BS EN 60310:2016

BSI Standards Publication

Railway applications — Traction transformers and inductors on board rolling Stock

bsi.

National foreword

This British Standard is the UK implementation of EN 60310:2016. It is identical to IEC 60310:2016. It supersedes BS EN 60310:2004 which is withdrawn.

The UK participation in its preparation was entrusted by Technical Committee GEL/9, Railway Electrotechnical Applications, to Subcommittee GEL/9/2, Railway Electrotechnical Applications - Rolling stock.

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

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English Version

Railway applications - Traction transformers and inductors on board rolling Stock (IEC 60310:2016)

Applications ferroviaires - Transformateurs de traction et bobines d'inductance à bord du matériel roulant (IEC 60310:2016)

Bahnanwendungen - Transformatoren und Drosselspulen auf Bahnfahrzeugen (IEC 60310:2016)

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

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European foreword

The text of document 9/2080/FDIS, future edition 4 of IEC 60310, prepared by IEC/TC 9 "Electrical equipment and systems for railways" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 60310:2016.

The following dates are fixed:

• latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2016-12-02
• latest date by which the national standards conflicting with the document have to be withdrawn	(dow)	2019-03-02

This document supersedes EN 60310:2004.

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The text of the International Standard IEC 60310:2016 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 60216-1	NOTE	Harmonized as EN 60216-1.
IEC 60216-5	NOTE	Harmonized as EN 60216-5.
IEC 60505	NOTE	Harmonized as EN 60505.
IEC 61287-1	NOTE	Harmonized as EN 61287-1.

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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

NOTE 1 When an International Publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

NOTE 2 Up-to-date information on the latest versions of the European Standards listed in this annex is available here: www.cenelec.eu

Publication	Year	Title	EN/HD	Year
IEC 60050-811	-	International electrotechnical vocabulary (IEV) - Chapter 811: Electric traction	-	-
IEC 60060-1	-	High-voltage test techniques - Part 1: General definitions and test requirements	EN 60060-1	-
IEC 60060-2	-	High-voltage test techniques - Part 2: Measuring systems	EN 60060-2	-
IEC 60076-1	2011	Power transformers - Part 1: General	EN 60076-1	2011
IEC 60076-2	-	Power transformers - Part 2: Temperature rise for liquid-immersed transformers	EN 60076-2	-
IEC 60076-3	-	Power transformers - Part 3: Insulation levels, dielectric tests and external clearances in air	EN 60076-3	-
IEC 60076-4	-	Power transformers - Part 4: Guide to the lightning impulse and switching impulse testing - Power transformers and reactors	EN 60076-4	-
IEC 60076-5	-	Power transformers - Part 5: Ability to withstand short circuit	EN 60076-5	-
IEC 60076-6	2007	Power transformers - Part 6: Reactors	EN 60076-6	2008
IEC 60076-7	-	Power transformers - Part 7: Loading guide for oil-immersed power transformers	-	-
IEC 60076-10	-	Power transformers - Part 10: Determination of sound levels	EN 60076-10	-
IEC 60076-11	-	Power transformers - Part 11: Dry-type transformers	EN 60076-11	-
IEC 60076-12	2008	Power transformers - Part 12: Loading guide for dry-type power transformers	-	-
IEC 60076-14	-	Power transformers - Part 14: Liquid-immersed power transformers using high-temperature insulation materials	EN 60076-14	-

Publication	Year	Title	EN/HD	Year
IEC 60076-18	-	Power transformers - Part 18: Measurement of frequency response	EN 60076-18	-
IEC 60077-1	-	Railway applications - Electric equipment for rolling stock - Part 1: General service conditions and general rules	EN 60077-1	-
IEC 60085	-	Electrical insulation - Thermal evaluation and designation	EN 60085	-
IEC 60270	-	High-voltage test techniques - Partial discharge measurements	EN 60270	-
IEC 60296	-	Fluids for electrotechnical applications - Unused mineral insulating oils for transformers and switchgear	EN 60296	-
IEC 60836	-	Specifications for unused silicone insulating liquids for electrotechnical purposes	EN 60836	-
IEC 60850	-	Railway applications - Supply voltages of traction systems	-	-
IEC 61039	-	Classification of insulating liquids	EN 61039	-
IEC 61099	-	Insulating liquids - Specifications for unused synthetic organic esters for electrical purposes	EN 61099	-
IEC 61373	2010	Railway applications - Rolling stock equipment - Shock and vibration tests	EN 61373	2010
IEC 61378-1	2011	Convertor transformers - Part 1: Transformers for industrial applications	EN 61378-1	2011
IEC 62497-1	-	Railway applications - Insulation coordination - Part 1: Basic requirements - Clearances and creepage distances for all electrical and electronic equipment	-	-
IEC 62498-1	-	Railway applications - Environmental conditions for equipment - Part 1: Equipment on board rolling stock	-	-
ISO 3746	-	Acoustics - Determination of sound power levels and sound energy levels of noise sources using sound pressure - Survey method using an enveloping measurement surface over a reflecting plane	EN ISO 3746	-
ISO 9614-1	-	Acoustics - Determination of sound power levels of noise sources using sound intensity - Part 1: Measurement at discrete points	EN ISO 9614-1	-
ISO 9614-2	-	Acoustics - Determination of sound power levels of noise sources using sound intensity - Part-2: Measurement by scanning	EN ISO 9614-2	-

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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RAILWAY APPLICATIONS – TRACTION TRANSFORMERS AND INDUCTORS ON BOARD ROLLING STOCK

FOREWORD

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International Standard IEC 60310 has been prepared by IEC technical committee 9: Electrical equipment and systems for railways.

This fourth edition cancels and replaces the third edition issued in 2004 and constitutes a technical revision.

This edition takes into account the new generic railway standards, more specifically general service conditions referring to IEC 62498-1 and shock and vibration considerations referring to IEC 61373. It also includes the following significant technical changes with regard to the previous edition:

– temperature limits;
– temperature-rise test;
– dielectric tests;
– partial discharge test;

– inductance measurement methods;
– voltage between terminals withstand test;
– thermal ageing and insulation lifetime (informative);
– examples of thermal endurance calculation (informative);
– wet dielectric tests (informative);
– load profiles (informative).

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

FDIS	Report on voting
9/2080/FDIS	9/2117/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

RAILWAY APPLICATIONS – TRACTION TRANSFORMERS AND INDUCTORS ON BOARD ROLLING STOCK

1 Scope

This International Standard applies to traction and auxiliary power transformers installed on board rolling stock and to the various types of power inductors inserted in the traction and auxiliary circuits of rolling stock, of dry or liquid-immersed design.

NOTE The requirements of IEC 60076 (all parts) are applicable to transformers and inductors where they do not conflict with this standard, or with the specialized IEC publications dealing with traction applications.

This standard can also be applied, after agreement between purchaser and manufacturer, to the traction transformers of three-phase a.c. line-side powered vehicles and to the transformers inserted in the single-phase or poly-phase auxiliary circuits of vehicles, except instrument transformers and transformers of a rated output below 1 kVA single-phase or 5 kVA poly-phase.

This standard does not cover accessories such as tap changers, resistors, heat exchangers, fans, etc., intended for mounting on the transformers or inductors, which are tested separately according to relevant rules.

