rules	EN 60071-1	
IEC 60076-1		Power transformers - Part 1: General	EN 60076-1	
IEC 60137		Insulated bushings for alternating voltages above 1 000 V	EN 60137	
IEC 60270		High-voltage test techniques - Partial discharge measurements	EN 60270	

CONTENTS

INTRODUCTION

This part of IEC 60076 specifies the insulation requirements and the corresponding insulation tests with reference to specific windings and their terminals. It also recommends external clearances in air (Clause 16).

The insulation levels and dielectric tests which are specified in this standard apply to the internal insulation only. Whilst it is reasonable that the rated withstand voltage values which are specified for the internal insulation of the transformer should also be taken as a reference for its external insulation, this may not be true in all cases. A failure of the non-self-restoring internal insulation is catastrophic and normally leads to the transformer being out of service for a long period, while an external flashover may involve only a short interruption of service without causing lasting damage. Therefore, it may be that, for increased safety, higher test voltages are specified by the purchaser for the internal insulation of the transformer than for the external insulation of other components in the system. When such a distinction is made, the external clearances should be adjusted to fully cover the internal insulation test requirements.

Annex E sets out some of the principles used in assigning the tests, test levels and clearances in air to the transformer according to the highest voltage for equipment U_m.

POWER TRANSFORMERS –

Part 3: Insulation levels, dielectric tests and external clearances in air

1 Scope

This International Standard applies to power transformers as defined by and in the scope of IEC 60076-1. It gives details of the applicable dielectric tests and minimum dielectric test levels. Recommended minimum external clearances in air between live parts and between live parts and earth are given for use when these clearances are not specified by the purchaser.

For categories of power transformers and reactors which have their own IEC standards, this standard is applicable only to the extent in which it is specifically called up by cross reference in the other standards.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-421, *International Electrotechnical Vocabulary (IEV) – Chapter 421: Power transformers and reactors*

IEC 60060-1, *High-voltage test techniques – Part 1: General definitions and test requirements*

IEC 60060-2, *High-voltage test techniques – Part 2: Measuring systems*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

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

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

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60076-1, IEC 60050-421 and the following apply.

3.1
highest voltage for equipment applicable to a transformer winding
U_m
highest r.m.s. phase-to-phase voltage in a three-phase system for which a transformer winding is designed in respect of its insulation

3.2
rated voltage of a winding
U_r
voltage assigned to be applied, or developed at no-load, between the terminals of an untapped winding, or a tapped winding connected on the principal tapping, for a three-phase winding it is the voltage between line terminals

Note 1 to entry: The rated voltages of all windings appear simultaneously at no-load when the voltage applied to one of them has its rated value.

Note 2 to entry: 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.

Note 3 to entry: For single phase transformers intended to be connected between phases of a network, the rated voltage is indicated as the phase-to-phase voltage.

Note 4 to entry: For the series winding of a three-phase series transformer, which is designed as an open winding, the rated voltage is indicated as if the windings were connected in star.

[SOURCE: IEC 60076-1:2011, 3.4.3]

3.3
rated insulation level
set of rated withstand voltages which characterise the dielectric strength of the insulation

3.4
rated withstand voltage
value of the assigned test voltage applied in one of the standard dielectric tests that proves that the insulation complies with the assigned test voltage

3.5
uniform insulation of a transformer winding
insulation of a transformer winding that has all its ends connected to terminals with the same rated insulation level

3.6
non-uniform insulation of a transformer winding
insulation of a transformer winding when it has a neutral terminal end for direct or indirect connection to earth, and is designed with a lower insulation level than that assigned to the line terminal

Note 1 to entry: Non-uniform insulation may also be termed graded insulation.

4 General

The insulation requirements for power transformers and the corresponding insulation tests are given with reference to specific windings and their terminals.

For liquid-immersed or gas-filled transformers, the requirements apply to the internal insulation only. Any additional requirements or tests regarding external insulation which are deemed necessary shall be subject to agreement between manufacturer and purchaser. If the purchaser does not specify any particular requirements for external clearances then the provisions of Clause 16 shall apply. If the purchaser intends to make the connections to the transformer in a way which may reduce the clearances provided by the transformer alone, this should be indicated in the enquiry.

Bushings shall be subject to separate type and routine tests according to IEC 60137 (including appropriate bushing test levels for the particular transformer test level), which verify their phase-to-earth insulation, external as well as internal.

When a transformer is specified for operation at an altitude higher than 1 000 m, clearances shall be designed accordingly. It may then be necessary to select bushings designed for higher insulation levels than otherwise required for operation at lower altitudes, see Clause 16 of this standard and IEC 60137.

The manufacturer may shield the bushing terminals if necessary during the dielectric tests but any shielding of the earthed parts closest to the terminals shall form part of the transformer structure in-service except for shielding required only during partial discharge measurement.

Bushings and tap-changers are specified, designed and tested in accordance with the relevant IEC standards. The dielectric tests on the complete transformer constitute a check on the correct application and installation of these components. In the case of tap-changers which according to IEC 60214-1 are not subjected to dielectric routine tests at the tap-changer manufacturer's works then the tests performed according to this standard also serve as the only dielectric tests routinely performed on this component.

The temperature of the insulation system shall not be less than 10 °C during the tests, but temperatures higher than those given in IEC 60076-1 may be used.

The transformer shall be completely assembled as in service in respect of all elements that might influence the dielectric strength of the transformer. It is normally assumed that the insulating liquid or gas is not circulated during the tests and coolers do not need to be assembled. Any equipment designed to collect or detect free gas produced by faults in the insulation shall be installed and monitored during the tests. If free gas is detected during any test, the nature and cause of the gas shall be investigated and any further actions shall be agreed between purchaser and manufacturer.

NOTE 1 External overvoltage protection devices such as surge arresters do not need to be assembled and bushing spark gaps can be removed or their spacing increased to avoid operation during the tests.

NOTE 2 It is common practice for larger transformers for oil samples to be taken for dissolved gas analysis before and after dielectric tests.

Liquid immersed transformers shall be tested with the same type (mineral, ester, silicone, etc.) and specification (with respect to the properties that might affect the test performance) of liquid that it will contain in service.

NOTE 3 Some purchasers can require that the insulating liquid be circulated on OD cooled transformers during an IVPD test to detect the possibility of static electrification, but this is a very specific requirement and is not covered by this standard.

Transformers for cable box connection or direct connection to metal-enclosed SF_6 installations should be designed so that temporary connections can be made for dielectric tests, using temporary bushings, if necessary. By agreement between manufacturer and purchaser, the service liquid to SF_6 bushings may be replaced by appropriate liquid to air bushings for test, in this case the design of the end of the bushing inside the transformer including the positions of the live parts and the clearances of the substitute bushings inside the transformer shall be the same (within the normal variation of dimensions of the bushing associated with manufacturing tolerances) as those of the in-service bushings.

When the manufacturer intends to use non-linear elements (for example surge arresters or spark gaps), built into the transformer or tap-changer or externally fitted, for the limitation of overvoltage transients, this shall be brought to the purchaser's attention by the manufacturer at the tender and order stage and shall be indicated on the transformer rating plate circuit diagram.

If any terminals of the transformer are to be left open when the transformer is energised in service then consideration needs to be given to the possibility of a transferred voltage occurring on the open terminals, see Annex B. During the lightning impulse tests all non-tested line and neutral terminals are normally connected to earth, see Clause 13.

5 Highest voltage for equipment and rated insulation level

A value of highest voltage for equipment U_m (see Clause 3) is assigned to both the line and neutral end of each winding, see IEC 60076-1.

The rules for dielectric testing depend on the value of U_m. When rules about tests for different windings in a transformer are in conflict, the rule for the winding with the highest U_m value shall apply for the whole transformer.

Series windings (for example found in autotransformers and phase shifting transformers) where the rated voltage of the winding is less than the rated voltage of the system, shall be assigned a value of U_m corresponding to the rated voltage of the highest voltage system to which the winding is connected.

Standardized values of U_m are listed in Table 2. Unless otherwise specified, the value to be used for a transformer winding is the one equal to, or nearest above, the value of the rated voltage of the winding.

NOTE 1 Single-phase transformers intended for connection in star to form a three-phase bank are designated by phase-to-phase rated voltage divided by $\sqrt{3}$, for example $400/\sqrt{3}$ kV. The phase-to-phase value determines the choice of U_m in this case, consequently, U_m = 420 kV (see also IEC 60076-1). The same principle applies to single-phase transformers intended for use in a single phase system in that the maximum phase to earth voltage is multiplied by $\sqrt{3}$ to obtain the equivalent U_m in order to define the test voltages.

NOTE 2 For transformer windings intended to be used for example in railway supply applications where two opposite phase to earth voltages are supplied, U_m relates to the phase to phase voltage unless otherwise specified.

NOTE 3 It might happen that certain tapping voltages are chosen slightly higher than a standardized value of U_m, but the system to which the winding will be connected has a system highest voltage which stays within the standard value. The insulation requirements are to be coordinated with actual conditions, and therefore this standard value can be accepted as U_m for the transformer, and not the nearest higher value.

NOTE 4 In certain applications with very special conditions the specification of other combinations of withstand voltages can be justified. In such cases, general guidance should be obtained from IEC 60071-1.

NOTE 5 In certain applications, delta-connected windings are earthed through one of the external terminals. In those applications, a higher withstand voltage with respect to the highest voltage for equipment U_m can be required for this winding and would need to be agreed between manufacturer and purchaser.

The highest voltage for equipment U_m and the rated insulation level (the set of assigned rated withstand voltages) determine the dielectric characteristics of a transformer. These characteristics are verified by a set of dielectric tests, see Clause 7.

The value of U_m and the rated insulation level which are assigned to each winding of a transformer are part of the information to be supplied with an enquiry and with an order. If there is a winding with non-uniform insulation, the assigned U_m and the rated insulation level of the neutral terminal may also be specified by the purchaser, see 7.4.

The rated insulation level shall be characterised as follows:

U_m / SI / LI / LIC / AC with the associated values (see examples below) for the line terminals of each winding

If the winding does not have an assigned SI or LIC withstand level then the abbreviation is omitted from the rating so for terminals without an assigned switching impulse withstand level or chopped wave lightning impulse withstand level and for neutral terminals the abbreviation would be:

U_m / LI / AC together with the associated values

If the neutral terminal of a winding has the same rated insulation level as the line terminal then the rated insulation level of the neutral does not need to be shown separately.

The abbreviations here and in the examples below have the following meaning:

SI is the rated switching impulse withstand voltage level for the line terminals of the winding with the highest U_m;

LI is the rated lightning impulse withstand voltage level for the terminal of each individual winding;

LIC is the rated lightning impulse withstand voltage level for the line terminals of each individual winding if a chopped wave lightning impulse test was performed;

AC is the highest rated AC withstand voltage level to earth designed for the terminals of each winding.

NOTE 6 The AC is the value for which the transformer is designed, this is generally the highest AC voltage required to be achieved on test.

HV high voltage;

LV low voltage;

MV medium voltage (intermediate voltage IEC 60076-1);

N neutral.

The rated withstand voltages for all windings shall appear on the rating plate.

The principles of the standard abbreviated notation are shown in some examples below.

EXAMPLE 1

Transformer with a nominal rated voltage of 66 / 11 kV U_m (HV) = 72,5 kV and U_m (LV) = 12 kV, both uniformly insulated, Y connected, the rating plate would read:

HV U_m 72,5 / LI 325 / AC 140 kV

LV U_m 12 / LI 75 / AC 28 kV

EXAMPLE 2

U_m (HV) line = 245 kV, Y connected (220 kV rated voltage);

U_m (HV) neutral = 52 kV;

U_m (MV) line = 72,5 kV, uniform insulation, Y connected (LIC not specified);

U_m (LV) line = 24 kV, D connected LIC not required.

The rating plate would read:

HV U_m 245 / SI 750 / LI 950 / LIC 1045 / AC 395 kV

HVN U_m 52 / LI 250 / AC 95 kV

MV U_m 72,5 / LI 325 / AC 140 kV

LV U_m 24 / LI 125 / AC 50 kV

6 Transformers with re-connectable windings

Unless otherwise specified, windings which are specified to be capable of being connected in more than one configuration for service shall be tested in each configuration.

7 Dielectric tests

7.1 Overview

The dielectric capability of the transformer insulation is verified by dielectric tests. The following is a general explanation of the different tests.

– **Full wave lightning impulse test for the line terminals (LI)**, see 13.2

The test is intended to verify the capability of the transformer to withstand fast rise time transients in service typically associated with lightning strikes. The test verifies the withstand strength of the transformer under test, when the impulse is applied to its line terminals. The test contains high frequency voltage components and produces non-uniform stresses in the winding under test different to those for an alternating voltage test.

– **Chopped wave lightning impulse test for the line terminals (LIC)**, see 13.3

As well as covering the intention of the LI test, this test is intended to verify the capability of the transformer to withstand some high frequency phenomena that may occur in service. For this test the lightning impulse test includes both full wave impulses and impulses chopped on the tail to produce a very high rate of change of voltage. The chopped wave test voltage impulse has a higher peak value and contains higher frequency components than the full wave impulse.

NOTE 1 According to this standard the LIC test is specified for each winding separately. For example, if a routine LIC test is required by this standard on the highest voltage winding this would not lead automatically to LIC tests being required on other winding(s) with $U_m \leq 170$ kV unless LIC tests are specified specifically for these windings by the purchaser.

– **Lightning impulse test for the neutral terminal (LIN)**, see 13.4

The test is intended to verify the impulse withstand voltage of the neutral terminal and it's connected winding(s) to earth and other windings, and along the winding(s) under test.

– **Switching impulse test for the line terminal (SI)**, see Clause 14

The test is intended to verify the capability of the transformer to withstand slow rise time transient voltages typically associated with switching operations in service. The test verifies the switching impulse withstand strength of the line terminals and the connected winding(s) to earth and other windings. The test also verifies the withstand strength between phases and along the winding(s) under test. This is a single-phase test. The voltage is inductively distributed through all windings of the transformer, line terminals are open circuit for the test and the line terminals of the tested phase experience a voltage during the test approximately determined by the transformer turns ratio.

The voltage distribution in the tested phase is similar to that experienced during an induced voltage withstand test.

– **Applied voltage test (AV)**, see Clause 10

The test is intended to verify the alternating voltage withstand strength of the line and neutral terminals and their connected windings to earth and other windings. The voltage is applied to all the terminals of a winding, including the neutral, simultaneously so there is no turn-to-turn voltage.

