BRITISH STANDARD

BS EN
60076-6:2008

Power transformers —

Part 6: Reactors

ICS 29.180

British Standards

National foreword

This British Standard is the UK implementation of EN 60076-6:2008. It is identical to IEC 60076-6:2007. It supersedes BS EN 60289:1995, which will be withdrawn on 1 June 2011.

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.

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

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Power transformers -
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(IEC 60076-6:2007)

Transformateurs de puissance -
Partie 6: Bobines d'inductance
(CEI 60076-6:2007)

Leistungstransformatoren -
Teil 6: Drosselspulen
(IEC 60076-6:2007)

This European Standard was approved by CENELEC on 2008-06-01. 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 Central Secretariat 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 Central Secretariat has the same status as the official versions.

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CENELEC
European Committee for Electrotechnical Standardization
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Foreword

The text of document 14/538/CDV, future edition 1 of IEC 60076-6, prepared by IEC TC 14, Power transformers, was submitted to the IEC-CENELEC Parallel Unique Acceptance Procedure and was approved by CENELEC as EN 60076-6 on 2008-06-01.

This European Standard supersedes EN 60289:1994 + A11:2002.

EN 60076-6:2008 includes the following significant technical changes with respect to EN 60289:1994:

- wide extension of the “Definitions”, “Rating” and “Tests” clauses,
- more consequent distinction between definition and rating,
- “Tests” subclauses take into account the latest revisions of relevant EN 60076 standards,
- dielectric testing of reactors is now in line with dielectric testing of transformer according to EN 60076-3:2001,
- consequent distinction between oil-immersed and dry-type reactor,
- document offers an easier handling and is a more stand-alone document than EN 60289,
- introduction of the discharge reactor as part of Clause 9,
- introduction of the turn-to-turn overvoltage test for dry-type reactors (Annex E),
- important background information given by newly introduced informative annexes,
  - Annex A (informative) – Information on shunt reactor switching and on special applications
  - Annex B (informative) – Magnetic characteristic of reactors
  - Annex C (informative) – Mutual reactance, coupling factor and equivalent reactances of three-phase reactors
  - Annex D (informative) – Temperature correction of losses for liquid-immersed gapped-core and magnetically shielded air-core reactors
  - Annex F (informative) – Short-circuit testing
  - Annex G (informative) – Resistors – Characteristics, specification and tests.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2009-03-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2011-06-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60076-6:2007 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 60143	NOTE Harmonized in EN 60143 series (not modified).
IEC 60168	NOTE Harmonized as EN 60168:1994 (not modified) + A1:1997 (not modified) + A2:2000 (not modified).
IEC 60273	NOTE Harmonized as HD 578 S1:1992 (not modified).
IEC 60529	NOTE Harmonized as EN 60529:1991 (not modified).
IEC 60871-1	NOTE Harmonized as EN 60871-1:2005 (not modified).
IEC 61378-1	NOTE Harmonized as EN 61378-1:1998 (not modified).
IEC 61378-2	NOTE Harmonized as EN 61378-2:2001 (not modified).
IEC 62271-110	NOTE Harmonized as EN 62271-110:2005 (not modified).

CONTENTS

INTRODUCTION

This part of IEC 60076 is intended to provide the basis for the specification and testing of the types of reactor given in the scope. The document also gives some important information on certain reactor applications to aid the preparation of a reactor specification.

Wherever possible, references to technical Clauses in the other parts of IEC 60076 which are relevant to power transformers have been made. However, because reactors have some fundamental differences to transformers there are special considerations that apply to the specification, testing and application of reactors. These are included in this part of IEC 60076.

Clauses 1 to 6 form the general parts of the document, which apply to all types of reactor. Clauses 7 to 12 deal individually with each different type of reactor. Generally, only one of the Clauses 7 to 12 will apply to a specific reactor.

This part of IEC 60076 has more than one definition Subclause. The general definitions given in Clause 3 apply to the whole document. Each of the Clauses 7 to 12 dealing with a certain type of reactor includes a definition Subclause relevant and applying only to that Clause.

Clauses 7 to 12 have been given a uniform structure. Within this structure, the Rating Subclause sets out the minimum information that a purchaser shall supply with the reactor specification. The test Subclause in each Clause defines the relevant tests that can be applied to that particular type of reactor and may include some additional items that shall be agreed on at the time of order.

Annexes A, B, C, D, F and G provide further information for certain reactor applications and testing. Annex E describes the dielectric turn-to-turn test.

This part of IEC 60076 covers both dry-type and liquid-immersed reactors and where Clauses or Subclauses apply to only one type this is made clear.

Where possible, the requirements of this part of IEC 60076 have been harmonised with the equivalent IEEE standard.

POWER TRANSFORMERS –

Part 6: Reactors

1 Scope

This part of IEC 60076 applies to the following types of reactors:

- shunt reactors;
- series reactors including current-limiting reactors, neutral-earthing reactors, power flow control reactors, motor starting reactors, arc-furnace series reactors;
- filter (tuning) reactors;
- capacitor damping reactors;
- capacitor discharge reactors;
- earthing transformers (neutral couplers);
- arc-suppression reactors;
- smoothing reactors for HVDC and industrial application;

with the exception of the following reactors:

- reactors with a rating less than 1 kvar single-phase and 5 kvar three-phase;
- reactors for special purposes such as high-frequency line traps or reactors mounted on rolling stock.

Where IEC standards do not exist for small or special reactors, this part of IEC 60076 may be applicable as a whole or in part.

2 Normative references

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

IEC 60060-1:1989, *High-Voltage test techniques – Part 1: General definitions and test requirements*

IEC 60076-1:1993, *Power transformers – Part 1: General*
Amendment 1 (1999)

IEC 60076-2:1997, *Power transformers – Part 2: Temperature rise*

IEC 60076-3:2000, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

IEC 60076-4:2002, *Power transformers – Part 4: Guide to lightning impulse and switching impulse testing – Power transformers and reactors*

IEC 60076-5:2006, *Power transformers – Part 5: Ability to withstand short-circuit*

IEC 60076-7:2005, *Power transformers – Part 7: Loading guide for oil-immersed power transformers*

IEC 60076-8:1997, *Power transformers – Part 8: Application guide*

IEC 60076-10:2005, *Power transformers – Part 10: Determination of sound levels*

IEC 60076-11:2004, *Power transformers – Part 11: Dry-type transformers*

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

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

IEC 60721-2-6, *Classification of environmental conditions – Part 2: Environmental conditions appearing in nature. Earthquake vibration and shock*

IEC 60815, *Guide for the selection of insulators in respect of polluted conditions*

IEC 60905:1987, *Loading guide for dry-type power transformers*

IEC 60943:1998, *Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals*

3 Terms and definitions

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

The definitions given in this Clause are of a general nature. Additional definitions are given in those Clauses of this part of IEC 60076 which are specific to a particular type of reactor or which are given a particular meaning when related to that type of reactor.

There are frequent references to technical Clauses in IEC 60076 concerning transformers and transformer testing. The terminology of those standards may not always be strictly relevant in the context of reactors. For example “induced a.c. withstand voltage test” is a test on a reactor where there is a test voltage across the winding although it is not “induced” from another winding, but applied directly from the test source.

3.1 Types of reactor

3.1.1
shunt reactor
reactor connected phase-to-earth, phase-to-neutral or between phases in a power system to compensate for capacitive current

3.1.2
current-limiting reactor
reactor connected in series in a power system to limit the current under system fault conditions

3.1.3
neutral-earthing reactor
reactor connected between the neutral of a power system and earth to limit the line-to-earth current under system earth fault conditions to a desired value

3.1.4
power flow control reactor
reactor connected in series in a power system to control the power flow

3.1.5
motor starting reactor
reactor connected in series with a motor to limit the inrush current during the motor starting operation

3.1.6
arc-furnace series reactor
reactor connected in series with an arc-furnace to increase the efficiency of the metal melting operation and reduce voltage variation on the power system

3.1.7
damping reactor
reactor connected in series with shunt capacitors to limit the inrush current when the capacitor is energised, limit the outrush current during close-in faults or adjacent capacitor switching and/or to detune capacitor banks in order to avoid resonance with the power system

3.1.8
filter reactor
reactor connected in series or in parallel with capacitors to reduce or block harmonics or control signals (ripple signals) with frequencies up to 10 kHz

3.1.9
discharge reactor
reactor used in the bypass/discharge circuit of high voltage power system series capacitor bank applications to limit the current under fault conditions

3.1.10
earthing transformer (neutral coupler)
three-phase transformer or reactor connected in a power system to provide a neutral connection for earthing either directly or via an impedance

NOTE Earthing transformers may in addition supply a local auxiliary load.

3.1.11
arc-suppression reactor
reactor connected between the neutral of a power system and earth to compensate for the capacitive line-to-earth current due to a single-phase earth-fault (resonant-earthed system)

3.1.12
smoothing reactor
reactor connected in series in a d.c. system to reduce the flow of alternating currents and transient overcurrents

3.2 Other definitions

3.2.1
highest voltage for equipment
U_m
the basis for the insulation level of the reactor according to IEC 60076-3

3.2.2
magnetic shield
ferromagnetic part of a reactor designed for flux control purposes located outside the reactor winding

NOTE This includes yokes, unwound limbs, magnetic tank shunts etc.

3.2.3
air-core reactor
a reactor designed without any ferromagnetic material inside or outside the winding for flux control purposes (usually dry-type reactors)

3.2.4
gapped-core reactor
reactor designed with a gapped ferromagnetic core inside the winding (usually liquid-immersed reactors)

3.2.5
magnetically-shielded air-core reactor
reactor designed without any ferromagnetic material inside the winding but incorporating a magnetic shield outside the winding for flux control purposes

3.2.6
air-core reactance of a gapped-core or magnetically-shielded air-core reactor
reactance calculated from the differential inductance (see Clause B.4) of a reactor which contains ferromagnetic material for flux control purposes when all the ferromagnetic parts of the reactor are fully saturated

3.2.7
magnetic characteristic
the magnetic characteristic of a reactor is the relationship of the linked flux of the reactor winding versus current (see Figure 1 and Figure 2).

NOTE The magnetic characteristic may be linear as shown in Figure 1a, non-linear as shown in Figure 1b or saturated as shown in Figure 1c.

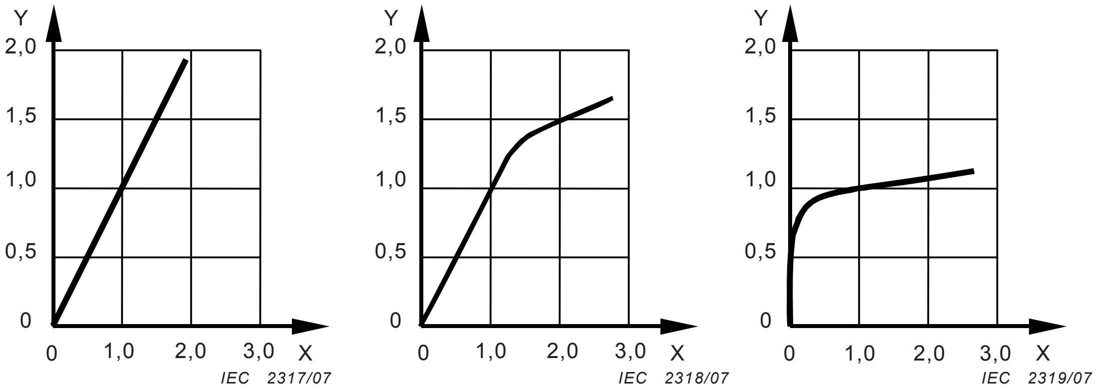


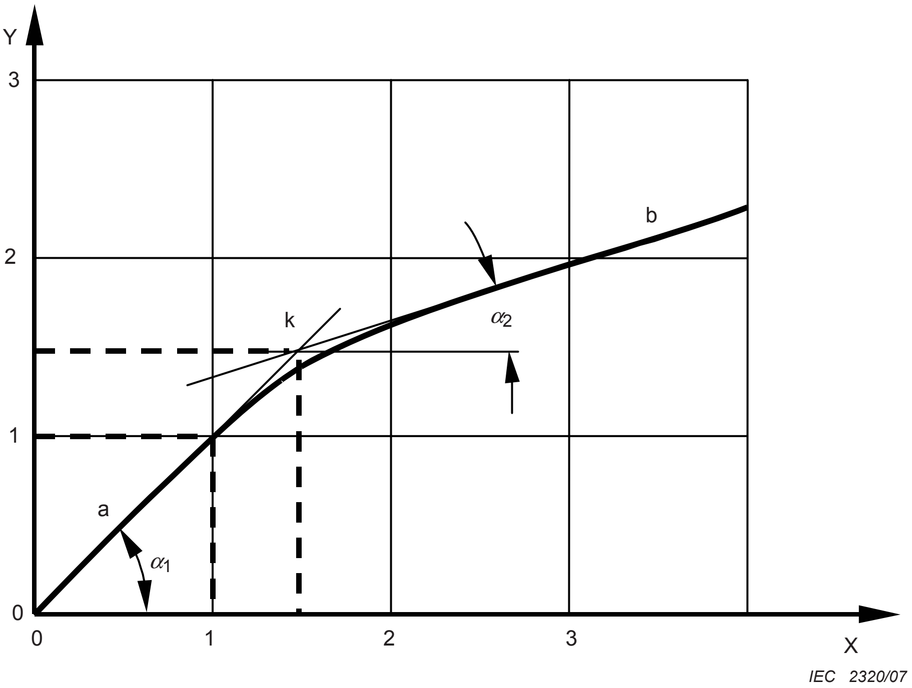
Figure 1a – Linear **Figure 1b – Non-linear** **Figure 1c – Saturated**

Key

X axis – instantaneous value of current expressed in p.u. of the rated value.

Y axis – instantaneous value of linked flux expressed in p.u. of the value at rated current.

Figure 1 – Types of magnetic characteristics for reactors



Key

X axis – instantaneous value of current expressed in p.u. of the rated value.

Y axis – instantaneous value of linked flux expressed in p.u. of the value at rated current.

α_1 = slope angle (differential inductance) of the characteristic in the non-saturated part.

α_2 = slope angle (differential inductance) of the characteristic in the saturated part.

k = saturation knee point, intersection of the two straight lines a and b.

Figure 2 – Parameters for non-linear magnetic characteristic

3.2.8
linear reactor

reactor having a constant reactance (for smoothing reactors: a constant inductance) within the tolerance given in the relevant Clause up to the relevant value of current or voltage

NOTE A linear reactor may have a linear magnetic characteristic as shown in Figure 1a if there is no ferromagnetic component, or a non-linear magnetic characteristic as shown in Figure 1b if the design incorporates a ferromagnetic core or shield.

3.2.9
saturated reactor

reactor specifically designed so that the reactance varies in value with the operating voltage or current

NOTE An example of a reactor with a saturated magnetic characteristic is provided in Figure 1c.

3.2.10
power frequency

rated frequency of the power system in which the reactor is to be installed

3.2.11
reference temperature

for liquid-immersed reactors, the reference temperature is 75 °C; for dry-type reactors, the reference temperature is as given in IEC 60076-11 according to the insulation class

NOTE For dry-type reactors where the temperature rise under normal operation is significantly less than that allowed for the particular insulation class, a lower reference temperature should be agreed upon.

4 Symbols and abbreviations

Symbol	Meaning	Units
f_r	Rated frequency (see NOTE)	Hz
f_rd	Rated discharge frequency	Hz
f_rIN	Rated inrush frequency	Hz
f_rt	Rated tuning frequency	Hz
I_equ	Equivalent current at power frequency	A
I_d	Rated continuous direct current	A
I_h	Harmonic current of the hth harmonic	A
I_Nr	Rated continuous neutral current	A
I_NSTr	Rated short-time neutral current	A
I_MSCr	Rated mechanical short-circuit current	A
I_r	Rated current (see NOTE)	A
I_rd	Rated discharge current	A
I_rIN	Rated inrush current	A
I_SCr	Rated thermal short-circuit current (see NOTE)	A
I_T	Equivalent direct test current	A
I_test	Test current	A
I_STr	Rated short-time current	A
k	Coupling factor (see NOTE)	
L_inc	Incremental inductance	H
L_r, L_SCr	Rated inductance (see NOTE)	H
Q_f	Quality factor	
R	d.c. resistance	Ω
T_NSTr	Rated short-time neutral current duration	s
T_r	Rated current duration	s
T_SCr	Rated thermal short-circuit current duration	s
T_STr	Rated short-time current duration	s
U_ac	AC withstand voltage	V
U_d	Rated d.c. voltage	V
U_dc	DC withstand voltage	V
U_dmax	Highest continuous d.c. voltage	V
U_m	Highest voltage for equipment (see IEC 60076-3:2000, 3.1)	V
U_max	Maximum operating voltage, Maximum continuous voltage (see NOTE)	V
U_pr	Polarity-reversal test voltage	V
U_r	Rated voltage (see NOTE)	V
U_test	Test voltage	V
X_0	Zero-sequence reactance	Ω
X_m	Mutual reactance	Ω
X_r, X_SCr	Rated reactance (see NOTE)	Ω
Z_0	Zero-sequence impedance	Ω
Z_r	Rated continuous impedance	Ω

Symbol	Meaning	Units
Z_{r1}	Rated single-phase continuous impedance	Ω
Z_{r3}	Rated three-phase continuous impedance	Ω
Z_{SCr}	Rated short-circuit impedance	Ω
Z_{SCr1}	Rated single-phase short-circuit impedance	Ω
Z_{SCr3}	Rated three-phase short-circuit impedance	Ω
Z_{STr}	Rated short-time impedance	Ω
Z_{STr1}	Rated single-phase short-time impedance	Ω
Z_{STr3}	Rated three-phase short-time impedance	Ω
NOTE The definition of this rating is given in the relevant Clause pertaining to the specific type of reactor.		

5 Service conditions

5.1 General

Normal service conditions for reactors and the requirements for unusual service conditions are the same as those specified for power transformers in IEC 60076-1 and IEC 60076-11, as applicable.

The purchaser shall identify in his enquiry any service conditions not covered by the normal service conditions as specified in IEC 60076-1 and IEC 60076-11.

NOTE Examples of such conditions are:

- high or low ambient temperature outside the limits prescribed in IEC 60076-1;
- altitude in excess of the limits prescribed in IEC 60076-1;
- an environment with a pollution level (see IEC 60137 and IEC 60815) that requires special consideration regarding the external insulation of the reactor or of the reactor itself; examples are:
  - damaging fumes and vapours;
  - excessive or abrasive dust;
  - industrial pollution;
  - salt spray;
  - tropical humidity.

This is of particular relevance to dry-type reactors. The manufacturer should state the measures to meet these pollution requirements (special coatings, weather shields, etc.) and the maintenance requirements for these measures.

5.2 Seismic conditions

Reactors for operation under seismic conditions should be qualified by calculation in accordance with IEC 60721-2-6, subject to agreement between manufacturer and purchaser.

6 Design, testing, tolerances and application

The application of tests to reactors generally follows the corresponding rules for transformers in IEC 60076, but there may be special factors applicable to certain reactors, set out in this part of IEC 60076, which may limit the test levels achievable. Any limitations on the achievable test levels shall be made clear to the purchaser by the manufacturer at the time of tender.

Irrespective of the actual test levels achievable, reactors shall be designed to withstand the appropriate test levels specified in IEC 60076. Where, exceptionally, the actual test levels are below the levels given in IEC 60076, the manufacturer shall demonstrate to the purchaser by calculation and reference to other similar tested designs that the insulation, clearances and other relevant factors are adequate to meet the IEC 60076 test levels.

Under some circumstances, the use of a test winding with a test core can be appropriate in order to achieve the full test levels.

The tests shall be carried out with the reactor erected substantially as in service, as far as features affecting the test results are concerned. Clause 10.1 of IEC 60076-1:1993 applies, however dry-type reactors may be tested at any ambient temperature.

The purchaser may request calculations and/or comparison with similar rated units instead of type or special tests where these tests have been previously performed on similar units.

As the power factor of reactors is normally very low, the measurement of loss using analog wattmeters may be subject to considerable errors. The measurement of loss using flux compensated current transformers, standard capacitors as voltage transducers and digital wattmeters may provide the required accuracy. A suitable bridge method may also provide the required accuracy. For more information see Clause 10 of IEC 60076-8:1997. At the purchaser’s request, satisfactory documentation regarding the accuracy of the proposed method shall be provided.

A dry-type reactor is not generally enclosed in a steel tank or enclosure. All parts of the reactor assembly shall be considered as live. Therefore, consideration shall be given to prevention of accidental contact by personnel when the reactor is in service. If the purchaser has a particular requirement for the reactor to be mounted in an elevated position, this shall be stated in the tender. Safety precautions such as fencing are likely to be required and shall be considered as part of the substation design. Where there are specific limits for the magnetic field strength specified by the purchaser, the manufacturer shall supply a plot indicating the magnetic field strength in the vicinity of the reactor.

The magnetic field in the immediate vicinity of a dry-type air-core reactor may be of sufficient magnitude to induce heating and reaction forces in nearby metallic objects. Where applicable, guidance concerning the appropriate magnetic clearance is to be supplied by the manufacturer.

The temperature, at specified maximum ambient temperature, of the winding terminals of dry-type reactors shall not exceed the limits given in Table 1.

Table 1 – Temperature limits for winding terminals of dry-type reactors

	Temperature
Bare terminals of copper, copper alloy, aluminium or aluminium alloy:	90 °C
Silver-plated or nickel-plated terminals made of copper, copper alloy, aluminium or aluminium alloy:	115 °C
Tin-plated terminals made of copper, copper alloy, aluminium or aluminium alloy:	105 °C

For more information see IEC 60943.

Tolerances on certain rated and guaranteed values are given in the relevant Clauses. For other quantities, when they are subject to guarantees, reference shall be made to IEC 60076-1, as applicable.

NOTE Other tolerances and tolerances on other quantities may be specified in the enquiry and in the order.

7 Shunt reactors

7.1 General

This Clause describes the requirements for reactors that are intended for connection phase-to-earth, phase-to-neutral or between phases in a power system to compensate for capacitive current. The absorbed reactive power at rated voltage can be fixed, or it may be adjusted by the use of additional means such as:

- phase-controlled switching by a power electronic device (e.g. in a static var scheme);
- d.c. magnetisation of the iron core;
- winding tapping for on-load or off-load setting.

NOTE Information on special applications is given in Annex A.

7.2 Design

With regard to design and installation, the reactor is identified as:

- single-phase or three-phase;
- dry-type or liquid-immersed;
- air-core or gapped-core;
- with or without magnetic shield;
- for indoor or outdoor installation;
- for fixed or variable reactance;
- linear or saturated.

Knowledge of the magnetic characteristic may be necessary for the purchaser and shall be provided on request. It may be determined by measurement or by calculation. For detailed information, see Annex B.

7.3 Terms and definitions

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

7.3.1
rated voltage

U_r

voltage at rated frequency assigned to be applied between the line terminals of a winding of a three-phase reactor, or between the terminals of a winding of a single-phase reactor.

NOTE For single-phase reactors intended to be associated in a three-phase bank, the rated voltage of each individual unit intended for star connection is indicated by a fraction, in which the numerator is the line-to-line voltage and the denominator is √3, for example:

$$U_\mathrm{r} = \frac{525}{\sqrt{3}}\ \mathrm{kV}$$

7.3.2
maximum operating voltage

U_max

specified highest voltage at rated frequency at which the reactor shall be capable of operating continuously

NOTE U_max is not the same as U_m (see 3.2.1) but in particular cases, it may have the same value.

7.3.3
rated power

reactive power of the shunt reactor specified for operation at rated voltage and rated frequency. See also note in 7.4.3.

In the case of reactors with adjustable reactance, the rated power refers to the setting of the reactor with highest reactive power, unless otherwise specified.

NOTE In the case of tapped reactors, the rated power refers to the tapping position with the minimum number of turns.

7.3.4
rated current

I_r

line current derived from rated power and rated voltage

NOTE For single-phase reactors intended to be associated in a three-phase bank, the rated current of each individual unit intended for delta connection is indicated by a fraction in which the numerator is the corresponding line current and the denominator is √3, for example:

$$I_r = \frac{500}{\sqrt{3}} \text{ A}$$

For reactors used in a static var scheme with phase-controlled current, the rated current is referred to the full load current with a sinusoidal waveform unless otherwise specified.

7.3.5
rated reactance (rated inductance)

X_r (L_r)

reactance specified at rated voltage and rated frequency in ohms per phase. It is derived from rated power and rated voltage. For reactors with phase-controlled current, the rated inductance ($L_r = X_r / (2\pi f_r)$) shall be specified.

7.3.6
zero-sequence reactance of a three-phase star-connected reactor

X_0

reactance per phase at rated frequency equal to three times the value of reactance measured between the line terminals connected together and the neutral terminal. The ratio X_0/X_r depends upon the reactor design. For more information, see Annex C.

7.3.7
mutual reactance of a three-phase reactor

X_m

ratio between the induced voltage in an open phase and the current in an excited phase at rated frequency in ohms per phase. It is normally expressed as per unit of the rated reactance.

7.3.8
inrush current level

ratio of the maximum peak current which may occur during reactor energizing and √2 times the rated current

7.4 Rating

The rating of a shunt reactor refers to continuous duty, unless otherwise specified.

For reactors used in a static var source scheme with phase-controlled current, the guaranteed values are referred to full load current with sinusoidal waveform, unless otherwise specified.

7.4.1 Rated voltage

The rated voltage U_r at rated frequency is assigned by the purchaser. The rated voltage provides the basis for the design, the manufacturer's guarantees and the tests unless otherwise specified in 7.8. The rated voltage would usually be specified as the normal operating voltage of the power system.

7.4.2 Maximum operating voltage

The maximum operating voltage U_{max} is specified by the purchaser. It shall not be less than the highest continuous operating voltage applied to the reactor in service. It may be equal to the rated voltage U_r.

7.4.3 Rated power

The rated power shall be specified by the purchaser.

NOTE Where three single-phase reactors are supplied for connection as a three-phase bank, the rated power is normally quoted as the power of a single-phase reactor. If three-phase power is specified, this shall be clearly stated.

7.4.4 Zero-sequence reactance of a three-phase star-connected reactor

Any specific ratio X_0/X_r preference shall be stated by the purchaser at the time of enquiry and shall be agreed upon between purchaser and manufacturer at the time of order.

NOTE For more information on the design dependence of the zero-sequence reactance, see Annex C.

7.4.5 Mutual reactance of a three-phase reactor

The maximum value of the mutual reactance X_m may be specified by the purchaser if it is important for the system.

NOTE 1 The mutual reactance will generally be negligible for:

- a bank of three separate single-phase liquid-immersed reactors;
- a bank of three single-phase air-core (dry-type) reactors in a side-by-side arrangement;
- a three-phase reactor having a magnetic shield for zero-sequence flux.

NOTE 2 For more information on the design dependence of the mutual reactance, see Annex C.

7.4.6 Inrush current level

Unless otherwise specified, the maximum peak inrush current calculation is based on rated voltage U_r, rated frequency and most onerous switching angle. The inrush current level shall be provided by the manufacturer on purchaser request.

NOTE More information on the inrush current characteristic is given in Clause B.6.

7.4.7 Linearity of the shunt reactor

Unless otherwise specified, the reactor shall be a linear reactor within the tolerance given in 7.9.3 up to U_{max}. Alternatively, a maximum harmonic current as a percentage of the fundamental component may be specified at U_r or U_{max}.

7.5 Temperature rise

The temperature rise limits given in IEC 60076-2 for liquid-immersed transformers and in IEC 60076-11 for dry-type transformers apply at the maximum operating voltage U_{max}.

7.6 Insulation level

For specification of the insulation level, see IEC 60076-3.

7.7 Rating plates

Each reactor shall be provided with a rating plate of weatherproof material, fitted in a visible position, showing in all cases the appropriate items indicated below. The entries on the plate shall be indelibly marked (for example by etching, engraving or stamping).

- type of reactor;
- outdoor/indoor application;
- number of this part of IEC 60076;
- manufacturer's name;
- manufacturer's serial number;
- year of manufacture;
- insulation level(s);
- number of phases;
- rated power (for tapped reactors, the power on each tapping position);
- rated frequency;
- rated voltage;
- rated current;
- maximum operating voltage;
- winding connection (where applicable);
- reactance at rated voltage and frequency or inductance at rated voltage, measured value;
- type of cooling;
- thermal class of insulation (for dry-type reactors only);
- temperature rise of top-oil and average winding (for liquid-immersed reactors only);
- total mass;
- transportation mass (for liquid-immersed reactors);
- untanking mass (for liquid-immersed reactors);
- mass of insulating liquid (where applicable);
- type of insulating liquid, if not mineral oil (where applicable);
- connection diagram showing tappings and instrument transformers (where applicable);
- type of tap changer (where applicable);
- zero-sequence reactance, measured value (where applicable on request);
- mutual reactance, measured value (where applicable on request).

7.8 Tests

7.8.1 General

The general requirements for routine, type and special tests are prescribed in IEC 60076-1.

7.8.2 Routine tests

The following routine tests shall be performed:

- measurement of winding resistance (IEC 60076-1);

- measurement of reactance (7.8.5);
- measurement of loss at ambient temperature (7.8.6);
- dielectric tests (7.8.10);
- measurement of insulation resistance and/or capacitance and dissipation factor (tan δ) of the winding insulation to earth for liquid-immersed reactors. (These are reference values for comparison with later measurements in the field. No limitations for the values are given here.)

7.8.3 Type tests

The following type tests shall be performed:

- temperature rise test (7.8.14);
- measurement of vibration for liquid-immersed reactors (7.8.13);
- measurement of acoustic sound level (7.8.12);
- dielectric tests (7.8.10);
- measurement of power consumption of fans and oil pumps, if any.

7.8.4 Special tests

The following special tests shall be performed when specifically requested by the purchaser:

- measurement of zero-sequence reactance on three-phase reactors (7.8.8);
- measurement of mutual reactance on three-phase reactors (7.8.9);
- measurement of harmonics of the current (7.8.7);
- measurement of loss close to reference temperature in the case of liquid-immersed reactors (7.8.6);
- determination of linearity of reactance (7.8.5.3);
- measurement of magnetic characteristic for gapped-core reactors and magnetically-shielded air-core reactors (7.8.11);
- dielectric tests (7.8.10);
- measurement of acoustic sound level close to service temperature (7.8.12).