2 Normative references

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

IEC 60050-811, *International Electrotechnical Vocabulary (IEV) – Chapter 811: Electric traction*

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

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

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

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

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

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

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

IEC 60076-6:2007, *Power transformers – Part 6: Reactors*

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

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

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

IEC 60076-12:2008, *Power transformers – Part 12: Loading guide for dry-type transformers*

IEC 60076-14, *Power transformers – Part 14: Liquid-immersed power transformers using high-temperature insulation materials*

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

IEC 60077-1, *Railway applications – Electric equipment for rolling stock – Part 1: General service conditions and general rules*

IEC 60085, *Electrical insulation – Thermal evaluation and designation*

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

IEC 60296, *Fluids for electrotechnical applications – Unused mineral insulating oils for transformers and switchgear*

IEC 60836, *Specifications for unused silicone insulating liquids for electrotechnical purposes*

IEC 60850, *Railway applications – Supply voltage of traction systems*

IEC 61039, *Classification of insulating liquids*

IEC 61099, *Insulating liquids – Specifications for unused synthetic organic esters for electrical purposes*

IEC 61373:2010, *Railway applications – Rolling stock equipment – Shock and vibration tests*

IEC 61378-1:2011, *Convertor transformers – Part 1: Transformers for industrial applications*

IEC 62497-1, *Railway applications – Insulation coordination – Part 1: Basic requirements – Clearances and creepage distances for all electrical and electronic equipment*

IEC 62498-1, *Railway applications – Environmental conditions for equipment – Part 1: Equipment on board rolling stock*

ISO 3746, *Acoustics – Determination of sound power levels and sound energy levels of noise sources using sound pressure – Survey method using an enveloping measurement surface over a reflecting plane*

ISO 9614-1, *Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 1: Measurement at discrete points*

ISO 9614-2, *Acoustics – Determination of sound power levels of noise sources using sound intensity – Part 2: Measurement by scanning*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60076-1 and IEC 60050-811 together with the following apply.

NOTE When the term “transformer” is used alone, it applies to both traction and auxiliary transformers.

The term “transformer(s)/inductor(s)” appears in clauses applicable to both transformers and inductors to avoid duplication of text.

The term “inductor” is used in this standard with the same meaning as the term “reactor” mentioned in IEC 60050-421, IEC 60050-811 and IEC 60076-6.

3.1 General definitions

3.1.1
load profile
current/power versus time under specified conditions including voltage

3.1.2
cooling medium
cooling medium used to extract the heat out of the transformer/inductor e.g. air, water, oil, heat sink, etc.

3.1.3
rated insulation voltage
U_{Nm}
r.m.s. withstand voltage value assigned by the manufacturer to the equipment or a part of it, characterising the specified permanent (over 5 min) withstand capability of its insulation

Note 1 to entry: U_{Nm} is a voltage between a live part of equipment and earth or another live part. For rolling stock, earth refers to the car body.

Note 2 to entry: For circuits, systems and sub-systems in railway applications this definition is preferred to "highest voltage for equipment" which is widely used in international standards.

Note 3 to entry: U_{Nm} is higher than or equal to the working voltage. As a consequence, for circuits directly connected to the contact line, U_{Nm} is equal to or higher than U_{max1} as specified in IEC 60850. For circuits connected to electronic converter U_{Nm} is higher than or equal to the d.c. link voltage.

Note 4 to entry: U_{Nm} is not necessarily equal to the rated voltage which is primarily related to functional performance.

3.1.4
nominal voltage
U_{n}
suitable approximate voltage used to designate or identify a given supply system

3.1.5
rated voltage
U_{r}
value of voltage assigned for a specific operating condition

3.1.6
rated impulse voltage
U_{Ni}
impulse voltage value, characterizing the specified withstand capability of its insulation against transient over-voltages

3.1.7
test voltage
U_a
r.m.s. value derived from U_{Nm} used for separate source voltage, induced voltage, voltage between terminals withstand, depending on test carried out

3.1.8
recurring peak voltage
U_{mT}, U_{mG}
maximum peak value of periodic excursions of the voltage waveform between terminals (U_{mT}) or between terminals and ground (U_{mG})

3.2 Definitions for transformers

3.2.1
voltage transmission ratio
VTR
ratio between the secondary voltage and the primary voltage when a specified impulse or a.c. square voltage is applied on the primary.

The VTR is expressed as a percentage of this applied voltage.

3.2.2
impedance voltage
voltage applied to reach the rated current in short-circuit.

This is expressed as a percentage of this applied voltage to the rated voltage at reference temperature.

Note 1 to entry: When expressed as a percentage or per unit, this is equal to the short circuit impedance referred in IEC 60076-1:2011, 3.7.

3.2.3
tolerance
permitted deviation between the declared value of a quantity and the measured value

[SOURCE: IEC 60050-411:2007, 411-36-19]

3.3 Definitions for inductors

Values of inductance for inductors are related to the different classes of utilisation and are defined as follows, with the understanding that they include an indication of the nature and value of the current used in their measurement.

3.3.1
a.c. inductance
inductance derived from the measurement of the alternating current carried by the inductor when it is supplied by a sinusoidal alternating voltage of specified value and frequency

3.3.2
differential inductance
inductance defined from the derivative of the linked flux as a function of current (equal to the slope of the magnetic characteristic)

Note 1 to entry: It is derived from the transient record of instantaneous voltage and current in the inductor or from the measurement of the variation of magnetic flux.

3.3.3
incremental inductance
inductance seen by the a.c. current of a particular value and frequency superimposed on a direct current through the inductor

Note 1 to entry: It should be mentioned that the ripple factor of a pulsating current, expressed as a percentage, is conventionally defined by the formula:

$$\frac{I_{max} - I_{min}}{I_{max} + I_{min}} \times 100$$

where I_{max} and I_{min} respectively represent the maximum and minimum values of the current wave.

Note 2 to entry: It is derived from a record of the terminal voltage.

4 Classification

4.1 Classification of transformers

The transformers mentioned above may be:

– traction transformers to supply the propulsion circuits, and optionally also other equipment;
– auxiliary transformers to supply electrical equipment except propulsion circuits.

Windings mentioned in the standard may be:

– line side windings which are directly connected to the power supply line;
– traction windings which supply the propulsion circuits;
– auxiliary windings which are used for other purposes.

4.2 Classification of inductors

According to their use, inductors can be classified as follows:

– inductors for alternating current:

  inductors that carry alternating current, such as transition inductors used for transition between tappings of tap changers, inductors for a.c. commutator motor braking circuits, interference suppression inductors, tuned filter inductors, etc.;

– inductors for direct current:

  inductors that carry direct current with small or negligible a.c. components, such as d.c. line filter inductors, inductive shunts for traction motors, inductors for d.c. motor braking circuits, etc.;

– inductors for pulsating current:

  inductors that carry direct or alternating current with a significant periodic ripple, such as smoothing inductors for traction motors, sinusoidal filter inductors in auxiliary converters, etc.

5 Service conditions

The normal service conditions for transformers and inductors shall be in accordance to IEC 62498-1. Special service conditions shall be agreed between the purchaser and manufacturer.

6 Rated current and load profile

6.1 Load profile

A transformer/inductor is designed to operate on the train in steady-state and transient (surge) conditions, both in normal and overload conditions.

The purchaser should specify the load profile according to Annex E (informative). The current frequency spectrum shall be specified by the responsible party.

6.2 Rated current

The rated current of a winding is the current this winding can sustain permanently at the reference temperature for continuous load.

The rated current shall be calculated according to either of following methods:

a) r.m.s. current derived from the load profiles;
b) considering thermal ageing of insulating materials according to Annex B (informative).

Special attention should be paid to varying cooling modes and to the averaging time window.

The reference temperature for continuous load is the cooling medium temperature at the external interface of the transformer/inductor. It shall:

c) either be directly specified by the purchaser;

   Specified values should be based on the air temperature external to vehicle as defined in IEC 62498-1.
d) or calculated by the manufacturer based on the temperature histogram provided by the purchaser and the method of Annex B (informative): see cooling medium reference temperature for lifetime calculation in B.4.2.

For a traction winding, the rated current shall correspond to the principal tapping. This definition of rated current applies when other windings, which are normally on load, deliver their rated loads.

7 Rated voltage and power of transformer windings

7.1 Rated line-side voltage

The rated line-side voltage is the r.m.s. voltage applicable in normal operating conditions to the line-side winding group. If this winding has tappings, the rated voltage shall be referred to the principal tapping.

Unless otherwise agreed between purchaser and manufacturer, the rated line-side voltage is specified as being equal to the nominal voltage of the traction system.