– **Line terminal AC withstand voltage test (LTAC)**, see Clause 12

The test is intended to verify the alternating voltage (AC) withstand strength of each line terminal to earth. During the test, voltage appears at one or more of the line terminals. The test allows the line terminals of a transformer with non-uniform insulation to be tested at the applied voltage test level applicable to the line terminals.

– **Induced voltage withstand test (IVW)**, see 11.2

The test is intended to verify the alternating voltage withstand strength of each line terminal and its connected winding(s) to earth and other windings, along the winding(s) under test and the withstand strength between phases. The test is performed with the transformer connected as for service. During the test, symmetrical voltages appear at all the line terminals and between turns, with no voltage at the neutral. The test is performed with a three phase voltage on three phase transformers.

– **Induced voltage test with PD measurement (IVPD)**, see 11.3

This test is intended to verify that the transformer will be free of harmful partial discharges under normal operating conditions. The test voltage is applied in the same way as the voltage that the transformer will experience in service. During the test, symmetrical voltages appear at all the line terminals and between turns, with no voltage at the neutral. The test is performed with a three phase voltage on three phase transformers.

– **Auxiliary wiring insulation test (AuxW)**, see Clause 9

This test verifies the insulation of the auxiliary wiring of the transformer that is not connected to the windings.

– **Lightning impulses applied to two or more terminals simultaneously (LIMT),** see 13.1.4.3

This test verifies that the transformer can withstand the internal voltage rises that may occur if two or more terminals are subjected to a lightning impulse simultaneously. The test is only applicable to some special types of transformer with either a series winding that may be shorted in service (for example some phase shifting transformers with an on-load bypass) or where impulses on two or more terminals may occur simultaneously in service.

NOTE 2 This test is also referred to as a 'double-ended lightning impulse test'.

7.2 Test requirements

7.2.1 General

The requirements for dielectric tests, both the required tests and the test voltage levels, depend on the highest voltage for equipment U_m for the highest voltage winding of the particular transformer. The required tests are summarised in Table 1 and specific requirements are given in 7.3.

NOTE Lightning impulses applied to two or more line terminals simultaneously is a special test for only a few special types of transformer irrespective of U_m and is not included in the table for clarity.

Any additional tests above the requirements of this standard and the test voltage levels shall be specified by the purchaser at the time of enquiry and order since they may affect the transformer design (see Annex C).

Reference shall be made to IEC 60060-1 for details of the tests. Where tolerances on test parameters and values are not specifically given in this standard then the values given in IEC 60060-1 shall be used.

Table 1 – Requirements and tests for different categories of windings

	$U_m \leq 72{,}5$ kV	72,5 kV < $U_m \leq 170$ kV		$U_m > 170$ kV
Insulation	**Uniform**	**Uniform**	**Non-uniform**	**Uniform and non-uniform**
Full wave lightning impulse test for the line terminals (LI)	Type	Routine	Routine	Not applicable (included in LIC)
Chopped wave lightning impulse test for the line terminals (LIC)	Special	Special	Special	Routine
Lightning impulse test for the neutral terminals (LIN)	Special	Special	Special	Special
Switching impulse test for the line terminal (SI)	Not applicable	Special	Special	Routine
Applied voltage test (AV)	Routine	Routine	Routine	Routine
Induced voltage withstand test (IVW)	Routine	Routine	Routine	Not applicable
Induced voltage test with PD measurement (IVPD)	Special[a]	Routine[a]	Routine[a]	Routine
Line terminal AC withstand voltage test (LTAC)	Not applicable	Special	Routine[b]	Special
Auxiliary wiring insulation test (AuxW)	Routine	Routine	Routine	Routine

[a] The requirements of the IVW test can be incorporated in the IVPD test so that only one test is required.

[b] The LTAC test for this category of transformers can be replaced by a switching impulse test by agreement between manufacturer and purchaser.

7.2.2 Test voltage levels

Levels of standard test voltages, identified by the highest voltage for equipment U_m of a winding are given in Table 2. The choice between the different levels of test voltages in these tables depends on the severity of overvoltage conditions to be expected in the system and on the importance of the particular installation. Guidance may be obtained from IEC 60071-1.

All test voltages are phase to earth.

The lowest values given in Table 2 for a particular value of U_m represent the minimum test voltage levels and shall be used if nothing else is specified. In general the values given in each row in Table 2 are co-ordinated. If only a lightning impulse voltage level is specified then the other values on the same row shall be used. The purchaser may specify any value higher than the minimum for the particular U_m for each test, preferably standard values for coordination, but not necessarily the values from a single row in Table 2. If higher levels are specified this shall be stated in the enquiry and order.

If, under special circumstances, the minimum levels given in Table 2 are considered too high by the purchaser then the values in Table 3 may be used. The values in Table 3 may only be used if special precautions have been taken to avoid overvoltage conditions beyond the capability of the transformer and either extensive studies have been completed or the values used represent proven existing practice applicable to the installation.

NOTE Certain installation conditions, particularly where energisation of the transformer is from the remote end of a cable or a long overhead line, can lead to severe exposure to overvoltages which might be frequent and repetitive. In such cases, higher test voltages, lightning impulse, switching impulse and other tests on individual units could be agreed between manufacturer and purchaser. For example a winding with a $U_m < 1{,}1$ kV might be tested at the values appropriate to a winding with a U_m of 3,6 kV. The specific voltage-time characteristic of the overvoltage is an important consideration when deciding the type and level of the test required to assure satisfactory operation.

In particular, failures have been reported at $U_m = 36$ kV and below where the transformer is energised/de-energised by a vacuum type circuit breaker from the remote end of a cable because a resonant condition might exist causing re-ignitions and repetitive transients. In certain cases increasing the insulation level might not be sufficient and other methods such as the installation of a snubber circuit could be considered. Further information is contained in IEEE C57.142:2010 and CIGRE report 12-14.

Table 2 – Test voltage levels *(1 of 2)*

Highest Voltage for equipment winding U_m kV	**Full Wave Lightning Impulse** (LI) kV	**Chopped Wave Lightning Impulse** (LIC) kV	**Switching impulse** (SI) kV	**Applied voltage or line terminal AC withstand** (AV) (LTAC) kV
<1,1	–	–	–	3
3,6	20	22	–	10
	40	44	–	10
7,2	60	66	–	20
	75[a]	83[a]	–	20
12	75	83	–	28
	95	105	–	28
	110[a]	121[a]	–	34[a]
17,5	95	105	–	38
	125[a]	138[a]	–	38
24	125	138	–	50
	145	160	–	50
	150[a]	165[a]	–	50
36	170	187	–	70
	200[a]	220[a]	–	70
52	250	275	–	95
72,5	325	358	–	140
	350[a]	385[a]	–	140
100	450	495	375[a]	185
123	550	605	460[a]	230
145	550	605	460[a]	230
	650	715	540[a]	275
170	650	715	540[a]	275
	750	825	620[a]	325
245	850	935	700[a]	360
	950	1 045	750[a]	395
	1 050	1 155	850[a]	460
300	950	1 045	750	395
	1 050	1 155	850	460
362	1 050	1 155	850	460
	1 175	1 290	950	510
420	1 175	1 290	950	510
	1 300	1 430	1 050	570
	1 425	1 570	1 175[a]	630

Table 2 *(2 of 2)*

Highest Voltage for equipment winding U_m kV	**Full Wave Lightning Impulse** (LI) kV	**Chopped Wave Lightning Impulse** (LIC) kV	**Switching impulse** (SI) kV	**Applied voltage or line terminal AC withstand** (AV) (LTAC) kV
550	1 300	1 430	1 050	570
	1 425	1 570	1 175	630
	1 550	1 705	1 300[a]	680
	1 675[a]	1 845[a]	1 390[a]	–
800	1 800	1 980	1 425	–
	1 950	2 145	1 550	–
	2 050[a]	2 255[a]	1 700[a]	–
	2 100	2 310	1 675[a]	–
1 100	1 950	2 145	1 425	–
	2 250	2 475	1 800	–
1 200	2 250	2 475	1 800	–

[a] These values are not given in IEC 60071-1:2011 for the particular value of U_m but are included either because they represent common practice in some parts of the world or for some switching impulse levels, because they represent a co-ordinated value for a particular value of lightning impulse level.

Table 3 – Test voltage levels used in special cases

Highest Voltage for equipment winding U_m kV	**Full Wave Lightning Impulse** (LI) kV	**Chopped Wave Lightning Impulse** (LIC) kV	**Switching impulse** (SI) kV	**Applied voltage or line terminal AC withstand** (AV) (LTAC) kV
7,2	40	44	-	20
12	60	66	-	28
17,5	75	83	-	38
24	95	105	-	50
36	145	160	-	70
60[a]	280[a]	308[a]	230[a]	115[a]
123[b]	450[b]	495[b]	375[a]	185[b]
170 [b]	550[b]	605[b]	460[a]	230[b]
245	650[b]	715[b]	550[a]	275[b]
	750[b]	825[b]	620[a]	325[b]
300	850	935	750	395
362	950	1 045	850	395
420	1 050	1 155	850	460
550	1 175	1 290	950	510

[a] These values are not given in IEC 60071-1:2011 for the particular value of U_m but are included because they represent existing practice in some parts of the world.

[b] these values require special consideration, refer to IEC 60071-1:2011

7.2.3 Test sequence

The tests shall be performed in the sequence given below:

a) lightning impulse tests (LI, LIC, LIN, LIMT);
b) switching impulse (SI);
c) applied voltage test (AV);
d) line terminal AC withstand test (LTAC);
e) induced voltage withstand test (IVW);
f) induced voltage test with partial discharge measurement (IVPD).

NOTE This is a comprehensive list, not all these tests will be applicable to a particular transformer.

By agreement between the manufacturer and purchaser, the switching impulse test may be performed before the lightning impulse test.

If an IVPD test is to be performed then by agreement between the manufacturer and purchaser, the test sequence may be varied except that the IVPD test shall be the last dielectric test.

7.3 Test requirements for specific transformers

7.3.1 Tests for transformers with $U_m \leq 72,5$ kV

7.3.1.1 Routine tests

a) Applied voltage test (AV)

An applied voltage test shall be performed according to the method given in Clause 10 on each separate winding of the transformer. Test voltages are given in Table 2.

NOTE Transformers with $U_m \leq 72,5$ kV are expected to have uniform winding insulation to satisfy this test.

b) Induced voltage withstand test (IVW)

An induced voltage withstand test shall be performed according to the method given in 11.2 with a (phase to earth) test voltage of $(2 \times U_r)/\sqrt{3}$. If agreed by the purchaser this test may be substituted by an IVPD test with an enhancement voltage of $(2 \times U_r)/\sqrt{3}$ see 7.3.1.3 a).

7.3.1.2 Type tests

Full wave lightning impulse test (LI)

A full wave lightning impulse test shall be carried out on the line terminals using the method given in 13.1 and 13.2. Test voltages are given in Table 2.

7.3.1.3 Special tests

a) Induced voltage test with partial discharge measurement (IVPD)

If specified by the purchaser, a test shall be carried out according to the method given in 11.3, with an enhancement (phase to earth) voltage level of $(1,8 \times U_r)/\sqrt{3}$ and a PD measurement voltage of $(1,58 \times U_r)/\sqrt{3}$. Alternative higher voltage levels may be used if specified by the purchaser. In particular an enhancement voltage of $(\sqrt{3} \times U_m)/\sqrt{3}$ and a PD measurement voltage of $(1,5 \times U_m)/\sqrt{3}$ may be used if higher.

If an enhancement voltage level of $(2 \times U_r)/\sqrt{3}$ is used this test can substitute for the routine induced voltage withstand test.

A shorter duration at the PD measurement voltage may be agreed between manufacturer and purchaser, a duration of 5 min is recommended.

b) Chopped wave lightning impulse test (LIC)

If specified by the purchaser the full wave lightning impulse test shall be substituted by a chopped wave lightning impulse test according to the method given in 13.1 and 13.3.

The extension of the lightning impulse test to include impulses chopped on the tail as a special test is recommended in cases where the transformer is directly connected to GIS by means of liquid to SF6 bushings or when the transformer is protected by rod gaps.

c) Lightning impulse test on the neutral terminal (LIN)

If specified by the purchaser a full wave lightning impulse test shall be carried out on the neutral terminal according to the method given in 13.1 and 13.4. This normally applies if the neutral is not directly connected to earth in service.

d) Lightning impulses applied to multiple line terminals simultaneously (LIMT)

If specified by the purchaser an additional lightning impulse test on two or more terminals connected together shall be performed according to the method given in 13.1 with the test connections given in 13.1.4.3. If not otherwise specified the type of test is LI.

7.3.2 Tests on transformers with 72,5 kV < U_m ≤ 170 kV

7.3.2.1 Routine tests

a) Full wave lightning impulse test (LI)

A full wave lightning impulse test shall be carried out on the line terminals using the method given in Clause 13 Test voltages are given in Table 2.

b) Applied voltage test (AV)

An applied voltage test in accordance with the method given in Clause 10 shall be performed on each separate winding of the transformer. Test voltages are given in Table 2 for transformers with uniform insulation. For transformers with non-uniform insulation the test shall be carried out at the test voltage for the neutral terminal see 7.4.2.

c) Induced voltage withstand test (IVW)

An induced voltage withstand test shall be performed according to the method given in 11.2 with a (phase to earth) test voltage of $(2 \times U_r)/\sqrt{3}$. If agreed by the purchaser this test may be substituted by an IVPD test with an enhancement voltage $(2 \times U_r)/\sqrt{3}$, see e) below.

d) Line terminal AC withstand voltage test for non-uniformly insulated transformers (LTAC)

For windings with non-uniform insulation this test shall be performed at the test level given for the applied voltage test applicable to the line terminal in Table 2 using the method given in Clause 12. This test may be omitted if a switching impulse test is performed by agreement between manufacturer and purchaser.

e) Induced voltage test with partial discharge measurement (IVPD)

A test shall be carried out according to the method given in 11.3, with and enhancement (phase to earth) voltage level of $(1{,}8 \times U_r)/\sqrt{3}$ and a PD measurement voltage of $(1{,}58 \times U_r)/\sqrt{3}$. Alternative higher voltage levels may be used if specified by the purchaser. In particular an enhancement voltage of $(\sqrt{3} \times U_m)/\sqrt{3}$ and a PD measurement voltage of $(1{,}5 \times U_m)/\sqrt{3}$ may be used if higher.