7.8.5 Determination of reactance and linearity of reactance

7.8.5.1 Method

a) The reactance shall be determined at rated frequency by applying an approximately sinusoidal voltage.

b) The reactance is determined from the applied voltage and the measured current (r.m.s. value). It is assumed that the resistive component of impedance is negligible.

c) The reactance of three-phase reactors shall be measured with symmetrical three-phase voltages applied to the reactor terminals.

The reactance shall be taken as $\dfrac{\text{line} - \text{to} - \text{line applied voltage}}{\text{average measured line current} \times \sqrt{3}}$

NOTE 1 Consideration should be given to the possible flow of zero-sequence current through the shunt reactor under test. This may impact the test result.

NOTE 2 For three-phase reactors with a magnetic shield for zero-sequence flux, by special agreement between manufacturer and purchaser, a reactance measurement may be made with single-phase excitation. In this case, a comparison at a lower voltage between single-phase and three-phase measurements should be made and a suitable correction factor agreed upon.

7.8.5.2 Measurement of reactance at rated voltage (routine test)

The measurement of the reactance shall be made according to 7.8.5.1 at rated voltage and rated frequency except for air-core reactors. In this case, measurements shall be made at rated frequency at any voltage up to rated voltage.

In exceptional cases, for example in the case of reactors with extremely large rated power and high system voltage, it may be difficult to perform the test at rated voltage. For gapped-core reactors and magnetically-shielded air-core reactors designed to be linear, the test voltage shall be the maximum available from the test plant, but at least 0,9 U_r. In this case, the reactor shall be shown to be a linear reactor according to 7.8.5.3. If the manufacturer is not able to measure at U_r, then the achievable test level shall be stated in the tender.

7.8.5.3 Determination of linearity of reactance (special test)

The reactance shall be measured with the method as described in 7.8.5.1 at ≤ 0,7 U_r, 0,9 U_r, U_r and U_{max} or other specified voltages up to maximum operating voltage or, by agreement between purchaser and manufacturer, slightly above this value.

Where the test plant is not adequate to perform the test at these voltages or it is desired to determine the linearity above U_{max}, the test may be done at a lower frequency (and the corresponding lower voltage). Alternatively, the reactor may be shown to be linear by measurement of the magnetic characteristic according to 7.8.11 and the reactance calculated.

NOTE For more information, see also Annex B.

7.8.6 Measurement of loss (routine test, special test)

7.8.6.1 General

Losses are based on reactor operation with rated current at rated frequency and at reference temperature. Measured losses shall be corrected to rated current and reference temperature.

Satisfactory documentation regarding the accuracy of the proposed method shall be provided on request.

For three-phase reactors, the measurement of loss shall be performed under three-phase excitation.

NOTE 1 In case of low loss three-phase reactors, the measured loss of the individual phases may be unequal or even negative in one phase. The arithmetic sum of the three loss values gives the total loss.

NOTE 2 For three-phase reactors with a magnetic shield for zero-sequence flux, by special agreement between manufacturer and purchaser, a measurement of loss may be made with single-phase excitation. In this case, a comparison, at lower voltage, between single-phase and three-phase measurement must be made and a suitable correction factor agreed upon.

7.8.6.2 Air-core reactors

For air-core reactors, the measurements may be made at any voltage up to rated voltage at rated frequency. The loss at rated current shall be obtained by multiplying the measured loss by the square of the ratio of rated current to the current measured at the reduced voltage.

The presence of metal parts in the vicinity around or under reactors will significantly affect the measurement of loss. Therefore metal parts that belong to the support structure when supplied by the manufacturer of the reactor shall be in place during the test and other metal parts shall be avoided.

The total loss is composed of ohmic loss and additional loss. The ohmic loss portion is taken to be equal to $I_r^2 \cdot R$, R being the measured d.c. resistance, I_r being the rated current. The additional loss portion is the difference between the total loss and the ohmic loss I_r^2R.

The measurement of loss may be performed at any convenient ambient temperature and corrected to reference temperature according to the method given in IEC 60076-1.

7.8.6.3 Gapped-core reactors and magnetically-shielded air-core reactors

For gapped-core reactors and magnetically-shielded air-core reactors, the loss shall be measured at rated voltage and rated frequency. The voltage shall be measured with a voltmeter responsive to the mean value of voltage, but scaled to read the r.m.s. value of a sinusoidal wave having the same mean value. If, at rated voltage, the current measured is different from the rated current, the measured loss shall be corrected to the rated current by multiplying the measured loss with the square of the ratio of rated current to measured current.

In exceptional cases, for example extremely large rated power and high system voltage, it may be difficult to meet this test condition. In these cases, the loss at rated current shall be obtained by multiplying the measured loss by the square of the ratio of rated current to the current measured at the reduced voltage. The test voltage shall be at least 0,9 U_r.

The total loss is composed of ohmic loss, iron loss and additional loss. The ohmic loss portion is taken to be equal to I_r^2R, R being the measured d.c. resistance, I_r being the rated current. Iron loss and additional loss cannot be separated by measurement. The sum of iron loss and additional loss is therefore the difference between the total loss and the ohmic loss.

The measurement of loss shall be performed as a routine test at the factory ambient temperature and corrected to reference temperature. The ohmic loss is corrected to reference temperature according to the method given in IEC 60076-1. A correction of iron loss and additional loss to reference temperature is not normally practical. Therefore, iron loss and additional loss shall be deemed independent of temperature. This assumption normally gives a slightly higher loss figure at the reference temperature than actually exists.

When a special measurement of loss test close to reference temperature is specified, the measurement of loss can be performed in conjunction with the temperature rise test. The routine measurement of loss at ambient temperature shall also be made on the same unit to establish a temperature coefficient for total loss (assuming linear variation). The loss figure of all reactors of the same design shall be corrected to reference temperature using the temperature coefficient established on this unit.

NOTE Annex D gives an example of temperature correction of losses.

7.8.7 Measurement of harmonics of the current (special test)

The harmonics of the current in all three phases are measured at rated voltage or, if specified, at maximum operating voltage, by means of a harmonic analyser. The magnitude of the relevant harmonics is expressed as a percentage of the fundamental component. Alternatively, or if the voltage test level cannot be achieved, the harmonics of the current at rated voltage or maximum operating voltage as specified, can be derived from the measured magnetic characteristic or by calculation. For more information on the magnetic characteristic, see Annex B.

The harmonics of the applied voltage shall be adequately measured at the same time.

NOTE 1 Unless the purchaser has particular harmonic current requirements, this test is not normally performed on linear shunt reactors.

NOTE 2 This measurement is practicable only if the distortion factor (see Clause B.5) of the applied voltage is less than 2 %.

7.8.8 Measurement of zero-sequence reactance on three-phase reactors (special test)

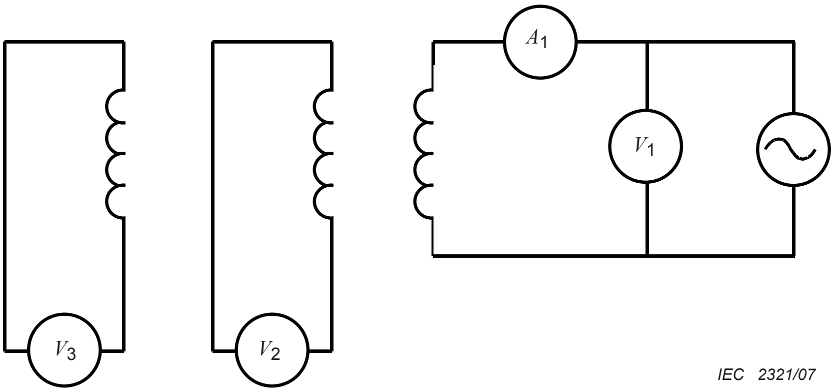
See IEC 60076-1.

This measurement shall be carried out at a voltage corresponding to a neutral current not exceeding the rated phase current. The current in the neutral and the duration of application may be limited to avoid any metallic constructional parts reaching an excessive temperature.

7.8.9 Measurement of mutual reactance on three-phase reactors (special test)

Unless otherwise specified, the measurement shall be made at rated voltage according to Figure 3 for gapped-core reactors and magnetically-shielded air-core reactors. For other reactors, any convenient voltage may be used for this measurement.

The current in the neutral and the duration of application may be limited to avoid any metallic constructional parts reaching an excessive temperature.



Key

V_1, V_2, V_3: voltmeter reading

A_1: ammeter reading

Mutual reactance $X_m = V_2/A_1$ or V_3/A_1 respectively

Figure 3 – Measurement of mutual reactance for three-phase reactors or banks of three single-phase reactors

7.8.10 Dielectric tests

7.8.10.1 General

The application of dielectric tests to shunt reactors in general follows the corresponding rules for transformers in IEC 60076-3, IEC 60076-4 and IEC 60076-11.

7.8.10.2 Separate source a.c. withstand voltage test (routine test, special test)

This test applies as a routine test for liquid-immersed reactors. See Clause 11 of IEC 60076-3:2000.

Dry-type air-core reactors usually employ standard station post or bus support insulators to form the reactor mounting and the insulation between reactor windings and earth, and between phases where two or more units are stacked. Therefore, this test is a test of the support insulators and will only be performed as a special test when specifically requested.

NOTE Unless otherwise indicated in the tender by the manufacturer, the support insulators are assumed to be designed according to IEC 60273 and tested in accordance with IEC 60168.

7.8.10.3 Induced a.c. withstand voltage test (routine test)

Test voltages U_1 and U_2 and the relevant test methods as specified in IEC 60076-3 shall be agreed upon between manufacturer and purchaser at the time of the order.

The induced a.c. withstand voltage test of reactors requires a high reactive power level at a high voltage level. A supply suitable for the high voltage level and the full power rating is necessary.

Exceptionally, the required test level according to IEC 60076-3 for the induced a.c. withstand voltage tests may not be practically achievable when testing large reactors. Any restrictions in the test levels achievable shall be stated by the manufacturer in the tender. In this case, by agreement between purchaser and manufacturer, the induced a.c. withstand voltage test may be performed at lower levels and the dielectric withstand capability of the reactor tested by additional lightning impulse tests for reactors with U_m < 170 kV and by additional lightning impulse tests and switching impulse tests for reactors with $U_m \geq$ 170 kV.

Furthermore special considerations apply to single-phase tests on three-phase reactors without magnetic shield for zero-sequence flux.

Reactors with $U_m \leq$ 72,5 kV and uniform insulation shall be tested according to IEC 60076-3:2000, 12.2.1 (short-duration a.c. withstand voltage test).

Reactors with 72,5 kV < $U_m \leq$ 170 kV and uniform insulation shall be tested according to IEC 60076-3:2000, 12.2.2 (short-duration a.c. withstand voltage test). Single-phase reactors shall be tested with the test level U_1 equal to two times the rated voltage across the winding.

If the power and voltage requirements for the test level U_1 exceeds those available at the test station this shall be stated by the manufacturer in the tender. In this case, the test level U_1 may be reduced or omitted and the test duration extended by agreement between purchaser and manufacturer.

Reactors with 72,5 kV < $U_m \leq$ 170 kV and non-uniform insulation shall be tested according to IEC 60076-3:2000, 12.3 a) and 12.3 b) (short-duration a.c. withstand voltage test). The excitation circuit applicable for all types of reactor design for the phase-to- earth test according 12.3 a) is given in Figure 4. In this case, the neutral will be subjected to a voltage of 1/3 U_{test}. In the special case of a reactor design with a magnetic shield for zero-sequence flux, the test circuit given in Figure 6, may also be used. In this case, there is no voltage stress on the neutral.

By agreement between manufacturer and purchaser, the three-phase test 12.3 b) of IEC 60076-3:2000 may be replaced by three single-phase tests as shown in Figure 5. In this case the test level U_1 is equal to 2 $U_r/\sqrt{3}$.

NOTE 1 During this test, the voltage between phases is lower by a factor of $1,5/\sqrt{3}$ than for a three-phase test.

For single-phase reactors, only test 12.3 a) of IEC 60076-3:2000 applies. The neutral is normally earthed during this test. Alternatively, the voltage at the neutral terminal may be raised by connection to an auxiliary booster transformer to limit the test voltage across the winding to two times the rated voltage across the winding. In such cases, the neutral shall be insulated accordingly.

If the power and voltage requirement for these tests exceeds those available at the test station, this shall be stated by the manufacturer in the tender. In this case, only the test 12.3 b) of IEC 60076-3:2000 may be performed with the test level U_1 being reduced or omitted and the test duration extended by agreement between manufacturer and purchaser.

Reactors with U_m > 170 kV and non-uniform insulation shall be tested according to IEC 60076-3:2000, 12.4 (long-duration a.c. withstand voltage test). For three-phase reactors the test may be performed as a three-phase test or as three single-phase tests with an excitation circuit as given in Figure 5. If the power and voltage requirement for these tests exceeds those available at the test station, by agreement between manufacturer and purchaser, the short-time application of the test level U_1 may be reduced or omitted and the test duration extended.

If the power and voltage requirement for these tests exceeds those available at the test station, for reactors with a magnetic shield for zero-sequence flux, the single-phase test application as given in Figure 6 may be agreed between purchaser and manufacturer.

NOTE 2 The circuit shown in Figure 6 is not in accordance with IEC 60076-3:2000, 12.4, Figure 3. In the circuit shown in Figure 6, the voltage induced along the windings is equal to the voltage induced during the test according 12.4 but the voltage between windings of different phases is only 2/3 of the voltage induced during the test according 12.4 and is slightly less than U_m.

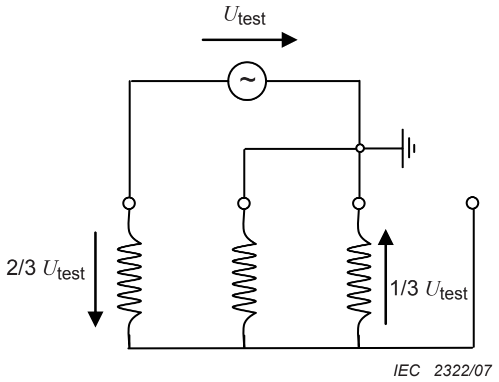


Figure 4 – Phase-to-earth test circuit for single-phase excitation

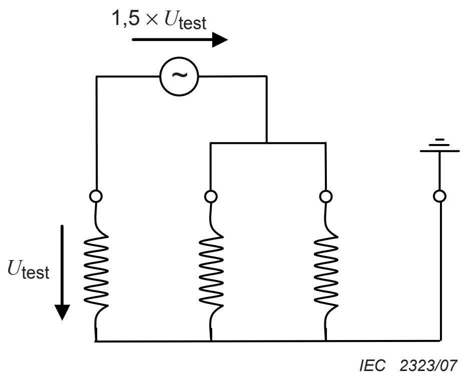


Figure 5 – Phase-to-phase test circuit for single-phase excitation

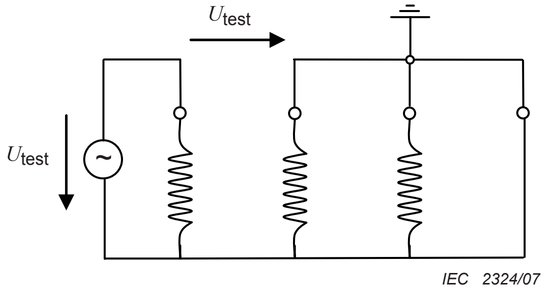


Figure 6 – Single-phase excitation circuit for reactors with magnetic shield for zero-sequence flux

Dry-type reactors shall be tested as single-phase units. By agreement between purchaser and manufacturer, the induced a.c. withstand voltage test may be replaced by additional lightning impulse voltage tests. Alternatively, the turn-to-turn overvoltage test as described in Annex E may be used as a replacement test for equipment with $U_m \leq 36$ kV unless otherwise specified.

7.8.10.4 Lightning impulse test (routine test)

A lightning impulse test including chopped waves shall be a routine test for liquid-immersed reactors, see Clauses 13 and 14 of IEC 60076-3:2000 and Clause 7 of IEC 60076-4:2002.

For dry-type reactors, a lightning impulse test according to Clause 13 of IEC 60076-3:2000 and Clause 7 of IEC 60076-4:2002 shall be applied. Alternatively, the turn-to-turn overvoltage test as described in Annex E may be used for reactors with $U_m \leq 36$ kV as a replacement test, unless otherwise specified.

7.8.10.5 Wet lightning impulse test applicable for dry-type reactors (special test)

When specified, the wet lightning impulse test shall be performed as described in 7.8.10.4 and with application of water spray as described in Clause 9 of IEC 60060-1:1989.

7.8.10.6 Switching impulse test (type test, routine test)

See Clause 15 of IEC 60076-3:2000 and 8.3 of IEC 60076-4:2002.

NOTE Usually, it is difficult to achieve the required waveshape during the test. When the manufacturer anticipates a difficulty in achieving the required waveshape, this should be discussed between manufacturer and purchaser at the earliest possible stage.

In the case of three-phase reactors, the voltage developed between phases during the switching impulse test will be less than 1,5 times the test voltage. The reactor shall however be designed to withstand 1,5 times the test voltage between phases.

7.8.11 Measurement of magnetic characteristic (special test)

Measurement of the magnetic characteristic may be specified when the magnetic characteristic of the reactor is non-linear (Figure 1b) or saturated (Figure 1c).

The linked flux of the reactor windings cannot be measured directly. Therefore, an indirect method shall be used to establish the magnetic characteristic. The methods of measurement include instantaneous measurements of voltage and current at rated frequency, lower frequency measurements or the d.c. discharge test method, see Annex B. Alternative methods of measurement with an equivalent accuracy may also be used.

NOTE In the case of reactors without magnetic shield for zero-sequence flux (usually three limb reactors), a single-phase measurement may not use a flux path representative of the three-phase service condition and this should be taken into account.

7.8.12 Measurement of acoustic sound level (type test, special test)

This measurement shall be made at rated voltage and frequency.

The test shall be made generally in accordance with IEC 60076-10. In some cases, the reactor noise may be disturbed by the noise of the test step-up transformer if it is placed near the reactor. Sound intensity measurements may be used to exclude any disturbing noise.

The test may be performed at any oil, winding and core temperature, but shall be carried out at an ambient temperature not lower than 10 °C. If the test is carried out as a special test, it shall be done at oil, winding and core temperatures as near as possible to service conditions, preferably in conjunction with the heat run test.

NOTE 1 The noise level of the reactor may be temperature dependent. Where a wide range of operating temperature is anticipated, noise measurements at two or more temperatures may be specified.

During measurements on dry-type reactors, sufficient safety clearances to the winding under test shall be ensured. The contour defined in Clause 7 of IEC 60076-10:2005 shall be located

2 m from the winding surface. The prescribed contour shall be located on a horizontal plane at half the winding height.

NOTE 2 For reactors with a high power rating, the test may be carried out on site subject to agreement between purchaser and manufacturer at the time of order, if the test cannot be carried out in the factory.

7.8.13 Measurement of vibration (type test)

7.8.13.1 General

The design and construction of liquid-immersed reactors shall be such as to avoid the detrimental effects of excessive stress due to vibration. Areas of primary concern in the control of vibration to ensure proper performance are as follows:

- vibration of core and coil assembly;
- vibration of tank with associated stresses developed in plates, braces, and welded seams;
- vibration of instruments, accessories, and cooling equipment.

7.8.13.2 Test conditions

The reactor under test shall be completely assembled in the service condition with cooling equipment, gauges, and accessories mounted and connected.

NOTE Where a reactor is equipped with a tank wall mounted noise enclosure, the test may need to be performed without the enclosure by agreement between purchaser and manufacturer.

The reactor shall be mounted on a level surface that will provide proper support for the base, in order to eliminate the generation of abnormal tank stresses.

The reactor shall be energized at maximum operating voltage and the rated frequency. Three-phase excitation is required for three-phase units. When the available test power is insufficient for testing at maximum operating voltage and/or three-phase excitation, the manufacturer shall demonstrate to the purchaser that reduced-voltage testing will produce sufficiently accurate results at the specified conditions. The test should preferably be performed at operating temperature, but may be done at ambient temperature.

7.8.13.3 Method of measurement

The vibration of reactor components shall be measured by transducers, optical detectors, or equivalent measuring devices. The peak-to-peak amplitude of the displacement shall be determined by direct measurement, or calculated from acceleration or velocity measurements. The accuracy of the measurement at twice the rated frequency shall be within 10 µm.

Measurements shall be taken on all four sides of the tank wall at a sufficient number of points to ensure that the maximum value of vibration has been measured.

Measurements or observations shall be made of the vibration of equipment mounted on the tank.

7.8.13.4 Maximum vibration level

The maximum amplitude of tank wall displacement shall not exceed 200 µm peak-to-peak.

For the equipment mounted on the tank, the manufacturer shall, where reasonable, demonstrate that the vibrations measured or observed on test have no long-term effects on the stability and performance of the equipment.

7.8.14 Temperature rise test (type test)

The test shall be made generally in accordance with IEC 60076-2. For dry-type reactors, the temperature class limits as stated in IEC 60076-11 apply.

This test shall be performed at maximum operating voltage U_{max} and rated frequency.

In exceptional cases, for example extremely large rated power and high system voltage, it may be difficult to maintain these test conditions. In this case, the test may be performed at reduced voltage, but not less than 0,9 times the rated voltage U_{r}. The test level shall be stated in the tender by the manufacturer and agreed upon between manufacturer and purchaser at the time of order.

The temperature rises shall be corrected to the maximum operating voltage.

For liquid-immersed reactors, the oil temperature rise shall be multiplied by $\left(\frac{U_{\text{max}}}{U_{\text{test}}}\right)^{2\cdot x}$ and the winding temperature rise above the oil temperature shall be multiplied by $\left(\frac{U_{\text{max}}}{U_{\text{test}}}\right)^{y}$ with x and y according to the following:

• for reactors with ON cooling	x = 0,8	y = 1,3
• for reactors with OF cooling	x = 1,0	y = 1,3
• for reactors with OD cooling	x = 1,0	y = 2,0

NOTE 1 OF and OD cooling would be unusual for a shunt reactor.

NOTE 2 For three-phase reactors with magnetic shield for zero-sequence flux, by agreement between manufacturer and purchaser, a temperature rise test may be made with d.c. current application to the windings. The oil temperature rises are measured at the d.c. current supplying the total corrected losses as determined according to 7.8.6.1. AC excitation of a single-phase at maximum voltage U_{max} is then used to measure the winding temperature rise above the oil temperature.

For dry-type reactors, the winding temperature rise above ambient temperature shall be multiplied by $\left(\frac{U_{\text{max}}}{U_{\text{test}}}\right)^{y}$ with y according to the following:

• for reactors with AN cooling	y = 1,6
• for reactors with AF cooling	y = 1,8

In most cases the total reactor loss at the steady-state condition is somewhat smaller than at reference temperature because the ambient temperature is normally lower than the design value during the test. This effect shall be neglected.

Care shall be taken in providing appropriate connectors and electrical leads to connect the reactor to the power supply during the temperature rise test. This is of particular importance for dry-type air-core reactors.

For dry-type air-core reactors, if requested, the temperature rise of the reactor terminals shall be measured during the reactor temperature rise test. In order to obtain meaningful terminal temperature rise measurements, the purchaser shall supply a connector and at least one meter of incoming conductor of the type that will be used on site, to the manufacturer for use during the temperature rise test. Terminal temperature rise limits shall be as given in Clause 6 (see also IEC 60943).

7.9 Tolerances

7.9.1 General

Unless otherwise specified, for shunt reactors with tappings, the tolerances apply to the principal tapping.

7.9.2 Tolerances on reactance at rated voltage and rated frequency

The tolerance shall be within ±5 % of rated reactance.

In the case of three-phase shunt reactors or banks of three single-phase reactors, the reactance in the three phases, when connected to a power system of symmetrical voltages, shall not deviate from the average by more than ±2 % but always within the above-mentioned ±5 % tolerance.

7.9.3 Tolerances on the linearity of reactance

For a linear reactor, the measurements of reactance made according to 7.8.5.3 shall be within ±5 % of the reactance value measured at rated voltage.

7.9.4 Tolerance on loss

The total loss measured and corrected according to 7.8.6 shall not exceed the guaranteed loss by more than 10 %.

8 Current-limiting reactors and neutral-earthing reactors

8.1 General

This Clause describes the requirements for reactors designed to be connected in series with the power system or between the neutral and earth to limit or control the current. These reactors include:

- Current-limiting reactors intended to limit the short-circuit or short-time current. During normal operation, a continuous current flows through this type of reactor.
- Single-phase neutral-earthing reactors for three-phase power systems, connected between the neutral of a power system and earth, for limiting the line-to-earth current under system fault conditions. Neutral-earthing reactors generally carry very little or no continuous current.

Reactors for other current-limiting or controlling purposes, not covered in other Clauses of this part of IEC 60076, are covered by this Clause. Examples of reactor applications covered by this Clause include:

- Single-phase neutral-earthing reactors connected between the neutral of shunt reactors and earth which are intended to suppress the arc during single-pole switching of a transmission line. For more information, see also Annex A.
- Bus tie reactors connected between two different bus sections or power systems to limit fault current transfer.
- Motor starting reactors connected in series with an a.c. motor for limiting the starting current.
- Power flow control reactors connected in series in a power system to control the power flow.
- Arc-furnace series reactors connected in series with an arc-furnace to increase the efficiency of the metal melting operation and reduce voltage variation on the power system.

- Insertion reactors momentarily connected across the contacts of a switching device for synchronising and/or for damping switching transients.
- Test reactors used in the electrical test circuit of a high power laboratory for adjusting the test current to the required value.
- Converter or phase reactors connected in series to a voltage source converter to accommodate the voltage caused by the dissimilar wave shapes at the converter terminals and the a.c. bus.

Depending on the specific application of such reactors, the requirements and tests as per Clause 8 of this part of IEC 60076 may not fully apply. Any deviation shall be agreed upon between manufacturer and purchaser.

8.2 Design

With regard to design and installation, reactors covered under this Clause are classified as:

- single-phase or three-phase;
- dry-type or liquid-immersed type;
- air-core or gapped-core;
- with or without magnetic shield;
- with or without taps;
- for indoor or outdoor installation;
- dry-type with each phase mounted side-by-side or in a vertical stack.

NOTE 1 The magnetic shield of a current-limiting reactor is generally designed to be saturated when the reactor carries a high short-circuit current. This will have the effect of reducing the reactance under short-circuit conditions. The rated reactance at short-circuit current is therefore smaller than the reactance at rated continuous current.

NOTE 2 The magnetic shield of a reactor to be connected to the neutral of a shunt reactor is generally designed not to be saturated up to the rated short-time current. Therefore the reactance is regarded as constant over its operational current range.

8.3 Terms and definitions

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

8.3.1

rated continuous current

I_{r}

specified steady-state r.m.s. value of current at rated frequency

8.3.2

rated thermal short-circuit current

I_{SCr}

specified r.m.s. value of the steady-state symmetrical component of the short-circuit current at rated frequency to be carried for the specified duration. This is valid for current-limiting reactors and for neutral-earthing reactors to be connected to the neutral of the power system.

8.3.3

rated thermal short-circuit current duration

T_{SCr}

specified duration of the rated thermal short-circuit current

8.3.4
rated mechanical short-circuit current

I_{MSCr}

specified asymmetrical (peak) fault current. If not specified, the asymmetrical (peak) fault current is derived from the rated thermal short-circuit current.

8.3.5
rated short-time current

I_{STr}

For motor-starting and for test reactors: the specified r.m.s. value of the current at rated frequency which is applied for a specified duty-cycle

For neutral-earthing reactors to be connected to the neutral of a shunt reactor: the specified r.m.s. value of the arc-suppression current of the faulted line at rated frequency

8.3.6
rated short-time current duration T_{STr} or duty-cycle

specified duration of the rated short-time current. The duty-cycle is the specified duration of each application, the interval between applications and the number of applications of the rated short-time current.

8.3.7
rated inductance

L_{SCr}

specified inductance at rated frequency and at rated thermal short-circuit current I_{SCr}. The rated inductance also includes mutual inductance, if applicable.

8.3.8
rated reactance

X_{SCr}

product of rated inductance and rated frequency multiplied by 2π. The rated reactance is expressed in Ohms per phase.

8.3.9
mutual reactance X_{m} of a three-phase reactor

ratio between induced voltage in an open phase and the current in an excited phase in Ohms per phase at rated continuous current I_{r} and rated frequency (see also Figure 7)

8.3.10
coupling factor

k

mutual reactance expressed in per unit or percent of rated reactance

8.3.11
rated short-circuit impedance

Z_{SCr}

specified impedance per phase at rated frequency and rated thermal short-circuit current $I_{\mathrm{SCr.}}$

The rated short-circuit impedance is the phasor sum of the rated reactance and the effective resistance (derived from the losses) of the reactor. Normally, the resistance is much smaller than the reactance.

8.3.11.1
rated three-phase short-circuit impedance

Z_{SCr3}

specified impedance per phase at rated frequency and rated three-phase thermal short-circuit current I_{SCr}, as an average of the three phases

8.3.11.2
rated single-phase short-circuit impedance

Z_{SCr1}
specified impedance per phase at rated frequency and rated thermal short-circuit current I_{SCr}, with the other two phases open-circuited

8.3.12
rated short-time impedance

Z_{STr}
specified impedance per phase at rated frequency and rated short-time current I_{STr}

8.3.12.1
rated three-phase short-time impedance

Z_{STr3}
specified impedance per phase at rated frequency and rated three-phase short-time current I_{STr}, as an average of the three phases

8.3.12.2
rated single-phase short-time impedance

Z_{STr1}
specified impedance per phase at rated frequency and rated short-time current I_{STr} with the other two phases open-circuited

8.3.13
rated continuous impedance

Z_{r}
specified impedance per phase at rated frequency and rated continuous current I_{r}

8.3.13.1
rated three-phase continuous impedance

Z_{r3}
specified impedance per phase at rated frequency and rated three-phase continuous current I_{r}, as an average for the three phases

8.3.13.2
rated single-phase continuous impedance

Z_{r1}
specified impedance per phase at rated frequency and rated continuous current I_{r} with the other two phases open-circuit

8.4 Rating

8.4.1 Rated continuous current

The rated continuous current I_{r} shall be specified by the purchaser. For reactors connected in series in each phase, the rated continuous current may be derived from the system voltage and throughput power specified by the purchaser.

Unless otherwise specified, for reactors connected in series in each phase, the rated continuous current is a symmetrical three-phase current.

In the case of neutral-earthing reactors (either to be connected at the neutral of a three-phase power system or at the neutral of a shunt reactor), a rated continuous current shall be specified by the purchaser if it is more than 5 % of the rated thermal short-circuit current or the rated short-time current.