NOTE IEC 60850 gives the list of the nominal voltages of traction systems.

7.2 Rated secondary voltage

The rated voltage of a secondary winding of a transformer is the r.m.s. no-load voltage at the terminals of the winding when the principal tapping of the line-side winding of the transformer is fed at its rated voltage and frequency.

7.3 Rated power of transformer

The rated power of a transformer winding is defined as the product of the rated voltage of this winding and its rated current.

NOTE Transformers usually have several secondary windings (e.g. traction, auxiliaries, train heating). The rated power of the line-side winding of a transformer can be less than the sum of the rated powers of its various secondary windings.

8 Transformer tappings

In order to permit variation of the voltage ratio of the transformer, one or more of its windings may be equipped with intermediate tappings, which shall be indicated on the diagram and in the specification, with a statement of their maximum operating characteristics.

The principal tapping is that which enables the rated traction motor voltage to be obtained at the terminals of the motors when they are taking their rated current, the transformer line-side winding being supplied at rated voltage and frequency.

When both line-side windings and traction windings have intermediate tappings, the principal tappings shall be indicated.

For multi-system vehicles, the principal tappings may be different for each system.

The no-load voltage ratio shall be defined for the principal tapping and for other tappings.

9 Cooling

9.1 Identification of transformers and inductors according to cooling method

Transformers and inductors shall be identified according to the cooling method employed. Letter symbols for use in connection with each cooling method shall be as given in Table 1.

Table 1 – Letter symbols for cooling method

Type of cooling medium	Symbol
Mineral oil or other insulating liquid with fire-point ≤ 300 °C	O
Insulating liquid with fire-point > 300 °C	K
Insulating liquid having a fire-point greater than its boiling-point	L
Gas	G
Water	W
Air	A
Type of circulation	**Symbol**
Natural	N
Forced non-directed	F
Forced-directed	D

In transformers and inductors with forced-directed circulation, a certain portion of the forced flow is channelled so as to pass through the windings. Some windings, however, may have a non-directed flow, for instance separate tapping windings, auxiliary windings and stabilizing windings.

The type of coolant shall be subject to approval by the purchaser.

9.2 Arrangement of symbols

9.2.1 Enclosed transformers and inductors

Transformers and inductors shall be identified by symbols of four letters for each cooling method for which a rating is specified by the manufacturer.

The order in which the symbols shall be used is given in Table 2. Oblique strokes shall be used to separate the group symbols for different cooling methods.

Table 2 – Order of symbols

1st letter	2nd letter	3rd letter	4th letter
Indicating the cooling medium that is in contact with the winding		Indicating the cooling medium that is in contact with the external cooling system	
Type of cooling medium	Type of circulation	Type of cooling medium	Type of circulation

Example: a liquid-immersed transformer with forced-directed liquid circulation and forced-air circulation would be designated by ODAF or KDAF.

For oil-immersed transformers in which the alternatives of natural or forced cooling with non-directed oil flow are possible, typical designations are: ONAN/ONAF, ONAN/OFAF.

For a dry-type transformer in a non-ventilated protective enclosure with natural air cooling inside and outside the enclosure, the designation is: ANAN.

9.2.2 Non-enclosed transformers and inductors

Dry-type transformers and inductors without protective enclosures are identified by two symbols only for the cooling medium that is in contact with the windings or the surface coating of windings with an overall coating (e.g. epoxy resin).

The cooling method of a dry-type transformer without a protective enclosure or with a ventilated enclosure and with natural air cooling is designated by: AN.

9.2.3 Air cooling

When transformers or inductors are cooled by the draught of air caused by the motion of the vehicle or by a forced-air cooling system which is not tested with the transformer or inductor, the air flow (or velocity) on which the rated power of the equipment is based shall be indicated by the purchaser.

10 Temperature limits

10.1 Classification of insulating materials

The different classes of solid materials (EIM – Electrical Insulating Material) and systems (EIS – Electrical Insulating System) used at present for the insulation of the windings of transformers and inductors to which this standard applies are defined in IEC 60085 and listed in Table 3.

For a given solid insulation material the thermal class may be different depending on the surrounding medium (air, mineral oil, ester fluids, etc.).

The thermal class of the solid materials used for the insulation of the windings shall be indicated by the manufacturer.

10.2 Temperature limits of solid insulation

The maximum temperature of the transformer and inductor components shall not exceed the limits given in Table 3.

Temperature limits apply to short time maximum temperature considering hot spot.

These absolute temperatures are related to the worst case specified operating conditions.

For the long time operation temperature limits refer to 13.2.11.6

Table 3 – Temperature limits of solid insulation

RTE (Relative Thermal Endurance) or ATE (Assessed Thermal Endurance)	Thermal class	Maximum temperature Immersed type °C [a)]	Maximum temperature Dry-type °C [b)]
RTE or ATE < 90	70	No guidance	No guidance
90 ≤ RTE or ATE < 105	90 (Y)	No guidance	No guidance
105 ≤ RTE or ATE < 120	105 (A)	120	130
120 ≤ RTE or ATE < 130	120 (E)	135	145
130 ≤ RTE or ATE < 155	130 (B)	170	155
155 ≤ RTE or ATE < 180	155 (F)	195	180
180 ≤ RTE or ATE < 200	180 (H)	220	205
200 ≤ RTE or ATE < 220	200 (N)	240	225
220 ≤ RTE or ATE < 250	220 (R)	260	245
250 ≤ RTE or ATE	250	No guidance	No guidance

a) For immersed type insulation systems, temperature limits are higher than for dry-type because of reduced oxidation of insulation materials. The exceptions are insulation systems based on cellulose (105 and 120 class), for which the temperature limits are based on IEC 60076-7.

b) Dry-type limits are according to IEC 60076-12:2008, Table 2.

Other limits may be adopted by agreement between purchaser and manufacturer when certain combinations of insulating materials are used. It becomes especially important when materials of different thermal classes are combined within one insulation system. Then, thorough evaluation of the thermal capacity of such created system is necessary.

To estimate life time refer to Annex B (informative) and Annex C (informative).

10.3 Temperature limits for liquid

The temperature of the liquid shall not exceed the limits of Table 4.

Table 4 – Temperature limits for liquid

	Mineral oil (IEC 60296)	Synthetic ester fluid (IEC 61099)	Silicon fluid (IEC 60836)
Fire point class (IEC 61039)	O	K	K
Maximum temperature for long term load, bulk fluid breathing or sealed °C	105	130	155

The values of temperature are based on IEC 60076-14. The recommended temperature limits are valid for the specific environment for insulation systems. Sealed systems limit the impact of oxygen and moisture as typical aging factors. For the free breathing system, maintenance has to be adapted.

10.4 Temperature limits for other parts

Tank surface maximum temperature shall be agreed between purchaser and manufacturer.

The temperature of the cores and other parts of the transformer or inductor shall in no case reach a value which will cause damage to these parts or adjacent ones, or undue ageing of the insulating liquid.

11 Mechanical design

The mechanical behaviour can be proved by Finite Element Analysis (FEA) calculation (method, model calibration and fatigue limits) to be agreed between the purchaser and manufacturer, or by the shock and vibration test. If the FEA method is chosen it should at least include the static load cases, the modal analysis up to 60 Hz and a relevant fatigue analysis that is based on the spectral power density defined by the IEC 61373 test conditions as input signal. A relevant damage evaluation shall be made with a recognized standard method (e.g. Single moment, Rayleigh, etc.). The material data have to be taken in accordance with this standard. The calculation shall take the welds into account and safety coefficient applied in accordance with the relevant standard agreed with the purchaser shall be used. The liquid has to be taken into account and the way it has been simulated has to be demonstrated.