If an enhancement voltage level of $(2 \times U_r)/\sqrt{3}$ is used this test can substitute for the routine induced voltage withstand test.

7.3.2.2 Special tests

a) Switching impulse test (SI)

If specified by the purchaser a switching impulse test using the method given in Clause 14 shall be performed on the line terminals. The test voltage is given in Table 2. If this test is carried out, then the Line Terminal AC Withstand Test (LTAC) may be omitted by agreement.

b) Chopped wave lightning impulse test (LIC)

If specified by the purchaser the full wave lightning impulse test shall be substituted by a chopped wave lightning impulse test according to the method given in 13.1 and 13.3.

The extension of the lightning impulse test to include impulses chopped on the tail as a special test is recommended in cases where the transformer is directly connected to GIS by means of liquid to SF6 bushings or when the transformer is protected by rod gaps.

c) Line terminal AC withstand voltage test (LTAC)

If specified by the purchaser for windings with uniform insulation, this test shall be performed at the test level given for the applied voltage test applicable to the line terminal in Table 2 using the method given in Clause 12.

d) Lightning impulse test on the neutral terminal (LIN)

If specified by the purchaser a full wave lightning impulse test shall be carried out on the neutral terminal. This normally applies if the neutral is not directly connected to earth in service.

e) Lightning impulses applied to multiple line terminals simultaneously (LIMT)

If specified by the purchaser an additional lightning impulse test on two or more terminals connected together shall be performed according to the method given in 13.1 with the test connections given in 13.1.4.3. If not otherwise specified the type of test is LI.

7.3.3 Tests on Transformers with U_m > 170 kV

7.3.3.1 Routine tests

a) Chopped wave lightning impulse test (LIC)

A chopped wave lightning impulse test shall be carried out on the line terminals using the method given in Clause 13. Test voltages are given in Table 2.

b) Switching impulse test (SI)

A switching impulse test using the method given in Clause 14 shall be performed on the line terminals. The test voltage is given in Table 2.

c) Applied voltage test (AV)

An applied voltage test shall be performed in accordance with the method given in Clause 10 on each separate winding of the transformer. Test voltages are given in Table 2 for transformers with uniform insulation. For transformers with non-uniform insulation the test shall be carried out at the test voltage for the neutral terminal see 7.4.2.

d) Induced voltage test with partial discharge measurement (IVPD)

A test shall be carried out using the method given in 11.3, with an enhancement (phase to earth) voltage level of $(1{,}8 \times U_r)/\sqrt{3}$ and a one hour PD measurement voltage of $(1{,}58 \times U_r)/\sqrt{3}$. Alternative higher voltage levels may be used if specified by the purchaser. In particular an enhancement voltage of $(\sqrt{3} \times U_m)/\sqrt{3}$ and a one hour PD measurement voltage of $(1{,}5 \times U_m)/\sqrt{3}$ may be used if higher.

NOTE For three phase transformers, the voltage between the phases at the IVPD-enhancement level can be higher than the phase to earth AC withstand voltages given in Table 2 – Test voltage levels.

7.3.3.2 Special tests

a) Lightning impulse test on the neutral terminal (LIN)

If specified by the purchaser a full wave lightning impulse test shall be carried out on the neutral terminal. This normally applies if the neutral is not directly connected to earth in service.

b) Line terminal AC withstand voltage test for non-uniformly insulated windings (LTAC)

If specified by the purchaser this test shall be performed at the test level given for the applied voltage test applicable to the line terminal in Table 2 using the method given in Clause 12.

c) Lightning impulses applied to multiple line terminals simultaneously (LIMT)

If specified by the purchaser an additional lightning impulse test on two or more terminals connected together shall be performed according to the method given in 13.1 with the test connections given in 13.1.4.3. If not otherwise specified the type of test is LIC.

7.4 Assigning U_m and test voltages to the neutral terminal of a winding

7.4.1 Transformers with $U_m \leq 72,5$ kV

The neutral shall be tested at the applied voltage test level for the line terminals. If a lightning impulse test on the neutral terminal is specified then the test level shall be given in the enquiry and order.

NOTE Transformers with $U_m \leq 72,5$ kV need to be designed with uniform winding insulation to satisfy the test requirements.

7.4.2 Transformers with $U_m > 72,5$ kV

7.4.2.1 Directly earthed neutral terminal

If the neutral terminal is to be permanently connected to earth in service, either directly or through a current transformer, but without any intentionally added impedance in the connection then the applied voltage test voltage shall be at least 38 kV ($U_m \geq 17,5$ kV). Higher test levels may be specified.

No impulse test on the neutral terminal is recommended but it may be specified.

7.4.2.2 Neutral terminal not directly earthed

The U_m and test voltages for the neutral terminal shall be given by the purchaser at the time of enquiry and order. The U_m of the neutral depends on whether the neutral terminal is intended to be left open or earthed via an impedance (see Annex D). The value of U_m and the test voltages shall preferably be selected from Table 2. U_m shall in no case be less than 17,5 kV.

If a lightning impulse test on the neutral terminal is specified, then the test level shall be given in the enquiry and order, and the rated impulse withstand voltage of the neutral terminal shall be verified by the test described in 13.4. A chopped wave lightning impulse test on the neutral is not applicable.

8 Dielectric tests on transformers that have been in service

Any transformer that is to be regarded as complying with this standard in the same way as a new transformer (for example following a warranty repair or complete rewind and refurbishment intended to restore the transformer to the ‘as new’ condition) shall be subject to all the routine tests required by this standard for the transformer at 100 % of the required test voltage level after the repair or refurbishment is complete.

Any transformer that is repaired to restore its functionality (for example after a breakdown following many years in service) but is still to be regarded as compliant with this standard shall be subject to the tests described in this standard necessary to verify the repair at a test voltage of between 80 % and 100 % of the original test voltage level. As a general guide any new part of a repaired transformer should be tested at 100 %, but 80 % of the original test voltage level may be regarded as an adequate test voltage level for verifying that used parts or components are suitable for continued use. Where both old and new parts are tested at the same time then an agreement on the test voltage level shall be reached. The IVPD test shall be performed at 100 % of the original test voltage level. The partial discharge criteria may need to be modified depending on the circumstances of the test and this shall be subject to agreement.

9 Insulation of auxiliary wiring (AuxW)

The wiring for auxiliary power, and control circuitry shall be subjected to a 1 min AC separate source test of 2 kV to earth. The test is passed if no voltage collapse or other sign of breakdown occurs. The test shall be carried out at the manufacturer's works, unless the transformer is to be installed on-site by the manufacturer in which case the test may be performed on-site instead of in the factory. Wiring disconnected or removed for transport which has been subject to a 2 kV test at the factory shall be tested at site following erection using either a repeat of the 2 kV AC test or a 1 kV DC insulation resistance measurement with a minimum measured resistance of 1 MΩ.

The wiring for current transformer secondary windings shall be tested at 2,5 kV AC to earth for 1 min. The test shall be carried out at the manufacturer's works. If the current transformer knee-point voltage exceeds 2 kV AC the test shall be performed at 4 kV AC. The test is passed if no voltage collapse or other sign of breakdown occurs.

Motors and other apparatus for auxiliary equipment shall fulfil insulation requirements according to the relevant IEC standard (which are generally lower than the value specified for the wiring alone, and which may sometimes make it necessary to disconnect them in order to test the circuits). All solid state and microprocessor based devices shall be excluded from the test circuit. All three phase undervoltage relays and withdrawable type devices shall be removed from the test circuit.

NOTE It is normal practice for all the auxiliary wiring to be checked on-site at 1 kV DC for 1 min before energisation.

10 Applied voltage test (AV)

The test shall be carried out on each separate winding of the transformer in turn.

The full test voltage shall be applied for 60 s between all accessible terminals of the winding under test connected together and all accessible terminals of the remaining windings, core, frame and tank or casing of the transformer, connected to earth.

The test shall be made with an approximately sinusoidal single-phase alternating voltage at not less than 80 % of the rated frequency. The peak value of voltage shall be measured. The peak value divided by $\sqrt{2}$ shall be equal to the test value.

NOTE Approximately sinusoidal can be taken to mean that the peak value divided by $\sqrt{2}$ does not differ from the r.m.s value of the waveform by more than about 5 % (see IEC 60060-1), but wider deviations may be accepted.

The test shall commence at a voltage not greater than one-third of the specified test value, and the voltage shall be increased to the test value as rapidly as is consistent with measurement. At the end of the test, the voltage shall be reduced rapidly to less than one-third of the test value before switching off.

The test is successful if no collapse of the test voltage occurs.

For windings with non-uniform insulation, the test is carried out with the test voltage specified for the neutral terminal.

In transformers where windings having different U_m values are connected together within the transformer (usually auto-transformers), the test voltages shall be determined by the insulation of the common neutral and its assigned U_m.

11 Induced voltage tests (IVW and IVPD)

11.1 General

The test shall be carried out with any accessible neutral terminals and any other terminals that are normally at earth potential in service earthed. For three phase transformers a symmetrical three phase test voltage shall be used. Any line terminals not connected to the test supply shall be left open.

NOTE 1 When voltage is induced in a winding with no neutral connection, the voltages with respect to earth at each terminal of this winding will depend on the capacitances to earth and other windings. Any flashover from one of the line terminals to earth during the test can result in voltages exceeding the applied voltage test level appearing at the other terminals of the winding. Suitable precautions can be required to take account of this possibility.

During the test, the test voltage appropriate to a winding without voltage variation shall appear at the terminals of that winding so that the voltages between turns and between phases will have the same ratio between test voltage and rated voltage. The voltage shall either be measured on the highest voltage terminals, or if this is not practical the voltage shall be measured at the terminals of the transformer connected to the supply.

For transformers with tappings, the test shall be carried out with the transformer on principal tap unless otherwise specified or agreed by the purchaser.

If the purchaser requires a specific test voltage for lower voltage windings higher than the voltage determined in this clause then this shall be clearly stated in the enquiry and tender and an agreement reached on the method of test and the test voltages that will appear on the higher voltage windings which may consequently exceed the specified test voltages.

The test shall be performed with the transformer excited exactly as it will be for service. The voltage may be induced from any winding or from a special winding or taps provided for test purposes.

An alternating voltage shall be applied to the terminals of one winding of the transformer. The form of the voltage shall be as nearly as possible sinusoidal and its frequency shall be sufficiently above the rated frequency to avoid excessive magnetizing current during the test.

The peak value, as defined in IEC 60060-1 divided by $\sqrt{2}$ and the r.m.s. value of the induced test voltage shall be measured and the lower of the peak value divided by $\sqrt{2}$ and the r.m.s. value shall be taken as the test value.

11.2 Induced voltage withstand test (IVW)

The test time at full test voltage shall be 60 s for any test frequency up to and including twice the rated frequency, unless otherwise specified. When the test frequency exceeds twice the rated frequency, the test time in seconds of the test shall be:

$$120 \times \frac{\text{rated frequency}}{\text{test frequency}}\text{, but not less than 15 s}$$

The test shall commence at a voltage not greater than one-third of the specified test value, and the voltage shall be increased to the test value as rapidly as is consistent with measurement. At the end of the test, the voltage shall be reduced rapidly to less than one-third of the test value before switching off.

The test is successful if no collapse of the test voltage occurs.

11.3 Induced voltage test with partial discharge measurement (IVPD)

11.3.1 General

When a particular type of bushing is specified by the purchaser that is expected to have a partial discharge level that will prevent accurate partial discharge measurements of the transformer on test it is permitted to exchange the bushings for a partial discharge free type during the testing of the transformer.

11.3.2 Test duration and frequency

The test time at the enhancement voltage shall be 60 s in case $U_m \leq 800$ kV and 300 s in case $U_m > 800$ kV for any test frequency up to and including twice the rated frequency, unless otherwise specified. When the test frequency exceeds twice the rated frequency, the test time in seconds of the test shall be:

$$120 \times \frac{\text{rated frequency}}{\text{test frequency}}\text{, but not less than 15 s for } U_m \leq 800\text{ kV}$$

or

$$600 \times \frac{\text{rated frequency}}{\text{test frequency}}\text{, but not less than 75 s for } U_m > 800\text{ kV}$$

The duration of the test, except for the enhancement level, shall be independent of the test frequency

11.3.3 Test sequence

The test sequence shall be as follows:

a) The voltage shall be switched on at a voltage not higher than $(0{,}4 \times U_r)/\sqrt{3}$.

b) The voltage shall be raised to $(0{,}4 \times U_r)/\sqrt{3}$ and a background PD measurement shall be made and recorded.

c) The voltage shall be raised to $(1{,}2 \times U_r)/\sqrt{3}$ and held there for a minimum duration of 1 min and only long enough to make a stable PD measurement.

d) The PD level shall be measured and recorded.

e) The voltage shall be raised to the one hour PD measurement voltage and held there for a minimum duration of 5 min and only long enough to make a stable PD measurement.

f) The PD level shall be measured and recorded.

g) The voltage shall be raised to the enhancement voltage and held there for the test time in 11.3.2.

h) Immediately after the test time, the voltage shall be reduced without interruption to the one hour PD measurement voltage.

i) The PD level shall be measured and recorded.

j) The voltage shall be held at the one hour PD measurement voltage for a duration of at least one hour following the PD measurement.

k) The PD level shall be measured and recorded every 5 min during the one hour period.

l) After the last PD measurement in the one hour period the voltage shall be reduced to $(1{,}2 \times U_r)/\sqrt{3}$ and held there for a minimum duration of 1 min and only long enough to make a stable PD measurement.

m) The PD level shall be measured and recorded.

n) The voltage shall be reduced to $(0{,}4 \times U_r)/\sqrt{3}$ and the background PD level shall be measured and recorded.

o) The voltage shall be reduced to a value below $(0{,}4 \times U_r)/\sqrt{3}$.

p) The voltage shall be switched off.