In the case of motor starting reactors, for applications where the reactor is not bypassed after the motor starting operation, a rated continuous current shall be specified by the purchaser.

8.4.2 Rated thermal short-circuit current

The rated thermal short-circuit current I_{SCr} shall be specified by the purchaser for current-limiting and neutral-earthing reactors connected to the neutral of a three-phase power system. It shall be specified by the purchaser as not less than the highest value of symmetrical r.m.s. current under recognized fault conditions, which may be seen by the reactor in service. Alternatively, the rated thermal short-circuit current may be derived from the specified system short-circuit power, system voltage and reactor impedance.

8.4.3 Rated thermal short-circuit current duration

The rated thermal short-circuit current duration T_{SCr}, where applicable, shall either be specified by the purchaser or otherwise the standard values as indicated below shall be used:

- for current-limiting reactors, 2 s.

NOTE 1 The duration selected should reflect the cumulative thermal effects of the utility's auto re-closure philosophy and the time a fault is allowed to exist before it is interrupted.

NOTE 2 The duration of thermal short-circuit current can impact the cost of the reactor where the short-circuit current exceeds about twenty-five times the rated continuous current.

- for neutral-earthing reactors connected to the neutral of a power system, 10 s.

If several successive faults may occur within a short period of time, the duration, the interval of time between applications, and the number of applications shall be specified by the purchaser. The rated thermal short-circuit current duration shall be selected accordingly.

8.4.4 Rated mechanical short-circuit current

The specified rated mechanical short-circuit current I_{MSCr} depends on the X/R ratio of the system and shall be calculated as per 4.2.3 of IEC 60076-5:2006. If the system impedance and X/R ratio are not specified by the purchaser, the rated mechanical short-circuit current shall be taken to be a value equal to 1,8 $\sqrt{2}$ times the rated thermal short-circuit current value ($I_{\mathrm{MSCr}} = 2{,}55\ I_{\mathrm{SCr}}$).

8.4.5 Rated short-time current

The rated short-time current I_{STr} shall be specified, where applicable, by the purchaser along with the associated rated short-time current duration, T_{STr} or duty-cycle.

For neutral-earthing reactors to be connected at the neutral of a shunt reactor, this current is the arc-suppression current of the faulty line following single-pole switching.

NOTE A rated short-time current can be specified for any type of reactor that is intended for applications where the current will be applied repetitively.

8.4.6 Rated short-time current duration or duty-cycle

The rated short-time current duration T_{STr} or duty-cycle shall be specified by the purchaser, where applicable. For example, it may be associated with motor starting operations or test circuit duty where a prescribed cycle of short-time current and zero current conditions is specified. Subsequent to the starting/test cycle, the reactor may carry rated continuous current or be removed from service.

All information regarding the short-time current duty-cycle shall be provided in the reactor specification, including, where applicable, the maximum magnitude and duration of short-time current, minimum duration between successive short-time current applications, the level of current between short-time current applications and the maximum number of consecutive applications of short-time current of the specified duration.

NOTE Several different duty-cycles may be specified for different operating conditions, for example for cold and warm starting of motors.

For neutral-earthing reactors to be connected to the neutral of a shunt reactor, the rated short-time current duration shall be specified by the purchaser. It is related to the time between the appearance of the fault and either the successful re-closing of the faulted phase or the disconnection of all three phases.

8.4.7 Coupling factor

Where the purchaser requires that the rated single-phase short-circuit impedance is to be approximately equal to the three-phase short-circuit impedance, the maximum allowable coupling factor shall be specified in the enquiry.

For a three-phase reactor, or a bank of separate single-phase reactors with defined installation, the manufacturer shall, on request, supply information on the coupling factors or mutual reactances between phases (see Annex C for details).

8.4.8 Rated short-circuit impedance

The rated short-circuit impedance Z_{SCr} shall be specified by the purchaser. Alternatively, the purchaser may specify the system short-circuit current or power and the desired thermal short-circuit current. The rated short-circuit impedance shall be derived from these values.

In the case of reactors that do not have a thermal short-circuit current rating, rated impedances shall be specified at the rated short-time current I_{STr} (see 8.4.9) and/or at the rated continuous current I_{r} (see 8.4.10), as applicable.

8.4.8.1 Reactors with a coupling factor less than 5 %

In the case of three-phase reactors where the coupling factor is less than 5 %, only the rated three-phase short-circuit impedance Z_{SCr3} as defined in 8.3.11.1 needs to be specified.

8.4.8.2 Reactors with a coupling factor of 5 % or more

If the coupling factor is 5 % or more (this will normally be the case for three-phase vertically stacked reactors), two different impedances shall be recognised: The rated three-phase short-circuit impedance Z_{SCr3} and the rated single-phase short-circuit impedance Z_{SCr1}.

The duty on three-phase current-limiting reactors is dependent on system earthing. If there is high impedance system earthing, the duty on reactors connected in series in each phase is to limit symmetrical three-phase fault currents. In this case, only Z_{SCr3} shall be specified.

If the power system is effectively earthed, both single-phase and three-phase system fault currents are to be evaluated, and both Z_{SCr3} and Z_{SCr1} shall be considered. One or both of these impedances shall be specified and the measured values provided upon request. If only one impedance value is specified, it is understood that both Z_{SCr3} and Z_{SCr1} shall meet the specified impedance value within the tolerances identified in 8.10. It shall be kept in mind that in some cases, such as where the reactors are mounted in vertical stacked arrangements and coupling factors of adjacent units are significant, reactor impedance during a single-phase fault may be significantly different than during a three-phase fault.

Generally, for the three-phase reactor applications dealt with in this Clause, each phase reactor is designed to have the same self-inductance. However, where it is desirable to vertically stack reactors and also maintain three equal current magnitudes during three-phase fault conditions, the purchaser shall specify this and the reactors shall be compensated for mutual inductance. In this case, the self-inductance of each phase reactor is uniquely adjusted. Therefore, the self-inductance of each phase reactor will not be the same as that of the other phases and the effective phase impedance during a single-phase fault will be lower than that for a three-phase fault. For more information, see Annex C.

8.4.9 Rated short-time impedance

A short-time impedance Z_{STr} together with the rated short-time current I_{STr}, and the rated short-time current duration T_{STr} or duty-cycle shall be specified by the purchaser, where applicable.

The reactor shall be a linear reactor for all currents up to and including the rated short-time current I_{STr}.

In the case of three-phase reactors where the coupling factor is less than 5 %, only the rated three-phase short-time impedance shall be specified.

If the coupling factor is 5 % or more (this will normally be the case for three-phase vertically stacked reactors), two different impedances shall be recognised: the rated three-phase short-time impedance Z_{STr3} and the rated single-phase short-time impedance Z_{STr1}. One or both of these impedances shall be specified and the measured values provided upon request (see also 8.4.8.2).

8.4.10 Rated continuous impedance

In the case of air-core reactors, the rated continuous impedance Z_{r}, rated short-time impedance Z_{STr}, and the rated short-circuit impedance Z_{SCr}, are identical.

In the case of three-phase reactors where the coupling factor is less than 5 %, only the rated three-phase short-time impedance shall be specified.

If the coupling factor is 5 % or more (this will normally be the case for three-phase vertically stacked reactors), two different impedances shall be recognised: The rated three-phase continuous impedance Z_{r3} and the rated single-phase continuous impedance Z_{r1}. One or both of these impedances shall be specified and the measured values provided upon request (see also 8.4.8.2).

For gapped-core reactors and magnetically-shielded air-core reactors, the rated continuous impedance Z_{r}, will be greater than the rated short-circuit impedance Z_{SCr} and rated short-time impedance Z_{STr}.

In this case, the purchaser may specify a maximum value for the rated continuous impedance where this is important for voltage control or other reasons. If this maximum value is not specified, the impedance for rated continuous current shall be provided by the manufacturer upon request, be measured, and appear on the rating plate.

The reactor shall be a linear reactor for all currents up to and including the rated continuous current I_{r}.

8.5 Ability to withstand rated thermal and rated mechanical short-circuit current

Current-limiting reactors and neutral-earthing reactors to be connected to the neutral of the power system shall be designed to withstand the thermal and dynamic effects of the rated short-circuit current including the associated electrical stress for its rated duration. Unless otherwise specified by the purchaser, the interval between fault conditions totalling the rated duration is at least 6 h. If the expected frequency of short-circuit application is more than approximately ten times per year on average, this shall be specified by the purchaser.

8.6 Temperature rise

8.6.1 Temperature rise at rated continuous current

The temperature rise limits given in IEC 60076-2 and in IEC 60076-11 respectively apply. Reactors connected in series in the power system shall be designed for loading and overload according to the guidelines set out in IEC 60076-7 for liquid-immersed and IEC 60905 for dry-type reactors.

8.6.2 Temperature due to rated thermal short-circuit current and rated short-time current loading

The calculated temperature of the winding after rated thermal short-circuit current I_{SCr} or rated short-time current I_{STr} loading shall not exceed the values prescribed for transformer windings under short-circuit conditions given in 4.1.4 of IEC 60076-5:2006.

8.7 Insulation level

8.7.1 General

For specification of the insulation level, see IEC 60076-3.

8.7.1.1 Insulation requirements for current-limiting reactors

The insulation requirements between phases and to earth shall generally correspond to the highest voltage of equipment U_{m}. The insulation requirements across the winding may be specified to be lower, particularly if surge arresters are connected in parallel with the winding. It is recommended that the rated voltage of the parallel connected surge arrester is selected to be not less than 1,2 times the voltage developed across the reactor by the rated thermal short-circuit current.

NOTE The manufacturer shall ensure the reactor is designed to withstand the voltages experienced across the winding during short-circuit conditions.

If the reactor is to be installed with a by-pass arrangement which may be closed when the reactor is energized, this shall be stated by the purchaser and a double-ended lightning impulse test should be specified.

8.7.1.2 Insulation requirements for neutral-earthing reactors

The insulation requirements shall correspond to the insulation of the neutral of the power system or the shunt reactor in which the reactor is to be installed. For the earth terminal, the selection of a reduced insulation level may be appropriate (non-uniform insulation).

8.8 Rating plates

Each reactor shall be provided with a rating plate of weatherproof material, fitted in a visible position, showing in all cases the appropriate items indicated below. The entries on the plate shall be indelibly marked (for example by etching, engraving or stamping).

- type of reactor;
- outdoor/indoor application;
- number of this part of IEC 60076;
- manufacturer’s name;
- manufacturer’s serial number;
- year of manufacture;
- insulation level(s);
- number of phases;
- rated frequency;
- highest voltage for equipment;
- rated continuous current (where applicable);
- rated thermal short-circuit current and duration (where applicable);

- rated mechanical short-circuit current (where applicable);
- rated short-time current and duration or duty-cycle (where applicable);
- impedance at rated continuous current at single-phase and at three-phase excitation, measured values (where applicable);
- impedance at rated short-circuit current, calculated or measured value (for gapped-core reactors and magnetically-shielded air-core reactors);
- impedance at rated short-time current, calculated or measured value (for reactors where short-time current is specified);
- type of cooling;
- thermal class of insulation (for dry-type reactors only);
- total mass;
- transportation mass (for liquid-immersed reactors);
- untanking mass (for liquid-immersed reactors);
- mass of insulating liquid (where applicable);
- type of insulating liquid, if not mineral oil (where applicable);
- insulation level of the earth terminal of the winding for neutral-earthing reactors with non-uniform insulation;
- connection diagram showing tappings and instrument transformers (where applicable);
- type of tap changer (where applicable).

8.9 Tests

8.9.1 General

The general requirements for routine, type and special tests shall be as prescribed in IEC 60076-1.

8.9.2 Routine tests

The following routine tests shall be performed:

- measurement of winding resistance (IEC 60076-1);
- measurement of impedance at rated continuous current (8.9.5);
- measurement of impedance at rated short-time current for neutral-earthing reactors to be connected to the neutral of a shunt reactor, starter reactors and test reactors (8.9.6);
- measurement of loss at ambient temperature (8.9.7);
- separate source a.c. withstand voltage test for liquid-immersed reactors (8.9.8);
- winding overvoltage test for current-limiting reactors (8.9.9);
- winding overvoltage test for neutral-earthing reactors (8.9.10);
- measurement of insulation resistance and/or capacitance and dissipation factor (tan δ) of the winding insulation to earth for liquid-immersed reactors. (These are reference values for comparison with later measurements in the field. No limitations for the values are given here).

8.9.3 Type tests

The following type tests shall be performed:

- temperature rise test at rated continuous current (8.9.11);
- lightning impulse test for current-limiting reactors (8.9.12);

- measurement of power consumption of fans and oil pumps, if any.

8.9.4 Special tests

The following special tests shall be performed when specifically requested by the purchaser:

- short-circuit test for current-limiting reactors, neutral-earthing reactors to be connected to a neutral of a power system and for test reactors (8.9.13);
- measurement of reactance of the winding in the case of gapped-core and magnetically-shielded air-core reactors (8.9.21);
- measurement of acoustic sound level (8.9.14);
- separate source a.c. withstand voltage test for dry-type reactors mounted on support insulators (8.9.8);
- measurement of loss close to reference temperature in case of liquid-immersed reactors (8.9.7);
- measurement of vibration at rated continuous current for liquid-immersed reactors (8.9.15);
- switching impulse test (8.9.16);
- double-ended lightning impulse test (8.9.17);
- measurement of coupling factor (8.9.18);
- wet winding overvoltage test (8.9.19);
- wet separate source a.c. withstand voltage test for dry-type reactors mounted on support insulators (8.9.20).

8.9.5 Measurement of impedance at rated continuous current (routine test)

The impedance shall be measured at rated frequency.

For air-core reactors, the measurements may be made at any current up to rated continuous current.

For gapped-core reactors and magnetically-shielded air-core reactors, the measurements shall be made at rated continuous current where a rated continuous current has been specified. If not specified, the highest available (practicable) continuous current to be used for test shall be agreed upon by the manufacturer and purchaser at the tender stage.

For three-phase reactors where the coupling factor between phases exceeds 5 %, the current in each phase shall be measured while applying a system of symmetrical three-phase voltages to the star-connected phase windings.

$$\text{The impedance shall be taken as } \frac{\text{line} - \text{to} - \text{line applied voltage}}{\text{average measured line current} \times \sqrt{3}}$$

For three-phase reactors with coupling factors greater than 5 %, the mutual reactances between each pair of phases shall be measured and their polarities shall be checked. For the method of measurement, see Figure 7. In the event that it is not possible to totally shield connecting leads from one another in order to prevent induced voltages, a more rigorous determination of mutual reactances can be obtained by measuring the reactances of each single-phase coil and of each pair of phase coils connected in series. The mutual reactances can be derived from the measured results by calculation.

For all air-core reactors, the single-phase impedance of each phase reactor shall also be measured with a single-phase source.

For three-phase reactors with a coupling factor less than or equal to 5 %, the impedance may be measured with a single-phase source only.

NOTE For air-core reactors, this test will also verify the rated short-circuit or short-time impedance.

8.9.6 Measurement of impedance at rated short-time current (routine test)

This measurement applies for neutral-earthing reactors that are to be connected to the neutral of a shunt reactor, starter reactors and test reactors having a gapped-core and/or a magnetic shield.

The impedance shall be measured at rated frequency and at rated short-time current. The duration of the measurement shall be limited to avoid excessive temperature appearing on any part of the reactor.

NOTE If this test is particularly onerous because of a requirement for a high power test facility, then by agreement, it may be performed at rated short-time current as a type test and at reduced current as a routine test.

8.9.7 Measurement of loss (routine test, special test)

8.9.7.1 General

This measurement applies only to reactors where a rated continuous current is specified.

Losses are based on reactor operation with rated continuous current at rated frequency and at reference temperature. Measured losses shall be corrected to rated continuous current and reference temperature.

Satisfactory documentation regarding the accuracy of the proposed method shall be provided on request.

For three-phase reactors, the measurement of loss shall be performed under three-phase excitation.

NOTE 1 In case of low loss three-phase reactors, the measured loss of the individual phases may be unequal or even negative in one phase. The arithmetic sum of the three loss values gives the total loss.

NOTE 2 For three-phase reactors with a magnetic shield for zero-sequence flux, by special agreement between manufacturer and purchaser, a measurement of loss may be made with single-phase excitation. In this case, a comparison, at lower voltage, between single-phase and three-phase measurements should be made and a suitable correction factor agreed upon.

8.9.7.2 Air-core reactors

The measurement of loss may be performed at any current at rated frequency and corrected to rated continuous current by multiplying the measured loss by the square of the ratio of rated continuous current to the test current.

Metal parts belonging to the support structure when supplied by the manufacturer of the reactor that might affect the measurement of loss, shall be in place for the test.

NOTE The presence of metal parts in the vicinity around or under reactors will significantly affect the measurement of loss. Therefore, metal parts that belong to the support structure of the reactor shall be present during the test and other metal parts shall be avoided.

The total loss is composed of ohmic loss and additional loss. The ohmic loss portion is taken to be equal to I_r^2R, R being the measured d.c. resistance, I_r being the rated continuous current. The additional loss portion is the difference between the total loss and the ohmic loss I_r^2R.

The measurement of loss may be performed at any convenient ambient temperature and corrected to reference temperature according to the method given in IEC 60076-1.

8.9.7.3 Gapped-core reactors and magnetically-shielded air-core reactors

The measurement of loss shall be performed at rated continuous current and at rated frequency.

In exceptional cases, for example extremely large rated power, it may be difficult to meet this test condition. In these cases, the loss at rated continuous current shall be obtained by multiplying the measured loss by the square of the ratio of rated continuous current to the test current. The test current shall be at least $0,9I_r$.

The total loss is composed of ohmic loss, iron loss and additional loss. The ohmic loss portion is taken to be equal to I_r^2R, R being the measured d.c. resistance and I_r being the rated continuous current. Iron loss and additional loss cannot be separated by measurement. The sum of iron loss and additional loss is therefore the difference between the total loss and the ohmic loss.

The measurement of loss shall be performed as a routine test at the factory ambient temperature and corrected to reference temperature. The ohmic loss is corrected to reference temperature according to the method given in IEC 60076-1. A correction of iron loss and additional loss to reference temperature is not normally practical. Therefore, iron loss and additional loss shall be deemed independent of temperature. This assumption normally gives a slightly higher loss figure at the reference temperature than actually exists.

When a special measurement of loss test close to reference temperature is specified, the measurement of loss can be performed in conjunction with the temperature rise test. The routine measurement of loss at ambient temperature shall also be made on the same unit to establish a temperature coefficient for total loss (assuming linear variation). The loss figure of all reactors of the same design shall be corrected to the reference temperature using the temperature coefficient established on this unit.

NOTE Annex D gives an example of temperature correction of losses.

8.9.8 Separate source a.c. withstand voltage test (routine test, special test)

The test shall be carried out in general accordance with Clause 11 of IEC 60076-3:2000 and is a routine test for all liquid-immersed reactors.

The test voltage shall be applied:

- between each winding and earth;
- between different windings where applicable.

Dry-type air-core reactors usually employ standard station post or bus support insulators to form the reactor mounting and the insulation between reactor windings and earth, and between phases where two or more units are stacked. Therefore, this test is a test of the support insulators and will only be performed as a special test when specifically requested.

NOTE Unless otherwise indicated in the tender by the manufacturer, the support insulators are assumed to be designed according to IEC 60273 and tested in accordance with IEC 60168.

8.9.9 Winding overvoltage test for current-limiting reactors (routine test)

Since the induced a.c. withstand voltage test cannot be carried out in accordance with Clause 12 of IEC 60076-3:2000 this test shall be carried out as a lightning impulse test on each end of each winding in turn with the other end of the winding directly earthed. The terminals of all other windings, where applicable, are also to be earthed. The test level shall be according to

IEC 60076-3. If reduced insulation requirements across the winding are specified, the lightning impulse test procedure shall be performed by using the specified reduced insulation level value.

Due to the low impedance of the reactor, the standard waveshape usually cannot be met. For more information see IEC 60076-4:2002, Clause A.3.

NOTE The correct time to half value may not be achievable. This shorter time should normally be accepted.

Alternatively, for dry-type reactors, the turn-to-turn overvoltage test as described in Annex E may be performed in lieu of the lightning impulse test for equipment with $U_\mathrm{m} \leq 36$ kV, unless otherwise specified.

8.9.10 Winding overvoltage test for neutral-earthing reactors (routine test)

This test shall be carried out as a lightning impulse test applied to the terminal which is to be connected to the transformer or shunt reactor neutral, with the other terminal earthed. The test is made in accordance with 13.3.2 b) of IEC 60076-3:2000. A longer duration of the impulse voltage front time is allowed, up to 13 µs.

NOTE The correct time to half value may not be achievable. This shorter time should normally be accepted.

Alternatively, for dry-type reactors, the turn-to-turn overvoltage test as described in Annex E may be performed in lieu of the lightning impulse test for equipment with $U_\mathrm{m} \leq 36$ kV, unless otherwise specified.

8.9.11 Temperature rise test at rated continuous current (type test)

The test shall be carried out in general accordance with IEC 60076-2. For dry-type reactors, the temperature class limits as stated in IEC 60076-11 apply.

This test shall be performed at rated continuous current I_r and rated frequency.

In exceptional cases, for example extremely large rated power, it may be difficult to meet this test condition. In these cases, the test may be performed at a reduced current value but not less than $0{,}9 \cdot I_\mathrm{r}$. The test level shall be stated in the tender by the manufacturer and agreed between manufacturer and purchaser at the time of order.

The temperature rises shall be corrected to the rated continuous current.

For liquid-immersed reactors, the oil temperature rise shall be multiplied by $\left(\frac{I_\mathrm{r}}{I_\mathrm{test}}\right)^{2 \cdot x}$ and the winding temperature rise above the oil temperature shall be multiplied by $\left(\frac{I_\mathrm{r}}{I_\mathrm{test}}\right)^{y}$ with x and y according to the following:

- for reactors with ON cooling $x = 0{,}8$ $y = 1{,}3$
- for reactors with OF cooling $x = 1{,}0$ $y = 1{,}3$
- for reactors with OD cooling $x = 1{,}0$ $y = 2{,}0$

NOTE For three-phase reactors with magnetic shield for zero-sequence flux, by agreement between manufacturer and purchaser, a temperature rise test may be made with d.c. current application to the windings. The oil temperature rises are measured at the d.c. current supplying the total corrected losses as determined according to 8.9.7.1. a.c. excitation of a single-phase at rated continuous current I_r is then used to measure the winding temperature rise above the oil temperature.

For dry-type reactors, the winding temperature rise above ambient temperature shall be multiplied by $\left(\frac{I_{\mathrm{r}}}{I_{\mathrm{test}}}\right)^{y}$ with y according to the following:

- for reactors with AN cooling $y = 1{,}6$
- for reactors with AF cooling $y = 1{,}8$

In most cases, the total reactor loss at the steady-state condition is somewhat smaller than at reference temperature because the ambient temperature is normally lower than the design value during the test. This effect shall be neglected.

For dry-type air-core reactors, if requested, the temperature rise of the reactor terminals shall be measured during the reactor temperature rise test. In order to obtain meaningful terminal temperature rise measurements, the purchaser shall supply a connector and at least one meter of incoming conductor of the type that will be used on site, to the manufacturer for use during the temperature rise test. Terminal temperature rise limits shall be as given in Clause 6 (see also IEC 60943).

8.9.12 Lightning impulse test for current-limiting reactors (type test)

For general information, see Clause 13 of IEC 60076-3:2000 and for dry-type reactors, Clause 21 of IEC 60076-11:2004. See also IEC 60076-4.

This test is intended to test the insulation between the tested terminals and earth.

The test voltage is applied to each terminal of the tested winding in turn, while the other terminal is earthed through a resistor, if necessary, to achieve the standard impulse waveshape. The terminals of the other windings, where applicable, shall also be earthed.

8.9.13 Short-circuit current test (special test)

8.9.13.1 General

For general information, IEC 60076-5 applies.

When a short-circuit current test is specified, it shall be carried out generally in accordance with 4.2.2 to 4.2.7 of IEC 60076-5:2006.

The specification for the short-circuit current test shall include the test current level, the duration of each applied shot, the number of test current shots and the tap terminal connection desired (in the case of tapped reactors).

If this information is not specified, the test shall consist of two test shots of 0,25 s on each reactor phase with the first peak of the applied current at the rated mechanical short-circuit current value. The test shall be performed at the maximum inductance tap position (in the case of tapped reactors).

Three-phase reactors, or a three-phase bank of separate reactors with defined installation, shall undergo three, three-phase short-circuit tests, each consisting of two shots. In each test, a different reactor phase shall be selected to experience the first maximum offset peak current.

The peak value of the current obtained during the test shall not deviate by more than 5 % from the respective specified value.

If a thermal short-circuit test is specified, it shall consist of one symmetrical current shot at the rated thermal short-circuit current I_{SCr} for the rated duration. If the rated thermal short-circuit current cannot be achieved, the duration shall be extended up to 6 s at reduced current to give at least the specified I^2t value.

The thermal short-circuit test may be also combined with the mechanical short-circuit test to reduce the total number of shots, provided all the test parameters can be met.

For more information see Annex F.

8.9.13.2 Acceptance criteria

The ability of the reactor to withstand the test shall be determined in accordance with 4.2 of IEC 60076-5:2006.

Before and after the short-circuit test, routine tests including measurement of impedance and losses and the performance of a winding overvoltage test according to 8.9.9 or 8.9.10 at 100 % of specified voltage shall be carried out on the reactor. Impedance and loss values shall be consistent within measurement tolerance limits. Oscillograms from the required dielectric test shall show no change; agreeing within the limits of the high voltage dielectric test systems.

For liquid-immersed reactors general information concerning fault detection is provided in 4.2.7 of IEC 60076-5:2006.

For dry-type reactors, visual inspection of the reactor and supporting structure shall give no indication that there has been any change in mechanical condition that will impair the function of the reactor. If after the short-circuit test program, the winding clamping system has deteriorated, or surface cracks have increased significantly in number or dimensions, the reactor is considered to have failed the short-circuit test. In case of doubt, up to three more short-circuit tests with fully offset current shall be applied to verify that the monitored condition has stabilized. If the deterioration continues, the reactor shall be considered to have failed the test. If conditions stabilize after one or two extra short-circuit tests and coupled with successful routine tests after short-circuit tests, the reactor shall be considered to have passed the short-circuit test. For more information, see Annex F.

8.9.14 Measurement of acoustic sound level at rated continuous current (special test)

This measurement shall be made at rated continuous current and rated frequency. The method prescribed in IEC 60076-10 applies. In some cases, the reactor noise may be disturbed by the noise of the test transformer if it is placed near the reactor. Sound intensity measurements may be used to exclude any disturbing noise.

During measurements on dry-type reactors, sufficient safety clearances to the winding under test shall be ensured. The contour defined in Clause 7 of IEC 60076-10 shall be located 2 m from the winding surface. The prescribed contour shall be located on a horizontal plane at half the winding height.

In order to simulate steady-state in service conditions (i.e. elevated winding temperature), this test should be performed toward the end of a full temperature rise test, where possible.

NOTE For reactors with a high power rating, the test may be carried out on site subject to agreement between purchaser and manufacturer at the time of order, if the test cannot be carried out in the factory.

8.9.15 Vibration measurement at rated continuous current (special test)

8.9.15.1 General

The design and construction of liquid-immersed reactors shall be such as to avoid the detrimental effects of excessive stress due to vibration. Areas of primary concern in the control of vibration to ensure proper performance are as follows:

- vibration of core and coil assembly;
- vibration of tank with associated stresses developed in plates, braces, and welded seams;
- vibration of instruments, accessories, and cooling equipment.

8.9.15.2 Test conditions

The reactor under test shall be completely assembled in the service condition with cooling equipment, gauges, and accessories mounted and connected.

NOTE Where a reactor is equipped with a tank wall mounted noise enclosure, the test may need to be performed without the enclosure by agreement between purchaser and manufacturer.

The reactor shall be mounted on a level surface that will provide proper support for the base, in order to eliminate the generation of abnormal tank stresses.

The reactor shall be energized at rated continuous current and rated frequency. Three-phase excitation is required for three-phase units. When the available test power is insufficient for testing at rated continuous current and/or three-phase excitation, the manufacturer shall demonstrate to the purchaser that reduced-current testing will produce sufficiently accurate results at rated conditions. The test should preferably be done at operating temperature, but may be done at ambient temperature.

8.9.15.3 Method of measurement

The vibration of reactor components shall be measured by transducers, optical detectors, or equivalent measuring devices. The peak-to-peak amplitude of the displacement shall be determined by direct measurement, or calculated from acceleration or velocity measurements. The accuracy of the measurement at twice the rated frequency shall be within 10 μm.

Measurements shall be taken on all four sides of the tank wall at a sufficient number of points to ensure that the maximum value of vibration has been measured.

Measurements or observations shall be made of the vibration of equipment mounted on the tank.

8.9.15.4 Maximum vibration level

The maximum amplitude of tank wall displacement shall not exceed 200 μm peak-to-peak.

For the equipment mounted on the tank, the manufacturer shall, where reasonable, demonstrate that the vibrations measured or observed on test have no long-term effects on the stability and performance of the equipment.

8.9.16 Switching impulse test (special test)

The switching impulse test is performed generally as outlined in IEC 60076-3. However, this test is only applicable for reactors with sufficiently high impedance to make this test practical. The method of test and wave-shape shall be discussed between manufacturer and purchaser.

8.9.17 Double-ended lightning impulse test (special test)

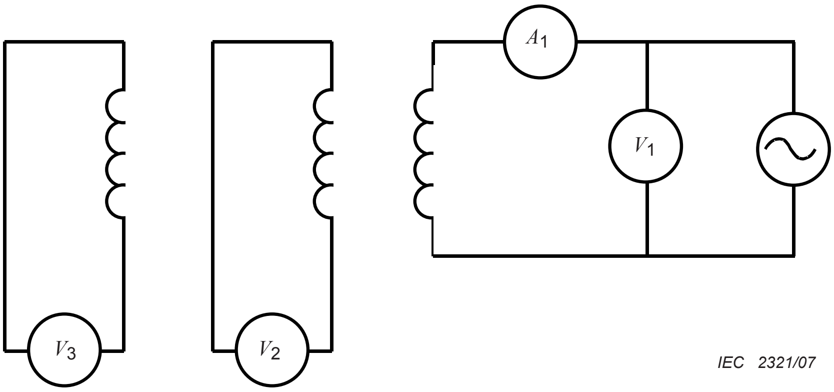
This test is applicable to reactors with a by-pass arrangement which may be closed when the reactor is energized.