12 Rating plates

Each unit that can be handled independently shall be provided with its own rating plate showing at least the items indicated below, unless otherwise agreed between purchaser and manufacturer:

– manufacturer's name;
– manufacturer’s type designation or number;
– manufacturer's serial number;
– date and place of manufacturing;
– connection diagram;
– tappings;
– rated power, voltage and frequency of each winding;
– rated current (r.m.s. value, or mean direct current);
– value of the inductance (at one or more specified reference current values);
– volume of cooling medium and type (only for the liquid filled);
– name of cooling fluid (only for the liquid filled);
– identification of cooling method;
– total mass.

The identification plate shall be placed in such a way that it will be easily inspected and cleaned in normal maintenance operations once the transformer is installed in the final application.

13 Tests

13.1 Categories of tests

13.1.1 General

There are three categories of tests:

– type tests;
– routine tests;
– investigation tests.

Descriptions of the different tests belonging to each category are given below.

13.1.2 Type tests

Type tests are carried out on a single piece of equipment of a given design. The test shall be carried out on one unit chosen among the first batch produced.

Bulk production equipment shall be deemed to have passed the type tests and shall be exempted from them if the manufacturer produces duly signed certificates of type tests already carried out on identical equipment constructed on a previous occasion.

Optional type tests are to be carried out only if they have been expressly specified in the order.

13.1.3 Routine tests

Routine tests are carried out on all equipment of the same order. For certain equipment, after agreement between purchaser and manufacturer, the routine tests may be replaced by tests carried out on a few items of equipment taken at random from the order.

13.1.4 Investigation tests

Investigation tests are special tests of an optional character carried out on a single equipment in order to obtain additional information on its performance; they are only to be carried out if they have been expressly specified in the order.

The results of these tests shall not influence the acceptance of the equipment unless agreement to the contrary has been specified in the order.

13.2 Tests on transformers

13.2.1 General – List of tests

The checks, measurements and tests to be made on traction and auxiliary transformers are indicated in Table 5, which also stipulates the category of the test and the clauses to which reference should be made.

As far as practicable, the tests on differential inductors which cannot be dissociated from the transformer shall be carried out together with the tests on the latter. Purchaser and manufacturer shall agree on the tests to be made, if necessary, on these inductors as separate equipment, so as to ensure that they fulfil all requirements of this standard.

When tap changers are an integral part of the transformers, they cannot be separated while the latter are tested.

Table 5 – List of checks and tests to be made on traction transformers

Nature of test	Clause or Subclause		
	Type	**Routine**	**Investigation**
Visual checks	**13.2.3**	**13.2.3**	-
Functional tests	**13.2.3 (optional)**	**13.2.3 (optional)**	-
Mass	**13.2.4**	**13.2.4 (optional)**	-
Measurement of winding resistance	**13.2.5**	**13.2.5**	-
Measurement of voltage ratios, polarities and vector groups	**13.2.6**	**13.2.6**	-
Measurement of no-load primary current and losses	**13.2.7.2**	**13.2.7.3**	-
Measurement of impedance voltage or short-circuit impedances	**13.2.8**	**13.2.8**	-
Measurement of load losses	**13.2.9.2**	**13.2.9.3**	-
Determination of total losses	**13.2.10**	-	-
Temperature-rise test	**13.2.11**	-	-
Insulation resistance test	**13.2.12 (optional)**	**13.2.12 (optional)**	
Wet dielectric tests	**13.2.13.1 dry-type only (optional)**	**13.2.13.1 dry-type only (optional)**	**13.2.13.1 dry-type only (optional)**
Induced voltage withstand test	**13.2.13.2**	**13.2.13.2**	-
Separate source voltage withstand test	**13.2.13.3**	**13.2.13.3**	-
Lightning impulse voltage withstand test	**13.2.13.4**	-	-
Voltage between terminals withstand test	**13.2.13.5 (optional)**	-	
Cabling dielectric test	**13.2.13.6**	**13.2.13.6**	-
Partial discharge test	**13.2.14 dry-type only**	**13.2.14 dry-type only (optional)**	**13.2.14 liquid-immersed type only**
Short-circuit withstand test	**13.2.15 (optional)**	-	-
Shock and vibration test	**13.2.16 (optional)**	-	-
Voltage Transmission Ratio – VTR	**13.2.17 (optional)**	-	-
Noise measurement	**13.2.18**	-	-
Leakage magnetic flux density measurement	**13.2.19 (optional)**	-	-
Electrical frequency response analysis FRA	-	-	**13.2.20**
Inrush current measurement	**13.2.21 (optional)**	-	-

13.2.2 Tolerances

Table 6 gives tolerances applicable to certain rated quantities and to other quantities when they are the subject of manufacturer's guarantees referring to this standard.

When a tolerance in one direction is omitted, there is no limit on the value in that direction.

Table 6 – Tolerances

Quantity	Subclause	Tolerances
1. Winding resistance	13.2.5	≤10 % [a]
2. a) Total losses b) Component losses	13.2.7, 13.2.9, 13.2.10	+10 % of the total losses. +15 % of each component loss provided that the tolerance on total losses is not exceeded
3. Voltage ratio at no-load on the principal tapping. Rated voltage ratio	13.2.6	±0,5 % of the ratio declared on the rating plate, or a percentage of the declared ratio equal to 1/10 of the actual percentage impedance voltage at rated load, whichever is the lesser value
4. Impedance voltage for principal tapping	13.2.8	±10 % of the declared impedance voltage for that tapping. Individual winding shall not deviate more than 3 % from the average value of identical windings inside the same transformer; unless otherwise agreed between purchaser and manufacturer [b]
5. No-load current	13.2.7	+30 % of the declared no-load current
6. Total mass	13.2.4	Type test: ±10 % (total mass < 100 kg) ±5 % (1 000 kg > total mass ≥ 100 kg) ±3 % (total mass ≥ 1 000 kg) Series production: ±3 %

[a] For series production a lower tolerance is expected and shall be provided by the manufacturer depending on wire size and winding tolerances.

[b] Smaller tolerance shall be subject to agreement between purchaser and manufacturer.

13.2.3 Visual checks (type, routine test) and functional tests (optional type and routine test)

Visual checks: mechanical interfaces (dimensions, markings, etc.), configuration level and rating plate.

Functional tests: on all auxiliaries (for example: oil flow indicator, voltage and current measurement devices, cooling system, etc.).

Upon agreement between the purchaser and manufacturer, additional type tests could be carried out.

13.2.4 Mass (type and optional routine test)

The transformer shall be weighed with all accessories included in the scope of supply.

If it is not possible to measure mass with the above mentioned parts combined, the parts shall be measured individually.

13.2.5 Measurement of winding resistance (type and routine tests)

The resistance of each winding between accessible terminals shall be measured when cold with direct current. Reference should be made to IEC 60076-1 for the precautions to be taken for the minimization of self-inductive effects and the proper determination of the temperature of the windings. The temperature at which the measurement is taken shall also be recorded.

Resistance of winding shall be corrected to reference temperatures from Table 7 according to IEC 60076-1:2011, Annex E.

Table 7 – Reference temperatures

Thermal class of insulation system	Reference temperature °C
105(A) 120(E)	85
130(B)	130
155(F) 180(H) 200 220	150

Other values of reference temperature can be found in IEC 60076-1 and IEC 60076-11 and can be used for transformers/inductors by agreement between purchaser and manufacturer.

For type tests:

a) if a winding is provided with tappings for the regulation of the voltage of the traction circuit, the total resistance of the live portion of the said winding shall be measured for each tapping;
b) if certain auxiliary windings have several sections, the resistance of each shall be measured.

For routine tests:

c) measurement a) may be limited to the principal tapping of the winding;
d) measurement b) may only be carried out on the whole of the auxiliary winding.

13.2.6 Measurement of voltage ratio, polarities and vector groups (type and routine tests)

The various voltage ratios between pairs of windings shall be measured for all accessible tappings of these windings.

If a transformer with a high-voltage control has several traction secondary windings and if correct voltage ratios have been recorded during measurement made between these secondary windings, it will be sufficient to measure the voltage ratio between one of these secondary windings and the line-side winding for all the tappings of the latter.