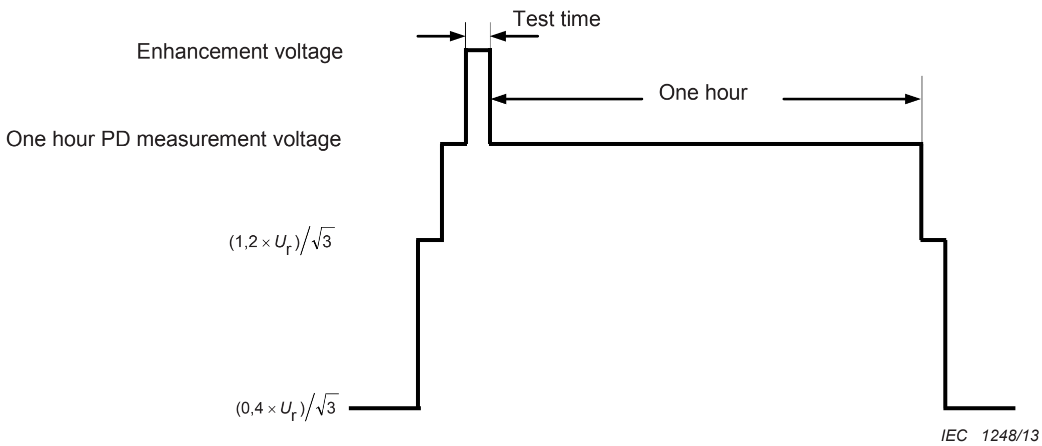
The partial discharge level shall be continuously observed on at least one measuring channel for the entire duration of the test.

During the test sequence the inception and extinction voltages of any significant PD activity should be noted to aid the evaluation of the test result if the test criteria are not met.

NOTE It can also be helpful to record the PD pattern (phase angle, apparent charge and number) of any significant PD activity to aid evaluation.

Enhancement voltage level and one hour PD measurement voltage are given in 7.3.1.3, 7.3.2.1 and 7.3.3.1 depending on the U_m of the transformer.

The main features of the test sequence are illustrated in Figure 1.



NOTE Enhancement voltage level and one hour PD measurement voltage are given in 7.3.1.3, 7.3.2.1 and 7.3.3.1

Figure 1 – Time sequence for the application of test voltage for induced voltage test with partial discharge measurement (IVPD)

11.3.4 Partial discharge (PD) measurement

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

Each PD measurement channel including the associated bushing or coupling capacitor shall be calibrated in terms of apparent charge (pC) according to the method given in IEC 60270.

The PD measurement shall be given in pC and shall refer to the highest steady-state repetitive impulses indicated by the measuring instrument.

Occasional bursts of high partial discharge level may be disregarded.

For each required PD measurement step in the test sequence, PD measurements shall be made and recorded on all the line terminals equipped with bushings with a $U_m \geq 72{,}5$ kV, during the test, however if there are more than six such terminals then only six measurements need to be made (one on each of the highest voltage terminals) unless otherwise specified.

NOTE Bushings with $U_m \geq 72,5$ kV are equipped with test taps according to IEC 60137 which can be used for the measurement, if this test is specified as a special test for transformers with a $U_m < 72,5$ kV then the method of measurement will have to be agreed between the manufacturer and purchaser.

11.3.5 Test acceptance criteria

The test can only be considered valid if the measured background PD level does not exceed 50 pC at both the beginning and the end of the test. For tests on shunt reactors a background PD level of up to 100pC may be accepted.

NOTE The higher background level for shunt reactors is because filtering of the test supply might not be possible where high current and high voltage is required.

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 $(1,2 \times U_r)/\sqrt{3}$ after the one hour period does not exceed 100 pC.

If the criteria c) or d) are not met, the one hour period may be extended and these criteria will be considered to have been met if they are fulfilled for a continuous period of one hour.

As long as no breakdown occurs, and unless very high partial discharges are sustained for a long time, the test is regarded as non-destructive. A failure to meet the partial discharge acceptance criteria shall therefore not warrant immediate rejection, but lead to consultation between purchaser and manufacturer about further investigations. Suggestions for such procedures are given in Annex A.

12 Line terminal AC withstand test (LTAC)

The test shall be arranged so that the test voltage appears between the tested terminal and earth. Each phase terminal of the tested winding shall be tested in turn. The test time, frequency and voltage application shall be as given for the induced voltage withstand test see 11.2.

For transformers with taps and a non-uniformly insulated lower voltage winding, the tap position for test shall be selected so that when the required test voltage appears on the highest voltage winding terminals, the voltage appearing on the lower voltage winding terminals shall be as close as possible to the required test value. For transformers with a uniformly insulated lower voltage winding subject to an applied voltage test, the tap position may be chosen by the manufacturer.

The test is successful if no collapse of the test voltage occurs.

NOTE This test is intended only as a withstand test for each line terminal of a non-uniformly insulated transformer to earth, it is not intended to test the phase to phase or turn to turn insulation so the test arrangement can be made in any convenient way, for example with voltage at the neutral to reduce the turn to turn voltage and the test will normally be carried out as three single phase tests. Under normal circumstances the switching impulse test fully covers the intent of this test. If required by the purchaser partial discharge measurements can be made during this test.

13 Lightning impulse tests (LI, LIC, LIN, LIMT)

13.1 Requirements for all lightning impulse tests

13.1.1 General

General definitions of terms related to impulse tests and requirements for test circuits are given in IEC 60060-1. General definitions of terms related to performance tests and routine checks on approved measuring devices are given in IEC 60060-2. Further information is given in IEC 60076-4.

For liquid-immersed transformers, the test voltage is normally of negative polarity, because this reduces the risk of erratic external flashovers in the test circuit. One, more or all of the impulses may be specified by the purchaser to be of positive polarity. If positive impulses are required by the purchaser this shall be stated in the enquiry and order. If a mixture of impulse polarities are used then additional reference impulses will be required and the test sequence shall be agreed between the manufacturer and purchaser.

Before an impulse of opposite polarity is applied, sufficient time should be allowed for any residual charge to dissipate.

13.1.2 Tap positions

If the tapping range is ± 5 % or less and the rated power of the transformer is ≤ 2 500 kVA then, the lightning impulse tests shall be made with the transformer connected on the principal tapping.

If the tapping range is larger than ± 5 % or the rated power of the transformer is > 2 500 kVA then, unless otherwise agreed, the two extreme tappings and the principal tapping shall be used, one tapping for each of the three individual phases of a three-phase transformer or the three single-phase transformers designed to form a three-phase bank.

Alternatively if specified by the purchaser and in special cases such as one single phase transformer, or multiple tap-changers, or when the tapping-range is not symmetrical, the tap-position which gives the highest internal voltages (determined either by calculation or by performing low voltage impulse measurements) shall be used. If different tap-positions give highest internal voltages in different parts of the insulation then by agreement those different tap positions may be tested, one on each phase of a three phase transformer.

NOTE Particular attention is drawn to the difference between the raise and lower positions at the change-over tap position(s) of a reversing type tapping winding or of a coarse-fine type tapping winding as these give different internal voltages.

In the case of a coarse-fine type tapping winding, if the tap-changer diverter is provided with a non-linear element or arcing gap, which might operate if the transformer is tested on a particular tap-position, then an alternative tap-position may be chosen. Guidance is given in IEC 60076-4.

13.1.3 Records of tests

The applied test voltage shall be recorded using a measurement system according to IEC 60060-2. The records obtained shall clearly show the applied voltage impulse shape (front time, time-to-half value and amplitude).

The recorded curve and the extreme value of the recorded curve (as defined in IEC 60060-1) shall be presented in the test record.

The value of the test voltage (after the application of any filtering or correction for overshoot, U_t see IEC 60060-1) shall be reported in the test record.

At least one more measurement channel shall be used. In most cases an oscillogram of the current flowing to earth from the tested winding (neutral current) or the capacitive probe current, i.e. the current transferred to the non-tested and shorted winding, will represent the best sensitivity for fault indication. The current flowing from tank to earth, or the transferred voltage in a non-tested winding, are examples of alternative suitable measuring quantities. The detection method chosen shall be agreed between manufacturer and purchaser.

Further recommendations about failure detection, suitable time-base durations, etc. are given in IEC 60076-4.

13.1.4 Test connections

13.1.4.1 Test connections during tests on line terminals

The impulse test sequence is applied to each of the line terminals of the tested winding in succession. The other line terminals of the transformer shall be earthed directly or, if needed to achieve the required waveshape, through an impedance. The impedance shall not exceed the surge impedance of the connected line (if a value is supplied by the purchaser) or 400 Ω whichever is lower. In all circumstances, the voltage appearing during the impulse test at the other line terminals shall not be more than 75 % of their rated lightning impulse withstand voltage for star-connected windings, or 50 % for delta-connected windings. The lowest value of impedance at each terminal needed to achieve the required waveshape shall be used.

If the winding has a neutral terminal, the neutral shall be earthed directly or through a low impedance such as a current measuring shunt. The tank shall be earthed. If the required waveshape cannot be obtained without the use of a resistor between neutral and earth, then an additional complete impulse test sequence shall be applied. In this case the first impulse test sequence tests the winding at the full voltage without the resistor but the required waveshape may not be achieved and the second sequence with the resistor achieves the waveshape. Chopped waves, if required, would not be repeated in the second sequence.

When a transformer is fitted with internal non-linear elements such as surge arresters which will limit the voltage on internal parts during the impulse test then the provisions of 13.2.3 apply. Any such internal non-linear elements which are present in the service condition shall be present during the tests. External non-linear elements and other external voltage control elements such as capacitors shall be disconnected for test.

The impulse circuit and measuring connections shall remain unchanged during reference and full voltage tests.

Exceptions from this main procedure are given in 13.3.2 and 13.3.3.

NOTE If an impulse test is required by the purchaser on an LV winding with $U_m \leq 1,1$ kV then this is normally applied to all the LV terminals (including the LV neutral) connected together with the higher voltage terminals earthed.

13.1.4.2 Test connections for lightning impulse on the neutral

Lightning impulses are applied directly to the neutral with all other terminals earthed.

When a transformer is fitted with internal non-linear elements such as surge arresters which will limit the voltage on internal parts during the impulse test then the provisions of 13.2.3 apply. Any such internal non-linear elements which are present in the service condition shall be present during the tests. External non-linear elements shall be disconnected for test.

For transformers having a tapped winding near the neutral end of the winding, the tapping connection with the maximum turns ratio shall be chosen for the impulse test, if not otherwise agreed between purchaser and manufacturer.

The impulse circuit and measuring connections shall remain unchanged during reference and full voltage tests.

13.1.4.3 Test connections for lightning impulses applied to multiple line terminals simultaneously (LIMT)

The purchaser shall specify the terminals which are to be connected together for this test.

Lightning impulses shall be applied simultaneously to the specified line terminals connected together with the other terminals earthed. The test levels and details of the test arrangement shall be agreed. The test shall be carried out on each phase in turn.

NOTE The voltages appearing within the winding during this test can significantly exceed the terminal voltages during this test.

13.2 Full wave lightning impulse test (LI)

13.2.1 Wave shape, determination of test voltage value and tolerances

The test impulse shall be a full standard lightning impulse: 1,2 ± 30 % / 50 μs ± 20 %..

The test voltage value shall be the test voltage value as defined in IEC 60060-1 (after the test voltage function is applied). If the maximum relative overshoot magnitude is 5 % or less, the test voltage value may be taken as the extreme value as defined in IEC 60060-1.

The tolerance on the test voltage value is ± 3 %.

It is important that the manufacturer assesses the adequacy of the test equipment to achieve a waveshape within the tolerances for the particular combination of transformer and test equipment at the bid stage and has a reasonable expectation of meeting the requirements. In circumstances where the manufacturer believes that it is not reasonably possible to meet the waveshape because of the transformer characteristics and the variations to the waveshape allowed in the following paragraphs will need to be applied then this shall be clearly stated in the tender. The value of the effective energy of the impulse generator shall be made available to the purchaser on request.

NOTE 1 The minimum impulse generator energy required to meet the tail time (50 μs) during an impulse test on a transformer can be estimated by using the following equation (this equation is only a guide and might underestimate the energy required. Information from previous experience of testing similar transformers can be used if available):

$$\mathrm{E}_{\mathrm{min}} = \frac{100 \times 2\pi \times f \times (t_2)^2}{z \times U^2} \times \left(\frac{U_{\mathrm{LI}}}{\eta}\right)^2 \times \mathrm{S}_{\mathrm{r}}$$

where

- E_{min} is the minimum energy required from the impulse generator in joules;
- f is the rated frequency of the transformer in hertz;
- t_2 is the tail time in seconds; t_2 equal 50×10^{-6} s;
- z is the short circuit impedance in % seen from the impulse terminal see IEC 60076-1;
- U is the winding rated voltage in volts, phase-to-phase;
- U_{LI} is the full wave lightning impulse test voltage of the tested winding in volts;
- η is the impulse generator efficiency per unit; $\eta = 1,0$;
- S_r is the three-phase power rating in volt-amperes for which the impedance '*z*' is defined.

If the standard impulse shape cannot reasonably be obtained because of low winding inductance or high capacitance to earth and the resulting impulse shape is oscillatory so that the relative overshoot magnitude exceeds 5 % then for windings that will receive a chopped wave lightning impulse test, the front time may be increased to reduce the overshoot. In all cases with $U_m \leq 800$ kV the front time shall not exceed 2,5 μs. If the relative overshoot magnitude exceeds 5 % at the full wave voltage level, then a test voltage function shall be applied in accordance with IEC 60060-1 to determine the test voltage value. It is permissible to apply the requirements of IEC 60060-1 Annex B to the evaluation of the parameters of the lightning impulse irrespective of the overshoot value.

NOTE 2 This clause gives two methods of dealing with an overshoot of more than 5 %. The front time can be increased, but if 1,2 μs + 30 % is exceeded then chopped waves are required to provide a high frequency test. Alternatively or in addition, the peak voltage of the impulse (maximum value of the recorded curve) is increased if the overshoot exceeds 5 % and the frequency of oscillation is higher than about 100 kHz by the application of the test voltage function in accordance with IEC 60060-1.

For transformers with a U_m > 800 kV there may be cases where a front time of less than 2,5 μs cannot be reasonably achieved because of a very high capacitance to earth. In these cases a longer front time may be accepted by agreement between purchaser and manufacturer.

If the minimum tail time is not achieved then by agreement between manufacturer and purchaser a shorter tail time may be accepted but the test voltage shall be increased by 1 % for each 2 μs by which the tail time is less than 40 μs. The minimum allowable tail time is 20 μs. In the case of the low voltage winding of generator step-up transformers where the connection is arranged so that a direct lightning impulse cannot occur in service then this requirement may be varied by agreement.

Further guidance may be obtained from IEC 60076-4.

13.2.2 Tests on transformers without non-linear elements

13.2.2.1 Test sequence

The test sequence shall consist of:

a) one reference impulse of a voltage between 50 % and 70 % of the full test voltage
b) three subsequent impulses at full voltage.