The test shall be carried out on each phase in turn, with both terminals of the tested winding connected together and the other terminals earthed.

For general information see Clause 13 of IEC 60076-3:2000.

8.9.18 Measurement of coupling factor (special test)

The measurement shall be made, according to Figure 7, preferably at rated continuous current for gapped-core reactors and magnetically-shielded air-core reactors. If this is impracticable, the test current chosen shall be as close as possible to rated continuous current. For other reactors, any convenient current may be used for this measurement.



Key

V_1, V_2, V_3: voltmeter reading

A_1: ammeter reading

Mutual reactance X_m = V_2/A_1 or V_3/A_1 respectively

Coupling factor k = Mutual reactance X_m / Rated reactance X_{SCr}

Figure 7 – Measurement of mutual reactance for three-phase reactors or banks of three single-phase reactors

8.9.19 Wet winding overvoltage test (special test)

When specified, the wet winding overvoltage test shall be performed as described in 8.9.9 or 8.9.10 with the application of water spray as described in Clause 9 of IEC 60060-1:1989 with the test levels multiplied by a factor of 0,75.

8.9.20 Wet separate source a.c. withstand voltage test (special test)

When specified, the wet separate source a.c. withstand voltage test shall be performed as described in 8.9.8 with the application of water spray as described in Clause 9 of IEC 60060-1:1989, with the full test levels.

8.9.21 Measurement of reactance of the winding in the case of gapped-core and magnetically-shielded air-core reactors (special test)

When specified, the reactance of one phase winding shall be measured. The measurement shall be performed without associated gapped-core, magnetic shield or any other ferromagnetic materials in the vicinity. This value is equivalent to the air-core reactance as defined in 3.2.6.

8.10 Tolerances

8.10.1 Tolerance on impedances of reactors without compensation for mutual coupling

For current-limiting reactors, neutral-earthing reactors to be connected to the neutral of the power system and other types of reactors whose primary function is to limit short-circuit currents: the tolerance on the impedance established by test and/or calculation at rated thermal short-circuit current shall be within ${}^{+10}_{-0}$ % of rated short-circuit impedance. The same tolerance applies for the specified impedance at rated continuous current.

For all other types of reactors covered in this Clause: The tolerance on the impedance established by test and/or calculation at rated short-time current shall be within ±5 % of rated short-time impedance. The same tolerance applies for the specified impedance at rated continuous current.

8.10.2 Tolerance on impedance of reactors with compensation for mutual coupling

When three-phase reactors are specified to be compensated for the effects of mutual impedance, the current measured in each phase winding, under the conditions defined in 8.9.5, shall not deviate by more than 5 % from the average value. In this case, the single-phase impedances (Z_{SCr1}, Z_{r1}, Z_{STr1}) of each phase reactor shall not be less than 85 % of the specified rated value. The measured impedance of each phase reactor including the effects of mutual coupling (Z_{SCr3}, Z_{r3}, Z_{STr3}) shall be within ${}^{+10}_{-0}$ % or ±5 % of the specified rated value, as applicable according 8.10.1.

NOTE The minimum value of single-phase impedance, Z_{SCr1}, is relevant when determining the maximum rated single-phase fault current for the reactor.

8.10.3 Tolerance on loss

The total loss measured and corrected according to 8.9.7 shall not exceed the guaranteed loss by more than 10 %.

9 Filter, damping and discharge reactors associated with capacitors

9.1 General

This Clause describes the requirements for reactors designed to be used in association with capacitors.

The typical applications include

- filter reactors connected in series or in parallel with capacitors to reduce or block harmonics or control signals (ripple signals) with frequencies up to 10 kHz;

  NOTE This part of IEC 60076 does not cover line traps (see IEC 60353) but it does cover reactors for the purpose of blocking control signals used for the remote switching of demand.

- damping reactors connected in series with shunt capacitors to limit the inrush current when the capacitor is energised, limit the outrush current during close-in faults or adjacent capacitor switching and/or to detune capacitor banks in order to avoid resonance with the power system;
- discharge reactors used in the bypass/discharge circuit of high voltage power system series capacitor bank applications to limit the current under fault conditions.

The steady-state voltage across these reactors is usually low compared to the system voltage; however switching will cause transient voltages at the resonant frequencies formed by the capacitors and reactors which may be considerably higher.

For filter and damping reactors under normal operation, the current flowing through the reactor is composed of a power frequency current and a superimposed harmonic current. For damping reactors, the power frequency current is usually much greater than the harmonic current whereas for filter reactors the specific application will determine the ratio of the two current components.

Discharge reactors do not carry a continuous current during normal service, but are normally specified with a continuous current to allow operation with the capacitor bypassed by the reactor.

Damping, discharge and some filter reactors are subject to high short-time current during switching and fault conditions. Damping reactors may be switched very frequently, often several times per day, and are therefore subject to routine transient overvoltages. In some applications, the fault currents arising from a short circuit across the capacitor need to be considered.

Discharge reactors are usually installed with the associated series capacitor bank on an insulated platform. Therefore, the reactor insulation requirements are dictated by the insulation coordination for the series capacitor arrangement rather than by the system voltage.

Reactors covered by this Clause are almost exclusively of a dry-type air-core design, the rating and testing parts of this Clause are generally only applicable to reactors of this design.

NOTE Guidance concerning shunt capacitors is provided in IEC 60871-1 and concerning series capacitors is provided in IEC 60143.

9.2 Design

With regard to design and installation, reactors covered under this Clause are a dry-type air-core design and shall be classified as:

- single-phase or three-phase;
- for indoor or outdoor installation;
- with each phase mounted side-by-side or in a vertical stack;
- with or without taps.

NOTE Other methods for variation of the inductance may be applied, but these are not specifically considered by this part of IEC 60076.

9.3 Terms and definitions

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

9.3.1
rated power frequency current
I_r
specified continuous r.m.s. value of current at power frequency

9.3.2
rated current spectrum
specified continuous r.m.s. values of current at specified frequencies other than power frequency

9.3.3
RSS current
root-sum-square of rated power frequency current and all the values of currents at the specified frequencies in the rated current spectrum

9.3.4
equivalent current at power frequency

I_{equ}

calculated r.m.s. value of current at power frequency which gives the same winding losses as those arising from the power frequency current and the rated current spectrum

9.3.5
rated inrush current

I_{rIN}

specified peak value of the highest transient current that may occur through a filter or damping reactor during energization of the associated capacitor or a nearby capacitor or due to system faults

NOTE Transient currents due to system faults or energization of a nearby capacitor are sometimes also called outrush current and are covered by this definition.

9.3.6
rated inrush frequency

f_{rIN}

for damping reactors, the specified resonant frequency associated with the rated inrush current

9.3.7
rated tuning frequency

f_{rt}

for filter reactors, the specified resonant frequency of the filter circuit in which the reactor is a component

9.3.8
rated discharge current

I_{rd}

for discharge reactors, the specified peak value of the highest current that will be experienced by the reactor

9.3.9
rated discharge frequency

f_{rd}

for discharge reactors, the specified resonant frequency of the reactor and the associated series capacitor

9.3.10
rated frequency

for filter reactors, the rated tuning frequency; for damping reactors, the rated inrush frequency and for discharge reactors, the rated discharge frequency

9.3.11
rated thermal short-circuit current

I_{SCr}

specified r.m.s. value of the steady-state symmetrical component of the short-circuit current at power frequency to be carried for the specified duration

9.3.12
rated thermal short-circuit current duration

T_{SCr}

specified duration of the rated thermal short-circuit current

9.3.13
rated mechanical short-circuit current
I_{MSCr}
specified asymmetrical (peak) fault current. If not specified, the asymmetrical (peak) fault current is derived from the rated thermal short-circuit current

9.3.14
rated inductance
L_{r}
specified inductance at rated frequency. The rated inductance also includes mutual inductance between phases, if applicable

9.3.15
rated reactance
X_{r}
for damping and discharge reactors, the specified reactance of the reactor at power frequency. The rated reactance is expressed in Ohms per phase

9.3.16
coupling factor
k
mutual inductance between two phases of a three-phase reactor expressed in per unit or percent of the square root of the product of the self inductances of the two individual phases

NOTE For phases 1 and 2, the coupling factor follows as $k = \dfrac{M_{12}}{\sqrt{L_1 \times L_2}}$.

9.3.17
effective resistance
resistance derived from the power loss of the reactor at the specified frequency and reference temperature

NOTE The power loss includes the ohmic loss and all additional stray losses at the specified frequency.

9.3.18
quality factor
Q_{f}
ratio of reactance to effective resistance at the specified frequency

9.4 Rating

9.4.1 Rated power frequency current

The rated power frequency current I_{r} shall be specified by the purchaser to be not less than the maximum continuous value of power frequency current that will be carried by the reactor in service. For damping reactors, see also 9.4.2.

In the case of discharge reactors, the rated power frequency current shall be specified to be not less than the current that may be carried by the reactor when operating as a series element in the transmission line.

9.4.2 Rated current spectrum

For filter reactors, the current at each frequency of the rated current spectrum shall be specified by the purchaser to be not less than the maximum continuous values that will be carried by the reactor in service.

NOTE 1 All available information on the current spectrum shall be provided by the purchaser to allow the proper thermal design of the reactor.

For damping reactors, the rated current spectrum may be, but is not normally specified. In the latter case, higher frequency current components shall be allowed for by specifying the power frequency current to be not less than the maximum permissible current of the associated capacitor bank.

NOTE 2 The presence of higher frequency currents through a filter or damping reactor requires special consideration as the higher frequency currents will both increase the losses in the reactor and increase the voltage drop across the reactor winding.

NOTE 3 The maximum permissible current according to IEC 60871-1 is a current with a r.m.s. value equal to 1,3 times the value obtained at rated sinusoidal voltage across the capacitor.

For discharge reactors, the rated current spectrum is normally not applicable.

9.4.3 Rated inrush current

The rated inrush current I_{rIN} shall be specified by the purchaser for filter and damping reactors to be not less than the peak current that may occur in all recognized cases of switching the associated capacitor and any nearby capacitors or due to system faults. The estimated number of switching operations per day shall be specified in the inquiry.

NOTE System faults referred to in this Clause are those which result in the discharge of the capacitor through the reactor, but do not result in a power frequency fault current through the reactor.

9.4.4 Rated inrush frequency

The rated inrush frequency f_{rIN} shall be specified by the purchaser.

9.4.5 Rated discharge current

The rated discharge current I_{rd} shall be specified by the purchaser for discharge reactors as not less than the highest peak value of current based on all recognized cases of discharge of the associated series capacitor. Both the high frequency capacitor discharge current and the power frequency fault current shall be evaluated in establishing the appropriate rated discharge current.

9.4.6 Rated discharge frequency

The rated discharge frequency f_{rd} shall be specified by the purchaser.

9.4.7 Rated thermal short-circuit current

For filter and damping reactors, the rated thermal short-circuit current I_{SCr} shall be specified by the purchaser to be not less than the steady-state symmetrical component of the short-circuit current at power frequency to be carried for the specified duration when the reactor shall be designed to withstand a particular short-circuit condition.

NOTE In the case where the reactor is connected on the neutral side of the capacitor or where the connection between the capacitor and reactor is very short, the probability for a short circuit may be sufficiently low that the specification of a rated thermal short-circuit current is not justified. The possibility of the inadvertent energization of the capacitor bank with maintenance earths in place should be considered.

For discharge reactors, the rated thermal short-circuit current I_{SCr} shall be specified by the purchaser to be not less than the highest value of symmetrical r.m.s. current under recognized fault conditions that may be seen by the reactor in service. Alternatively, it may be derived from the specified system short-circuit power, system voltage and reactor impedance.

9.4.8 Rated thermal short-circuit current duration

The rated thermal short-circuit current duration T_{SCr}, where applicable, shall either be specified by the purchaser or otherwise, a standard value of 1 s for filter and damping reactors and 2 s for discharge reactors shall be used.

NOTE 1 The duration selected should reflect the cumulative thermal effects of the utilities auto re-closure philosophy and the time a fault is allowed to exist before it is interrupted.

NOTE 2 The duration of thermal short-circuit current can impact the cost of the reactor where the short-circuit current exceeds about twenty-five times the rated continuous current.

NOTE 3 If several successive faults may occur within a short period of time, the duration, the interval of time between applications, and the number of applications shall be specified by the purchaser. The rated thermal short-circuit current duration shall be selected accordingly.

9.4.9 Rated mechanical short-circuit current

For reactors where a thermal short-circuit current I_{SCr} is specified, the purchaser shall specify the rated mechanical short-circuit current. This current depends on the X/R ratio of the system and shall be calculated as per 4.2.3 of IEC 60076-5:2006. If the system impedance and X/R ratio are not specified by the purchaser, the rated mechanical short-circuit current I_{MSCr} shall be taken to be a value equal to 1,8 $\sqrt{2}$ times the rated thermal short-circuit current value (I_{MSCr} = 2,55 I_{SCr}).

9.4.10 Rated inductance

The rated inductance L_{r} of the reactor shall be specified by the purchaser. It shall be the value required to provide the desired filter, damping or discharge characteristic.

Where filter reactors are to be installed in a three-phase stacked configuration, the inductance of each single-phase reactor shall be compensated for the effects of mutual coupling, to provide the specified inductance value in the stacked arrangement with a three-phase supply. In order for the manufacturer to design each reactor for the proper self inductance value, the purchaser shall provide the value of impedance between the neutral of the filter bank and the system earth.

Where damping reactors are to be installed in a three-phase stacked configuration, the inductance of each single-phase reactor shall not be compensated for the effects of mutual coupling, unless otherwise specified. For more information see Annex C.

In the case of discharge reactors, that are normally installed in a non-stacked configuration, and side-by-side mounted filter and damping reactors, the mutual coupling factors are generally very small. Therefore these units are not inductively compensated.

9.4.11 Quality factor

When a specific damping factor for transients is desired, a maximum quality factor Q_{f} at the rated frequency shall be specified for the reactor in the inquiry. In the case where a quality factor has not been specified, the manufacturer shall, on request, supply information about the expected quality factor of the reactor at the rated frequency.

For filter reactors, the quality factor Q_{f} at a particular frequency or frequencies and the tolerance shall be specified by the purchaser if it is important for the performance of the filter circuit or the control of losses.

9.5 Ability to withstand rated thermal and rated mechanical short-circuit current

When a short-circuit current is specified for a reactor, it shall be designed to withstand the thermal and dynamic effects of the rated thermal short-circuit current and the rated mechanical short-circuit current including the associated electrical stress for its rated duration. Unless otherwise specified by the purchaser, the interval between fault conditions totalling the rated duration is at least six hours. If the expected frequency of short-circuit application is more than approximately ten times per year on average, this shall be specified by the purchaser.

The capability of the reactor to withstand the rated mechanical short-circuit current shall be demonstrated either

- by tests, or
- by calculation and design considerations.

The choice of demonstration method shall be subject to agreement between the purchaser and the manufacturer prior to placing the order.

The thermal capability of the reactor to withstand the rated thermal short-circuit current for the rated thermal short-circuit current duration shall be demonstrated by calculation. A test may also be specified in addition to the calculation. The method used to calculate the average temperature attained by the winding after application of the rated short-circuit current for its rated duration is as described in 4.1.5 of IEC 60076-5:2006. This calculated average winding temperature shall not exceed the values prescribed for transformer windings under short-circuit conditions given in 4.1.4 of IEC 60076-5:2006.

9.6 Ability to withstand inrush or discharge current

When a rated inrush current or rated discharge current is specified for a reactor, it shall be designed to withstand the thermal and dynamic effects of these currents including the associated electrical stress. Due to the repetitive nature of the inrush or discharge duty, the reactor shall not have mechanical resonances within 10 % of twice the rated inrush or rated discharge frequency, as applicable. When requested, this and the ability to withstand the thermal and dynamic effects of the inrush or discharge current shall be demonstrated by calculation or, if specified, by test see 9.10.13, 9.10.14 and 9.10.16.

9.7 Temperature rise

9.7.1 Temperature rise at equivalent current at power frequency

The temperature rise limits given in Clause 11 of IEC 60076-11:2004 apply.

Discharge reactors connected in series in the power system shall be designed for loading and overload according to the guidelines set out in IEC 60905.

9.7.2 Temperature due to rated thermal short-circuit current loading

The calculated temperature of the winding after rated thermal short-circuit current I_{SCr} loading shall not exceed the values prescribed for transformer windings under short-circuit conditions given in 4.1.4 of IEC 60076-5:2006.

9.8 Insulation level

9.8.1 General

For specification of the insulation level, see IEC 60076-3.

9.8.2 Insulation requirements

For filter and damping reactors, the insulation requirements between phases and to earth shall generally correspond to the highest voltage for equipment U_{m} of the system in which the reactor is to be installed. A reduced insulation level may be specified by the purchaser where this is justified by the application. The voltage level shall be chosen with regard to the voltage developed across the reactor when carrying the short-circuit current or the maximum voltage developed during switching, discharge or continuous operation, if greater.

For discharge reactors, the insulation level depends on the insulation coordination of the associated series capacitor. The maximum voltage across the capacitor shall be used as the basis for the insulation level to be specified. The lightning and switching impulse levels across the reactor and between the reactor and the platform shall be specified by the purchaser.

Since discharge reactors are usually installed on an insulated platform, the need for reactor mounted corona shielding depends on the mounting location of the reactors on the platform. Therefore, the requirement for reactor corona shielding shall be specified, if applicable, by the purchaser.

9.9 Rating plates

Each reactor shall be provided with a rating plate of weatherproof material, fitted in a visible position, showing in all cases the appropriate items indicated below. The entries on the plate shall be indelibly marked (for example by etching, engraving or stamping).

- type of reactor;
- outdoor/indoor application;
- number of this part of IEC 60076;
- manufacturer’s name;
- manufacturer’s serial number;
- year of manufacture;
- rated lightning impulse withstand voltage;
- highest voltage for equipment;
- rated power frequency;
- rated power frequency current;
- rated thermal short-circuit current and duration (where specified);
- rated mechanical short-circuit current (where specified);
- RSS current (for filter reactors);
- rated inrush current (for filter and damping reactors, where specified);
- rated discharge current (for discharge reactors);
- rated tuning frequency (for filter reactors);
- rated damping frequency (for damping reactors);
- rated discharge frequency (for discharge reactors);
- measured inductance at rated tuning frequency (for filter reactors);
- measured inductance at rated damping frequency (for damping reactors);
- measured inductance at rated discharge frequency (for discharge reactors);
- measured inductance at power frequency (as applicable);
- measured quality factor and associated frequency (where applicable);
- thermal class of insulation;
- total mass.

9.10 Tests

9.10.1 General

The general requirements for routine, type and special tests shall be as prescribed in IEC 60076-1.

9.10.2 Routine tests

The following routine tests shall be performed:

- measurement of winding resistance (IEC 60076-1);
- measurement of inductance (9.10.5);
- measurement of loss and quality factor (9.10.6);
- winding overvoltage test (9.10.7).

9.10.3 Type tests

The following type tests shall be performed:

- measurement of inductance (9.10.5);
- measurement of loss and quality factor (9.10.6);
- temperature rise test (9.10.8);
- lightning impulse test (9.10.9).

9.10.4 Special tests

The following special tests shall be performed when specifically requested by the purchaser:

- short-circuit current test (9.10.10);
- measurement of acoustic sound level (9.10.11);
- separate source a.c. withstand voltage test (9.10.12);
- inrush current withstand test for filter and damping reactors (9.10.13);
- discharge current test for discharge reactors (9.10.14);
- modified short-circuit/discharge current test for discharge reactors (9.10.15);
- mechanical resonance test (9.10.16).

9.10.5 Measurement of inductance (routine test, type test)

The inductance shall be measured at power frequency and at rated frequency.

For filter reactors, the inductance shall be measured at the rated frequency only. Where more than one tuning frequency is specified, the inductance shall be measured at the lowest tuning frequency.

Where taps are provided, the measurement shall be made at all tap positions for the type test. For the routine test, the measurement shall be made at the rated, minimum and maximum inductance tappings. The correct position of other taps shall be verified by physical inspection.

For reactors with continuously adjustable inductance, the inductance shall be measured at a minimum of five settings evenly distributed over the range for both routine and type test.

For three-phase stacked reactors, as a type test, the inductance shall be measured with three-phase excitation with the reactor assembled as in service. For the routine test, inductance measurements on individual phases may be used to obtain the inductance per phase (including mutual inductance) using the mutual inductances (coupling factors) obtained from the type test. In this case, the type test shall include inductance measurements on individual phases and the measurement of the coupling factors in the service arrangement.

For three-phase reactors with side-by-side arrangement (reactors with a coupling factor less than 5 %), inductance measurement may be made with single-phase excitation.

9.10.6 Measurement of loss and quality factor (routine test, type test)

The measurement of loss shall be carried out at power frequency, rated frequency and at each frequency specified in the rated current spectrum.

The measurement of loss may be made at any current and any convenient ambient temperature and shall be corrected to the respective rated current values by multiplying the measured loss by the square of the ratio of respective rated current to the test current and to reference temperature.

The total loss is composed of ohmic loss and additional loss. The ohmic loss portion is taken to be equal to I_r^2R, R being the measured d.c. resistance, I_r being the respective rated current. The additional loss portion is the difference between the total loss and the ohmic loss I_r^2R.

The quality factor is usually derived from loss and inductance measurement. The determination of the quality factor shall be carried out at the rated frequency and any other frequencies required by the purchaser. For three-phase stacked reactors, the quality factor is derived from one third of the total loss of the three-phase arrangement.

The quality factor is based on the reference temperature for filter reactors and on a temperature of 20 °C for damping and discharge reactors, if not otherwise specified.

The temperature correction of resistance shall be performed according to the method given in IEC 60076-1.

For three-phase stacked reactors, as a type test, the loss and quality factor shall be measured with three-phase excitation with the reactor assembled as in service. For the routine test, loss and quality factor measurements on individual phases may be used to obtain the total loss of the three-phase reactor, taking into account the additional losses of the three-phase stack.

NOTE 1 For a three-phase stacked arrangement, the measured loss of the individual phases may be unequal or even negative in one phase. The arithmetic sum of the three loss values gives the total loss.

The presence of metal parts in the vicinity around or under reactors may significantly affect the measurement of loss. Therefore, metal parts belonging to the support structure of the reactor shall be in place during the test and other metal parts shall be avoided.

9.10.7 Winding overvoltage test (routine test)

This test is carried out as a lightning impulse test on one end of each winding in turn with the other end of the winding directly earthed. The test level shall be according to IEC 60076-3. Due to the low impedance of the reactor, the standard waveshape usually cannot be met. For more information see IEC 60076-4:2002, Clause A.3.

NOTE 1 The correct time to half value may not be achievable. This shorter time should normally be accepted.

NOTE 2 The induced a.c. withstand voltage test cannot usually be carried out in accordance with Clause 12 of IEC 60076-3:2000 due to the high test power requirement.

The turn-to-turn overvoltage test as described in Annex E may be performed in lieu of the impulse test for equipment with $U_m \leq 36$ kV.

9.10.8 Temperature rise test at rated continuous current (type test)

The test shall be carried out in general accordance with IEC 60076-2. The temperature class limits as stated in IEC 60076-11 shall apply.

This test shall be performed at the equivalent current I_{equ} at power frequency.

In exceptional cases, where it is not possible to achieve the equivalent current at power frequency for the temperature rise test, the test may be performed at a reduced current value, but not less than 0,9 I_{equ}. The test level shall be stated in the tender by the manufacturer and agreed upon between manufacturer and purchaser at the time of order.

The temperature rises shall be corrected to the equivalent current at power frequency.

The winding temperature rise above ambient temperature shall be multiplied by $\left(\frac{I_{\text{r}}}{I_{\text{test}}}\right)^{y}$ with y according to the following:

- for reactors with AN cooling $y = 1{,}6$
- for reactors with AF cooling $y = 1{,}8$

If requested, the temperature rise of the reactor terminals shall be measured during the reactor temperature rise test. In order to obtain meaningful terminal temperature rise measurements, the purchaser shall supply a connector and at least one meter of incoming conductor of the type that will be used on site, to the manufacturer for use during the temperature rise test. Terminal temperature rise limits shall be as given in Clause 6 (see also IEC 60943).

9.10.9 Lightning impulse test (type test)

For general information, see Clause 13 of IEC 60076-3:2000 and Clause 21 of IEC 60076-11:2004. See also IEC 60076-4.

The test voltage is applied to each terminal of the tested winding in turn, while the other terminal is earthed through the smallest possible resistor necessary to achieve the standard impulse waveshape. If reduced insulation levels across the winding or from winding to earth are specified, the lightning impulse test procedure shall be performed by using the specified reduced insulation level value.

9.10.10 Short-circuit current test (special test)

9.10.10.1 General

For general information, IEC 60076-5 applies.

When a short-circuit current test is specified it shall be carried out generally in accordance with 4.2.2 to 4.2.7 of IEC 60076-5:2006.

The specification for the short-circuit current test shall include the test current level, the duration of each applied shot, the number of test current shots and the tap terminal connection desired (in the case of tapped reactors).

If this information is not specified, the test shall consist of two test shots of 0,25 s on each reactor phase with the first peak of the applied current at the rated mechanical short-circuit current value. The test shall be performed at the maximum inductance tap position (in the case of tapped reactors).

Three-phase reactors, or a three-phase bank of separate reactors with defined installation, shall undergo three, three-phase short-circuit tests, each consisting of two shots. In each test, a different reactor phase shall be selected to experience the first maximum offset peak current.

The peak value of the current obtained during the test shall not deviate by more than 5 % from the respective specified value.

If a thermal short-circuit test is specified, it shall consist of one symmetrical current shot at the rated thermal short-circuit current I_{SCr} for the rated duration. If the rated thermal short-circuit current cannot be achieved, the duration shall be extended up to 6 s at reduced current to give at least the specified I^2t value.

The thermal short-circuit test may be also combined with the mechanical short-circuit test to reduce the total number of shots, provided all the test parameters can be met.

For more information see Annex F.

9.10.10.2 Acceptance criteria

The ability of the reactor to withstand the test shall be determined in accordance with 4.2 of IEC 60076-5:2006.

Before and after the short-circuit test, routine tests including measurement of inductance and losses and the performance of a winding overvoltage test according 9.10.7 at 100 % of the specified voltage shall be carried out on the reactor(s). Inductance and loss values shall be consistent within measurement tolerance limits. Oscillograms from the required dielectric test shall show no change; agreeing within the limits of the high voltage dielectric test systems.

Visual inspection of the reactor and supporting structure shall give no indication that there has been any change in mechanical condition that will impair the function of the reactor. If after the short-circuit test program, the winding clamping system has deteriorated, or surface cracks have increased significantly in number or dimensions, the reactor is considered to have failed the short-circuit test. In case of doubt, up to three more short-circuit tests with fully offset current shall be applied to verify that the monitored condition has stabilized. If the deterioration continues, the reactor shall be considered to have failed the test. If conditions stabilize after one or two extra short-circuit tests and coupled with successful routine tests after short-circuit tests, the reactor shall be considered to have passed the short-circuit test. For more information, see Annex F.

9.10.11 Measurement of acoustic sound level at rated continuous current (special test)

The method prescribed in IEC 60076-10 applies.

During measurements sufficient safety clearances to the winding under test shall be ensured. The contour defined in Clause 7 of IEC 60076-10 shall be located 2 m from the winding surface. The prescribed contour shall be located on a horizontal plane at half the winding height.

In order to simulate steady-state in service conditions (i.e. elevated winding temperature), this test should be performed towards the end of a full temperature rise test, where possible.

The sound radiated from the reactor depends on current at the power frequency and, where applicable, currents at all other frequencies. Unless otherwise specified, only the most significant currents from the rated current spectrum need to be considered.

Since currents at power frequency and at other frequencies usually cannot be applied simultaneously for testing, the reactor may be successively tested with power frequency current and currents at other frequencies. In this case, the reactor shall also be tested at currents and frequencies which reflect the interaction of currents having different frequencies. If the test cannot be carried out by the manufacturer at all the significant frequencies and currents, this shall be stated in the tender and an agreement on the test method and values shall be reached with the purchaser.

For a reactor current spectrum with currents I_1, I_2, I_3... these sound equivalent currents are given as follows:

Amplitude of test current	**Frequency of test current**	**Sound frequency**
I_1	f_1	$2f_1$
I_2	f_2	$2f_2$
I_3	f_3	$2f_3$

For any pair of reactor currents in the table above, for instance I_1 and I_2, the following test currents shall be considered due to interactive effects:

Amplitude of test current	**Frequency of test current**	**Sound frequency**
$(2 I_1 I_2)^{1/2}$	$(f_1 + f_2)/2$	$f_1 + f_2$
$(2 I_1 I_2)^{1/2}$	$(f_1 - f_2)/2$	$f_1 - f_2$

NOTE f_1, f_2, f_3 ... are the frequencies of the reactor r.m.s. currents I_1, I_2, I_3 ... that are interacting. Usually, f_1 is the power frequency and f_2, f_3... are the frequencies of the significant currents of the rated current spectrum.

The total sound power level shall be calculated using the following formula, see also Annex A of IEC 60076-10:

$$L_{\text{tot}} = 10 \cdot \log\left(\sum_i 10^{L_i/10}\right)$$

with

L_{tot} the total sound level, and

L_{i} the sound level of each individual component.

Significant sound levels from the current components not included in the test shall be estimated by calculation and included in the total sound level.

9.10.12 Separate source a.c. withstand voltage test (special test)

The test shall be carried out in general accordance with Clause 11 of IEC 60076-3:2000.

The test voltage shall be applied between winding and earth.

Dry-type air-core reactors usually employ standard station post or bus support insulators to form the reactor mounting and the insulation between reactor windings and earth, and between phases where two or more units are stacked. Therefore, this test is a test of the support insulators.

NOTE Unless otherwise indicated in the tender by the manufacturer, the support insulators are assumed to be designed according to IEC 60273 and tested in accordance with IEC 60168.

9.10.13 Inrush current withstand test (special test)

A test at power frequency following the procedure given in 9.10.10 shall be carried out at rated inrush current.

9.10.14 Discharge current test (special test)

When a discharge current test is specified, the discharge reactor shall be subjected to a test current not less than 1,1 times the value of the rated discharge current. The test current shall be comprised of a half-cycle current wave of power frequency. The test shall be repeated 25 times.

The test set-up guidance and acceptance criteria as described in 9.10.10 shall apply, where applicable. Since each discharge reactor phase is usually mounted on a separate platform, the discharge current test shall be performed as a single-phase test on one unit only, unless otherwise specified.