The measurement of the voltage ratio of a fixed ratio traction transformer forming a part of a transformer with high-voltage control is a type test.

Together with the voltage ratio measurement, the polarities and vector groups shall be checked according to IEC 60076-1.

13.2.7 Measurement of no-load primary current and losses (type and routine tests)

13.2.7.1 General

Measurement shall be made at rated frequency, the waveform of the applied voltage being sinusoidal.

In case of a non-sinusoidal test voltage, reference should be made to IEC 60076-1 for the method of correction which may be used. The voltage shall be applied to a suitable winding of the transformer; if the transformer has high-voltage control, the tap changer and the primary of the fixed ratio traction transformer shall remain in circuit but, in any case, all other windings shall be open-circuited.

Current measurement shall include mean and total r.m.s. values.

13.2.7.2 Type test

The measurement of the no-load current and losses shall be made for line-side voltages of U_{min2}, U_{min1}, U_{n}, U_{max1} and U_{max2} (IEC 60850). Other values may be considered if agreed between manufacturer and purchaser.

For an auxiliary transformer, the peak no load current shall be measured at U_{r}, and if required at 1,1 U_{r} and 1,2 U_{r}.

If the transformer has tappings or is specified for multi-voltage operation, the measurements shall be made for specified tappings or voltages, one of them corresponding to the principal tapping.

The purchaser may require the voltage and current waveforms and harmonic analysis.

13.2.7.3 Routine test

The measurements shall be made as in 13.2.7.2 but only for rated voltage U_{r} and for the principal tapping.

13.2.8 Measurement of impedance voltages or short-circuit impedances (type and routine tests)

13.2.8.1 General

Due to the diversity of winding arrangements of traction and auxiliary transformers, all the combinations in pairs of windings on which impedance voltages are to be measured shall be fixed by agreement between purchaser and manufacturer. The type tests should provide sufficient data to allow plotting of the on-load characteristics of the transformer on all positions of the tap changing equipment as well as for calculating the fault currents.

Impedance voltages shall be measured according to the procedure in IEC 60076-1 for the following combinations of windings:

a) line-side winding to all traction windings in common (type and routine tests);
b) line-side winding to each group of windings commutating at, or almost, the same time (type test);
c) line-side winding to each independent traction winding separately (type and routine tests);
d) line-side winding to each auxiliary winding separately (type test).

In type tests a), b) and c), measurements shall be taken on all tappings, while for type test d) and for the routine tests measurements need only be taken on the principal tapping for the line-side winding and on a specified tapping for the auxiliary windings.

If additional measurements on other tappings or in other combinations of windings are required, these shall be agreed between purchaser and manufacturer. The impedance voltage shall be measured at rated frequency using an approximately sinusoidal voltage supply. The measurements may be made at any current between 25 % and 100 % of the rated current. The voltage applied to any winding should not exceed 50 % of the rated voltage of the said winding and the current through it should not exceed to its rated value.

The measured value shall be corrected by increasing it in the ratio of rated current to test current. The values so derived shall be corrected to the appropriate reference temperature indicated in Table 7.

The short circuit impedance shall be derived from the impedance voltage and split into short-circuit resistance and inductance (see IEC 60076-1:2011, 3.7).

13.2.8.2 Measurement of differential inductance (type test)

If required, for non-linear short-circuit inductance characteristics, the differential inductance shall be measured according to 13.3.7.4.

The purchaser may require to measure the variation of impedance (resistance and inductance) with frequency.

13.2.9 Measurement of fundamental load losses (type and routine tests)

13.2.9.1 General

Fundamental load losses shall be recorded during the impedance voltage type and routine tests (see 13.2.8) and the values so obtained shall be corrected by multiplying them by the square of the ratio of rated current to test current.

The fundamental load losses so derived shall be corrected to the appropriate reference temperature given in 13.2.8.1, taking the I^2R (R = d.c. resistance) as varying directly with resistance and all the other losses varying inversely with resistance. Resistance shall be determined as specified in 13.2.5.

Fundamental load losses shall be determined for the following combinations in pairs of windings:

a) Line-side winding/all traction secondary windings in parallel or in series, as appropriate.
b) Line-side winding/each one of the auxiliary secondary windings.

Fundamental load losses shall be corrected to reference temperatures from Table 7 according to IEC 60076-1:2011, Annex E.

NOTE 1 The total losses for all circuits cannot be obtained by simple arithmetic addition of the losses measured on pairs of windings as prescribed above.

NOTE 2 They may in some cases be calculated from the d.c. resistance of each winding and the appropriate current, adding the additional losses derived from the tests.

13.2.9.2 Type test

Fundamental load losses shall be determined for combinations a) and b) defined in 13.2.9.1. For combination a), the determination shall be made for three positions of the tap changing equipment corresponding respectively:

– to the principal tapping;
– to the tapping giving the highest load losses in the traction windings;
– to another tapping.

13.2.9.3 Routine test

Fundamental load losses shall be determined for combination a) of 13.2.9.1 only and limited to the principal tapping.

13.2.10 Determination of total losses (type test)

The total losses are the sum of the no-load losses (13.2.7), and the load losses (13.2.9 fundamental and harmonics) after correction of the latter to the appropriate reference temperature of the windings, which is given in Table 7. Harmonic losses induced by converter operation shall be calculated according to IEC 61378-1:2011, Annex A, or any other method to be agreed between purchaser and manufacturer, and will be added to the losses measured at fundamental frequency.

The total losses for the traction circuits of a traction transformer are calculated for the principal tapping and for the tapping giving the highest traction load losses.

The total losses for the traction transformers are calculated for the combination of rated traction load and rated auxiliary circuit loads. Subject to agreement between purchaser and manufacturer, the losses associated with the train heating load are usually included in this calculation. The power consumption of the transformer auxiliary equipment (oil pump, fan, etc.) is not included in its total losses.

Unless otherwise specified, for transformers other than traction transformers, the total losses are calculated for rated load in all windings simultaneously.

13.2.11 Temperature-rise test (type test)

13.2.11.1 General

The details of the temperature-rise test conditions are subject to agreement between purchaser and manufacturer.

The temperature-rise test shall be performed:

a) at the rated power/current of the transformer/inductor (see Clause 6) in order to determine the thermal parameters for inclusion in the conformity assessment report;
b) and, unless otherwise agreed, in the overload conditions; in order to verify that the maximum short time temperatures will not exceed the limits of Tables 3 and 4;

and in two steps:

– step 1 – A temperature-rise test shall be performed in the factory of the manufacturer, at rated current/power with constant a.c. or d.c. current, unless the manufacturer is able to reproduce the specified waveforms;
– step 2 – If step 1 has not been performed with the specified waveforms, an additional test shall be performed on a test bench with the associated converter.

NOTE 1 For a dry-type transformer/inductor mounted inside a cubicle, step 2 using equivalent load connected to the converter is also used to validate the impact of the installation on the temperature-rises.

NOTE 2 For a liquid immersed transformer/inductor the purpose of step 2 is to measure the harmonic losses.

Tapped windings shall be tested at their maximum losses tap or other specified tapping.

During the test, all accessories for circulation and cooling of the cooling medium are arranged in conditions equivalent to those obtained on the vehicle (e.g. specified clogging of heat exchanger and external pressure drop, etc.).

The temperature of oil pump, fan motors and heat exchanger mounted on the transformer/inductor shall be measured and checked against their operating temperature range.

Specific temperature tests may be agreed between the purchaser and the manufacturer to validate the different modes of the cooling system (e.g. operation with motor fans at reduced speed or with only one pump).

For transformers/inductors with forced-air cooling, or similar type of cooling as covered in 9.2.3, the test shall be carried out with the specified air flow or velocity, or with the calculated air flow taking into account the additional external pressure drop resulting from transformers/inductors integrated on the vehicle.

The purchaser shall define the temperature of the cooling medium at the external interface of the transformer/inductor.