If, during any of these applications, an external flashover in the circuit or across a bushing spark gap occurs, or if the recording fails on any of the specified measuring channels, that application shall be disregarded and a further application made.

NOTE Additional impulses at amplitudes not higher than the reference impulse voltage level can be used, these do not need to be shown in the test report.

13.2.2.2 Test acceptance criteria

The test is successful if there are no significant differences between voltage and current transients recorded from the reference impulse and those recorded at the full test voltage.

NOTE The detailed interpretation of the test records and the discrimination between marginal differences and differences indicating failure requires a great deal of skill and experience. Further information is given in IEC 60076-4.

If there is a voltage collapse or deviation and it is agreed between the manufacturer and purchaser that the test is not immediately failed, the test sequence shall be completed and then the full test sequence repeated using the original reference impulse. If any further voltage collapse or deviation is observed then the test is failed.

Additional observations during the test (abnormal sounds, etc.) may be used to confirm the interpretation of the records, but they do not constitute evidence in themselves.

13.2.3 Tests on transformers with non-linear elements

13.2.3.1 Test sequence

If non-linear elements or surge arresters are built into the transformer for the limitation of transferred overvoltage transients, they may operate during the test procedure and this may cause differences between impulse records made at different voltages. There will be a threshold voltage at which the differences caused by the non-linear elements start to appear and the test sequence shall include at least one record below this threshold.

The test sequence shall consist of:

a) one reference impulse at between 50 % and 60 % of the full test voltage;
b) one reference impulse at between 60 % and 75 % of the full test voltage;
c) one reference impulse at between 75 % and 90 % of the full test voltage;
d) three consecutive 100 % full wave impulses;
e) a comparison impulse at as nearly as possible the same voltage as c) above;
f) a comparison impulse at as nearly as possible the same voltage as b) above;
g) a comparison impulse at as nearly as possible the same voltage as a) above.

The reference impulse voltages shall be at least 10 % (of the 100 % level) different from each other.

If none of the 100 % full wave records differ from the lowest voltage record of the reference impulse records, then impulses e), f) and g) above may be omitted.

NOTE Additional impulses at amplitudes not higher than the reference impulse voltage level can be used, these do not need to be shown in the test report.

If, during any of these applications, an external flashover in the circuit or across a bushing spark gap should occur, or if the recording should fail on any of the specified measuring channels, that application shall be disregarded and a further application made.

13.2.3.2 Test criteria

The test is successful if there are no significant differences between voltage and current transients recorded from the lowest voltage reference impulse and those recorded at the full test voltage.

If this is not the case then the records of current and voltage from the following impulses shall be compared:

– a) and g)
– b) and f)
– c) and e)
– all the 100 % level impulse records.

The test is successful if there is no significant difference between the compared records (beyond that which can reasonably be explained by small differences in the test voltage) and any changes between successive records are progressive and smooth, consistent with the proper operation of the non-linear element.

NOTE Further information is given in IEC 60076-4.

If there is a voltage collapse or deviation and it is agreed between the manufacturer and purchaser that the test is not immediately failed, the test sequence shall be completed and then the full test sequence repeated using the original reference impulse. If any further voltage collapse or deviation is observed then the test is failed.

Additional observations during the test (abnormal sounds, etc.) may be used to confirm the interpretation of the records, but they do not constitute evidence in themselves.

13.3 Chopped wave lightning impulse test (LIC)

13.3.1 Wave shape

The wave shape of the full wave impulses shall be as given in 13.2.1. The chopped wave lightning impulse shall have a time to chopping between 3 μs and 6 μs. The time to first voltage zero after the instant of chopping shall be as short as possible. The test shall be made without the deliberate addition of impedance in the chopping circuit, but if the overswing observed during a reduced voltage application is more than 30 % then the minimum impedance required to bring the overswing below 30 % may be added to the chopping circuit.

A time to chopping of between 2 μs and 3 μs can be accepted by agreement provided that the peak value of the lightning impulse wave is achieved before the chop.

NOTE Transformers are normally designed to withstand an overswing to the opposite polarity of 30 % of the amplitude of the chopped wave lightning impulse. If the transformer is to be tested by a third party the overswing is to be limited to this value.

Usually, the same settings of the impulse generator and measuring equipment are used, and only the chopping gap equipment is added.

Different time bases may be used to record the chopped wave lightning impulses.

It is recommended to use a triggered-type chopping gap with adjustable timing, although a plain rod-rod gap is allowed.

The peak value of the chopped wave lightning impulse shall be as given in Table 2.

13.3.2 Tests on transformers without non-linear elements

13.3.2.1 Test sequence

The test is combined with the full impulse test in a single sequence. Unless otherwise specified the order of the different impulse applications shall be:

a) one full wave reference impulse at between 50 % and 70 % of the full wave lightning impulse test voltage;
b) one full wave impulse at the full wave lightning impulse test voltage;
c) two chopped impulses at the chopped wave lightning impulse test voltage;
d) two full wave impulses at the full wave lightning impulse test voltage.

The same types of measuring channels and oscillographic records are specified as for the full-wave impulse test.

NOTE Additional impulses (full or chopped) at amplitudes not higher than the reference impulse voltage level can be used, these do not need to be shown in the test report

If, during any of these applications, an external flashover in the circuit or across a bushing spark gap should occur, or if the recording should fail on any of the specified measuring channels, that application shall be disregarded and a further application made.

As far as possible the same time to chop shall be used for all chopped wave lightning impulses in the sequence.

13.3.2.2 Test criteria

The test is successful if there are no significant differences between voltage and current transients recorded from the reference reduced level full impulse and those recorded at the full test voltage including the chopped impulses up to the time of chop. In the case of the chopped impulses differences after the chopping time may be due to minor variations in the performance and timing of the chopping gap.

NOTE The detailed interpretation of the test records and the discrimination between marginal differences and differences indicating failure requires a great deal of skill and experience. Further information is given in IEC 60076-4.

If there is a voltage collapse or deviation and it is agreed between the manufacturer and purchaser that the test is not immediately failed the test sequence shall be completed and then the full test sequence repeated using the original reference impulse. If any further voltage collapse or deviation is observed then the test is failed.

Additional observations during the test (abnormal sounds, etc.) may be used to confirm the interpretation of the records, but they do not constitute evidence in themselves.

13.3.3 Tests on transformers with non-linear elements

13.3.3.1 Test sequence

The test is combined with the full impulse test in a single sequence.

If non-linear elements or surge diverters are built into the transformer for the limitation of transferred overvoltage transients, they may operate during the test procedure and this may cause differences between impulse records made at different voltages. There will be a threshold voltage at which the differences caused by the non-linear elements start to appear and the test sequence shall include at least one record below this threshold.

The test sequence shall consist of:

a) one full wave reference impulse at between 50 % and 60 % of the full wave lightning impulse test voltage;
b) one full wave reference impulse at between 60 % and 75 % of the full wave lightning impulse test voltage;
c) one full wave reference impulse at between 75 % and 90 % of the full wave lightning impulse test voltage;
d) one full wave impulse at the full wave lightning impulse test voltage;
e) two chopped impulses at the chopped wave lightning impulse test voltage;
f) two full wave impulses at the full wave lightning impulse test voltage;
g) a comparison impulse at as nearly as possible the same voltage as c) above;
h) a comparison impulse at as nearly as possible the same voltage as b) above;
i) a comparison impulse at as nearly as possible the same voltage as a) above.

The reference impulse voltages shall be at least 10 % (of the 100 % level) different from each other.

If none of the 100 % full wave records differ from the lowest voltage of the reference impulse record then impulses g), h) and i) above may be omitted.

The time interval between the application of the last chopped wave and the first full wave after the chop waves shall be as short as practicable.

NOTE Additional impulses (full or chopped) at amplitudes not higher than 75 % of the full level can be used, these do not need to be shown in the test report.

If, during any of these applications, an external flashover in the circuit or across a bushing spark gap should occur, or if the recording should fail on any of the specified measuring channels, that application shall be disregarded and a further application made.

The same types of measuring channels and oscillographic records are specified as for the full-wave impulse test.

As far as possible the same time to chop shall be used for all chopped impulses in the sequence.

13.3.3.2 Test criteria

The test is successful if there are no significant differences between voltage and current transients recorded from the lowest voltage reference impulse and those recorded at the full test voltage including the chopped wave impulses up to the time of chop. In the case of the chopped impulses differences after the chopping time may be due to minor variations in the performance and timing of the chopping gap.

If this is not the case then the records of current and voltage from the following impulses shall be compared:

– a) and i);
– b) and h);
– c) and g);
– all the 100 % level impulse records;
– both the chopped wave records up to the time of chop.

The test is successful if there is no significant difference between the compared records (beyond that which can reasonably be explained by small differences in the test voltage) and any changes between successive records should be progressive and smooth, consistent with the proper operation of the non-linear element.

NOTE 1 Further information is given in IEC 60076-4.

If there is a voltage collapse or deviation and it is agreed between the manufacturer and purchaser that the test is not immediately failed, the test sequence shall be completed and then the full test sequence repeated using the original reference impulse. If any further voltage collapse or deviation is observed then the test is failed.

Additional observations during the test (abnormal sounds, etc.) may be used to confirm the interpretation of the records, but they do not constitute evidence in themselves.

NOTE 2 The information given in IEC 60076-4 with reference to waveshape evaluation is based on the visual observation of oscillographic records. Under certain circumstances it might be appropriate to evaluate the waveshape parameters of non-standard waveshapes and perform the interpretation of deviations manually rather than relying completely on software tools.

13.4 Lightning impulse test on a neutral terminal (LIN)

13.4.1 General

Full wave lightning impulses at the impulse voltage level specified for the neutral are applied directly to the neutral with all other terminals earthed.

13.4.2 Waveshape

The wave shape of the full wave impulses shall be as given in 13.2.1 except that the duration of the front may be up to a maximum of 13 μs.

13.4.3 Test sequence

The test sequence shall be as given in 13.2.2.1 for transformers without a non-linear element and 13.2.3.1 for transformers with a non-linear element.

13.4.4 Test criteria

The test criteria shall be as given in 13.2.2.2 for transformers without a non-linear element and 13.2.3.2 for transformers with a non-linear element.

14 Switching impulse test (SI)

14.1 General

During switching impulse tests, the voltages developed across different windings are approximately proportional to the ratio of numbers of turns.

The switching impulse test voltage shall be as specified for the winding with the highest U_m value. If the ratio between the windings is variable by tappings, the tappings shall be used to bring the test voltage for the winding with lower U_m as close as possible to the corresponding test value given in Table 2. The windings with lower U_m values may not receive their full test voltage; this shall be accepted. If lower voltage windings do not have a switching impulse level given in Table 2 then the manufacturer may choose the tap position for test unless otherwise specified by the purchaser.

In a three-phase transformer, the voltage developed between line terminals during the test shall be approximately 1,5 times the voltage between line and neutral terminals.

14.2 Test connections

The impulses are applied either directly from the impulse voltage source to a line terminal of the highest voltage winding, or to a lower voltage winding so that the test voltage is inductively transferred to the highest voltage winding. The specified test voltage shall appear between the line terminal of the highest voltage winding and earth. The voltage shall be measured at the line terminal of the highest voltage winding.

A three-phase transformer shall be tested phase by phase.

Star connected windings with the neutral brought out shall be earthed at the neutral terminal either directly or through a low impedance such as a current measuring shunt. A voltage of opposite polarity and about half amplitude appears on the two remaining line terminals which may be connected together but not connected to earth. To limit the voltage of opposite polarity to approximately 50 % of the applied level, it is permissible to connect high resistance damping resistors (5 kΩ to 20 kΩ) to earth at the non-tested phase terminals.

For delta connected windings the terminal corresponding to the end of the phase under test shall be earthed either directly or through a small measuring impedance, the other terminals shall be open circuit. Tests on a three-phase transformer shall be arranged so that a different terminal of the delta is earthed for each phase test. Delta connected windings with more than three terminals brought out shall have the delta closed for the test.

For a single phase transformer with one or more windings which will have both ends connected to a line in service and with a switching impulse test specified, then the switching impulse test shall be applied to both ends of the winding.

For a star connected winding with a neutral connection not brought out and not connected to earth internally, it is not always possible to achieve the appropriate test voltages by earthing one or more line terminals, in this case the test connection shall be agreed between manufacturer and purchaser.

Bushing spark gaps may be removed or their spacing increased to prevent sparkover during the test.

14.3 Waveshape

The test voltage is normally of negative polarity to reduce the risk of erratic external flashover in the test circuit.

The voltage impulse shall have a time to peak (T_p as defined in IEC 60060-1) of at least 100 μs, a time above 90 % (T_d as defined in IEC 60060-1) of the specified amplitude of at least 200 μs, and a time to zero (T_z as defined in IEC 60060-1) of a minimum of 1 000 μs.

NOTE 1 The impulse wave shape is purposely different from the standard waveshape of 250 / 2 500 μs recommended in IEC 60060-1, since IEC 60060-1 is intended for equipment without a saturable magnetic circuit. The time to peak is chosen to be long enough to give an essentially linear voltage distribution along the winding.

The time to zero can be increased by inducing a remnant flux into the core of opposite direction to that induced during the test before each full-voltage test impulse. This is normally accomplished by applying impulses of similar shape but opposite polarity at a voltage not exceeding 70 % of the full test level, but other methods may be used. A time to zero of less than 1 000 μs is permissible if as far as practicable full reverse saturation of the core is achieved.

NOTE 2 During the test considerable flux is developed in the magnetic circuit. The impulse voltage can be sustained up to the instant when the core reaches saturation and the magnetizing impedance of the transformer becomes drastically reduced.

For test objects without a magnetic core or with a gapped core design, it is permissible to have a time to zero of less than 1 000 μs. See IEC 60076-4.

14.4 Test sequence

The test sequence shall consist of one reference impulse of a voltage between 50 % and 70 % of the full test voltage and three impulses at full voltage. Sufficient reverse polarity applications shall be made before each full impulse to ensure the magnetization of the core is similar before each full wave impulse in order to make the time to first zero as uniform as possible.

NOTE If the core does not saturate during the full voltage applications then reverse polarity applications might not be required.

Oscillographic records shall be made of the impulse wave-shape on the line terminal under test and the current between the tested winding and earth. If during any of these applications an external flashover in the circuit or across a bushing spark gap should occur, or if the recording should fail on any of the specified measuring channels, that application shall be disregarded and a further application made.