9.10.15 Modified short-circuit/discharge current test (special test)

For discharge reactors, as an alternative to performing the tests as indicated in 9.10.10 and 9.10.14, the following test may be considered:

A power frequency short-circuit current test with 10 cycles of symmetrical test current with a peak value equal to 1,1 times the rated discharge current level shall be applied to the reactor.

The acceptance criteria shall be as given in 9.10.10.2.

9.10.16 Mechanical resonance test (special test)

The manufacturer shall propose, agree with the purchaser and perform a suitable test procedure to demonstrate that the reactor winding mechanical resonances deviates by at least 10 % from a value of twice the rated inrush or discharge frequency, as applicable.

9.11 Tolerances

9.11.1 Tolerance on rated inductance

For damping and discharge reactors, the measured inductance at rated frequency shall be within ${}^{+10}_{-0}$ % of the specified value.

For filter reactors, where a means of adjusting inductance is not provided, the tolerance on the rated inductance shall be specified. Where taps are specified, a tolerance for each tap, or minimum tap range and maximum tap step size shall be specified.

9.11.2 Tolerance on measured loss and quality factor

The measured loss shall not exceed the guaranteed value by more than 10 %.

The measured quality factor shall be within ±20 % of the value stated by the manufacturer in the tender.

10 Earthing transformers (neutral couplers)

10.1 General

Earthing transformers are used to provide a neutral connection for earthing a three-phase network.

The neutral connection of the earthing transformer may be connected to earth by one of the following methods:

- directly;

- by means of a current-limiting reactor (Clause 8 of this part of IEC 60076);
- by means of a resistor;
- by means of an arc-suppression reactor (Clause 11 of this part of IEC 60076).

Where the earthing transformer is the only means of earthing in the network, then the zero-sequence impedance of the earthing transformer plus any impedance between the neutral and earth determines the current that flows in the single-phase to earth fault.

NOTE Normally, the duration of the current that flows through the neutral under fault conditions is limited to a few seconds, except where the neutral is connected to an arc-suppression reactor. In this case, the neutral current may be of limited amplitude, but longer duration (hours or even continuous rating). In some cases, the transformer is capable of carrying a continuous small current caused by the voltage unbalance of the system.

Earthing transformers are often provided with a secondary (low-voltage) winding to supply a local auxiliary load, for example, the 400 V equipment within the substation. The provisions of IEC 60076 apply to the earthing transformer with respect to its function of supplying the secondary load.

10.2 Design

Earthing transformers are of a three-phase design, usually liquid-immersed, natural cooled for indoor or outdoor installation.

Earthing transformers can be of two different configurations:

- a zigzag-connected main winding;
- a star-connected main winding with a delta connected stabilizing winding. The delta winding may be left open in order to permit the insertion of an internal or external resistor or reactor to adjust the zero-sequence impedance.

The earthing transformer may be designed with an arc-suppression reactor incorporated in a common tank. This combination is covered by this Clause, but with references to Clause 11 of this part of IEC 60076 where applicable, if the neutral terminal of the transformer is not accessible.

Where a secondary winding is specified, this is usually a star-connected winding suitable for continuous loading.

An auxiliary winding may be included for measuring purposes.

10.3 Terms and definitions

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

10.3.1
main winding
winding of the earthing transformer between the line terminals which are intended to be connected to the phases of the power system to be earthed

10.3.2
rated voltage
U_r
rated line-to-line voltage at rated frequency assigned to be applied between the line terminals of the main winding

10.3.3
maximum operating voltage

U_{max}

specified highest line-to-line voltage at rated frequency at which the earthing transformer shall be capable of operating continuously

NOTE U_{max} is not the same as U_{m} (see 3.2.1), but in particular cases it may have the same value.

10.3.4
stabilizing winding

supplementary delta-connected winding provided in a star-connected transformer to decrease its zero-sequence impedance

NOTE A winding is referred to as a stabilizing winding only if it is not intended for three–phase connection to an external circuit.

10.3.5
rated zero-sequence impedance

Z_0

specified impedance in Ohms per phase at rated frequency equal to three times the value of impedance between the line terminals connected together and the neutral terminal, with any secondary winding open circuit and any stabilizing winding in service condition

In the case of the combination of an earthing transformer and an arc-suppression reactor, the rated zero-sequence impedance is the specified value in Ohms per phase equal to three times the value between the line terminals connected together and the reactor terminal intended to be connected to earth.

NOTE In the case of a variable zero-sequence impedance, this is normally the value with the lowest impedance, but additional rated values can be specified.

10.3.6
rated continuous neutral current

I_{Nr}

specified current flowing through the neutral terminal of the main winding at rated frequency to be carried continuously

NOTE In the case of the combination of an earthing transformer and an arc-suppression reactor, this current flows through both the neutral of the transformer and the arc-suppression reactor.

10.3.7
rated short-time neutral current

I_{NSTr}

specified current flowing through the neutral terminal of the main winding at rated frequency to be carried for the rated short-time neutral current duration

NOTE In the case of the combination of an earthing transformer and an arc-suppression reactor, this current flows through both the neutral of the transformer and the arc-suppression reactor.

10.3.8
rated short-time neutral current duration

T_{NSTr}

specified duration of the rated short-time neutral current

10.3.9
secondary winding

a winding provided on an earthing transformer intended to be connected to an auxiliary load

10.3.10
rated voltage of secondary winding

specified no-load voltage at rated frequency induced at the line terminals of the secondary winding with rated voltage applied to the main winding

10.3.11
rated power of secondary winding

specified power at continuous loading of the secondary winding. This rated power is a reference value for guarantees and tests concerning load losses and temperature rises for the main and secondary winding.

10.3.12
short-circuit impedance between main and secondary winding

specified equivalent series impedance in Ohms per phase at rated frequency and reference temperature, at the terminals of the main winding, when the terminals of the secondary winding are short-circuited and any auxiliary windings, if existing, are open-circuited

NOTE This value can also be given in percentage notation based on the secondary winding rating, see 3.7.1 of IEC 60076-1:1993.

10.3.13
further definitions

In the case of the combination of an earthing transformer and an arc-suppression reactor, the definitions in Clause 11 are also applicable.

10.4 Rating

10.4.1 Rated voltage

The rated voltage U_r at rated frequency shall be specified by the purchaser. The rated voltage provides the basis for the design, the manufacturer's guarantees and the tests, unless otherwise specified in 10.9.

NOTE The rated voltage is usually specified as the nominal line-to-line voltage of the associated power system.

In the case of the combination of an earthing transformer and an arc-suppression reactor, the rated voltage of the arc-suppression reactor (for the definition, see 11.3) shall be derived from the short-time neutral current and the impedance of the arc-suppression reactor.

10.4.2 Maximum operating voltage

The maximum operating voltage U_{max} may be specified by the purchaser. It shall not be less than the highest continuous operating line-to-line voltage applied to the earthing transformer in service. If it is not specified, it shall be 1,1 times rated voltage.

NOTE The specification of U_{max} is particularly important in cases where the earthing transformer is expected to operate at voltages significantly above rated voltage. This is a relevant aspect in the design of the earthing transformer. Measurement of no-load losses and current at U_{max} can be specified as a special test by the purchaser.

10.4.3 Rated zero-sequence impedance

The value of rated zero-sequence impedance may be specified by the purchaser for example in case when the earthing transformer is to be used with a separate neutral current-limiting device.

If the neutral of the earthing transformer is to be directly earthed, or in the case of a combination of earthing transformer and arc-suppression reactor, the rated zero-sequence impedance may be derived from the maximum operating voltage and the rated short-time neutral current. The rated short-time neutral current shall be specified if the rated zero-sequence impedance is not specified.

10.4.4 Rated continuous neutral current

The purchaser may specify a continuous neutral current. The rated continuous neutral current shall be specified to be not less than the highest value of continuous neutral current under service conditions. This current is caused by a voltage unbalance in the power system.

Where the continuous neutral current is expected to have a high harmonic content this shall be stated by the purchaser.

In the case of the combination of an earthing transformer and an arc-suppression reactor, this is the current flowing through both the neutral of the earthing transformer and the arc-suppression reactor. The maximum continuous voltage of the arc-suppression reactor (see definition in 11.3) is the rated continuous neutral current times the impedance of the arc-suppression reactor.

NOTE If the earthing transformer is to be used together with an arc-suppression reactor, the rated continuous neutral current of the earthing transformer should be coordinated with the rating of the arc-suppression reactor (see 11.4).

10.4.5 Rated short-time neutral current

The rated short-time neutral current may either be specified by the purchaser or left open, in which case, the rated zero-sequence impedance shall be specified. If specified, it shall not be less than the highest value of current caused by a phase-to-earth fault.

If not specified, the rated short-time neutral current shall be calculated by the maximum operating voltage and the zero-sequence impedance.

NOTE The rated short-time neutral current is given in this case by

$$I_{\mathrm{NSTr}} = 3 \times \frac{U_{\mathrm{max}}}{\sqrt{3} \times Z_0}$$

This is the worst case for the short-time neutral current. If this is considered to be too high, then instead of applying this formula, both the rated short-time neutral current and the rated zero-sequence impedance should be specified by the purchaser.

10.4.6 Rated short-time neutral current duration

The purchaser shall either specify the rated short-time neutral current duration or, if successive faults may occur within a short period of time, the time intervals between applications, the duration of the faults and the number of applications. In the latter case, the short-time current duration shall be selected accordingly by the manufacturer.

10.4.7 Rated voltage of the secondary winding

If a secondary winding is specified, the rated voltage of the secondary winding shall be specified by the purchaser.

NOTE The rated voltage of the secondary winding is normally equal to or slightly higher than the rated line-to-line voltage of the auxiliary system, taking into consideration the voltage drop caused by the short-circuit impedance of the transformer when loaded.

10.4.8 Further ratings for the combination of an earthing transformer and an arc-suppression reactor

In the case of the combination of an earthing transformer and an arc-suppression reactor, the ratings in Clause 11 of this part of IEC 60076 are applicable for the arc-suppression reactor. The rated voltage, the maximum continuous voltage and the rated current (see 11.4.1 to 11.4.3) do not need to be specified by the purchaser. These ratings shall be calculated by the manufacturer.

10.5 Ability to withstand the rated short-time neutral current

Earthing transformers shall be designed to withstand the thermal and dynamic effects of the rated short-time neutral current without any damage.

When the transformer is provided with a secondary winding, the transformer shall also be designed to withstand the thermal and dynamic effects of the current caused by a fault in the auxiliary network without any damage. IEC 60076-5 applies to the short-circuit requirements in respect to short-circuits on the secondary winding terminals.

10.6 Temperature rise

10.6.1 Temperature rise at rated voltage, rated continuous neutral current and rated power of the secondary winding

The temperature rise limits given in IEC 60076-2 for liquid-immersed transformers and in IEC 60076-11 for dry-type transformers apply.

The losses causing the temperature rise are the core loss at rated voltage, winding loss at rated continuous neutral current and the load-loss associated with the load on the secondary winding.

When the transformer is provided with a secondary winding, the transformer shall not exceed the temperature rise limits at the rated power of the secondary winding or a combination of the rated power of the secondary winding and the continuous neutral current, when a continuous neutral current is specified.

In the case of the combination of an earthing transformer and an arc-suppression reactor, the temperature rise limits according to 11.5 apply to the reactor at the rated continuous neutral current.

10.6.2 Temperature after rated short-time neutral current loading

Short-time loading is the application of the rated short-time neutral current for the rated short-time neutral current duration. The temperature of the transformer and the arc-suppression reactor, if applicable, before short-time loading shall be that reached at rated continuous neutral current and at rated power of the secondary winding.

If the rated short-time neutral current duration is less than or equal to 10 s: Following short-time loading, the temperature of the winding shall not exceed the values prescribed for transformer windings under short-circuit conditions in 4.1.4 of IEC 60076-5:2006.

If the rated short-time neutral current duration is longer than 10 s: The average temperature rise of the windings and the top-oil temperature rise following the application of rated short-time loading shall not exceed the values given in 11.5.

In the case of the combination of an earthing transformer and an arc-suppression reactor, the average temperature rise of the windings refers to both the transformer and the reactor separately if they can be measured separately or to the combination of the two if not.

10.7 Insulation level

The insulation level for the line terminals of the main winding of an earthing transformer shall be selected according to IEC 60076-3.

For the neutral terminal, the selection of a reduced insulation level may be appropriate (non-uniform insulation).

10.8 Rating plates

Each transformer shall be provided with a rating plate of weatherproof material, fitted in a visible position, showing in all cases the appropriate items indicated below. The entries on the plate shall be indelibly marked (for example by etching, engraving or stamping).

- type of transformer;
- outdoor/indoor application;
- number of this part of IEC 60076;
- manufacturer's name;
- manufacturer's serial number;
- year of manufacture;
- insulation level(s);
- rated frequency;
- rated voltage;
- rated neutral current and duration;
- type of cooling;
- thermal class of insulation (for dry-type only);
- temperature rise of top-oil and average winding, (for liquid-immersed transformers);
- total mass;
- mass of insulating liquid (where applicable);
- type of insulating liquid, if not mineral oil (where applicable);
- winding connection or connection diagram;
- zero-sequence impedance, if not a combination of an earthing transformer and an arc-suppression reactor, measured value.

Additional entries if a secondary winding for loading is specified:

- no-load voltage of secondary winding;
- short-circuit impedance, measured value;
- rated power of the secondary winding.

Additional entries if an arc-suppression reactor is included:

- type of reactor;
- type of regulation (continuous or finite steps, if applicable);
- type of tap changer (where applicable);
- table or graph indicating the adjustment range of the zero-sequence impedance or, if specified by the purchaser, current at rated voltage (for reactors with variable inductance).

10.9 Tests

10.9.1 General

The general requirements for routine, type and special tests are prescribed in IEC 60076-1.

In the case of the combination of an earthing transformer and an arc-suppression reactor, the two parts usually cannot be tested separately. If individual testing of each component is required by the purchaser, then the necessary provisions for separate testing should be agreed between manufacturer and purchaser at the time of order.

10.9.2 Routine tests

The following tests shall be performed:

- measurement of winding resistance (IEC 60076-1);

- measurement of zero-sequence impedance (10.9.5);
- measurement of no-load loss and current (IEC 60076-1);
- dielectric tests (10.9.7).

In the case of an earthing transformer with a secondary winding:

- measurement of voltage ratio and check of voltage vector relationship (IEC 60076-1);
- measurement of short-circuit impedance and load loss (IEC 60076-1);
- separate source a.c. withstand voltage test of the auxiliary winding and of the control and measuring wiring, where appropriate (Clause 10 of IEC 60076-3:2000).

In the case of the combination of an earthing transformer and an arc-suppression reactor:

- measurement of zero-sequence impedance over the whole adjustment range, if the reactor has variable inductance (10.9.5);
- operation test of tap-changer, core air-gap mechanism or any other switching equipment and of associated control and measuring equipment, where appropriate (a), b), c) of 10.8.1 of IEC 60076-1:1993 or otherwise specified by the purchaser).

10.9.3 Type tests

The following tests shall be performed:

- dielectric tests (10.9.7);
- temperature rise tests (10.9.6).

In the case of the combination of an earthing transformer and an arc-suppression reactor:

- measurement of neutral current with three-phase excitation under single-phase fault condition (10.9.10).

10.9.4 Special tests

The following special tests shall be performed when specifically requested by the purchaser:

- demonstration of ability to withstand rated short-time neutral current (10.9.8);
- measurement of no-load loss and current at maximum operating voltage $U_{\max}$ (IEC 60076-1);
- measurement of acoustic sound level (IEC 60076-10).

In the case of an earthing transformer with a secondary winding:

- short-circuit test of the transformer with the secondary winding short-circuited (IEC 60076-5).

In the case of the combination of an earthing transformer and an arc-suppression reactor:

- measurement of loss at rated continuous neutral current (10.9.9);
- endurance and climatic tests of the device for inductance regulation (11.8.12);
- measurement of linearity (11.8.10).

10.9.5 Measurement of zero-sequence impedance (routine test)

The zero-sequence impedance may be measured at any current in the range of 0,1...1,0 times the rated short-time neutral current.

In the case of a combination of an earthing transformer and an arc-suppression reactor, the zero-sequence impedance shall be measured at rated short-time neutral current, unless otherwise agreed between manufacturer and purchaser.

For the method of measurement see IEC 60076-1.

In the case of the combination of an earthing transformer and an adjustable arc-suppression reactor, the zero-sequence impedance shall be measured over the whole range of adjustment. For reactors with finite steps, the measurement shall be made at each step.

10.9.6 Temperature rise test (type test)

10.9.6.1 Temperature rise test at rated continuous neutral current and rated power of secondary winding

The measurement shall be carried out in accordance with IEC 60076-2 including the provisions for incorporating the no-load loss in the oil temperature rise measurement.

Where both a rated continuous neutral current and a secondary winding are specified, the average and top-oil temperature rise shall be measured at a current which supplies the total loss associated with the rated continuous neutral current, if specified, the current corresponding to the rated power of the secondary winding, if any, and the no-load loss. The temperature rise of the main winding shall be measured at a current corresponding to the sum of the continuous current and the appropriate current corresponding to the rated power of the secondary winding. The temperature rise of the secondary winding shall be measured at the current corresponding to the rated power of the secondary winding taking into account the previously measured oil temperature rise at total loss.

NOTE 1 For some winding configurations (for example star-star-delta), an additional temperature rise test may be considered at rated continuous neutral current to prove the capability of the stabilizing winding and the neutral.

In the case of the combination of an earthing transformer and an arc-suppression reactor, a temperature rise test at rated continuous neutral current is required. Both the reactor and transformer are tested simultaneously. In this case, the measured winding temperature is the average temperature of both parts. If the arc-suppression reactor is adjustable, the temperature rise test shall be performed on the setting with the highest losses.

The winding temperature after test shall be determined by using the resistance method, see IEC 60076-2.

NOTE 2 In case of the combination of an earthing transformer and an arc-suppression reactor, two resistance measurements can be performed to determine the gradient of the main winding of the transformer and the gradient of the winding of the reactor; one measurement between a line terminal and the reactor terminal intended to be connected to earth and one measurement between two line terminals.

10.9.6.2 Temperature rise test at rated short-time neutral current

In the case of an earthing transformer with a rated short-time neutral current duration of not more than 10 s, the thermal ability is demonstrated by calculation according to 4.1.5 of IEC 60076-5:2006.

If the rated short-time neutral current duration is more than 10 s and less than 10 min, the temperature rise shall be determined by calculation or measurement by agreement between manufacturer and purchaser.

Where the rated short-time neutral current duration is 10 min or more, a mean winding temperature rise measurement by resistance shall be performed following the application of rated short-time neutral current for the rated short-time neutral current duration.

At the beginning of the test, the initial value of the top-oil temperature shall be close to the top-oil temperature measured with the total losses injected according to 10.9.6.1. A correction shall be applied to the measured average winding temperature rise if the top-oil temperature at the beginning of the test is not exactly as previously measured.

10.9.7 Dielectric tests (routine test, type test)

The rated withstand voltages shall be verified by the following dielectric tests.

10.9.7.1 Uniform insulation

- separate source a.c. withstand voltage test (Clause 11 of IEC 60076-3:2000, (routine test));
- induced a.c. withstand voltage test (12.2 of IEC 60076-3:2000 (routine test));
- lightning impulse test (Clause 13 of IEC 60076-3:2000 (type test)).

10.9.7.2 Non-uniform insulation

- separate source a.c. withstand voltage test for the earth terminal of the main winding (Clause 11 of IEC 60076-3:2000 (routine test));
- induced a.c. withstand voltage test (12.3 of IEC 60076-3:2000 (routine test));
- in the case of the combination of an earthing transformer and an arc-suppression reactor, the induced a.c. withstand voltage test consists of two separate tests, one with single-phase excitation and one with three-phase excitation.
- lightning impulse test (Clause 13 of IEC 60076-3:2000 (type test)).
- in the case of the combination of an earthing transformer and an arc-suppression reactor with an adjustable inductance: arc-suppression reactors with continuously variable inductance shall be set for minimum current during these tests. If the reactor has a tapped winding, the principles set out in IEC 60076-3:2000, Clause 8 shall be applied.

10.9.8 Demonstration of ability to withstand rated short-time neutral current (special test)

The ability to withstand the dynamic effects of rated short-time neutral current shall be demonstrated by tests or by reference to tests on similar units.

Two alternative test connections are possible:

- the earthing transformer shall be connected to a symmetrical three-phase supply and a short-circuit shall be established between one line terminal and the neutral terminal;
- the earthing transformer shall be connected to a single-phase supply between the three line terminals connected together and the neutral terminal.

Unless otherwise specified by the purchaser, two tests shall be performed with the duration of each test being 0,5 s ± 0,05 s.

The first peak of the short-circuit current shall have a value determined by the rated short-time neutral current multiplied by the appropriate k-factor given in 4.2.3 of IEC 60076-5:2006. The k-factor shall have a minimum value of $1,8\sqrt{2} = 2,55$.

The interval between subsequent tests should be sufficient to avoid an undue accumulation of heat. Otherwise, the test shall be carried out in accordance with 4.2 of IEC 60076-5:2006.

In the case of the combination of an earthing transformer and an arc-suppression reactor, both parts shall be tested simultaneously. If the arc-suppression reactor is adjustable, the tests shall be performed on the extreme positions, when the reactor is tapped. If the reactor has a continuously adjustable inductance, it shall be tested at the setting with the lowest zero-sequence impedance. In the case of a reactor consisting of individual windings the arrangement with the lowest zero-sequence impedance shall be tested first followed by testing of each individual winding of the reactor in turn.

10.9.9 Measurement of loss at rated continuous neutral current (special test)

The measurement of loss shall be performed at rated continuous neutral current. This test shall be performed as described in 11.8.9 of this part of IEC 60076.

In the case of the combination of an earthing transformer and an arc-suppression reactor both parts are tested simultaneously. If the arc-suppression reactor is adjustable, this test shall be performed on at least the two extreme settings.

10.9.10 Measurement of neutral current with three-phase excitation under single-phase fault condition (type test)

This test is performed for the combination of an earthing transformer and an arc-suppression reactor to measure the neutral current in the case of a single-phase to earth fault under three-phase excitation. This test shall be performed as described in 11.8.5. The reactor terminal intended to be connected to earth shall be connected to one line terminal of the power supply and is normally also connected to earth during this test (see Figure 8). If the test voltage supply in the test facility has an earthed neutral, the reactor terminal intended to be connected to earth cannot be earthed and shall be able to withstand the phase to earth voltage (see Figure 9).

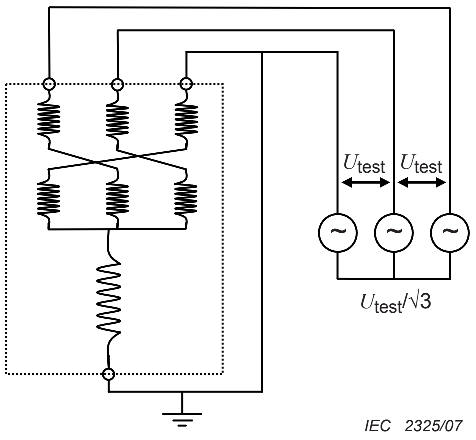


Figure 8 – Single-phase fault test circuit with earthed neutral

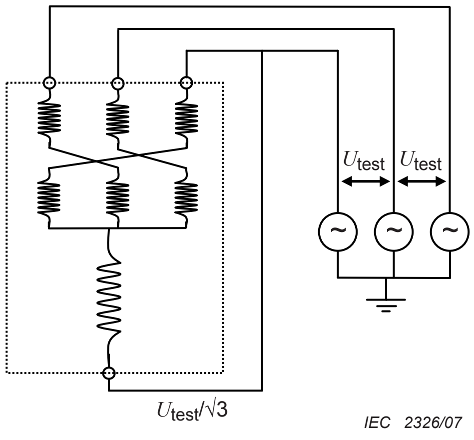


Figure 9 – Single-phase fault test circuit with earthed voltage-supply

10.10 Tolerances

Table 2 gives tolerances to be applied to the rated quantities.

Table 2 – Tolerances

Quantities		Tolerances
1a)	Zero-sequence impedance	$^{+20}_{-0}$ % of the rated value
1b)	Zero-sequence impedance in case of the combination of an earthing transformer and an arc-suppression reactor	±5 % of the rated value at minimum setting ±10 % of the rated value on all other settings
2)	Voltage ratio of auxiliary and secondary windings to the main winding	±0,5 % of specified values

Lower tolerances may be required by the purchaser and shall, in that case, be given in the inquiry.

11 Arc-suppression reactors

11.1 General

Arc-suppression reactors are single-phase reactors used to compensate for the capacitive current occurring in the case of line-to-earth faults in a power system. They are connected between the neutral of a power transformer or an earthing transformer and earth in a three-phase power system.

11.2 Design

Arc-suppression reactors are usually liquid-immersed natural cooled, for indoor or outdoor installation.

NOTE The arc-suppression reactor and the associated earthing transformer may be incorporated in a common tank. This configuration is covered by Clause 10 of this part of IEC 60076.

Arc-suppression reactors usually have an inductance adjustable, either in steps or continuously, over a specified range to permit tuning with the network capacitance.

An arc-suppression reactor shall be a linear reactor, see 11.4.8.

Arc-suppression reactors may be provided with an auxiliary winding for measuring purposes and/or a secondary winding for connection of a loading resistor. For more information on loading resistors see Annex G.

11.3 Terms and definitions

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

11.3.1
rated voltage
U_r
specified voltage at rated frequency assigned to be applied between the terminals of the main winding of the arc-suppression reactor

11.3.2
maximum continuous voltage
U_max
specified voltage at rated frequency that may be applied continuously between the terminals of the main winding of the arc-suppression reactor

11.3.3
rated current
I_r
current flowing through the main winding when rated voltage is applied at rated frequency. If the inductance is adjustable over a certain range, the rated current refers to the minimum inductance setting. Alternatively, the purchaser may specify another inductance setting for the definition of rated current.

11.3.4
rated current duration
T_r
specified duration of the rated current

11.3.5
adjustment range
for an adjustable-inductance arc-suppression reactor, the specified ratio between the rated current and the current (at rated voltage) at the maximum inductance setting

11.3.6
auxiliary winding
a winding for measuring and control purposes, intended for a low voltage and a low current

11.3.7
secondary winding
an additional winding intended for the connection of a resistor for short-time service duty in order to increase the resistive component of the earth-fault current

NOTE The secondary winding may also be used to connect equipment for measuring, control and earth-fault protection purposes.

11.4 Rating

11.4.1 Rated voltage

The rated voltage U_r shall be specified by the purchaser to be at least equal to the highest voltage which may occur between the neutral of the power transformer, or earthing transformer, and earth during an earth fault.

NOTE Usually, the rated voltage is specified to be equal to the line-to-neutral voltage of the power system.

11.4.2 Maximum continuous voltage

The maximum continuous voltage U_{max} shall be specified by the purchaser to be not less than the voltage occurring at the neutral due to the voltage unbalance of the power system under normal operating conditions, unless this value is less than 10 % of the rated voltage.

If the maximum continuous voltage is not specified, it shall be taken as 10 % of the rated voltage.

11.4.3 Rated current

The rated current I_r shall be specified by the purchaser to be not less than the highest value of current under line-to-earth fault conditions.

The reactor shall be designed to carry this current continuously or for the rated current duration, if specified.

11.4.4 Rated current duration

The rated current duration T_r shall be specified by the purchaser to be not less than the expected maximum duration of an earth-fault unless the rated current duration is continuous.

If successive faults may occur within a short period of time, the time intervals between applications and the number of applications shall be specified by the purchaser. The specified duration of rated current shall be selected accordingly.

NOTE Commonly used durations are 10 s, 30 min, 2 h and continuous. For arc-suppression reactors, a continuous duration would generally be specified for durations of more than 2 h.

11.4.5 Adjustment range

The current corresponding to rated voltage at rated frequency may be adjusted in one of the following ways:

- by adding additional sections of the main winding in finite steps with an off-load or on-load tap-changer;
- by reducing the air gap of the magnetic circuit by mechanical means;
- by switching of single coils from a set of coils intended for parallel connection.

NOTE In the case of item a), an adjustment range of not more than 2,5 is recommended.

11.4.6 Auxiliary winding

If the purchaser requires an auxiliary winding, the current and voltage and the tolerances on these values shall be specified.

NOTE A typical rating for an auxiliary winding would be 100 V, 1 A.

11.4.7 Secondary winding

If the purchaser requires a secondary winding, the current and voltage shall be specified.

NOTE A typical rating for a secondary winding would be 500 V, 100 A.

11.4.8 Linearity of the arc-suppression reactor

The reactor shall be a linear reactor within the tolerance given in 11.9 up to 1,1 times the rated voltage U_r unless otherwise specified.

11.5 Temperature rise

The temperature rises under the maximum continuous voltage shall be taken as the initial values for calculating the temperature rises due to rated current.

The average temperature rise of the windings and the temperature rise of the top-oil at rated current shall not exceed the following values when tested according to 11.8.7:

- 80 K for the windings and 75 K for the oil, where the rated current duration is continuous;
- 100 K for the windings and 90 K for the oil, where the rated current duration is 2 h or less.

NOTE The values of temperature rise take into account the fact that power system earth faults occur infrequently and have limited duration.

Where short-time loading of a secondary winding of up to 10 s is specified, the temperature of the secondary winding shall not exceed the values prescribed for transformer windings under short-circuit conditions in 4.1.4 of IEC 60076-5:2006. The temperature rise of the top-oil shall not exceed 90 K.

11.6 Insulation level

Unless otherwise specified, the insulation level of the arc-suppression reactor shall be equal to that of transformer neutrals in the power system. For the terminal of the arc-suppression reactor connected to earth, a lower insulation level may be specified (non-uniform insulation). For values of insulation levels, see IEC 60076-3.

11.7 Rating plates

Each reactor shall be provided with a rating plate made of weatherproof material, fitted in a visible position, showing in all cases the appropriate items indicated below. The entries on the plate shall be indelibly marked (for example by etching, engraving or stamping).