13.2.11.2 Temperature determination methods

Three methods shall be used to determine temperature, depending on the test performed:

a) direct temperature measurement:

   the temperature is measured directly with a temperature sensor (resistive thermometer, thermocouple, optical fiber, temperature sensitive sticker, infrared camera, etc.);

b) indirect temperature measurement:

   the temperature is derived from the measurements of other physical parameters such as voltage, current, resistance, etc. For instance, the average temperature of a winding can be determined from the variation of the d.c. resistance;

c) temperature calculation method:

   sometimes the zone where maximum temperature may exist is not easily accessible for direct measurement of the temperature. In such cases, the temperature is directly measured at a point close to the critical zone. The temperature-rise from this point to the critical zone of maximum temperature shall then be calculated. The manufacturer shall be able to provide information about the calculation method and the results of tests on a similar transformer/inductor used as reference.

13.2.11.3 Temperature-rise test of liquid-immersed type transformers/inductors

For liquid-immersed transformers and inductors, it is not always practical to measure directly hot-spot temperatures.

The hot-spot winding temperatures can be determined by direct measurement as a special test by agreement between manufacturer and purchaser.

Otherwise, the hot-spot winding temperature-rise shall be determined through calculation based on the result of a temperature-rise test as follows:

– the average temperature of the winding shall be measured (indirect temperature measurement by variation of d.c. resistance);
– the manufacturer shall submit to the purchaser the results of a study concerning the location of the hot-spots, and the relation between the hot-spot temperature and the winding average temperature.

The study should be based on:

– the leakage flux field and the distribution of additional losses;
– the circulation pattern of the insulating liquid inside the windings in the areas where the additional losses are higher.

In the factory of the manufacturer, temperature-rises shall be established in three steps:

– step 1 – liquid temperature–rise test:

  This test shall be carried out by injecting a test current in the windings which will generate the total losses of the transformer/inductor according to 13.2.10 and the total losses of other components inside the same tank.

  If agreed between purchaser and manufacturer the test can be carried out with lower losses, but not less than 80 % of total losses, and extrapolated to total losses according to 13.2.10.

  For a multiple voltage transformer/inductor the voltage system generating the highest losses shall be considered.

  The following data shall be measured:

  - liquid temperature at heat exchanger inlet and outlet;
  - cooling medium temperature at the external interface and flow rate.

– step 2 – Winding temperature-rise tests:

  This test shall be carried out with the rated current injection method according to IEC 60076-2 for each line voltage system.

  If agreed, this test shall also be performed in specified overload conditions.

– step 3 – Test consolidation:

  After the temperature-rise tests the manufacturer shall consolidate the results and calculate oil and winding temperatures for the specified conditions (including the installation constraints) and shall submit the conformity assessment report to the purchaser.

  At this stage the calculation shall include all current components affecting the core and winding temperatures during normal equipment operation which were not possible to reproduce during the previous steps 1 and 2. (e.g. harmonic losses).

Load profile temperatures shall be calculated based on the test results.

The standard method for the determination of the winding temperature-rise is current injection. For transformers current injection is achieved by the short-circuit method according to IEC 60076-2.

In special cases, if agreed, the test can be performed applying rated voltage and current by connection to a suitable load. This is mainly applicable to transformers with low rated power.

A back-to-back method may also be agreed. In this method, two transformers, one of which is the transformer under test, are connected in parallel and excited at the rated voltage of the transformer under test. By means of different voltage ratios or an injected voltage, rated current is made to flow in the windings of the transformer under test.

Some guidance can be found in IEC 60076-2 for:

a) terms and definitions;
b) the measurement of various temperatures;
c) the duration of tests;
d) the determination of liquid and winding temperatures;
e) necessary corrections of measurements.

13.2.11.4 Temperature-rise test of dry-type transformers/inductors

In dry-type transformers/inductors:

– the temperature gradient between the hot-spot and the average temperature of the winding, or the surface temperature of the winding, may be significantly high;
– thermal coupling between core(s) and windings may be strong;
– temperature sensors are easier to fit.

For direct measurement of the temperature, temperature sensors shall be fitted in positions, to be agreed between manufacturer and purchaser.

In addition, the average temperature of the windings shall be measured indirectly by the variation of their d.c. resistance.

The gradient between sensor readings and the average temperature of the windings shall be examined to help confirm that the hotspot of each winding has been measured.

In the factory of the manufacturer, temperature-rises shall be established in three steps, unless otherwise agreed:

– step 1 – Current injection test:

  A test current shall be injected in the windings which will generate the total losses of the transformer/inductor according to 13.2.10, until the steady state condition of the windings and magnetic core are reached.

  For transformers current injection is achieved by the short-circuit method.

  The ultimate temperature-rise is reached when the temperature-rise becomes constant; this is considered to have been achieved when the temperature-rise does not vary by more than 2 K per hour in the windings and the magnetic core(s). The winding temperatures shall then be measured.

  If agreed between purchaser and manufacturer the test can be carried out with lower losses, not less than 80 % of the total losses, and extrapolated to total losses according to 13.2.10.

– step 2 – Open-circuit test (for transformer only):

  The open-circuit test, at rated voltage and rated frequency, shall be continued until steady state condition of the winding(s) and magnetic core(s) is obtained. The individual winding temperature-rises shall then be measured.

  The open-circuit test can be carried out before or after the current injection test.

– step 3 – Test consolidation:

  The total winding temperature-rise of each winding, with losses in the winding(s) and normal excitation of the core(s), shall be calculated by the manufacturer who shall submit a conformity assessment report to the purchaser.

  This calculation shall include all current components affecting the core and winding temperatures during actual equipment operation but which were not possible to reproduce during step 1 and 2.

  For example, core and winding losses related to harmonics are included at this stage. If applicable, special attention is paid to the contribution of harmonic losses generated in a core (e.g. in the shunt core of a transformer with integrated inductor).

  The core contribution to winding hot-spot temperature-rise at no load should be the value given below or the value measured by the manufacturer during the temperature-rise test on the transformer/inductor:

  • 5 K for outer winding;
  • 25 K for inner winding.

  Load profile temperatures shall be calculated based on the test results.

  In special cases, if agreed, the test can be performed applying rated voltage and current by connection to a suitable load. This is mainly applicable to transformers with low rated power.

A back-to-back method may also be agreed.

13.2.11.5 Correction of temperature determinations

Temperature measurements may need to be corrected before being checked against the criteria:

- when the average temperature of a winding is determined from the variation of the d.c. resistance, it shall be extrapolated at the instant of shutdown according to IEC 60076-2;
- if the specified values of injected power or current have not been obtained during the temperature-rise test, the results shall be corrected according to IEC 60076-2 for immersed-type transformers/inductors and IEC 60076-12 for dry-types. This correction shall include the effect of temperature on the d.c. resistance and consequently on the losses (this is an iterative calculation process);
- if the temperature-rise test has not been performed at the specified cooling medium temperature, the results shall be corrected to take into account the effect of temperature on the d.c. resistance and consequently on the losses (this is an iterative calculation process): see 13.2.9.1 for guidance.

13.2.11.6 Temperature-rise test criteria

The test is declared successful if, for any component of the transformer/inductor:

- The consolidated hot-spot temperature, at rated power/current (see 6.2 and 7.3) and reference cooling medium temperature:
  - either, does not exceed the temperature limit agreed between purchaser and manufacturer;
  - or, is compatible with the specified lifetime; a method and an example to evaluate lifetime is given in Annex B (informative) and Annex C (informative);
- The consolidated hot-spot temperature, in the worst case conditions does not exceed the temperature of Tables 3 and 4.

13.2.12 Insulation resistance test (optional type and routine test)

Before starting the dielectric tests, the insulation resistance shall be measured by a megohmmeter applying at least 1 000 V d.c. between windings and between winding and the earth. Oil temperature at test shall be recorded. If required the insulation resistance measurement shall be repeated after test completion.