14.5 Test criteria

The test is successful if there is no sudden collapse of voltage or discontinuity in the voltage or current indicated on the oscillographic records.

Additional observations during the test (abnormal sounds, etc.) may be used to confirm the oscillographic records, but they do not constitute evidence in themselves.

NOTE Successive oscillograms might differ because of the influence of magnetic saturation on impulse duration.

15 Action following test failure

If the transformer fails any of the dielectric tests then the complete sequence of dielectric tests shall be repeated at the full level following repair. However, under circumstances where it is clear that some parts of the transformer that have been fully tested are not involved in the failure or repair, then at the discretion of the purchaser these parts may not need to be tested again. Particular account needs to be taken of the possibility of contamination or internal transients having damaged other parts of the transformer.

If a transformer fails to meet its test requirements and the fault is in a bushing, provided that the purchaser is satisfied that the transformer is not in any way affected by the failure, it is permissible to replace this bushing and continue the test on the transformer to completion without delay.

If a test failure occurs as the result of a flashover external to the transformer, then the particular test may be repeated and if successful the test sequence may be completed and no repeat of previously successful tests is required.

16 External clearances in air

16.1 General

This part of the standard is applicable when clearances in air are not specified by the purchaser. Where such clearances are specified, the manufacturer may use higher values if required for test.

Clearance in air is understood as the shortest distance between any metallic part of the bushing terminal and any part of the transformer, taking a line which does not pass through the bushing insulator.

This standard is not applicable to the clearance between parts of the bushing itself and the length of the bushing may need to be greater than the given clearances to pass the required tests on the bushing.

This standard does not consider the risk from intrusion of birds and other animals.

The line to earth clearance figures given in this standard are based on those given in IEC 60071-1 for a rod to structure electrode configuration for $<$ 850 kV lightning impulse level and the conductor to structure clearance for higher lightning impulse levels. The highest clearance determined by switching impulse or lightning impulse is used. The phase-to-phase clearances are based on those given in IEC 60071-1 for a conductor-to-conductor electrode structure based on the switching impulse level with a phase-to-phase divided by phase-to-earth value of 1,5. It is therefore assumed that at $\geq$ 850 kV lightning impulse level the bushing ends and any connections normally have rounded electrode shapes.

It is assumed that conductor clamps with their associated shield electrodes are suitably shaped so that they do not reduce the flashover voltage. It is also assumed that the arrangement of incoming conductors does not reduce the effective clearances provided by the transformer itself. The design shall provide for suitable conductors to be connected to the bushing terminals leading away from the transformer without infringing the clearances given in this document.

If the purchaser intends to make the connection in a particular way which is likely to reduce the effective clearances, this shall be stated in the enquiry.

In general, the provision of adequate clearances in air becomes technically difficult mainly at high system voltages, particularly for relatively small units, or when the installation space is restricted. The principle followed in this standard is to provide minimum, non-critical clearances which are satisfactory without further discussion or proof under various system conditions and in different climates. Other clearances based on past or current practice shall be subject to agreement between purchaser and manufacturer.

The recommended clearances are referred to the rated withstand voltages of the internal insulation of the transformer, unless otherwise specified in the enquiry and order. When the clearances of the transformer are equal to or larger than the values specified in this standard and the bushings have properly selected ratings according to IEC 60137, then the external insulation of the transformer shall be regarded as satisfactory without further testing.

NOTE 1 The impulse withstand strength of the external insulation is polarity dependant, in contrast to what is assumed for the internal insulation. The tests prescribed for the internal insulation of the transformer do not automatically verify that the external insulation is satisfactory. The recommended clearances are dimensioned for the more onerous polarity (positive).

NOTE 2 It is recognised that in some countries, clearances can be different if based on LI and AC withstand voltages only.

NOTE 3 If a clearance smaller than that according to the paragraph above is to be used, a type test either using the general methods given in Clauses 10 to 14 of this standard using the test voltages applicable to the transformer, or the tests given in another standard (for example IEC 62271-1) applicable to the connected substation equipment might be required on an arrangement simulating the actual clearance.

If the transformer is specified for operation at an altitude higher than 1 000 m, the clearance requirements shall be increased by 1 % for every 100 m by which the altitude exceeds 1 000 m.

Requirements are given for the following clearances:

– clearance phase-to-earth and phase-to-neutral;
– clearance phase-to-phase between phases of the same winding;
– clearance between a line terminal of the high voltage winding and a line terminal of a lower voltage winding (see 16.2).

It follows from the above that the recommended values are in effect minimum values. The design clearances shall be stated on the outline drawing. These are nominal values subject to normal manufacturing tolerances and they have to be selected so that the actual clearances will be at least equal to the specified values.

These statements shall be taken as proof that the transformer complies with the recommendations of this standard, or with the modified values which may have been agreed for the particular contract.

16.2 Clearance requirements

The clearance requirements are given in Table 4 for each value of lightning and switching impulse voltage for each value of U_m.

The phase-to-phase clearance applies only between line terminals of the same winding, the phase to earth clearance applies to all other distances including to the line terminals of other windings and neutral terminals.

Table 4 – Minimum clearances in air *(1 of 2)*

Highest Voltage for equipment U_m kV	Full Wave Lightning Impulse (LI) kV	Switching impulse (SI) kV	Minimum air clearance	
			Line to earth mm	Phase to phase mm
<1,1	-	-		
3,6	20	-	60	60
	40	-	60	60
7,2	60	-	90	90
	75[a]	-	120	120
12	75	-	120	120
	95	-	160	160
	110[a]	-	200[a]	200[a]
17,5	95	-	160	160
	125[a]	-	220	220
24	125	-	220	220
	145	-	270	270
	150[a]	-	280[a]	280[a]
36	170	-	320	320
	200[a]	-	380	380
52	250	-	480	480
72,5	325	-	630	630
	350[a]	-	630	630
100	450	375[a]	900	900
123	550	460[a]	1 100	1 100
145	550	460[a]	1 100	1 100
	650	540[a]	1 300	1 500[a]
170	650	540[a]	1 300	1 500[a]
	750	620[a]	1 500	1 700[a]
245	850	700[a]	1 600	2 100[a]
	950	750[a]	1 700	2 300
	1 050	850[a]	1 900	2 600
300	950	750	1 700	2 300
	1 050	850	1 900	2 600
362	1 050	850	1 900	2 600
	1 175	950	2 200	3 100
420	1 175	950	2 200	3 100
	1 300	1 050	2 600	3 600
	1 425	1 175[a]	3 100	4 200
550	1 300	1 050	2 600	3 600
	1 425	1 175	3 100	4 200
	1 550	1 300[a]	3 600	5 000[a]
	1 675[a]	1 390[a]	4 000[a]	5 600[a]

Table 4 *(2 of 2)*

Highest Voltage for equipment U_m kV	Full Wave Lightning Impulse (LI) kV	Switching impulse (SI) kV	Minimum air clearance	
			Line to earth mm	Phase to phase mm
800	1 800	1 425	4 200	5 800[a]
	1 950	1 550	4 900	6 700[a]
	2 050[a]	1 700[a]	5 800[a]	7 900[a]
	2 100	1 675[a]	5 600	7 700[a]
1 100	1 950	1 425	[b]	[b]
	2 250	1 800	6 300	[c]
1 200	2 250	1 800	6 300	[c]

[a] These values are not given in IEC 60071-1:2011 for the particular value of U_m but are included either because they represent common practice in some parts of the world or for some switching impulse levels, and clearances because they represent a co-ordinated value for a particular value of lightning impulse level.

[b] No clearance values are given for this value of rated insulation level because it is not applicable to air insulation according to IEC 60071-1.

[c] No value of phase-phase clearance is given as transformers with this value of rated insulation level are usually single phase.

Annex A
(informative)

Application guide for partial discharge measurements on transformers

A.1 General

This annex is particularly applicable to the partial discharge measurements made during induced voltage test with partial discharge measurement (IVPD) according to 11.3 but it may be applied to any other partial discharge measurements made.

A partial discharge (PD) is an electric discharge that only partially bridges electrically stressed insulation. In a transformer, such a partial discharge causes a transient change of the voltage to earth at every externally available winding terminal.

Measuring impedances are connected effectively between the earthed tank and the terminals, usually through a bushing tap or through a separate coupling capacitor, as detailed in A.2.

The actual charge transferred at the site of a partial discharge cannot be measured directly, instead the apparent charge q as defined in IEC 60270 is measured at the terminal as determined by a suitable calibration, see A.2.

A particular partial discharge gives rise to different values of apparent charge at different terminals of the transformer. The comparison of simultaneously collected indications at different terminals may give information about the location of the partial discharge source within the transformer, see A.5.

The acceptance test procedure specified in 11.3 calls for measurements of apparent charge at the winding line terminals.

A.2 Connection of measuring and calibration circuits – Calibration procedure

The measuring technique and equipment is described in IEC 60270.

The principle of the measurement is to determine the voltage change at the terminal caused by the injection of a calibrated amount of charge. The voltage change is measured using a series coupling capacitance (usually a condenser type bushing) and a measuring impedance. The normal arrangement for transformer tests is to have the measuring impedance directly connected to the bushing test tap.

The measuring equipment may be connected to the measuring impedance by a matched coaxial cable. The impedance of the cable and the matched input impedance of the measuring instrument may form part of the measuring impedance. Some systems use a fiber optic cable between the measuring impedance and the recording equipment. Normally the measuring impedance, the cable and the measuring instrument are supplied together so that the overall performance of the measuring system is optimised.

During the measurement of partial discharge between a line terminal of a winding and the earthed tank, the normal arrangement is to install the measuring impedance Z_m between the condenser bushing test tap and the earthed flange of the bushing, see Figure A.1. If a test tap is not provided, it is also possible to insulate the bushing flange from the tank and use it as the measuring terminal. The capacitances between the central conductor and the measuring terminal, and between the measuring terminal and earth, act as a capacitive voltage divider for the partial discharge signal. The calibration is therefore made between the top terminal of the bushing and earth. As much of the de-energised test circuit as possible should be connected to the terminal during calibration to take account of additional capacitance and any filter circuits.

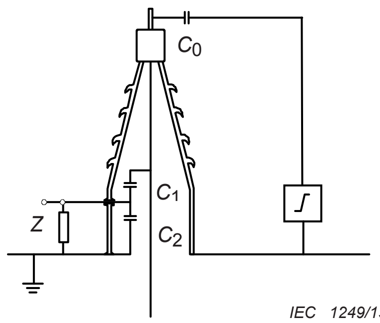


Figure A.1 – Calibration circuit for partial discharge measurement using the test tap of condenser type bushing

If PD measurements need to be made at a terminal where a bushing test tap or insulated flange is not available then a separate high-voltage coupling capacitor is used. A partial discharge free capacitor is required and its capacitance value C should be suitably large in comparison with the calibration generator capacitance C_0 (see IEC 60270 for specific requirements). The measuring impedance (with a protective gap) is connected between the low voltage terminal of the capacitor and earth, see Figure A.2.

The calibration of the complete measuring system is made by the injection of a known charge into the transformer terminal. According to IEC 60270, a calibration generator consists of a step voltage pulse generator with short rise time and a small series capacitor of known capacitance C_0. C_0 should be small in comparison to C_1 (see IEC 60270 for specific requirements regarding rise time and the choice of C_0). When this generator is connected between the transformer terminal and earth the injected charge from the pulse generator will be:

$$q_0 = U_0 \times C_0$$

where

- q_0 is the calibration apparent charge
- U_0 is the voltage step chosen to give the required q_0
- C_0 is the value of the series capacitance

The calibration level q_0 should be representative of the specified discharge level limit (usually between 50 % and 200 %). Additional measurements using the calibrator at different values of q_0 may be useful to check the operation of the measuring instrument.

It is convenient if the calibration generator has a repetition frequency synchronised to the power frequency so that the resulting pulse can be viewed on an instrument also synchronised to the power frequency.

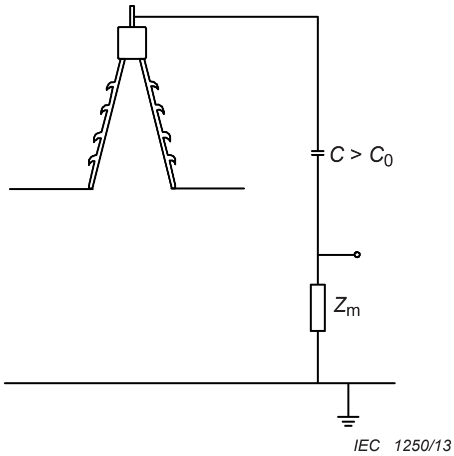


Figure A.2 – Circuit for partial discharge measurement using a high-voltage coupling capacitor

To avoid errors the leads between the terminal and the calibrator and between the calibrator and earth (at the bushing flange) should be kept as short as practicable. The calibration pulse generator should preferably be battery-operated and have small physical dimensions for convenient use at the transformer terminals.

This method of calibration provides for measurement of apparent charge at the terminal, which is the basis of this standard, but it does not give the real value of a partial discharge occurring away from the terminal because the transmission path between the discharge and the terminal is not included in the calibration.

A.3 Instruments, frequency range

The characteristics of the measuring instruments should be as specified in IEC 60270.

A graphical display of any detected partial discharge is generally useful, particularly because it offers a possibility of discriminating between true partial discharge in the transformer and certain forms of external disturbances. This is based on rate of repetition, point on the wave, polarity differences, etc.

The level of partial discharge should be observed continuously or at frequent intervals throughout the test period. Continuous recording of the signal is not obligatory.

Measuring systems for partial discharges are classified as narrow-band or wideband systems. A narrow-band system operates with a bandwidth of about 10 kHz or less at a certain tuning frequency (for example, radio noise meters). A wideband system utilises a relatively large ratio between lower and upper limits of the frequency band, for example 50 kHz to 800 kHz.

By the use of a narrow-band system, interference from local broadcasting stations may be avoided by suitably adjusting the mid-band frequency, but a check has to be made to show that winding resonances near the measuring frequency do not greatly affect the measurement. The narrow-band instrument should be operated at a frequency no higher than 500 kHz, and preferably less than 300 kHz. There are two reasons for this. First, the transmission of the discharge pulse entails a high attenuation of the higher frequency components, and second, when applying a calibration pulse to the line terminal, the pulse is likely to excite local oscillations at and near the terminal, and this will complicate the calibration when mid-band frequencies greater than 500 kHz are used.