- type of reactor;
- outdoor/indoor application;
- number of this part of IEC 60076;
- manufacturer's name;
- manufacturer's serial number;
- year of manufacture;
- insulation level(s);
- rated frequency;
- rated voltage (no-load voltages of auxiliary and secondary windings, if applicable);
- maximum continuous voltage (if specified);
- rated current (of all windings) and specified duration;
- type of regulation (continuous or in finite steps);
- type of cooling;
- thermal class of insulation (for dry-type reactors only);
- temperature rise of top-oil and average winding for rated current and duration (top-oil rise for liquid-immersed reactors only);
- total mass;
- transportation mass (for liquid-immersed reactors);
- untanking mass (for liquid-immersed reactors);
- mass of insulating liquid (where applicable);
- type of insulating liquid, if not mineral oil (where applicable);
- connection diagram regarding tappings and instrument transformers (where applicable);
- type of tap changer (where applicable);
- a table or graph indicating the adjustment range in Amperes or as a ratio (for reactors with adjustable inductance).

11.8 Tests

11.8.1 General

The general requirements for routine, type and special tests shall be as prescribed in IEC 60076-1.

11.8.2 Routine tests

The following routine tests shall be performed:

- measurement of winding resistance (IEC 60076-1);
- measurement of current (11.8.5);
- measurement of no-load voltage of the auxiliary and secondary windings, where appropriate (11.8.6);
- dielectric tests of the main winding (11.8.8);
- separate source a.c. withstand voltage test of the auxiliary and secondary windings and of the control and measuring wiring, where appropriate (Clause 10 of IEC 60076-3:2000);
- operation test of tap-changer, core air-gap mechanism or any other switching equipment and of associated control and measuring equipment, where appropriate (a), b), c) of 10.8.1 of IEC 60076-1:1993 or otherwise specified by the purchaser).

11.8.3 Type tests

The following type tests shall be performed:

- measurement of current at rated voltage (11.8.5);
- temperature rise test (11.8.7);
- dielectric tests (11.8.8).

11.8.4 Special tests

The following special tests shall be performed when specifically requested by the purchaser:

- measurement of loss (11.8.9);
- measurement of magnetic characteristic up to 1,1 times rated voltage (11.8.10);
- measurement of acoustic sound level (11.8.11);
- endurance tests of the inductance regulation mechanism (11.8.12);
- demonstration of ability to withstand the dynamic effects of the rated current (11.8.13).

11.8.5 Measurement of current at rated voltage (type test), measurement of current (routine test)

As a type test, the current in the reactor shall be measured at rated voltage and rated frequency. If this is impracticable, the test voltage chosen shall be as close as possible to the rated voltage and shall be agreed upon between manufacturer and purchaser, preferably at the time of order.

As a routine test, this measurement may be performed at a lower voltage and corrected to rated voltage.

For both type and routine tests, the measurement shall be made over the whole range of adjustment. For reactors with finite steps, the measurement shall be made at each step. For reactors with continuously adjustable inductance, the current shall be measured at a minimum of five settings evenly distributed over the range.

11.8.6 Measurement of no-load voltage of the auxiliary and secondary windings (routine test)

The measurement of no-load voltages of any of the auxiliary and secondary windings shall be made over the whole adjustment range, at rated voltage on the main winding. If this is impracticable, the test voltage chosen shall be as high as possible.

11.8.7 Temperature rise test (type test)

The test shall be made in accordance with IEC 60076-2. The terminals of any auxiliary and secondary winding shall be open during the test.

If the rated current duration is not continuous, and the maximum continuous voltage is more than 30 % of the rated voltage, the temperature rise test shall start with an application at maximum continuous voltage until the steady-state temperature is achieved. In all cases following the application of the rated current for the rated current duration, the winding temperature shall be determined using the resistance method and the top-oil temperature shall be measured by thermometers (see IEC 60076-2).

If the maximum continuous voltage is less than or equal to 30 % of the rated voltage and the application at maximum continuous voltage may not be carried out, the initial temperature may be determined by calculation and shall be added to the temperature rise measured by the temperature rise test.

11.8.8 Dielectric tests (routine test, type test)

The rated withstand voltages shall be verified by the following dielectric tests:

- separate source a.c. withstand voltage test (Clause 11 of IEC 60076-3:2000 (routine test));
- induced a.c. withstand voltage test (12.2 of IEC 60076-3:2000 (routine test));
- lightning impulse test (13.3.2 of IEC 60076-3:2000 (type test)).

The separate source a.c. withstand voltage test level is determined by the insulation level of the earth terminal.

Arc-suppression reactors with adjustable inductance shall be set for minimum current during these tests. By agreement between manufacturer and purchaser, a special inductance setting may be used.

The lightning impulse test is applied on the terminal for connection to the neutral of the power or earthing transformer. The test is made in accordance with 13.3.2 method b) of IEC 60076-3:2000.

NOTE An impulse voltage front time of up to 13 µs is allowed in 13.3.2, method b) of IEC 60076-3:2000.

If the reactor has a tapped winding, the lightning impulse test shall be performed with the reactor on maximum tapping and repeated with the reactor on minimum tapping.

If the induced a.c. withstand voltage test is impracticable, the test may be replaced by a lightning impulse test, subject to agreement between purchaser and manufacturer at the time of the order.

11.8.9 Measurement of loss (special test)

Arc-suppression reactors with adjustable inductance shall be measured at at least 5 positions over the whole adjustment range including the position for rated current. The loss shall be measured at rated voltage and rated frequency. If, at rated voltage with the inductance set for rated current, the current measured is different from the rated current, the measured loss shall be corrected to rated current by multiplying the measured loss by the square of the ratio of rated current to measured current.

The measurement of loss shall be performed at factory ambient temperature and corrected to reference temperature according to the method given in IEC 60076-1.

The total loss is composed of ohmic loss, iron loss and additional loss. The ohmic loss portion is taken to be equal to I_r^2R, R being the measured d.c. resistance, I_r being the rated current. Iron loss and additional loss cannot be separated by measurement. The sum of iron loss and additional loss is therefore the difference between the total loss and the ohmic loss.

The ohmic loss is corrected to reference temperature according to the method given in IEC 60076-1. A correction of iron loss and additional loss to reference temperature is not normally practical. Therefore, iron loss and additional loss shall be deemed independent of temperature. This assumption normally gives a slightly higher loss figure at the reference temperature than actually exists.

The total loss at reference temperature is then the sum of ohmic loss corrected to reference temperature and the measured iron loss and additional loss.

11.8.10 Measurement of linearity (special test)

For arc-suppression reactors with adjustable inductance, this measurement shall be made at both maximum and minimum current settings.

The measurement shall be made by applying a voltage in steps of approximately 10 % at rated frequency up to 1,1 times the rated voltage. The linearity is determined by plotting a graph of the r.m.s. value of the voltage versus the r.m.s. value of current. The measured current at any point on this curve shall not deviate by more than ±5 % from a straight line drawn from zero through the point determined at rated voltage.

11.8.11 Measurement of acoustic sound level (special test)

The measurement shall be made in general accordance with IEC 60076-10 at rated voltage with the arc-suppression reactor set to rated current position. Further measurements at other currents in case of arc-suppression reactors with adjustable inductance shall be agreed upon between manufacturer and purchaser.

11.8.12 Endurance tests of the inductance regulation mechanism (special test)

Where an arc-suppression reactor has a mechanism for adjusting the inductance, the purchaser may require, in agreement with the manufacturer, additional endurance tests or verification procedures to demonstrate the integrity and satisfactory performance of the mechanism of the reactor.

The test shall consist of a number of regulation operations of the arc-suppression reactor reflecting the number of operations anticipated during the life time of the unit. A typical endurance test may consist of 1 000 regulation operations over the full adjustment range. The ambient temperature during testing, for example –20 °C, 20 °C or 40 °C should also be agreed upon between manufacturer and purchaser.

NOTE The mechanism may consist of, for example, a motor drive, switches, etc.

11.8.13 Demonstration of ability to withstand the dynamic effects of the rated current (special test)

The ability of the arc-suppression reactor to withstand the dynamic effects of rated current shall be demonstrated by tests or by reference to tests on similar units in accordance with 4.2 of IEC 60076-5:2006.

Unless otherwise specified by the purchaser, two tests shall be performed with the duration of each test being 0,5 s ± 0,05 s. For the test, the reactor shall be set to the rated current position. Secondary and auxiliary windings shall be open circuited.

NOTE 1 Other current settings may be agreed upon between manufacturer and purchaser.

The first peak of the current shall have a value determined by the rated current multiplied by the appropriate k-factor given in 4.2.3 of IEC 60076-5:2006. The k-factor shall have a minimum value of 1,8 $\sqrt{2}$ = 2,55.

NOTE 2 Because of saturation effects in the core, the k factor may be higher than 2,55. The purchaser may require a specific test arrangement to simulate the network condition in order to take this into account.

11.9 Tolerances

Table 3 gives the tolerances to be applied to the rated quantities.

Table 3 – Tolerances

Quantities		Tolerances
1)	Current of main winding at minimum inductance and rated voltage	±5 % of the rated value
2)	Currents at other settings	±10 % of specified values
3)	No-load voltage of auxiliary and secondary windings with rated voltage applied to the main winding, over the whole adjustment range	±10 % of specified values
4)	Linearity (see 11.8.10)	±5 %

12 Smoothing reactors

12.1 General

Smoothing reactors are intended for series connection in d.c. systems to provide a high impedance to the flow of harmonic currents and to reduce the current rise on failures in d.c. systems. Two main application fields for smoothing reactors are defined as follows:

a) Industrial applications. The d.c. usually has large superimposed harmonic components. These smoothing reactors are usually designed for indoor installation and the d.c. system voltages are generally not higher than 10 kV.

b) HVDC power transmission applications. The d.c. usually has small superimposed harmonic components. The d.c. system voltages are generally higher than 50 kV.

12.2 Design

With regard to design and installation, the reactor is identified as:

- dry-type or liquid-immersed;
- air-core or gapped-core;
- with or without magnetic shield;
- for indoor or outdoor installation;
- with natural air, forced air or directly liquid cooled windings (for dry-type reactors);
- with a constant inductance (linear reactor) or, for some industrial applications, with an inductance varying with current.

12.3 Terms and definitions

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

12.3.1
rated voltage
U_d
specified d.c. voltage assigned to be applied between the line terminals of the reactor winding and earth

12.3.2
maximum operating voltage
U_{dmax}
specified highest continuous d.c. voltage between the line terminals of the reactor and earth

12.3.3
rated continuous direct current
I_{d}
specified continuous d.c. current of the reactor

NOTE The rated direct current excludes any a.c. current components.

12.3.4
rated continuous current spectrum
specified continuous steady-state r.m.s. values of the currents at specified frequencies other than d.c.

12.3.5
short-time overload direct current
specified short-time d.c. current of the reactor to be applied for the short-time overload current duration or duty-cycle

12.3.6
short-time overload current spectrum
specified short-time overload r.m.s. values of the currents at specified frequencies other than d.c. to be applied for the short-time overload current duration or duty-cycle

12.3.7
short-time overload current duration or duty-cycle
specified duration of the short-time overload current. The duty-cycle is the specified duration of each application, the interval between applications, and the number of applications of the short-time overload current.

12.3.8
rated transient fault current
specified peak value and the waveshape of the current due to system faults

12.3.9
rated incremental inductance
L_{inc}
specified incremental inductance at a specified frequency and at rated direct current I_{d}

NOTE 1 The incremental inductance is the inductance seen by the a.c. current of a particular value and frequency superimposed on the direct current through the reactor.

NOTE 2 For air-core reactors, the incremental inductance is independent of the direct current. For gapped-core or magnetically-shielded air-core reactors, the incremental inductance is a function of direct current level.

NOTE 3 For further information regarding incremental inductance, see Clause B.4.

12.4 Rating

12.4.1 Rated voltage

The rated voltage shall be specified by the purchaser.

12.4.2 Maximum operating voltage

The maximum operating voltage shall be specified by the purchaser. It shall be not less than the highest continuous operating d.c. voltage applied to the reactor in service.

12.4.3 Rated continuous direct current

The rated continuous direct current shall be specified by the purchaser.

12.4.4 Rated continuous current spectrum

The rated currents along with the frequencies shall be specified by the purchaser.

NOTE Different operating conditions may result in different current spectra. All these current spectra shall be included in the specification and one shall be designated as the rated continuous current spectrum.

12.4.5 Short-time overload current, current spectrum and current duration or duty-cycle

The short-time overload current together with the short-time overload current spectrum shall be specified, where applicable, by the purchaser along with the associated short-time overload current duration or duty-cycle and the ambient temperature. Several currents and associated durations or duty-cycles may be specified.

A duty-cycle shall give information on the maximum magnitude and duration of short-time overload current, minimum duration between successive short-time overload current applications, the level of current between short-time overload current applications and the maximum number of consecutive applications of short-time overload current of the specified duration. All information regarding short-time overload current duty-cycles shall be provided in the reactor specification, where applicable.

12.4.6 Rated transient fault current

The peak value and the waveshape of the most severe transient fault current that the reactor shall be designed to withstand shall be specified by the purchaser. Additionally, the purchaser shall supply the I^2t value or sufficient information shall be given to allow the manufacturer to calculate the I^2t value. If a transient fault current test is not performed, the ability of the reactor to withstand the rated transient fault current shall be demonstrated by the manufacturer.

12.4.7 Rated incremental inductance

The incremental inductance at a particular frequency and at rated direct current shall be specified by the purchaser as a minimum value. This value shall be subject to the tolerance given in 12.9, unless otherwise specified. If the frequency is not specified, the manufacturer shall choose an appropriate frequency.

If the a.c. current magnitude is significant compared to the d.c. current, it shall be taken into account in the design to achieve the rated incremental inductance.

12.4.8 Linearity of the smoothing reactor

Unless otherwise specified by the purchaser, the reactor shall be a linear reactor within the tolerances given in 12.9 up to rated direct current.

If required by the application, the purchaser may specify lower minimum values of incremental inductance at one or more d.c. currents above the rated value. In this case, the maximum value of the incremental inductance at all specified d.c. currents will be the rated value plus the positive tolerance.

12.4.9 Additional requirements for reactors with directly liquid cooled windings

In the case of dry-type reactors with directly liquid-cooled windings (usually a water mixture), the maximum temperature and associated pressure of the liquid at the inlet and outlet, the maximum available flow rate and the relevant details of the cooling fluid shall be specified by the purchaser or agreed between the manufacturer and the purchaser.

12.5 Temperature rise

The temperature rise limits given in IEC 60076-2 for liquid-immersed transformers and in IEC 60076-11 for dry-type transformers apply at rated continuous direct current and superimposed rated continuous current spectrum and, if specified, at the short-time overload direct current, current spectrum and current duration or duty-cycle.

NOTE The temperature rise is verified by the application of an equivalent d.c. current given by the formula in 12.8.13.

12.6 Insulation levels

The insulation levels shall be specified by the purchaser to coordinate with the insulation levels of the associated d.c. system at the position of the reactor in the system.

The following insulation levels may not apply to reactors for industrial application covered by item a) of 12.1 with the exception of 12.6.5 (separate source a.c. withstand voltage level). However, in cases where a turn-to-turn overvoltage test is required, these levels may also be specified by the purchaser.

12.6.1 Lightning impulse levels

The lightning impulse level of the reactor shall be specified for each winding terminal to earth and between the terminals.

12.6.2 Switching impulse levels

The switching impulse level of the reactor shall be specified for each winding terminal to earth and between the terminals.

12.6.3 Separate source d.c. withstand voltage level

The d.c. withstand voltage level shall be $U_{\mathrm{dc}} = 1{,}5\ U_{\mathrm{dmax}}$.

This voltage shall be applied between the winding terminals connected together and earth.

NOTE Specific requirements regarding creepage distance for external insulation shall be subject to agreement between manufacturer and purchaser.

12.6.4 Polarity-reversal withstand voltage level

The polarity-reversal withstand voltage level shall be $U_{\mathrm{pr}} = 1{,}25\ U_{\mathrm{dmax}}$.

This voltage shall be applied between the winding terminals connected together and earth.

12.6.5 Separate source a.c. withstand voltage level

The a.c. withstand voltage level shall be

- for reactors covered by item a) of 12.1 $U_{\mathrm{ac}} = \frac{2{,}5 \cdot U_{\mathrm{dmax}}}{\sqrt{2}}$
- for reactors covered by item b) of 12.1 $U_{\mathrm{ac}} = \frac{1{,}5 \cdot U_{\mathrm{dmax}}}{\sqrt{2}}$

This voltage shall be applied between the winding terminals connected together and earth.

NOTE In particular applications where high superimposed a.c. voltages may be experienced in service, a higher separate source a.c. withstand voltage level may be specified by the purchaser.

12.7 Rating plates

Each reactor shall be provided with a rating plate of weatherproof material, fitted in a visible position, showing in all cases the appropriate items indicated below. The entries on the plate shall be indelibly marked (for example by etching, engraving or stamping).

- type of reactor;
- outdoor/indoor application;
- number of this part of IEC 60076;
- manufacturer's name;
- manufacturer's serial number;
- year of manufacture;
- insulation level(s);
- maximum operating voltage;
- rated continuous direct current;
- information on short-time overload current and current duration;
- incremental inductance at rated continuous direct current;
- type of cooling;
- thermal class of insulation (for dry-type reactors only);
- details regarding liquid-cooling (for reactors with directly liquid cooled windings);
- temperature rise limits for top-oil and average winding (for liquid-immersed reactors only);
- total mass;
- transportation mass (for liquid-immersed reactors);
- untanking mass (for liquid-immersed reactors);
- mass of insulating liquid (where applicable);
- type of insulating liquid, if not mineral oil (where applicable);
- connection diagram including instrument transformers (where applicable).

12.8 Tests

12.8.1 General

The general requirements for routine, type and special tests are prescribed in IEC 60076-1.

12.8.2 Routine tests

The following routine tests shall be performed:

12.8.2.1 Reactors covered by item a) of 12.1

- measurement of winding resistance (IEC 60076-1);
- measurement of incremental inductance (12.8.5);
- separate source a.c. withstand voltage test (12.8.7);
- test of the tightness of the liquid cooling circuit for reactors with directly liquid cooled windings (12.8.16).

12.8.2.2 Reactors covered by item b) of 12.1

- measurement of winding resistance (IEC 60076-1);
- measurement of the harmonic current loss (12.8.6);
- measurement of incremental inductance (12.8.5);
- separate source a.c. withstand voltage test for liquid-immersed reactors (12.8.7);
- separate source d.c. withstand voltage test for liquid-immersed reactors (12.8.8);
- polarity-reversal withstand test for liquid-immersed reactors (12.8.9);
- lightning impulse test (12.8.10);
- switching impulse test for liquid-immersed reactors (12.8.11);
- measurement of insulation resistance and/or capacitance and dissipation factor (tan δ) of the winding insulation to earth for liquid-immersed reactors. (These are reference values for comparison with later measurements in the field. No limitations for the values are given here.)

12.8.3 Type test

The following type tests shall be performed:

- temperature rise test (12.8.13);
- switching impulse test for dry-type reactors covered by item b) of 12.1 (12.8.11);
- measurement of the pressure drop for reactors with directly liquid cooled windings (12.8.17);
- wet separate source d.c. withstand voltage test for dry-type reactors (12.8.12);
- measurement of power consumption of fans and oil pumps, if any.

12.8.4 Special tests

The following special tests shall be performed when specifically requested by the purchaser:

- measurement of acoustic sound level (12.8.14);
- measurement of high frequency impedance (12.8.15);
- transient fault current test (12.8.18);
- chopped wave impulse test for liquid-immersed reactors (12.8.19).

12.8.5 Measurement of incremental inductance (routine test)

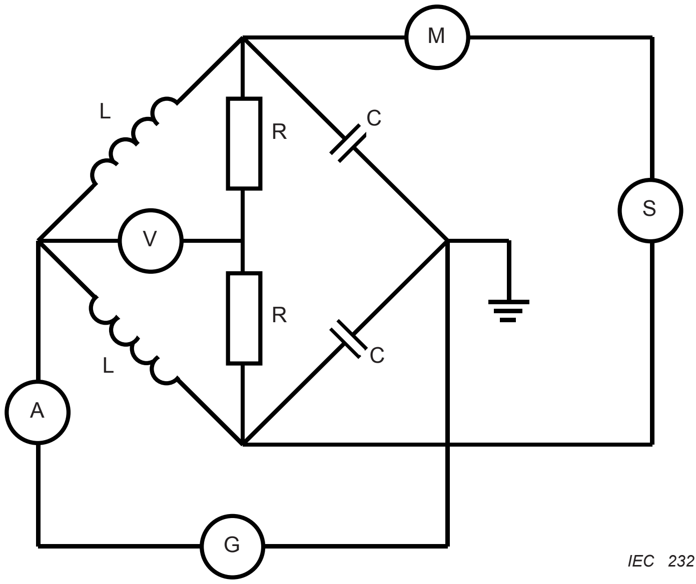
The incremental inductance shall be measured at the specified harmonic frequency with a representative value of current superimposed on rated direct current I_d (rated incremental inductance value) and at zero direct current (no-load incremental inductance value) as well as at other values of direct current between these extreme values to verify that the reactor is a linear reactor.

NOTE 1 Where the a.c. currents are small (less than 10 %) compared to the d.c. current, the exact value of the a.c. test current is not critical to the measurement.

The measurement should be made using a bridge connection of two identical smoothing reactors as shown by the connection diagram in Figure 10 to apply a.c. and d.c. currents simultaneously. However, other methods may be used subject to agreement between purchaser and manufacturer, particularly if only one single reactor is available for testing.

NOTE 2 Alternatively, the differential inductance derived from the measured magnetic characteristic (see Clause B.7) may be used in lieu of the incremental inductance, subject to agreement between manufacturer and purchaser.

For air-core reactors, only the no-load incremental inductance shall be measured since the inductance is independent of current.



Key

A = measuring device for a.c. current

C = blocking capacitor to avoid d.c. current leakage

G = a.c. supply

L = smoothing reactors under test

M = measuring device for d.c. current

R = auxiliary resistor for measurement of a.c. voltage

S = d.c. supply

V = voltmeter for measurement of a.c. voltage

Figure 10 – Measuring circuit for determining incremental inductance of two identical smoothing reactors

12.8.6 Measurement of the harmonic current loss and calculation of the total loss (routine test)

The measurement shall be performed at each frequency and current of the specified harmonic current spectrum at zero direct current at factory ambient temperature. The losses shall be corrected to the reference temperature.

The total harmonic loss is composed of ohmic loss, additional loss and in the case of gapped-core and magnetically-shielded air-core reactors, iron loss. The ohmic loss portion is taken to be equal to $I_h^2 R$, R being the measured d.c. resistance, I_h being the harmonic current. Iron loss and additional loss cannot be separated by measurement. The sum of iron loss and additional loss is therefore the difference between the total harmonic loss and the total ohmic loss.

The ohmic loss is corrected to reference temperature according to the method given in IEC 60076-1. A correction of iron loss and additional loss to reference temperature is not normally practical. Therefore, iron loss and additional loss shall be deemed independent of temperature. This assumption normally gives a slightly higher loss figure at the reference temperature than actually exists.

If the measurement is performed with current magnitudes other than those specified, the losses shall be corrected to the specified magnitudes of the harmonic current spectrum by the square of the ratio of the specified current to the measured current.

The total loss of the reactor is calculated from the sum of the winding d.c. loss (corrected to reference temperature according to the method given in IEC 60076-1) at rated direct current and the total harmonic current loss.

12.8.7 Separate source a.c. withstand voltage test (routine test)

The test shall be made at 50 Hz or 60 Hz. The voltage shall be applied between both winding terminals connected together and earth. The duration of the test is 1 min.

For liquid-immersed reactors covered by item b) of 12.1, a partial discharge measurement shall be made according to the applicable parts of annex A of IEC 60076-3:2000, with measuring equipment as specified in IEC 60270. In this case the duration of the test shall be 1 h.

NOTE The use of equipment to detect and locate partial discharges is recommended, in particular, to distinguish between any partial discharges occurring within the reactor from those that may occur in the test circuit.

The partial discharge level shall not exceed 500 pC.

Annex A of IEC 60076-3:2000 lists suggested actions to be taken following an unsuccessful test.

12.8.8 Separate source d.c. withstand voltage test for liquid-immersed reactors (routine test)

12.8.8.1 Test procedure

The oil temperature of the reactor shall be (20 ± 10) °C. The voltage shall be applied between both winding terminals connected together and earth. Positive polarity shall be used.

The bushings shall be earthed for a minimum of 2 h prior to the test and no preconditioning of the reactor insulation structure at a lower voltage level is allowed. The voltage shall be brought up to the test level within 1 min and held for 120 min, after which the voltage shall be reduced to zero in 1 min or less.

Partial discharge measurements shall be performed throughout the entire separate source d.c. withstand voltage test.

NOTE 1 After the separate source d.c. withstand voltage test is complete, the insulation structure may retain a considerable electrical charge. Unless adequately discharged, subsequent partial discharge measurements may be affected.

NOTE 2 The use of equipment to locate partial discharges is recommended, in particular, to distinguish between any partial discharges occurring within the reactor from those that may occur in the test circuit.

12.8.8.2 Acceptance criteria

The partial discharge measurements shall be made according to the applicable parts of Annex A of IEC 60076-3:2000, with measuring equipment as specified in IEC 60270.

The results shall be considered acceptable when, during the last 30 min of the test, no more than 30 pulses ≥ 2 000 pC are noted with no more than 10 pulses ≥ 2 000 pC in the last 10 min. If this condition is not met, the test may be extended for 30 min. If the acceptance criteria are still not met during this extended period, the reactor shall be considered to have failed the test.

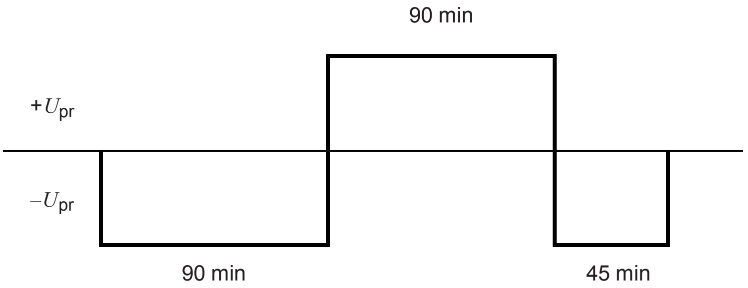
Partial discharge pulses occurring before the final 30 min of the test shall be recorded for information purposes only.

If the acceptance criteria are not met and no break-down occurs, this shall not lead to an immediate rejection of the reactor, but a consultation between the purchaser and manufacturer with a view to further investigations and actions is required. The purchaser may require a successful partial discharge test before the reactor is accepted.

12.8.9 Polarity-reversal withstand test for liquid-immersed reactors (routine test)

12.8.9.1 Test procedure

The oil temperature of the reactor shall be (20 ± 10) °C. The voltage shall be applied between both winding terminals connected together and earth. A double reversal test shall be used as shown in the Figure 11.



IEC 2328/07

Figure 11 – Double reversal test voltage profile

The bushings shall be earthed for a minimum of 2 h prior to the test and no preconditioning of the reactor insulation structure at a lower voltage level is allowed. The test shall be made with two reversals. The test sequence shall include 90 min at negative polarity followed by 90 min at positive polarity and finally 45 min at negative polarity. Each reversal of the voltage from one polarity to the other shall be completed within 2 min. The polarity reversal is completed when the voltage has reached 100 % of the test value.

Partial discharge measurements shall be performed throughout the entire polarity reversal withstand test.

NOTE 1 After the polarity-reversal withstand test is complete, the insulation structure may retain a considerable electrical charge. Unless adequately discharged, subsequent partial discharge measurements may be affected.

NOTE 2 The use of equipment to locate partial discharges is recommended, in particular, to distinguish between any partial discharges occurring within the reactor from those that may occur in the test circuit.

12.8.9.2 Acceptance criteria

The partial discharge measurements shall be made according to applicable parts of Annex A to IEC 60076-3:2000, with measuring equipment as specified in IEC 60270.

In terms of interpreting the partial discharge measurements, the results shall be considered acceptable and no further polarity reversal test required when no more than 10 pulses ≥2 000 pC occur in any 10 min period. Because some discharge activity is normal during d.c. voltage changes, the partial discharges counted during the first five minutes of the test, during the polarity reversal and the first five minutes thereafter shall be disregarded. However, discharge pulses of 500 pC or higher during these periods shall be measured and recorded for information purpose only.

If the acceptance criteria are not met and no break-down occurs, this shall not lead to an immediate rejection of the reactor but a consultation between the purchaser and manufacturer with a view to further investigations and actions is required. The purchaser may require a successful partial discharge test before the reactor is accepted.

12.8.10 Lightning impulse test (routine test)

This test shall be carried out in general accordance with Clauses 13 and 14 of IEC 60076-3:2000, Clause 7 of IEC 60076-4:2002 and Clause 21 of IEC 60076-11:2004 for dry-type reactors. The test shall be carried out on each terminal in succession with the opposite terminal earthed.

For dry-type reactors the test shall be made with both negative and positive polarity.

NOTE If the insulation requirements between the winding terminals differ from those between the terminals and earth, the impulse test procedure shall be subject to agreement between purchaser and manufacturer.

12.8.11 Switching impulse test (routine test, type test)

This test shall be carried out generally in accordance with Clause 15 of IEC 60076-3:2000 and Clause 8 of IEC 60076-4:2002.

A switching impulse test shall be performed between the two terminals connected together and earth. The voltage impulse shall be of negative polarity and the waveshape as specified in IEC 60060-1.

The switching impulse test between the terminals may not be practical because the energy available from the test generator is not sufficient. In this case, the capability of the reactor to withstand the test level shall be demonstrated by the manufacturer.

For dry-type reactors, the tests shall be of positive and negative polarity, the test procedure shall be consistent with IEC 60060-1. If such reactors are for outdoor application, wet tests shall be subject to agreement between purchaser and manufacturer.

12.8.12 Wet separate source d.c. withstand voltage test for dry-type reactors (type test)

This test is applied to the insulators of dry-type smoothing reactors. The d.c. test voltage U_{dc} (for test level see 12.6.3) shall be applied for 1 h under wet conditions.

The test shall be performed with the insulators arranged in the service condition.

NOTE 1 Achieving the service condition may not require the actual reactor to be used for the test. A suitable structure equivalent to the reactor may be used instead.

The water spray shall be applied in accordance with IEC 60060-1 to one support insulator for at least 30 min prior to testing and during the application of the test voltage. No flashover is allowed during the test.

NOTE 2 The test may be performed on a single isolated insulator upon agreement by the purchaser and manufacturer at the tender stage.

12.8.13 Temperature rise test (type test)

The test shall be carried out in general accordance with IEC 60076-2 and shall be carried out with an equivalent direct test current I_{T} providing the total losses as determined in 12.8.6. For dry-type reactors, the temperature class limits as stated in IEC 60076-11 apply.