The insulation resistance shall be higher than the value agreed between purchaser and manufacturer.

13.2.13 Dielectric tests (type and routine tests)

13.2.13.1 General

The dielectric tests on new transformers/inductors are carried out in the manufacturer's workshop with the transformer/inductor at room temperature and equipped with those accessories which could influence the tests.

The relevant standards are IEC 60076-3 and IEC 60060-1 and IEC 60060-2.

The clearance and creepage distances should be checked following IEC 62497-1 for all the parts that are not immersed in the dielectric fluid.

In view of the number of likely variations, the arrangement of connections to be adopted for these tests shall be defined in each particular case.

However:

- the earth connection shall be retained on those points of the windings which are so connected in service;
- all non-tested conductive parts such as core, frame, tank or casing of the transformer/inductor, temperature sensors, dielectric screens, shall be connected to earth;
- for traction transformers with high-tension control, the tap changer shall be connected to the principal tapping.

Dielectric tests include:

- induced voltage withstand tests (see 13.2.13.2);
- separate source voltage withstand tests at industrial frequency (see 13.2.13.3);
- in addition, for dry-type transformers/inductors, wet dielectric tests may be required by the purchaser according to Annex D (informative);
- lightning impulse voltage withstand test (see 13.2.13.4);
- voltage between terminals withstand test (see 13.2.13.5);
- partial discharge measurement (see 13.3.11).

For induced and separate source voltage tests, the test voltages to be used are given as r.m.s. values in Table 8. The direct measurement of r.m.s. voltage may be replaced by the measurement of the voltage peak value; this peak value divided by square root of two should be equal to the r.m.s. value given in the Table 8.

The dielectric test voltages of Table 8 are defined for a basic insulation of the transformer/inductor.

For all windings connected to a power converter generating steep voltage waves:

- the purchaser shall specify the recurring peak voltage amplitudes (U_{mT} and U_{mG}), the d.c. link voltage, the voltage rise rate and the repetition frequency;
- a detailed design review should be carried out to ensure that the insulation concept has taken into account recurring dielectric stresses induced by the high dv/dt and the associated voltage overshoot.

Table 8 – Dielectric test voltage

Nominal voltage U_n [V]	Rated insulation voltage U_{Nm} (up to and excluding) [V][a)]	Winding directly connected to the contact line or protected according to OV3 U_a/U_{Ni} [kVr.m.s./kVpeak]	Winding protected according to OV2 U_a/U_{Ni} [kVr.m.s./kVpeak]
600	720	3,3 / 5	2,8 / 4
750	900	4,0 / 6	3,4 / 5
1 500	1 800	6,0 / 12	5,6 / 10
-	2 300[b)]	7 / 15,5	6,6 / 12
3000	3 700	11,5 / 25	10 / 18
-	4 800[b)]	13 / 25	11,6 / 18
-	6 500 [b)]	17 / 30	15 / 25
11 000	17 250	38 / 95	N.A.
12 000	17 250	38 / 95	N.A.
12 500	17 250	38 / 95	N.A.
15 000	17 250	38 / 95	N.A.
20 000	24 000	44 / 125	N.A.
25 000	27 500[c)]	60 / 150	N.A.
50 000	60 000	120 / 300	N.A.

NOTE The windings directly connected to the contact line shall be protected by an overvoltage protection. OV3 and OV2 only are considered.

a) For lower voltages refer to IEC 60077-1.

b) This voltage is used for intermediate d.c. link voltages.

c) For higher U_{Nm}, test voltages shall be agreed between purchaser and manufacturer.

13.2.13.2 Induced voltage withstand test (type and routine test)

The main purpose of this test is to check insulation between turns, coils and tappings of all the windings concerned.

For all windings which have one extremity or one tapping permanently earthed, this test constitutes simultaneously a separate source voltage withstand test for the non-earthed extremity of the winding.

During the test, one end of the coupled windings other than the one used for the supply, shall be connected to earth by one of their terminals.

The test voltages U_a shall be according to Table 8 unless otherwise agreed.

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

The peak value of the induced test voltage shall be measured. The peak value divided by square root of two shall be equal to the test value.

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

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

$$120 \times (\textit{assigned frequency / test frequency}) \text{ but not less than 15 s.}$$

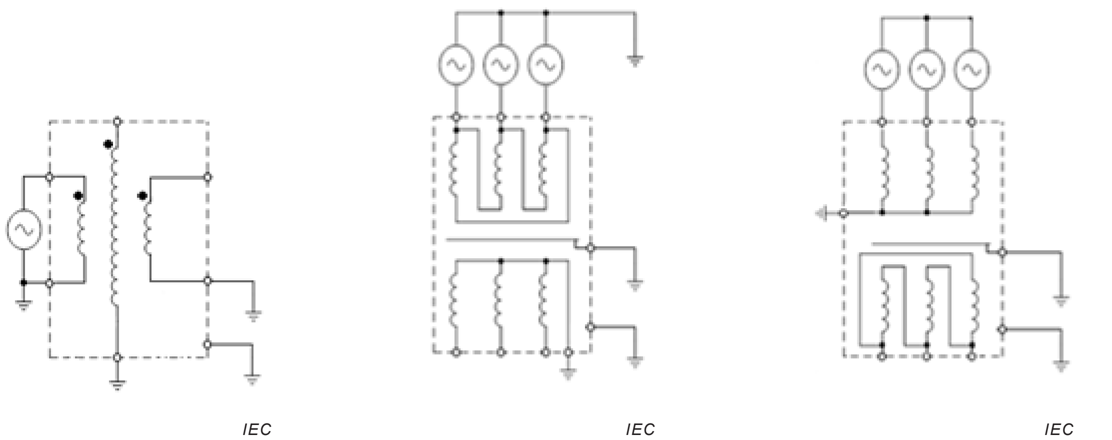
During the induced voltage test on a winding, care should be taken that the voltages induced in the various windings on the same magnetic circuit do not exceed the maximum test values.

For auxiliary transformers, unless otherwise specified, the induced voltage will be $2 \times U_r$ (rated voltage). See IEC 60076-3.

For traction transformers primary winding, the test voltages listed in Table 8 will apply.

For auxiliary transformers, the induced voltage test also realizes a phase-to-phase voltage test.

The induced test set up for traction transformer and for auxiliary transformer is shown in Figure 1. Note that the supply can be made from primary or secondary side for the auxiliary transformers.



(a) Traction transformer **(b) Applied from delta side for auxiliary transformer** **c) Applied from star side for auxiliary transformer**

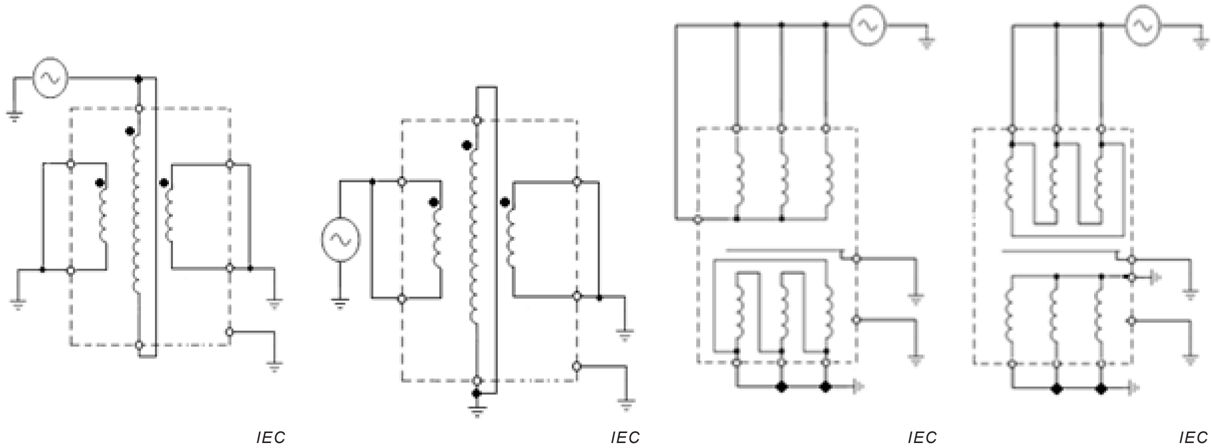
Figure 1 – Examples of set up for induced voltage withstanding tests

The test is successful if voltage and current remain stable during the test.