A wideband measuring system is less critical as to attenuation and response to different pulse shapes, but is more receptive to disturbances in test locations without electromagnetic shielding. Band-stop or other types of filters may be used to reduce the interference from external influences such as radio transmitters.

The choice of measuring bandwidth does not affect the partial discharge pulse pattern and the statistical behaviour of the discharge which can be used to identify the discharge source.

In summary a wide-band measuring system is the first preference because of the greater chance of detecting a partial discharge, the bandwidth should not be less than 100 kHz. A narrow band system may be required in certain circumstances to eliminate interference. Care should however be taken over the choice of measuring centre frequency to ensure a reasonable sensitivity to PD in the transformer.

A.4 Procedure after an unsuccessful test

In 11.3.5 PD level acceptance criteria are given. If there has been no voltage collapse, but the test has been unsuccessful because of a PD level above the acceptance criteria then the test shall initially be regarded as non-destructive and the test object should not be rejected immediately upon such a result, but further investigations should be undertaken to identify and locate the partial discharge source.

A further important consideration is whether phase correlated partial discharges are sustained below the operating voltage level, when triggered at the test level, because such partial discharges are most likely to be detrimental to the transformer in service.

The testing environment should first be investigated to find any obvious sign of irrelevant sources of partial discharges. This should be followed by consultations between the manufacturer and purchaser to agree on further supplementary tests or other action to show either the presence of serious partial discharge, or that the transformer is satisfactory for service operation.

Below are some suggestions which may be useful during the above courses of action.

– Investigation as to whether the indications are truly correlated to the test sequence or just represent coincident, irrelevant sources. This is often facilitated by oscillographic monitoring or recording of the pattern of the partial discharges, external disturbances may for example be identified by their being asynchronous with the test voltage.
– Investigation as to whether the partial discharge may be transmitted from the supply source. Low-pass filters on the supply leads to the transformer under test can help in such cases.
– Investigation to determine whether the partial discharge source is within the transformer or outside (spitting from objects at floating potential in the hall, from live parts in air, or from sharp edges on earthed parts of the transformer). As the test concerns the internal insulation, provisional electrostatic shielding on the outside is permitted and recommended.
– Investigation of the probable location of the source(s) in terms of the electrical circuit diagram of the transformer, for example single phase and applied voltage tests may be useful. There are several known and published methods to locate discharges. One is based on correlation of readings and calibrations at different pairs of terminals (in addition to the obligatory readings between line terminals and earth). It is also possible to identify individual pulse shapes during the test with corresponding calibration waveforms, if records from wideband circuits are used. A particular case is the identification of partial discharge in the dielectric of the capacitance graded bushings.
– Investigation by acoustic or ultrasonic detection of the location of the source(s) within the tank.
– Investigation of the location and nature of the source using ultra high frequency electromagnetic sensors introduced into the tank.

- Determination of the probable physical nature of the source by conclusions drawn from variation with test voltage level, hysteresis effect, pulse pattern along the test voltage wave, development of the partial discharge with time, etc.
- Partial discharge in the insulation system may be caused by insufficient drying or insufficient liquid impregnation, generally this will be apparent from the pattern of the partial discharge. Re-processing of the transformer, or a period of rest, and subsequent repetition of the test may therefore be tried in this case.
- Even a limited exposure to a relatively high partial discharge may lead to local cracking of oil or liquid and temporarily reduced extinction and re-inception voltages, but the original conditions may be self-restored in a matter of hours.
- Relatively limited variation of the partial discharge level with voltage increase, a partial discharge pattern typical of a floating particle in the electrical field and an absence of an increase of level with time, may be accepted as evidence that the transformer is suitable for service. In this case it may be agreed to repeat the test, possibly with extended duration, and possibly with an increased voltage level, as this may reduce the discharge level over time.
- Traces of partial discharges visible after untanking are usually not found unless the transformer has been exposed for a considerable duration of time to levels which are very high in comparison with the acceptance limit. Such a procedure may be the last resort if other means of improving the behaviour of the transformer or identifying the source have failed.

Annex B
(informative)

Overvoltage transferred from the high-voltage winding to a low-voltage winding

B.1 General

The problem of transferred overvoltage is treated from a system point of view in IEC 60071-2. The information given below concerns only problems associated with the transformer itself under particular conditions of service. The transferred overvoltages to be considered are either transient surges or overvoltages.

NOTE It is the responsibility of the purchaser to define the loading of a low-voltage winding. If no information can be given, the manufacturer can provide information about the expected transferred voltages when the low-voltage terminals are open-circuited, and about the values of resistors or capacitors which are needed to keep the voltages within acceptable limits.

B.2 Transfer of surge voltage

B.2.1 General

A study of particular transformer installation with regard to transferred surge overvoltages is, in general, justified only for large generator transformers, which have a large voltage ratio, and for large high-voltage system transformers with a low-voltage tertiary winding.

As single phase auto transformers are tested separately, the transferred voltages appearing on the tertiary terminals when the transformers are connected as a three-phase bank needs to be considered

In order to ensure that the transferred voltages do not exceed the specified level, or to confirm that surge arresters are not required, transferred surge measurements can be made using a low voltage recurrent surge generator. Alternatively these measurements can be made at a reduced voltage during impulse tests.

It is convenient to distinguish between two mechanisms of surge transfer, namely capacitive transfer and inductive transfer.

B.2.2 Capacitive transfer

The capacitive transfer of overvoltage to a low-voltage winding may in the first approximation be described as a capacitive voltage division. The simplest equivalent circuit as seen from the low-voltage winding consists of an electromotive force (e.m.f.) source in series with a transfer capacitance C_t, see Figure B.1.

The equivalent e.m.f. is a fraction s of the incoming surge on the high-voltage side. C_t is of the order of 10^{-9} F; s and C_t are not well-defined quantities but dependent on the shape of the surge front. They can be determined together by oscillographic measurements. Pre-calculation is uncertain.

A loading of the secondary terminals with switchgear, short cables or added capacitors (a few nF), which act as lumped capacitance C_s directly on the terminals (even during the first microsecond), will reduce the transferred overvoltage peak. Longer cables or busbars are represented by their characteristic impedance. The resulting shape of secondary overvoltage will normally have the character of a short (microsecond) peak, corresponding to the front of the incoming surge.

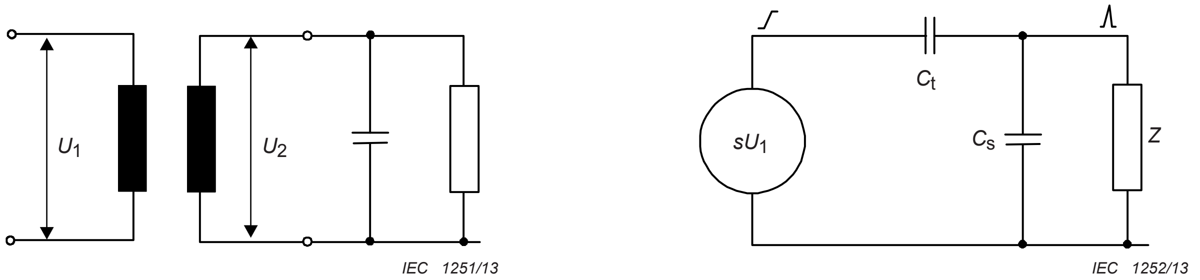


Figure B.1 – Equivalent circuit for capacitive transfer of overvoltage

B.2.3 Inductive transfer

The inductive transfer of surge voltage depends on the flow of surge current in the high-voltage winding.

If no external loading is applied to the secondary winding, the voltage transient usually has a superimposed damped oscillation with a frequency determined by leakage inductance and winding capacitances.

A reduction of the inductively transferred overvoltage component can be effected either by resistive damping through a surge diverter or by modification of the oscillation with capacitive loading. If capacitors are used, the capacitance value has usually to be of the order of tenths of microfarads. (They will therefore automatically eliminate the capacitively transferred component as long as the circuit inductance is low.)

The transformer parameters which are involved in inductive surge transfer are better defined and less dependent on rate of rise (or frequency) than those involved in capacitive transfer. For further information, see the literature on the subject.

B.3 Power-frequency transferred overvoltage

If a low-voltage winding which is physically adjacent to the high-voltage winding is left without connection to earth or with only a high-impedance connection to earth while the high-voltage winding is energised, there is a risk of power frequency overvoltage by capacitance division.

The risk is obvious for a single-phase winding, but it can also exist for a three-phase winding if the primary winding voltage becomes asymmetric, as occurs during earth faults. In particular circumstances, resonance conditions may arise.

Tertiary windings and stabilizing windings in large transformers are also subjected to the same risk. It is the responsibility of the purchaser to prevent a tertiary winding from being accidentally left with too high an impedance to earth. A stabilizing winding should normally be arranged for permanent connection to earth (tank) either externally or internally.

The overvoltage is determined by capacitances between windings and between windings and earth. These can be measured at low frequency from the terminal of the transformer in different combinations, and they can also be calculated with sufficient accuracy.

Annex C
(informative)

Information on transformer insulation and dielectric tests to be supplied with an enquiry and with an order

C.1 General

For each winding of the transformer the following information should be supplied with the enquiry and order according to the U_m of the winding.

NOTE Although SI and IVW can be specified for a lower voltage winding on a transformer the values might not be achieved during the test depending on the ratio of the transformer.

It is recommended that test connections and procedures should be discussed at the time of placing the order or at the design review stage, particularly with regard to the connection for induced withstand voltage tests on complicated transformers with non-uniformly insulated high-voltage windings (see 12.3, note) and the method to be used for impulse tests on high-power low-voltage windings and neutral terminals (see 13.3). The application of non-linear protection devices, built into the transformer is to be indicated by the manufacturer at the enquiry and at the order stage, and should be shown in the connection diagram on the rating plate.

C.2 For transformers and windings with $U_m \leq 72,5$ kV

In all cases:

– value of U_m;
– value of U_r;
– applied voltage test level (AV);
– full wave lightning impulse test level (LI).

In special cases:

– whether partial discharge measurements are required and whether this is to be done with the induced voltage test or separately, and whether it is to be done on only one unit (type test unit) or all units. The length of time at the PD measurement voltage should be given if this is less than one hour;
– whether a lightning impulse test is required on any or all units to be supplied under the order rather than just on the first unit of the design;
– whether chopped wave lightning impulse tests are required and whether it is to be done on only the first or on all units;
– whether a lightning impulse test on the neutral terminal is required and whether it is to be done on only the first or on all units;
– whether a lightning impulse applied to multiple line terminals simultaneously is required and whether it is to be done on only the first or on all units;
– clearances in air if different from the clearances given in Clause 16.

The values of U_m, LI and AV should preferably be chosen from a single line of Table 2 as they will then be a co-ordinated set, however it is permissible to choose values from different lines within the same U_m or from a higher U_m to match existing system insulation co-ordination. The LIC value, if specified, should be taken from the same line in Table 2 as the LI value. Any mix of values coming from different lines may result in over design in respect of some parameters.

C.3 For transformers and windings with 72,5 kV < U_m ≤ 170 kV

In all cases:

- value of U_m;
- value of U_r;
- applied voltage test level;
- full wave lightning impulse test level.

Additionally for transformers with non-uniform insulation:

- line terminal AC test level or the switching impulse test level if specified as an alternative;

In special cases:

- whether alternative higher voltage levels are to be used for the induced voltage test with partial discharge measurement and whether it can be combined with the IVW test;
- whether chopped wave lightning impulse tests are required and whether it is to be done on only the first or on all units;
- whether a lightning impulse test on the neutral terminal is required and whether it is to be done on only the first or on all units;
- whether the required test voltage for the induced test voltage differs from twice rated voltage;
- whether a switching impulse test is required and whether it is to be done on only the first or on all units and whether the SI test replaces the LTAC test;
- whether a lightning impulse applied to multiple line terminals simultaneously is required and whether it is to be done on only the first or on all units;
- whether a line terminal AC withstand voltage test is required for transformers with non-uniformly insulated windings and if so the test voltage required;
- clearances in air if different from the clearances given in Clause 16.

The values of U_m, LI, AV, and if specified LTAC and SI should preferably be chosen from a single line of Table 2 as they will then be a co-ordinated set, however it is permissible to choose values from different lines within the same U_m or from a higher U_m to match existing system insulation co-ordination. The LIC value, if specified, should be taken from the same line in Table 2 as the LI value. Any mix of values coming from different lines may result in over design in respect of some parameters.

C.4 For transformers and windings U_m >170 kV

In all cases:

- value of U_m;
- value of U_r;
- lightning impulse test level;
- switching impulse test level;
- applied voltage test level.

In special cases:

- whether alternative higher voltage levels are to be used for the induced voltage test with partial discharge measurement;
- whether a lightning impulse test on the neutral terminal is required and whether it is to be done on only the first or on all units;

- whether a lightning impulse applied to multiple line terminals simultaneously is required and whether it is to be done on only the first or on all units;
- whether a line terminal AC withstand voltage test is required for transformers with non-uniformly insulated windings and if so the test voltage required;
- clearances in air if different from the clearances given in Clause 16.

The values of U_m, LI, SI, AV and if specified, LTAC should preferably be chosen from a single line of Table 2 as they will then be a co-ordinated set, however it is permissible to choose values from different lines within the same U_m or from a higher U_m to match existing system insulation co-ordination. The LIC value should be taken from the same line in Table 2 as the LI value. Any mix of values coming from different lines may result in over design in respect of some parameters.

Annex D
(informative)

Neutral insulation voltage level calculation

D.1 General

The recommendations in this annex allow the determination of the minimum withstand voltage for the neutral terminal of a transformer with non-uniform insulation which is not directly earthed. To control fault levels or for other reasons the neutral terminal may be connected to earth through a considerable impedance (for example an arc-suppression reactor, earthing reactor or resistor).

The determination of the withstand voltage of the neutral terminals of a transformer designed for use with a separate neutral end voltage regulating transformer is not covered by this annex.

When the neutral terminal is not directly earthed, an overvoltage protective device shall be installed between the neutral terminal and earth in order to limit transient voltages. It is the responsibility of the purchaser to select the overvoltage protective device, to determine its impulse protection level, and to specify the corresponding impulse withstand voltage for the neutral terminal of the transformer.

NOTE For non-uniform insulation the manufacturer might design the winding with a higher than specified neutral insulation level because of the line terminal withstand test (special test).

The AC withstand voltage shall be higher than the maximum overvoltage arising under system fault conditions. There should be a margin between the impulse level of the neutral terminal and the operating voltage of the protective device, both of these voltages shall be above the maximum voltage arising under system fault conditions. The formulae below give guidance for the calculation of the maximum voltages which can occur at a neutral terminal earthed through an impedance.