The equivalent direct test current I_{T} of the reactor shall be calculated by the following relation:

$$I_T = \sqrt{\frac{R_{ref} \cdot I_d^2 + P_h}{R}}$$

with

I_T equivalent direct test current;

R_{ref} measured d.c. winding resistance corrected to reference temperature;

R measured d.c. winding resistance at the test temperature;

I_d rated direct current;

P_h total harmonic loss according to 12.8.6.

In exceptional cases, for example where a high test voltage, current or power is required, it may be difficult to maintain these test conditions. In this case, the test may be performed at a reduced test current I_{test} but not less than 0,9 times I_T. The test level shall be stated in the tender by the manufacturer and agreed upon between manufacturer and purchaser at the time of order. The temperature rises shall be corrected to the equivalent direct test current I_T.

For liquid-immersed reactors, the oil temperature rise shall be multiplied by $\left(\frac{I_T}{I_{test}}\right)^{2x}$ and the winding temperature rise above the oil temperature shall be multiplied by $\left(\frac{I_T}{I_{test}}\right)^{y}$ with x and y according to the following:

- for reactors with ON cooling $x = 0,8$ $y = 1,3$
- for reactors with OF cooling $x = 1,0$ $y = 1,3$
- for reactors with OD cooling $x = 1,0$ $y = 2,0$

For dry-type reactors the winding temperature rise above ambient temperature shall be multiplied by $\left(\frac{I_T}{I_{test}}\right)^{y}$ with y according to the following:

- for reactors with AN cooling $y = 1,6$
- for reactors with AF cooling $y = 1,8$

In most cases, the total reactor loss at the steady-state condition is somewhat smaller than at reference temperature because the ambient temperature is normally lower than the design value during the test. This effect shall be neglected.

Care shall be taken in providing appropriate connectors and electrical leads to connect the reactor to the power supply during the temperature rise test. This is of particular importance for dry-type air-core reactors.

For dry-type air-core reactors, if requested, the temperature rise of the reactor terminals shall be measured during the reactor temperature rise test. In order to obtain meaningful terminal temperature rise measurements, the purchaser shall supply a connector and at least one meter of incoming conductor of the type that will be used on site, to the manufacturer for use during the temperature rise test. Terminal temperature rise limits shall be as given in Clause 6 (see also IEC 60943).

12.8.14 Measurement of acoustic sound level (special test)

This test shall be carried out generally in accordance with IEC 60076-10 with the rated d.c. current applied simultaneously with each of the significant a.c. currents of the specified harmonic current spectrum in turn.

A test circuit as shown in Figure 10 may be used. This circuit requires two identical reactors which are acoustically isolated from each other. The a.c. source may be a variable frequency sine-wave generator of sufficient power. To increase the harmonic current driven through the reactors, the capacitors may be tuned for resonance at the specific harmonic frequency.

The total sound power level shall be calculated using the following formula, see also Annex A of IEC 60076-10:

$$L_{\text{tot}} = 10\log\left(\sum_i 10^{L_{\text{i}}/10}\right)$$

with

L_{tot} the total sound level, and

L_{i} the sound level of each individual component.

If the specified currents cannot be achieved, correction from measured to rated currents may be made by calculation according to the following formula, by agreement between manufacturer and purchaser:

$$L_{\text{W-rated}} = L_{\text{W-meas}} + 20\,\log\left(\frac{I_{\text{DC-rated}} \times I_{\text{h-rated}}}{I_{\text{DC-meas}} \times I_{\text{h-meas}}}\right)\ \text{dB(A)}$$

with

$L_{\text{W-rated}}$ sound power of the reactor at rated d.c. and rated harmonic current

$L_{\text{W-meas}}$ sound power of the reactor at d.c. and harmonic current during measurement

$I_{\text{DC-rated}}$ rated d.c. current

$I_{\text{h-rated}}$ rated harmonic current

$I_{\text{DC-meas}}$ DC current at sound measurement

$I_{\text{h-meas}}$ harmonic current at sound measurement.

12.8.15 Measurement of high frequency impedance (special test)

The impedance of the reactor shall be measured over a frequency range and in a manner to be agreed upon between the manufacturer and the purchaser.

NOTE Typical frequency ranges for the measurements range between power frequency and a few kHz and between 30 kHz and 500 kHz. The method of test will depend on the use for which the information is required.

12.8.16 Test of the tightness of the liquid cooling circuit for reactors with directly liquid cooled windings (routine test)

A test shall be performed to demonstrate the liquid cooling circuit is free of leaks. The test shall be performed at the factory ambient temperature, with all components (pipes, hoses, fittings, manifolds, gauges, etc.) of the cooling circuit assembled substantially as in service, as far as features affecting the test result are concerned. The cooling circuit shall be filled with coolant essentially free from any air bubbles. Unless otherwise specified a static pressure of at least 1,5 times the maximum operating pressure of the cooling system to which the reactor is connected plus two bars shall be applied for a duration of at least 6 hours.

During the application of pressure, the reactor shall be carefully inspected for possible leaks, in particular at critical locations such as joints and fittings. The test shall be considered successful if no leaks are apparent.

12.8.17 Measurement of the pressure drop for reactors with directly liquid cooled windings (type test)

A measurement of the pressure drop between inlet and outlet of the cooling circuit of the reactor shall be made. The measurement shall be performed at the factory ambient temperature, with all components (pipes, hoses, fittings, manifolds, gauges, etc.) of the cooling circuit assembled substantially as in service, as far as features affecting the test result are concerned. The coolant as specified by the purchaser (pure water or water / glycol mixture, for example) shall be pumped through the cooling circuit of the reactor at the specified rate. The coolant flow rate (in litres per minute) of the coolant and the pressure at the water inlet and outlet shall be measured. The pressure drop at rated coolant flow rate shall not exceed the guaranteed value.

If specified by the purchaser, this measurement shall also be performed at a number of different flow rates so that a graph of pressure drop versus flow rate can be drawn.

12.8.18 Transient fault current test (special test)

12.8.18.1 General

If a transient fault current test is required by the purchaser this shall be specified at the time of order and the test method shall be agreed upon between the manufacturer and the purchaser. The specification for the transient fault current test shall include the test current peak value, the I^2t value and the number of test current shots.

The transient fault current test shall be carried out using a method that achieves the specified test current peak value and the I^2t value. If not otherwise specified, the number of full test current shots shall be two.

NOTE 1 Different test methods are possible, one such method is described in Annex C of IEEE Std 1277-2000.

NOTE 2 If the ratio of the peak transient fault current to the rated current is low (typically less than 10) the application of the transient fault current test is usually not justified.

NOTE 3 For HVDC smoothing reactors, the requirements to perform a full transient fault current test usually exceed the capability of commercially available high power test stations.

12.8.18.2 Acceptance criteria

Before and after the transient fault current a measurement of inductance at zero d.c. current and a lightning impulse test according to 12.8.10 at 100 % of specified voltage shall be carried out on the reactor. The inductance values shall be consistent within measurement tolerance limits. Oscillograms from the required dielectric test shall show no change; agreeing within the limits of the high voltage dielectric test systems.

For liquid-immersed reactors, general information concerning fault detection is provided in 4.2.7 of IEC 60076-5:2006.

For dry-type reactors, visual inspection of the reactor and supporting structure shall give no indication that there has been any change in mechanical condition that will impair the function of the reactor. If after the transient fault current test program, the winding clamping system has deteriorated, or surface cracks have increased significantly in number or dimensions, the reactor shall be considered to have failed the transient fault current test. In case of doubt, up to three more tests with peak current shall be applied to verify that the monitored condition has stabilized. If the deterioration continues, the reactor shall be considered to have failed the test. If conditions stabilize after one or two extra transient fault tests and coupled with successful routine tests after transient fault tests, the reactor shall be considered to have passed the transient fault test. For more information, see Annex F, as applicable.

12.8.19 Chopped wave impulse test for liquid-immersed reactors (special test)

This test shall be carried out as prescribed in Clause 14 of IEC 60076-3:2000 on each terminal in turn with the other terminal earthed.

12.9 Tolerances

The tolerance on the rated incremental inductance shall be ${}^{+20}_{-0}$ %.

The measurement of incremental inductance at zero d.c. current made according to 12.8.5 shall be within ${}^{+10}_{-0}$ % of the incremental inductance value measured at rated d.c. current.

The total loss measured and corrected according to 12.8.6 shall not exceed the guaranteed loss by more than 10 %.

Annex A
(informative)

Information on shunt reactor switching and on special applications

A.1 Shunt reactor switching

A.1.1 Terms

SIWL	– Switching Impulse Withstand Level of the reactor
LIWL	– Full Wave Lightning Impulse Withstand Level of the reactor
LICWL = 1,1×LIWL	– Chopped Wave Lightning Impulse Withstand Level of the reactor
SIPL	– Switching Impulse Protection Level of the surge arrestor connected to the terminals of the reactor
LIPL	– Lightning Impulse Protection Level of the surge arrestor connected to the terminals of the reactor

A.1.2 Switching phenomena

Switching of shunt reactors is often a daily event (e.g. switching on during light load conditions and switching off during full load conditions of the line or grid). The stresses on the circuit breaker and on the insulation of the shunt reactor during these switching operations are complex (see IEC 62271-110 and IEEE C57.21). During switching off, the circuit breakers may cause transient voltages due to current chopping and re-ignition. These may lead to a severe stress on the shunt reactor insulation.

The current chopping of the circuit breaker stresses the reactor with switching overvoltage containing frequencies in the range of a few kHz. The SIWL of the reactor and the overvoltage shall be coordinated. The amplitude can be calculated from the level of chopping current of the circuit breaker, the reactor inductance and the parallel capacitance of the reactor winding (normally in the range of 100 pF up to 5 nF). The method of calculation is given in IEC 62271-110. When the SIPL of the surge arrester is more than about 30 % below the SIWL of the reactor, the insulation of the reactor should be protected by the surge arrester against the current chopping overvoltage.

Re-ignition occurs in a circuit breaker, when the transient recovery voltage (TRV) applied to the contacts of the circuit breaker exceeds the voltage withstand capability of the opening contacts after current extinction. Re-ignitions are very common in circuit breakers switching shunt reactors unless specific measures are applied to avoid them. In this case, the shunt reactor is stressed with high frequency voltage oscillations in the MHz range with the peak-to-peak amplitude limited by the surge arresters to twice the LIPL. The rate of change of voltage caused by the re-ignition is comparable to that occurring during the chopped wave test.

The characteristics of the circuit breaker (the level of current chopping and the range of arcing time for which the probability of re-ignition is small) may be evaluated by the tests given in IEC 62271-110. With these characteristics, the overvoltage stress seen by the reactor during switching operation can be verified.

In most cases re-ignition can be avoided by controlled switching of the circuit breaker (see ELECTRA No. 185, August 1999). The opening of the circuit breaker contacts can be controlled in such a way, that the arcing time always falls within re-ignition free time window.

NOTE The voltage stress during shunt reactor switching is higher when the neutral of the reactor is not solidly earthed.

For reactors with $U_m \leq 52$ kV (with the reactor neutral normally not earthed) the capability of the reactor to withstand the rate of change of voltage during re-ignition can be verified by a chopped wave test. The protection given by the surge arresters is likely to be sufficient for the reactor insulation.

For reactors with 52 kV < $U_m \leq 170$ kV, the stress on the reactor due to the rate of change of voltage during re-ignition is in the same range as the stress applied during a chopped wave test. For these reactors, the higher LIWL values corresponding to the U_m in accordance with IEC 60076-3 should be chosen and the circuit breaker should be qualified for shunt reactor switching in accordance with IEC 62271-110.

For reactors with $U_m > 170$ kV (with the reactor neutral normally solidly earthed), the stress on the reactor due to the rate of change of voltage during re-ignition normally exceeds the rate of change of voltage applied during a chopped wave test. For these reactors, the higher LIWL values corresponding to the U_m in accordance with IEC 60076-3 should be chosen and the circuit breaker should be qualified for shunt reactor switching in accordance with IEC 62271-110. In addition, re-ignition should be avoided by controlled switching of the circuit breaker. In the case where the SIPL of the surge arrester is less than about 30 % below the SIWL of the reactor, the chopping overvoltage calculated from the parameters of the circuit breaker should be not more than about 70 % of the SIWL of the reactor.

Reactors with $U_m > 170$ kV, intended for line compensation, may be connected with off-load disconnectors. In this case, normally no critical overvoltages are expected at the reactor during switching-out of the line and protection by surge arresters is sufficient. However, for double circuit lines, when the reactor and the capacitance between the lines form a natural resonance, isolation of the reactor with the disconnector may be a problem.

A.2 Reactors with on-load tap changer (OLTC)

Reactors equipped with an OLTC are intended to allow adjustment of the reactive compensation depending on the load condition of the line/network. During light loading (e.g. night time) the maximum reactive compensation at the tap with the minimum number of turns is used and for the full load condition (e.g. day time), the reactor is switched to the tap with the maximum number of turns. A typical tapping range allows a reduction of the reactive power from 100 % to approximately 50 %. The OLTC shall be specially selected for zero power factor switching. Also the maximum number of operations of the OLTC shall be considered.

A.3 Shunt reactors connected to the tertiary winding of transformers

Shunt reactors with $U_m \leq 52$ kV are often connected to the tertiary winding of a power transformer to provide reactive compensation for the system with higher voltage. Usually, these shunt reactors are connected in a star. The neutral point is normally not connected to earth.

There are two possible methods of connecting the shunt reactor to the transformer:

a) Connecting the line terminals of the shunt reactor through a circuit breaker to the tertiary terminals of the transformer. The reactor terminals may be protected with surge arresters to limit the overvoltage during switching off (see also Clause A.1).

b) Connecting the line terminals of the shunt reactor through a disconnector to the tertiary terminals of the transformer and providing a circuit beaker on the neutral end of the three-phase windings of the reactor. The reactor is switched on by forming the star point with the circuit breaker. Usually no surge arresters to limit the overvoltage are required. The disconnector is used to isolate the reactor after the neutral point is opened.

In order to avoid overvoltages at the HV side of the transformer during switching off the transformer, it is useful to switch off first the reactor and then to disconnect the power transformer from the grid. This sequence, however, is not possible during fault clearing. The overvoltage protection of the transformer shall be designed for that case (see Electra No. 138 (1991)).

A.4 Shunt reactors for lines with single-pole auto re-closing

Shunt reactors connected to a line or grid with an effectively earthed neutral, are normally earthed at the reactor neutral. In some cases of transmission systems where the line has single-pole auto re-closing installed, it may be preferable to control the secondary arc current and transient recovery voltage for single line-to-earth faults. This may be done by either adding a neutral reactor to connect the shunt reactor neutral to earth, or by an open neutral with suitably rated surge arrester protection. Both methods require a higher insulation level at the shunt reactor neutral to meet the temporary overvoltage requirements during unbalanced conditions.

For more information on this subject see:

E.W. Kimbark, Suppression of Ground Fault Arcs on Single-Pole-switched EHV Lines by Shunt Reactors, IEEE Transmission and Distribution, March 1964.

Annex B
(informative)

Magnetic characteristic of reactors

B.1 General

While the voltage to current relationship of a reactor is the main characteristic of interest from the power system's perspective, the linked flux to current relationship is more appropriate to describe the magnetic properties of the reactor itself. The linked flux is the time integral of the voltage. When the linked flux to current relationship is known, it is possible to calculate the voltage to current relationship for both steady-state a.c. and transient cases.

Reactors, where at least part of the magnetic flux passes through ferromagnetic materials (core, magnetic shield etc.), will show a non-linear behaviour caused by the magnetic saturation characteristic of the ferromagnetic material. The characteristic of the whole reactor is then such that at low flux levels, there is a linear relationship between the flux and the magnetisation current. For high values of the flux, when the ferromagnetic materials are fully saturated, there is also a linear relationship between the change of flux and the change of magnetisation current. Between these two linear parts, there is a progressive change of the relationship. The point where the extrapolation of these two linear parts crosses is called knee point. This is illustrated in Figure 2.

In Figure 1, three different types of magnetic characteristic are illustrated. Figure 1a illustrates a linear relationship between magnetising current and linked flux, which can be seen in reactors without ferromagnetic material in the flux path. In Figure 1b, there is some non-linearity between linked flux and current when the flux density in parts of the ferromagnetic flux path starts to be saturated at higher than normal operating levels. Figure 1c illustrates the situation where the ferromagnetic materials become fully saturated under rated operational conditions.

B.2 Definition of the magnetic characteristic

Fundamentally, there is a non-linear relation between the flux density B and the magnetic field strength H in ferromagnetic materials. In a reactor, normally the flux density is different in different parts of the flux path. This means that the different parts of the flux path are saturated at different flux levels. Therefore, the relation between flux Φ and current is of greater interest then the relation between flux density and magnetic field strength.

The linked flux of a winding is the total flux linked to the winding taking into account the number of winding turns. The relation that forms the magnetic characteristic (Figure 2) of a reactor is the instantaneous linked flux, ψ, versus the instantaneous current, i.

The hysteresis phenomenon can be neglected for reactors, since the magnetic characteristic is mainly influenced by the air-gaps.

B.3 Magnetic characteristic and reactance

As stated in Clause B.2 the magnetic characteristic is the relation between the instantaneous value of the linked flux ψ and the instantaneous value of the current i whereas the reactance is the ratio between the applied voltage and the current, both given as r.m.s. values (assuming the resistive component of the impedance to be negligible). The reactance for a given voltage magnitude and waveshape can be derived from the magnetic characteristic.

If there is a linear relationship between the linked flux and current, there will also be a linear relationship between voltage (in r.m.s.) and current (in r.m.s.) and the reactance is constant. If the linked flux to current relationship is non-linear, then the relationship between voltage (in r.m.s.) and current (in r.m.s.) is also non-linear and will have a different characteristic to the relationship between the linked flux and current. In this case, the reactance will vary with the applied voltage.

The relationship between linked flux and current will be linear for lower applied voltages (where the linked flux level is well below the knee point) but will become non-linear at higher voltages when the flux starts to cause saturation. When a sinusoidal voltage of such a magnitude that the magnetic characteristic is non-linear is applied, the current will not be sinusoidal. This is illustrated in Figure B.1.

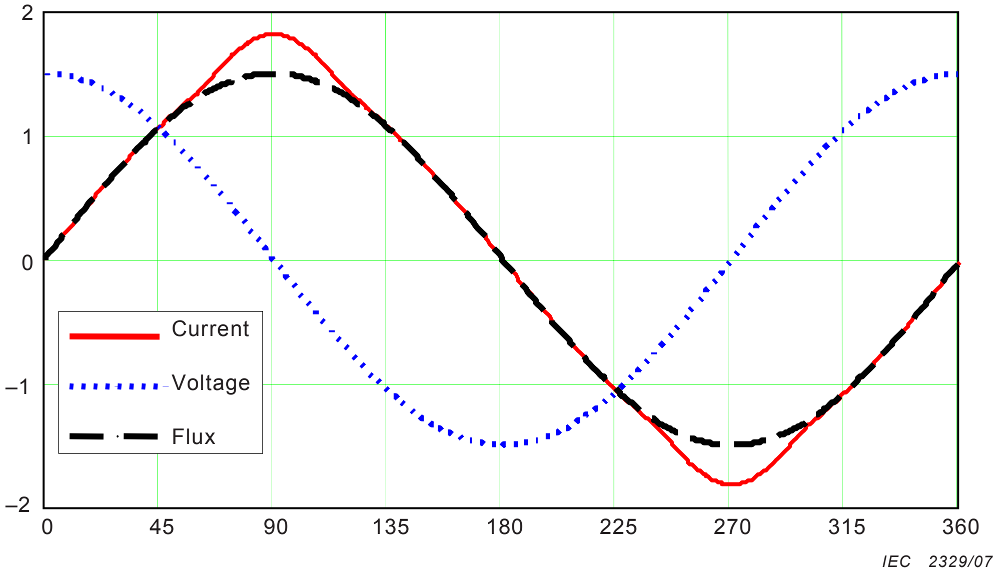


Figure B.1 – Illustration of linked flux and current waveshapes with a sinusoidal voltage applied to a reactor with a non-linear magnetic characteristic according to Figure B.6

B.4 Inductance

The inductance of a reactor can be defined in different ways. In this part of IEC 60076, the differential inductance, the incremental inductance and the inductance derived from the reactance are used. The definitions for each reactor type indicate which one is used for the particular application.

The differential inductance is defined from the derivative of the linked flux as a function of current (equal to the slope of the magnetic characteristic):

$$L_{\mathrm{d}} = \frac{d\psi}{di} \tag{B1}$$

Where there is an a.c. current superimposed on a d.c. current an incremental inductance is defined as follows:

$$L_{\mathrm{inc}} = \left.\frac{X_{\mathrm{a.c.}}}{2\pi f_{\mathrm{a.c.}}}\right|_{I_{\mathrm{d.c.}}} \tag{B2}$$

where $X_{\text{a.c.}}$ is the reactance derived from a.c. voltage and a.c. current measurement at the d.c. current level $I_{\text{d.c.}}$. At lower frequencies $f_{\text{a.c.}}$ the resistive part might be neglected.

The inductance derived from reactance is defined as

$$L_{\text{reac}} = \frac{X}{2\pi f} \tag{B3}$$

where X is the reactance derived from voltage and current both given as r.m.s. values.

NOTE In the International Electrotechnical Vocabulary (IEV) the inductance is defined as the relation between linked flux and current:

$$L = \frac{\Psi}{i}$$

This definition of inductance has limited value for reactors with nonlinear or saturated magnetic characteristic and is not used in this part of IEC 60076.

B.5 Harmonics

Both, harmonics in the applied voltage and a non-linear magnetic characteristic of the reactor will cause harmonics in the current. When there is a non-linear relationship between linked flux and current, harmonics will be introduced in the current with a pure sinusoidal voltage applied. It is possible to calculate the harmonic content introduced in the current if the magnetic characteristic is known.

Normally for linear reactors, measurement or evaluation of the harmonic content is not necessary.

Measurement of the harmonic currents is sometimes difficult to perform with sufficient accuracy because the harmonic currents themselves can introduce distortion of the applied voltage. Calculation of harmonic currents from the magnetic characteristic is an alternative to measurements where practical difficulties make these inaccurate.

The Total Harmonic Distortion factor THD is defined as the r.m.s. value of the harmonics in relation to the r.m.s. value of the fundamental. THD_{I} for a current can then be calculated according to

$$THD_{\text{I}} = \frac{I_{\text{rms,harmonics}}}{I_{\text{rms,fundamental}}} \approx \sqrt{\frac{I_{\text{rms}}^2 - I_{\text{rms, fundamental}}^2}{I_{\text{rms, fundamental}}^2}} = \sqrt{\frac{I_{\text{rms}}^2}{I_{\text{rms, fundamental}}^2} - 1} \tag{B4}$$

or more practically as

$$THD_{\text{I}} = \sqrt{\sum_{h=2}^{n} i_h^2} \tag{B5}$$

$i_h = I_h / I_1$

I_h – r.m.s. current value of the hth harmonic
I_1 – r.m.s. current value of the fundamental
n – highest harmonic taken into account

NOTE n may be taken as 7 in practice for the purposes of this part of IEC 60076.

B.6 Inrush current

During steady-state conditions there is almost a 90° phase shift between the voltage across a reactor and the current flowing through it. The zero crossing of the current is at the peak value of the voltage. When the reactor is connected to the network, there is a transient condition. Depending on the frequency and point on the voltage wave at which the reactor is connected to the network, an inrush current will be experienced with a peak value higher than the peak value of rated current.

The worst condition occurs when the reactor is connected at the zero crossing of the voltage wave. This will give a linked flux that is about twice the value at steady-state. For a reactor with a linear magnetic characteristic the peak value of the inrush current is then about twice the peak value of the current at steady-state.

For reactors with a non-linear magnetic characteristic, the inrush current peak can be more than twice the peak steady-state current. The inrush current level can be derived from the magnetic characteristic.

The inrush current phenomenon is the same as that experienced in transformers but the ratio of the peak current to the rated current is lower. Magnetic remanence effects do not influence the inrush current for reactors.

The reactor winding losses mainly determine the damping of the inrush current assuming that the power system has a small resistive component.

B.7 Measurement of magnetic characteristic

An indirect method is needed to get the magnetic characteristic since the linked flux cannot be measured directly. Calculation of the magnetic characteristic is possible from measurements made of the instantaneous values of the current and voltage when an a.c. voltage of sufficient magnitude to cause saturation is applied for at least one cycle. If a measurement of the characteristic is requested for currents above the maximum service current, a method shall be used that does not overload the reactor, for instance the d.c. method described in B.7.1. The magnetic characteristic for currents well above nominal current can then be evaluated.

B.7.1 DC current charging – discharging method (theory)

By charging the reactor with a d.c. current (higher than nominal peak current) the magnetic linked flux will increase following the magnetisation curve (switch 1 and 3 are closed in Figure B.2). The reactor is then short-circuited and the decaying current with time is recorded (switch 2 closes and switch 1 and 3 open in Figure B.2). From this decaying current, the magnetic characteristic (linked flux to current relation) can be calculated according to the following:

With the reactor short-circuited (U_R = U_L as shown in Figure B.3), the following equation applies:

$$R \times i(t) = -\frac{d\psi(t)}{dt} = -\frac{d\psi(i)}{di} \times \frac{di(t)}{dt} = \left[-L_d \times \frac{di(t)}{dt} \right] \qquad \text{(B6)}$$

where R is the known ohmic resistance of the whole circuit (winding + connecting leads + current shunt). From the measured current $i(t)$ the rate of change of current $di(t)/dt$ can be calculated.

This means that $\psi(i)$ can be calculated as

$$\int_{i_0}^{i'} \frac{R \times i(t)}{\frac{di(t)}{dt}} di = -\int_{\psi_0}^{\psi'} d\psi = \psi_0 - \psi' = \psi(i) . \qquad \text{(B7)}$$

At $t = 0$ (closing of switch 2) the initial current and linked flux are i_0 and ψ_0. The change of the linked flux from the initial value ψ_0 (initially unknown) to ψ is in (equation B7) named ψ'. At infinite time the linked flux and current in the reactor will both be zero and that means that $\psi'(t = \infty) = \psi_0$.

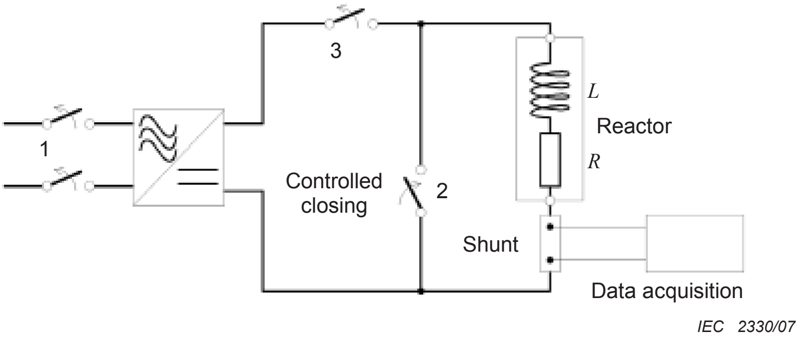


Figure B.2 – Circuit for measurement the magnetic characteristic according to B.7.1

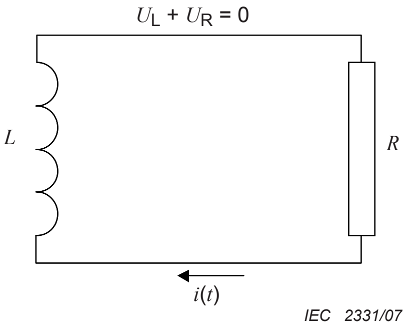


Figure B.3 – Equivalent circuit with the reactor short-circuited

When the linked flux to current relationship is in the linear part (low currents) the measurement can be stopped since at this time, the current decreases exponentially and therefore

$$\frac{i(t)}{\frac{di}{dt}} = \text{constant} = \tau \qquad \text{(B8)}$$

The remaining linked flux ψ_1, when the measurement stops, can then be calculated by extrapolation from the latest measured current i_1 and the calculated $d\psi/di$ down to $i = 0$ or even more simply by

$$\psi_1 = \tau \times R \times i_1 \qquad \text{(B9)}$$

It is then possible to establish ψ_0 and to calculate $\psi(i)$.

B.7.2 DC current charging – discharging method (application)

Measurements and calculation of the magnetic characteristic of a reactor by d.c. current charge and discharge can be made according to the following:

1) The reactor should be charged as quickly as possible in order not to introduce a resistance change caused by temperature rise. Measurement of the current can start during charging of the reactor. The current measurement can be stopped at the point where the current is exponentially decaying (equation B8). This is favourable because measurements of low currents are subjected to larger proportionate errors. Figures B4a and B4b show the result of a measurement.

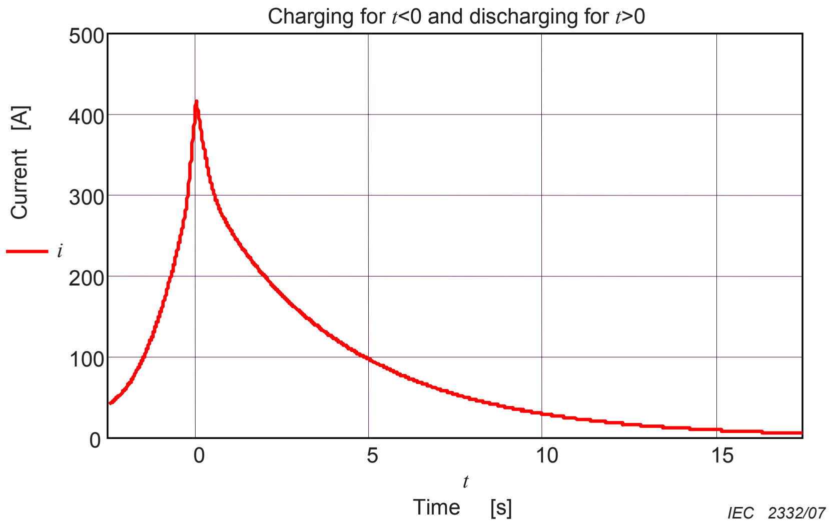


Figure B.4a – Graph of the charge and discharge current

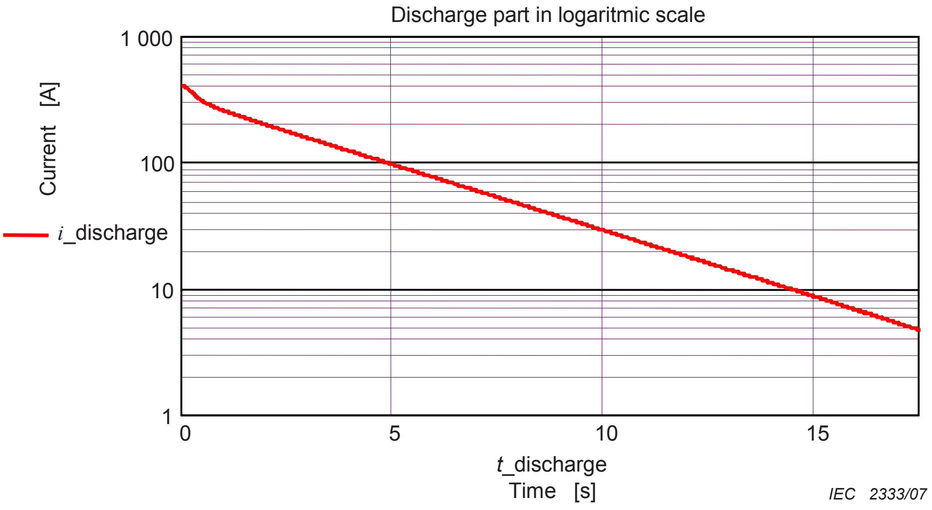
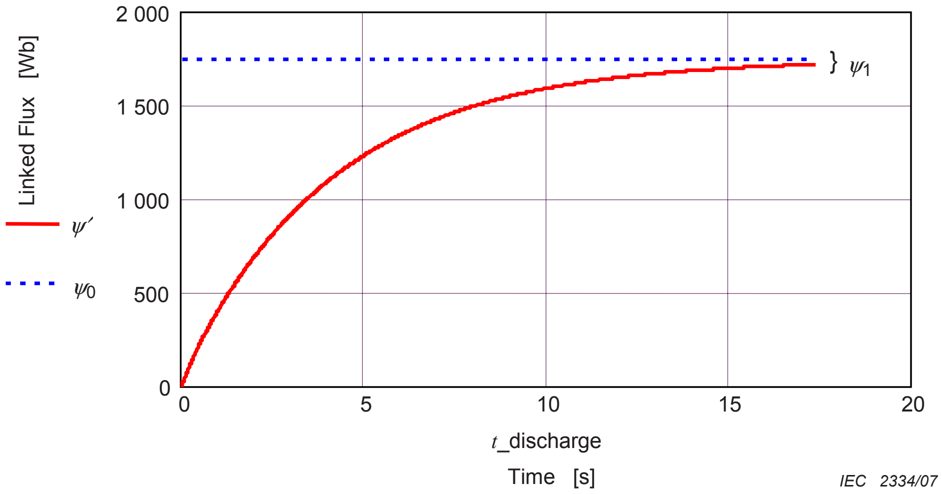


Figure B.4b – Graph of the discharge current with logarithmic current scaling

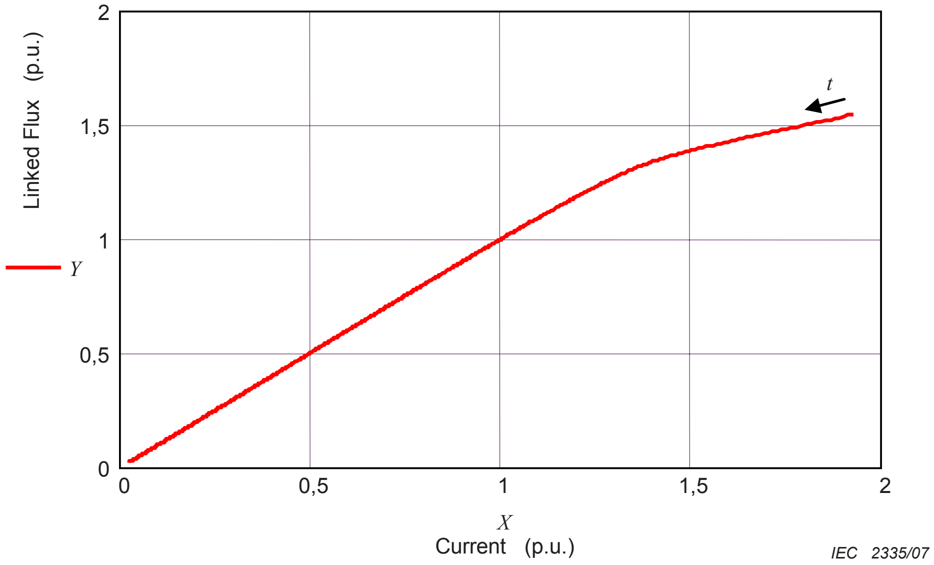
Figure B.4 – Measured curves of a reactors d.c. charge and discharge current

2) The measured signal shall be digitally filtered since stochastic variations in the recorded current may result in substantial errors in calculating the derivative $di(t)/dt$ of the current.
3) With the recorded and digitally filtered current, the time constant τ (equation B8) can be calculated.
4) From any current value where the time constant is constant it is possible to calculate the linked flux at that current (equation B9).
5) Since $i(t)/(di/dt)$ and the resistance R is known, the linked flux can be integrated from the start of discharge until a low current value is reached (equation B7). The total linked flux change is then the integrated value plus the remaining linked flux at the low current value i_1 and is illustrated in Figure B.5. The magnetic characteristic derived from the measurement is illustrated in Figure B.6.



IEC 2334/07

Figure B.5 – Calculated linked flux during discharge period (see equations B7 and B9)



IEC 2335/07

Figure B.6 – Magnetic characteristic

6) From the magnetic characteristic, it is possible to calculate several other relationships that might be of interest.

Annex C
(informative)

Mutual reactance, coupling factor and equivalent reactances of three-phase reactors

C.1 Uniform magnetic coupling between phases

This Subclause mainly applies to shunt reactors in star connection.

The magnetic behaviour of a three-phase reactor with uniform magnetic coupling between the phases can be represented by an equivalent scheme given in Figure C.1.

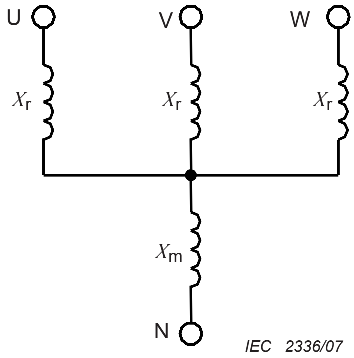


Figure C.1 – Equivalent scheme of a three-phase reactor including the magnetic coupling between phases

The zero-sequence reactance X_0, the mutual reactance X_m and the reactance at single-phase excitation $X_{\text{single-phase}}$ as used below are expressed relative to the rated reactance X_r (X_r is the positive sequence impedance of the reactor). Similarly, for single-phase excitation between one terminal and neutral, the flux between upper and lower yoke through the air and the tank Φ_{yoke} as well as the flux through the non-excited phase windings Φ_{return} are expressed relative to the linked flux of the winding represented by X_r. The size of the reactances and fluxes depends on the design of the magnetic circuit. Table C.1 below gives some information on coupling values in per cent. This data has been extracted from measurements on different types of shunt reactors. The recalculation in p.u. formulation is given by

$$x_0 = x_r + 3\,x_m$$

$$x_{\text{single-phase}} = x_r + x_m$$

$$\varphi_{\text{yoke}} = 1 + 2\,x_m$$

$$\varphi_{\text{return}} = (-\,x_m) / (x_r + x_m)$$

NOTE The mutual reactance x_m is always a negative value.

Table C.1 – Reactance and flux ratios for reactors with uniform magnetic coupling

	Bank of three single-phase liquid-immersed reactors or a three-phase, five limb liquid-immersed gapped-core reactor	Three-phase, three limb liquid-immersed reactor with gapped-core and with magnetic shielding at the tank wall	Bank of three single-phase air-core reactors without magnetic shields, mounted side by side
Rated reactance x_r	100 %	100 %	100 %
Mutual reactance x_m	0 %	–8 % … –10 % *)	~0… –3 %
Zero-sequence reactance x_0	100 %	70 % … 76 % *)	91 %… ~100 %
Reactance at single-phase excitation $x_{\text{single-phase}}$	100 %	90 % … 92 % *)	97 % …~100 %
φ_{yoke} for single-phase excitation between one terminal and neutral	0 %	80 % … 84 % *)	Not applicable
φ_{return} for single-phase excitation between one terminal and neutral	0 %	9 % … 11 % *)	~0… 3 %

*) Values depend on the voltage applied during single-phase testing. The magnetic coupling values (reactances) decrease with increasing current due to the saturation of the magnetic shields at the tank wall. The given values are based on measurements made at close to rated current.

C.2 Non-uniform magnetic coupling between phases

This Clause is relevant to reactors with a vertically stacked coil arrangement. For such arrangements, it is general practise that the middle phase has a coil with the opposite winding sense to that of the other two coils, resulting in a positive magnetic coupling between adjacent coils under three-phase current loading. In this case, the major stress on the axial supports (insulators), due to a three-phase short-circuit condition, is less than in the case where the winding senses are the same.

NOTE 1 For three-phase stacked reactors where the winding sense of all coils is the same, a positive magnetic coupling may be achieved by connecting the terminals of the middle coil in the opposite sense to those of the other two coils.

The selection of the self-inductance of the individual coils and the consequences of the non-uniform coupling on the effective inductance of the reactor during short-circuit conditions depends on the method of earthing of the neutral, effectively or non-effectively earthing of the power system, to which the reactor is connected.

NOTE 2 Non-uniform magnetic coupling will cause a zero-sequence voltage or current (depending on the type of system neutral earthing) which may disturb the protection system.

The self-inductance of the individual coils may be selected either for a compensated or a non-compensated arrangement of the three-phase stacked reactor:

- non-compensated arrangement

  In this case, each phase reactor is designed to have the same self-inductance. Due to non-uniform magnetic coupling between phases, this arrangement will result in unequal current magnitudes during three-phase fault conditions. However, for power systems with effectively earthed neutral, the single-phase fault current magnitude will be the same for all three phases. Consequently, a non-compensated arrangement is preferable for reactors installed in systems with an effectively earthed neutral.

- compensated arrangement

  In this case, the self-inductance of each phase reactor is uniquely adjusted to obtain three equal current magnitudes during an unearthed three-phase fault. However, for power systems with effectively earthed neutral, the single-phase fault current magnitude will be unequal for the three phases. It is important to note that the self-inductance may be lower than the rated value and hence single-phase fault currents in effectively earthed systems may exceed rated values.

A comparison of the non-compensated versus compensated arrangements is provided in Table C.2 below, where

$L_{11} = L_{33}$ – self inductance of the bottom and top coil,

L_{22} – self inductance of the middle coil,

m_{13} – mutual inductance M_{13} between the bottom and top coil as a percentage of L_{11} ,

$m_{12} = m_{23}$ – mutual inductance M_{12} or M_{23} between the middle coil and the bottom or top coil as a percentage of $\sqrt{(L_{11} \times L_{22})}$,

z_{SCr1} – single-phase impedance Z_{SCr1} expressed relative to the rated three-phase short-circuit impedance Z_{SCr3}

Table C.2 – Coupling values for reactors with non-uniform magnetic coupling

	Non-compensated $L_{11} = L_{22} = L_{33}$	**Compensated** $L_{11} = L_{33} \neq L_{22}$
$m_{12} = m_{23}$	–5 %... –15 %	–5 %... –15 %
m_{13}	1 %... 2 %	1 %... 2 %
z_{SCr1} (outer phases)	100 %	101 %... 102 %
z_{SCr1} (middle phase)	100 %	89 %... 72 %
Short-circuit current unbalance with unearthed three-phase fault	–4 %... –11 %	0 %

NOTE 1 The mutual inductances given in the table are typical figures.

NOTE 2 Because the middle coil has an opposite winding sense, m_{12} and m_{23} have a negative sign.

NOTE 3 The three-phase short-circuit current unbalance is the largest deviation from the average three-phase short-circuit current in percent.

Annex D

(informative)

Temperature correction of losses for liquid-immersed gapped-core and magnetically-shielded air-core reactors

D.1 Method for routine and type test

The losses are measured at ambient temperature. The I^2R losses are recalculated in accordance with the method given in IEC 60076-1. The additional losses are deemed to be independent of temperature.

Example:

Temperature Θ	I^2R	Additional losses	Total losses P_{tot}
19,5 °C (measured mean oil temperature)	57,95 kW	24,16 kW	82,11 kW (measured and recalculated to rated current)
Reference temperature 75 °C	70,59 kW	24,16 kW	94,75 kW

D.2 Method for special test

The losses are measured at ambient temperature as well as during the steady-state condition of the heat run test. With these two measurements, a temperature coefficient is established.

Example:

Measurement during the heat run test on the same reactor as in D.1:

Temperature Θ	I^2R	Additional losses	Total losses P_{tot}
60,5 °C (winding average temperature)	67,29 kW	22,20 kW	89,49 kW (measured and recalculated to rated current)

Establishing the temperature coefficient for total losses:

$$\Delta P_{tot} / \Delta\Theta = (89{,}49 - 82{,}11)\ \text{kW} / (60{,}5 - 19{,}5)\ ^\circ\text{C} = 0{,}18\ \text{kW} / ^\circ\text{C}$$

Recalculation to reference temperature 75 °C with temperature coefficient:

$$P_{tot}\ (75\ ^\circ\text{C}) = P_{tot}\ (60{,}5\ ^\circ\text{C}) + \Delta P_{tot} / \Delta\Theta \times (75 - 60{,}5)\ ^\circ\text{C}$$

$$P_{tot}\ (75\ ^\circ\text{C}) = 89{,}49\ \text{kW} + 0{,}18\ \text{kW} / ^\circ\text{C} \times (75 - 60{,}5)\ ^\circ\text{C} = 92{,}1\ \text{kW}$$

This value is less than the estimated value according method described in D.1 and applies as measured loss value for guarantee.

Measurement on a second identical unit at ambient temperature (routine test):

Temperature Θ	I^2R	Additional losses	Total losses P_{tot}
24,0 °C (measured mean oil temperature)	59,10 kW	25,20 kW	84,30 kW (measured and recalculated to rated current)

Recalculation to reference temperature 75 °C with temperature coefficient:

P_{tot} (75 °C) = P_{tot} (24,0 °C) + $\Delta P_{\text{tot}} / \Delta\Theta$ × (75 – 24,0) °C

P_{tot} (75 °C) = 84,30 kW + 0,18 kW / °C × (75 – 24,0) °C = 93,48 kW

This value is the measured loss value for guarantee for the second identical unit.

Annex E
(normative)

Turn-to-turn overvoltage test for dry-type reactors

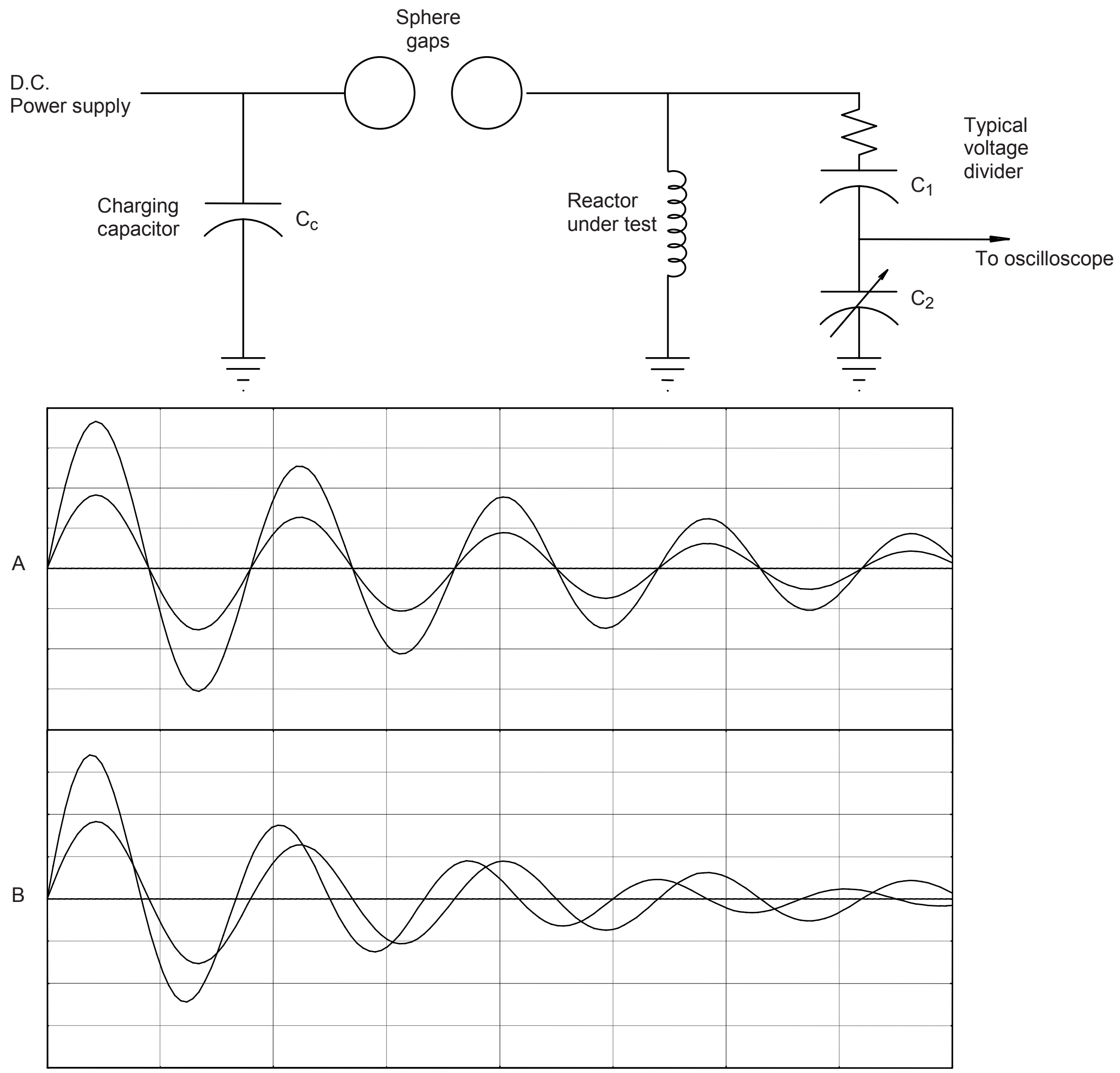
The turn-to-turn overvoltage test is performed by repeatedly charging a capacitor and discharging it, through sphere gaps, into the reactor windings. The type of overvoltage that the reactor is subjected to is similar to a switching impulse with an exponentially decaying sinusoidal wave shape. Figure E.1. illustrates the test set-up and the overvoltage wave shape. The test duration is for one minute and the initial crest value of each discharge shall be 1,33√2 (for outdoor units) or √2 (for indoor units) times the rated short-duration induced or separate source a.c. withstand voltage level (r.m.s.) as indicated in Table 2 and Table 3 of IEC 60076-3:2000. The ringing frequency is a function of the coil inductance and charging capacitor, and is typically in the order of 100 kHz. The test shall consist of not less than 7 200 overvoltages of the required magnitude.

NOTE 1 The front time of the waveshape applied during a turn-to-turn overvoltage test is typically much shorter than the front time of a standard lightning impulse.

NOTE 2 The value of the test voltage shall be determined by a mean curve drawn through any overshoot and high frequency oscillation on the first peak of the waveform. This method is the same as that described for similar impulse wave shapes in 19.2 and Figure 10 of IEC 60060-1.

Primary verification of winding insulation integrity shall be based on oscillographic methods. A surge oscilloscope and camera or digital data acquisition system are used to record the last discharge superimposed on a reduced voltage discharge. A change in period or rate of envelope decay, between the reduced and full waves, would indicate a change in coil impedance and thus an inter-turn failure.

Secondary verification of insulation integrity is done by observation. A failure can be detected by noise, smoke or spark discharge in the reactor windings.



IEC 2337/07

Figure E.1 – Test circuit for turn-to-turn overvoltage test and sample oscillograms

A Oscillogram from a reactor which passed the turn-to-turn overvoltage test.

B Oscillogram from a reactor of the same rating as in Oscillogram **A** but having a turn-to-turn fault. Note the shift in frequency and the increased damping.

Annex F
(informative)

Short-circuit testing

F.1 General information

During a short-circuit current test, the current offset usually decays to zero in under ten cycles. The high offset peak currents during the initial portion of the fault impose the highest mechanical stresses on the reactor while the longer duration symmetrical fault current may subject the reactor to high temperatures and significant mechanical loads simultaneously.

Certain relevant power system operational factors should be taken into consideration when specifying the number of short-circuit test shots and the duration of each applied shot:

- the number of auto re-closures allowed should be considered when specifying the number of mechanical peak shots performed during the mechanical short-circuit test, e.g., 1, 2 or 3;
- the duration of each applied shot of the mechanical short-circuit test should reflect the utility’s interrupting practice.

F.2 Guideline for arrangement, bus connection and inspection for short-circuit testing of dry-type reactors

Reactors may be short-circuit tested in a number of configurations. The single-phase short-circuit test may be performed on one unit or a three-phase short-circuit test may be performed on a three-phase in-line, three-phase triangular or three-phase stacked configuration. Three-phase reactor configurations are tested with three-phase short-circuit currents applied to the input terminals and with the output terminals connected together.

It is preferable to test the reactor(s) in a test set-up with components and configurations as close as possible to service condition.

Interactive forces generated by the reactor's field and current feeds (bus, cable, etc.) are an important aspect of design and any deviation in configuration or in components utilized for the test should be fully assessed.

In cases when it is not possible to test the reactor as in service set-up, the interaction force effects created by the magnetic field of the reactor and the supply circuit current should be minimized.

Forces transmitted to the reactor under test as a result of poorly restrained bus, inadequate fixing of the reactor to the test bay floor, etc. are not representative of field installed conditions. Therefore, proper test set-up is important to ensure realistic results.

Test set-up notes:

- all base brackets shall be bolted to floor;
- all bolts shall be tightened to the correct torque value;
- incoming/outgoing bus connection to the reactor shall be by means of a flexible connector or link with a maximum length of 0,2 m;
- incoming/outgoing bus shall be rigidly supported at the flexible connection or link;

- final test set-up shall be fully assessed and agreed upon by the manufacturer, purchaser and test facility, or equivalent.

The winding encapsulation should be carefully inspected for surface cracks before and after the short-circuit tests. Coating cracks at discontinuities, such as at the winding clamping system interface etc. are not usually indications of a mechanical problem and are typically due to the inelastic nature of most paints and other coating materials.

Annex G
(informative)

Resistors – Characteristics, specification and tests

G.1 General

This annex is intended to be a guide for the specification of single-phase resistors connected to the secondary winding of an arc-suppression reactor as described by Clause 11 of this part of IEC 60076.

NOTE 1 This annex may also be used as a guide for stand alone resistors applied to distribution class networks.

Usually, the resistors are designed for short-time service duty during a system earth-fault. They are intended to increase the resistive component of the earth-fault current for improving the reliability of operation of the earth-fault protection device.

The resistor will normally be required to carry a current for a significantly shorter time than the arc-suppression reactor. The current duration or duty-cycle is governed by the operation of the earth-fault protection system.

The design of the resistor is typically determined by the current duration or duty-cycle as well as the resistance and current magnitude. Therefore, correctly specifying the current duration or duty-cycle is important.

NOTE 2 The resistors can also be used to reduce the time constant of the network during a single line-to-earth fault.

G.2 Characteristics

The main characteristics of the resistors are:

- rated resistance R_r at ambient temperature;
- rated current I_r or rated voltage U_r;
- rated current or voltage duration T_r or associated duty-cycle;
- rated insulation level.

The resistors may be air-insulated or liquid-immersed, both naturally cooled, for indoor or outdoor installation. Air-insulated resistors are supplied with a protective enclosure, liquid-immersed resistors are built either into the tank of the arc-suppression reactor or in a separate tank.

The maximum permissible temperature rise of the active elements of air-insulated resistors will depend on the material used for their construction. The maximum temperature rise is typically several hundred Kelvin. For this reason, attention should be paid to the material used for the insulation, protective enclosure, bushings, terminals and accessories. Because of the high temperature, attention should also be paid to the safety of the installation.

NOTE 1 For stainless steel, which is mainly used for this component, the maximum permissible temperature rise is about 600 K.

The resistance variation caused by the temperature rise should also be considered.

NOTE 2 As an example, stainless steel has a temperature coefficient of about 0,001 K^{-1}. Taking into account 600 K of temperature rise, the resistance can reach a value of 1,6 R_r.

For liquid-immersed resistors, the temperature rise limits as given for arc-suppression reactors in 11.5 may be applied.

G.3 Resistor specification

The following parameters should be specified by the purchaser:

- rated resistance;
- maximum increase of resistance following the application of rated current or voltage duration, if required;
- rated current or rated voltage, depending on the application and whether the voltage or current is constant as the resistance varies with temperature;
- rated current or voltage duration and associated duty-cycle (maximum duration of current or voltage application, number of successive applications and the minimum time interval between successive applications);
- maximum continuous voltage across the resistor or current through the resistor, if required;
- insulation level between the terminals of the resistor and earth, usually specified as the separate source a.c. withstand voltage;
- type of installation (indoor/outdoor);
- IP Code for air-insulated resistors (IP Code – Degree of protection provided by enclosures, as described in IEC 60529);
- type of insulation (air-insulated, liquid-immersed);
- permissible maximum temperature rise for active resistor elements. If not specified by the purchaser, the manufacturer should declare this value.

G.4 Tests

The following tests are suggested.

a) Routine tests:

- measurement of resistance at ambient temperature;
- separate source a.c. withstand voltage test (verification of insulation between resistor and enclosure or tank).

b) Type tests:

- temperature rise test (verification of temperature rise and, if required, increase of resistance). The temperature rise of the resistor should be verified following the application of rated current or rated voltage for the rated current or voltage duration. Voltage or current (as specified) should be kept approximately constant during the test. The temperature of the hottest element should be measured, unless otherwise agreed. Following the test, it should be verified that insulating and other components have not been damaged. The resistance should be measured during the test.

c) Special tests:

- lightning impulse test (for resistors directly connected to systems with U_m > 1 kV);
- verification of the IP code of the enclosure.

G.5 Rating plate

The following entries should be reported on the rating plate:

- outdoor/indoor application;

- manufacturer's name;
- manufacturer's serial number;
- year of manufacture;
- rated resistance at ambient temperature;
- rated current or rated voltage;
- rated current or voltage duration and associated duty-cycle, if applicable;
- maximum continuous voltage or current, if applicable;
- IP Code (for air-insulated resistors);
- maximum permissible temperature rise of resistor elements (for air-insulated resistors);
- total mass.

G.6 Tolerance

The tolerance for the rated resistance at 20 °C should be within ±10 %. Lower values of tolerance may be agreed between manufacturer and purchaser.

Bibliography

IEC 60143, *Series capacitors for power systems*

IEC 60168:2001, *Tests on indoor and outdoor post insulators of ceramic material or glass for systems with nominal voltages greater than 1 000 V*

IEC 60273:1990, *Characteristic of indoor and outdoor post insulators for systems with nominal voltages greater than 1 000 V*

IEC 60353, *Line traps for a.c. power systems*

IEC 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 60871-1:2005, *Shunt capacitors for a.c. power systems having a rated voltage above 1000V – Part 1: General*

IEC 61378-1:1997, *Converter transformers – Part 1: Transformers for industrial applications*

IEC 61378-2:2001, *Converter transformers – Part 2: Transformers for HVDC applications*

IEC 62271-110, *High-voltage switchgear and controlgear – Part 110: Inductive load switching*

IEEE C57.21-1990, *IEEE standard requirements, terminology, and test code for shunt reactors rated over 500 kVA*

IEEE 1277-2000, *IEEE trial-use standard general requirements and test code for dry-type and oil-immersed smoothing reactors for DC power transmission*

E.W. Kimbark, *Suppression of Ground Fault Arcs on Single-Pole-switched EHV Lines by Shunt Reactors*, IEEE Transmission and Distribution, March 1964.

Controlled switching of HVAC circuit-breakers. Guide for application lines – reactors – capacitors – transformers. 2nd Part. ELEKTRA No. 185, 1999

Interruption of small inductive currents. Chapter 6: Switching of reactor-loaded transformers. ELEKTRA No. 138, 1991

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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

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 60060-1	1989	High-voltage test techniques -		
+ corr. March	1990	Part 1: General definitions and test requirements	HD 588.1 S1	1991
IEC 60076-1 (mod)	1993	Power transformers -	EN 60076-1	1997
A1	1999	Part 1: General	A1	2000
			+ A11	1997
			+ A12	2002
IEC 60076-2 (mod)	1993	Power transformers - Part 2: Temperature rise	EN 60076-2	1997
IEC 60076-3	2000	Power transformers -		
+ corr. December	2000	Part 3: Insulation levels, dielectric tests and external clearances in air	EN 60076-3	2001
IEC 60076-4	2002	Power transformers - Part 4: Guide to the lightning impulse and switching impulse testing - Power transformers and reactors	EN 60076-4	2002
IEC 60076-5	2006	Power transformers - Part 5: Ability to withstand short circuit	EN 60076-5	2006
IEC 60076-7	2005	Power transformers - Part 7: Loading guide for oil-immersed power transformers	-	-
IEC 60076-8	1997	Power transformers - Part 8: Application guide	-	-
IEC 60076-10	2001	Power transformers - Part 10: Determination of sound levels	EN 60076-10	2001
IEC 60076-11	2004	Power transformers - Part 11: Dry-type transformers	EN 60076-11	2004
IEC 60137	- 1)	Insulated bushings for alternating voltages above 1 000 V	EN 60137	2003 2)
IEC 60270	- 1)	High-voltage test techniques - Partial discharge measurements	EN 60270	2001 2)
IEC 60721-2-6	- 1)	Classification of environmental conditions - Part 2: Environmental conditions appearing in nature - Earthquake vibration and shock	HD 478.2.6 S1	1993 2)
IEC/TR 60815	- 1)	Guide for the selection of insulators in respect of polluted conditions	-	-

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1) Undated reference.

2) Valid edition at date of issue.

Publication	Year	Title	EN/HD	Year
IEC 60905	1987	Loading guide for dry-type power transformers	-	-
IEC/TR3 60943	1998	Guidance concerning the permissible temperature rise for parts of electrical equipment, in particular for terminals	-	-

BS EN 60076-6:2008

British Standards Institution (BSI)

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Revisions

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