D.2 Neutral fault current calculation

The maximum neutral fault current I_{fault} for a two winding three phase transformer (single phase earth fault on a star connected winding) can be calculated according to the following formula:

$$I_{fault} = \frac{3 \times E}{(Z_{1t} + Z_{1s} + Z_{2t} + Z_{2s} + Z_{0t} + Z_{0s}) + 3 \times Z_N + 3 \times Z_{fault}}$$

where

E is the phase to earth voltage taken as $U_m/\sqrt{3}$ in V

Z_{1s} is the positive sequence impedance of the network in Ω

Z_{2s} is the negative sequence impedance of network in Ω

Z_{0s} is the zero sequence impedance of the network in Ω

Z_{1t} is the positive sequence impedance of the transformer in Ω

Z_{2t} is the negative sequence impedance of the transformer in Ω

Z_{0t} is the zero sequence impedance of the transformer in Ω (including any tertiary or stabilizing winding)

Z_N is the impedance between the neutral and earth in Ω

Z_{fault} is the fault impedance in Ω (taken as zero)

NOTE As a guide, in accordance with common practice to calculate the worst case, the following values might be used:

$E = U_m/\sqrt{3}$
$Z_{1s} = 0$
$Z_{2s} = 0$
$Z_{0s} = 0$
$Z_{fault} = 0$

D.3 Minimum insulation level

D.3.1 Applied voltage minimum insulation level

The minimum AV level for the neutral should be chosen from Table 2 of this standard to be greater than $U_{ACneutral}$ Where:

$$U_{ACneutral} = I_{fault} \times Z_N$$

D.3.2 Minimum impulse level

The impulse level should be chosen to provide a margin above the operating level of the protective device, which should be chosen so that it does not operate under system short-circuit fault conditions. The highest asymmetrical peak voltage under these conditions is given by

$$U_{neutral\ max} = U_{ACneutral} \times K_v \times \sqrt{2}$$

where

K_v is the voltage asymmetry factor.

In the case of a purely resistive Z_N, K_v is the same as the current asymmetry factor k as defined in IEC 60076-5, but for an inductive Z_N, K_v will be lower because of the DC component of current. The factor K_v can be taken as 2 in the worst case of a very high transformer X/R and a small resistive Z_N but will be < 2 in practical cases. In the case of a purely inductive Z_N, K_v can be taken as 1,05 as this represents the worst case with a transformer X/R of about 7. It is recommended that $U_{neutral\ max}$ is calculated using a system model.

D.4 Example

A transformer connected Ynd11 with a rated HV voltage of 155 kV (i.e. U_m is 170 kV) and a rated power of 100 MVA with a 12 % positive sequence impedance on a 100 MVA base and a zero sequence impedance of 10,8 %, and with the HV neutral earthed through a 39 Ω reactor will experience the following fault current in the HV neutral for an HV line to earth fault considering an infinite short circuit power of the network:

$$I_{fault} = \frac{3 \times E}{(Z_{1t} + Z_{1s} + Z_{2t} + Z_{2s} + Z_{0t} + Z_{0s}) + 3 \times Z_N + 3 \times Z_{fault}}$$

$$I_{fault} = \frac{3 \times 170\,000 / \sqrt{3}}{(28{,}83 + 0 + 28{,}83 + 0 + 25{,}95 + 0) + 3 \times 39 + 0} \text{ A}$$

$$I_{fault} = 1\,468 \text{ A}$$

which gives a voltage of:

$$U_{\text{ACneutral}} = I_{\text{fault}} \times Z_{\text{N}}$$

$$U_{\text{ACneutral}} = 1\,468 \times 39\ \text{V}$$

$$U_{\text{ACneutral}} = 57\,243\ \text{V}$$

therefore the minimum AV level from Table 2 is 70 kV

Assuming K_{v} = 1,05 for a reactive neutral impedance, the highest voltage on the neutral under system fault conditions is:

$$U_{\text{neutral max}} = 57\ 243 \times 1{,}05 \times \sqrt{2}\ \text{V}$$

$$U_{\text{neutral max}} = 85{,}0\ \text{kV}$$

Since the protective device should not operate at a peak level of 85 kV its highest continuous AC level should not be less than $85/\sqrt{2}$ kV = 60,1 kV. A suitable surge arrester for this voltage (10 second withstand) has a 10 kA protective level of 140 kV and allowing a margin on this gives an LI level of 170 kV for the neutral.

A lightning impulse level of 170 kV corresponds to a U_{m} of 36 kV and this would be specified for the neutral.

Annex E
(informative)

Basis for dielectric tests, insulation levels and clearances

E.1 General

It is the intention of this standard that the line to earth, neutral to earth, phase to phase and turn to turn insulation of the transformer shall be properly tested.

Depending on the voltage level and on the type of transformer different tests have been selected to achieve this, and appropriately coordinated test voltage levels are given in Table 2.

This annex summarises the rules, which prevailed during the revision of this standard. In general the revision has been aimed at simplifying the required testing and clarifying the requirements without increasing or reducing the overall level of testing, which is considered to have given good performance in service over many years.

E.2 Tests

E.2.1 Tests for transformers with $U_m \leq 72,5$ kV

These transformers include distribution transformers, which are often produced in large quantities of a particular design. The testing of such transformers should remain quick and affordable.

As all transformers and windings with a U_m of 72,5 kV and below are produced with uniform insulation, the line to earth and neutral to earth insulation are both verified during the applied voltage test (AV).

The induced test withstand (IVW), therefore, only needs to check the turn to turn insulation, and as in the previous edition a test at twice the normal operating voltage have been considered as offering a sufficient margin.

The design of the phase to phase and phase to earth insulation is also proven with the lightning impulse (LI) test but in order to limit the testing equipment necessary for this category of transformer the lightning impulse test has been retained as a type rather than a routine test.

The chopped wave lightning impulse test (LIC) is not regarded as necessary in general. This test is defined as a special test available at the request of the purchaser for use only when there are particularly onerous service conditions.

The induced test with partial discharge measurement (IVPD) has been considered also as too costly and too long for general application on these transformers, and furthermore its goals are covered by the IVW and AV tests. This test is defined as a special test available if required possibly with a reduced duration at the request of the purchaser for use when there are special service conditions.

E.2.2 Tests for transformers with a 72,5 kV < $U_m \leq 170$ kV

Transformers in this middle range are generally built to order but because of the higher powers transmitted, requirements for higher quality checks are included. As both uniform and non-uniform insulation can be specified the list of tests has been prepared to accommodate both possibilities.

The neutral to earth insulation and for uniformly insulated transformers the line to earth insulation is proven with the applied voltage test (AV). For non-uniform insulation as the test level is limited by the neutral insulation it is insufficient to prove the line to earth insulation. For this reason a line terminal AC (LTAC) test is routine for non-uniformly insulated transformers, but this can be replaced by agreement with a switching impulse (SI) test so that this class of transformer can be tested in a similar manner to larger units.

The phase-to-phase and phase to earth insulation is also tested with the routine lightning impulse (LI) test. The chopped wave lightning impulse test is a special test for these voltage levels to be specified only when required by the purchaser for particular service conditions.

To test the turn-to-turn insulation and phase-to-phase insulation, an induced voltage withstand test (IVW) at twice rated voltage and an induced voltage test with partial discharge measurement (IVPD) are specified as routine tests. In order to shorten the test time and not to reproduce twice the same type of dielectric stress in the transformer, the opportunity to combine these tests is given as the enhancement of the IVPD test gives similar stresses to the IVW and both are made in a configuration similar to the service conditions.

E.2.3 Tests for transformers with U_m > 170 kV

This category of transformer covers the largest transmission and generation transformers. The limited number of units as well as the necessary quality checks for these large and important units leads to the following tests:

To check the insulation to earth an applied voltage test is required as a routine test.

The IVPD test checks the quality of the turn to turn and line to earth and phase to phase insulation connected in the service condition. The switching impulse test (SI) proves the phase to phase and line to earth withstand. It is considered therefore that a separate induced voltage withstand test is not necessary but the enhancement voltage of the IVPD test can be increased if desired for example to twice rated voltage.

Lightning impulse tests including chopped waves are included as a routine test for these transformers as it is considered important to prove the ability of the transformer to withstand impulses including those containing higher frequency components.

For the purchaser who wishes to further test the line to earth insulation with an AC test, the single phase line terminal AC test (LTAC) can be specified as a special test. This test is derived from the previous induced voltage withstand test.

E.3 Test voltages

The test voltages contained in Table 2 have been established based on IEC 60071-1. All values below the acceptable limits given in this insulation coordination standard have been excluded from Table 2, but Table 3 has been introduced with lower values which may be used to co-ordinate with existing practice. Table 2 continues to give a range of possible test voltage values for each U_m to allow the specification of a transformer to match a particular system requirement, whilst providing a minimum standard.

The general rule, which prevailed when establishing the values given in Table 2 is based on the behaviour of insulation containing cellulose-based solid insulation and mineral oil. The studies made on this type of insulation have shown that the switching impulse withstand (SI) is usually between 0,8 and 0,85 times the lightning impulse withstand. IEEE C57.12.00-2010 gives figures based on a ratio of 0,83.

In Table 2 the values were rounded up whenever this did not introduce an excessive bias to the general rule.

The induced voltage withstand (IVW) of the line to earth is usually around 50 % of the switching impulse voltage i.e. about 40 % to 43 % of the lightning impulse withstand voltage (LI). The values in Table 2 have been set using this general principle and the standardized figures for the IVW present in the IEC 60071-1. Except for U_m below 36 kV where the practices in use are somewhat different, the general rule is followed with only limited discrepancies to reflect existing practice.

The $(1{,}58 \times U_r)/\sqrt{3}$ value for the PD measurement level is 1,5 × U_r plus 5 % and is the level used in IEEE C57.12.00-2010 $(1{,}8 \times U_r)/\sqrt{3}$ is 1,7 × U_r plus 5 % to account for the changed basis from U_m to U_r and to harmonise with IEEE C57.12.00-2010.

E.4 Clearances

The values given in the line to earth column of Table 4 are the highest of those given in IEC 60071-1:2011 for the relevant lightning impulse or switching impulse level. Rod to structure values have been used for lightning impulse levels ≤ 750 kV and conductor to structure values above 750 kV. Where figures are not given in IEC 60071-1 they have been obtained by linear interpolation rounded to the nearest 10 mm or 100 mm.

The values given in the phase-phase clearance column of Table 4 have been obtained by re-basing the conductor to conductor values given in IEC 60071-1:2011 to a phase to phase divided by phase to earth value of 1,5 which is relevant to transformers with a delta winding. Where exact figures are not available from IEC 60071-1 a third order polynomial regression was used to interpolate between the figures re-based to a phase to phase divided by phase to earth value of 1,5. An example of the re-basing would be the clearance of 7 200 mm at 1 425 kV and 1,7 is taken to be equivalent to 1 615 kV and 1,5.

Bibliography

IEC 60071-2, *Insulation co-ordination – Part 2: Application guide*

IEC 60076-4, *Power transformers – Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors*

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

IEC 61083-1, *Instruments and software used for measurement in high-voltage impulse tests – Part 1: Requirements for instruments*

IEC 61083-2, *Instruments and software used for measurement in high-voltage impulse tests – Part 2: Requirements for software*

IEC 62271-1, *High-voltage switchgear and controlgear – Part 1: Common specifications*

IEEE C57.12.00-2010, *Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*

IEEE C57.142-2010, *IEEE guide to describe the occurrence and mitigation of switching transients induced by transformers, switching device and system interaction*

CIGRÉ-report 12-14 (1984), *Resonance behaviour of high voltage transformers*. Paper presented in the name of Study Committee 12 by Working Group 12.07

____

This page deliberately left blank

British Standards Institution (BSI)

BSI is the national body responsible for preparing British Standards and other standards-related publications, information and services.

BSI is incorporated by Royal Charter. British Standards and other standardization products are published by BSI Standards Limited.

About us

We bring together business, industry, government, consumers, innovators and others to shape their combined experience and expertise into standards -based solutions.

The knowledge embodied in our standards has been carefully assembled in a dependable format and refined through our open consultation process. Organizations of all sizes and across all sectors choose standards to help them achieve their goals.

Information on standards

We can provide you with the knowledge that your organization needs to succeed. Find out more about British Standards by visiting our website at bsigroup.com/standards or contacting our Customer Services team or Knowledge Centre.

Buying standards

You can buy and download PDF versions of BSI publications, including British and adopted European and international standards, through our website at bsigroup.com/shop, where hard copies can also be purchased.

If you need international and foreign standards from other Standards Development Organizations, hard copies can be ordered from our Customer Services team.

Subscriptions

Our range of subscription services are designed to make using standards easier for you. For further information on our subscription products go to bsigroup.com/subscriptions.

With **British Standards Online (BSOL)** you'll have instant access to over 55,000 British and adopted European and international standards from your desktop. It's available 24/7 and is refreshed daily so you'll always be up to date.

You can keep in touch with standards developments and receive substantial discounts on the purchase price of standards, both in single copy and subscription format, by becoming a **BSI Subscribing Member**.

PLUS is an updating service exclusive to BSI Subscribing Members. You will automatically receive the latest hard copy of your standards when they're revised or replaced.

To find out more about becoming a BSI Subscribing Member and the benefits of membership, please visit bsigroup.com/shop.

With a **Multi-User Network Licence (MUNL)** you are able to host standards publications on your intranet. Licences can cover as few or as many users as you wish. With updates supplied as soon as they're available, you can be sure your documentation is current. For further information, email bsmusales@bsigroup.com.

Revisions

Our British Standards and other publications are updated by amendment or revision.

We continually improve the quality of our products and services to benefit your business. If you find an inaccuracy or ambiguity within a British Standard or other BSI publication please inform the Knowledge Centre.

Copyright

Useful Contacts:

Customer Services
Tel: +44 845 086 9001
Email (orders): orders@bsigroup.com
Email (enquiries): cservices@bsigroup.com

Subscriptions
Tel: +44 845 086 9001
Email: subscriptions@bsigroup.com

Knowledge Centre
Tel: +44 20 8996 7004
Email: knowledgecentre@bsigroup.com

Copyright & Licensing
Tel: +44 20 8996 7070
Email: copyright@bsigroup.com

BSI Group Headquarters

389 Chiswick High Road London W4 4AL UK