13.2.13.3 Separate source voltage withstand test (type and routine test)

The purpose of this test is to check the insulation between groups of windings, tappings and to earth. See Figure 2.

This test is applicable to all windings of transformers. The separate source voltage test shall be made by using a separate source, supplying an alternative single-phase voltage, which shall be applied in turn between each of the windings to be tested and all terminals of the remaining windings, connected together to earth. For the waveshape of the test voltage, the minimum frequency, the details for applying the voltage of test, reference should be made to IEC 60076-3.



(a) Applied to primary of traction transformer **(b) Applied to secondary of traction transformer** **(c) Applied for star side of auxiliary transformer** **(d) Applied for delta side of auxiliary transformer**

Figure 2 – Examples of set up for separate source voltage withstanding tests

The test voltage shall be according to U_a in Table 8, and the full test voltage shall be applied for 60 s.

Windings connected to the contact line with non-uniform insulation and not permanently earthed in the transformer shall be subjected to a separate source voltage withstand test at a voltage value to be agreed between purchaser and manufacturer.

The test is successful if voltage and current remain stable during the test.

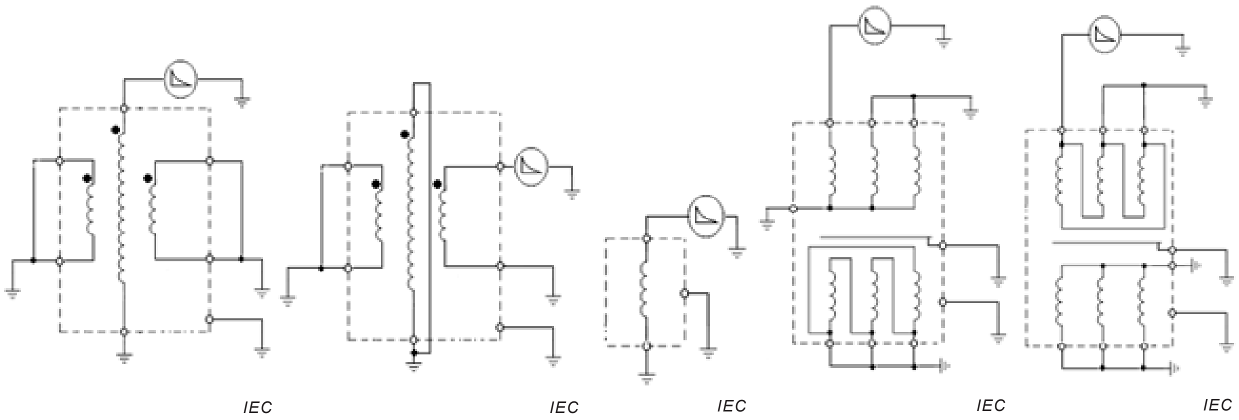
13.2.13.4 Lightning impulse voltage withstand test (type test)

13.2.13.4.1 General

The purpose of this test is to check the winding internal, coil to coil and coil to earth insulations against lightning overvoltage and fast transients. This test is mandatory for traction and auxiliary transformer windings directly supplied from the contact line.

During the test:

– all non-tested accessible terminals shall be directly earthed (see Figure 3);
– the earthed end of the line-side winding shall be earthed either directly or through an impedance of low value;
– any overvoltage protective devices associated with the line-side terminal in service shall be removed or disconnected;
– if high-tension control is used, the tap changer shall be connected to the principal tapping.



(a) Applied to primary of traction transformer **(b) Applied to secondary of traction transformer** **(c) Inductor** **(d) Applied for star side of auxiliary transformer** **(e) Applied for delta side of auxiliary transformer**

Figure 3 – Examples of impulse test connections for traction, inductor and auxiliary transformers

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

Unless otherwise agreed, the peak value of the applied voltage shall be U_{Ni} according to Table 8.

There are cases, however, where this standard impulse shape cannot reasonably be obtained, because of low winding inductance or high capacitance to earth. The resulting impulse shape is then often oscillatory. Wider tolerances may, in such cases, be accepted by agreement between purchaser and manufacturer. See IEC 60076-4.

When the low-voltage winding cannot be subjected to lightning overvoltages from the low voltage system, this winding may, by agreement between manufacturer and purchaser, be impulse tested with surges transferred from the high-voltage winding. The method is described in IEC 60076-3.

When the neutral terminal is connected to the earth, impulse voltage withstand test for the neutral terminal is not required.

When the neutral terminal of a winding has a specified impulse withstand voltage, the test is carried out according to IEC 60076-3.

13.2.13.4.2 Test sequence

The test sequence shall consist of one impulse of a voltage between 50 % and 75 % of the full test voltage, and three subsequent impulses at full voltage. If, during any of these applications, an external flashover in the circuit or across a bushing spark gap should occur, or if the oscillographic recording should fail on any of the specified measuring channels, that application shall be disregarded and a further application made.

13.2.13.4.3 Test criteria

The absence of significant differences between voltage and current transients recorded at reduced voltage and those recorded at full test voltage constitutes evidence that the insulation has withstood the test. The detailed interpretation of the oscillographic or digital test records and discrimination of marginal disturbances from true records of failure require a great deal of skill and experience. Further information is given in IEC 60076-4. If there is doubt about the interpretation of possible discrepancies between transient records, three subsequent impulses at full voltage shall be applied, or the whole impulse test on the terminal shall be repeated.

The test shall be considered successfully passed if no further and progressive deviations are observed. Additional observations during the test (abnormal sound effects, etc.) may be used to confirm the interpretation of the transient records, but they do not constitute evidence in themselves. Any difference in the wave shape between the reduced full wave and final full wave detected by comparison of the two current transient records may be an indication of failure or deviations due to non-injurious causes. They should be fully investigated and explained by a new reduced wave and full-wave test. Examples of possible causes of different wave shapes are operation of protective devices, core saturation, or conditions in the test circuit external to the transformer.

13.2.13.5 Voltage between terminals withstand test (optional type test)

The voltage between terminals withstand test shall be carried out according to 13.3.10.4.

This test is only applicable to transformer windings repeatedly subjected to steep front voltage waveforms.

NOTE For example this test is not applicable to the line side winding of a traction transformer or to the windings of 3ph transformer supplied through a sinusoidal filter, etc.

13.2.13.6 Cabling dielectric test (type and routine test)

The low voltage cabling (auxiliary) shall be tested with voltage level according to IEC 62497-1.

This subclause applies only to galvanic insulated conductors used for low voltage circuits and auxiliary components supply (ex: thermal sensor, pump, etc.).

13.2.14 Partial discharge test (type or optional routine test for dry-type, investigation test for immersed type)

The purpose of this test is to evaluate the ability of the insulation system to perform over lifetime. The principle is to perform partial discharge measurements to verify that the transformer/inductor will operate safely under normal conditions. For immersed type transformers/inductors partial discharge investigation tests may be agreed between purchaser and manufacturer referring to IEC 60076-3 for the induced voltage test. In case of plug-in bushing transformers/inductors, an appropriate method shall be adopted to avoid partial discharge within the bushing.

Further information about partial discharge measurements may be obtained in IEC 60270.

For dry-type transformers/inductors this is a type test. This test may be required by the purchaser as a routine test. The test shall be performed as follows. The level of apparent charge Q and the voltage are measured when a r.m.s. a.c. voltage (50 Hz or 60 Hz) is applied (separate source voltage) in turn between each of the windings to be tested and all terminals of the remaining windings connected to earth.

Up to six values shall be recorded during the test, according to Figure 4 and Table 9.

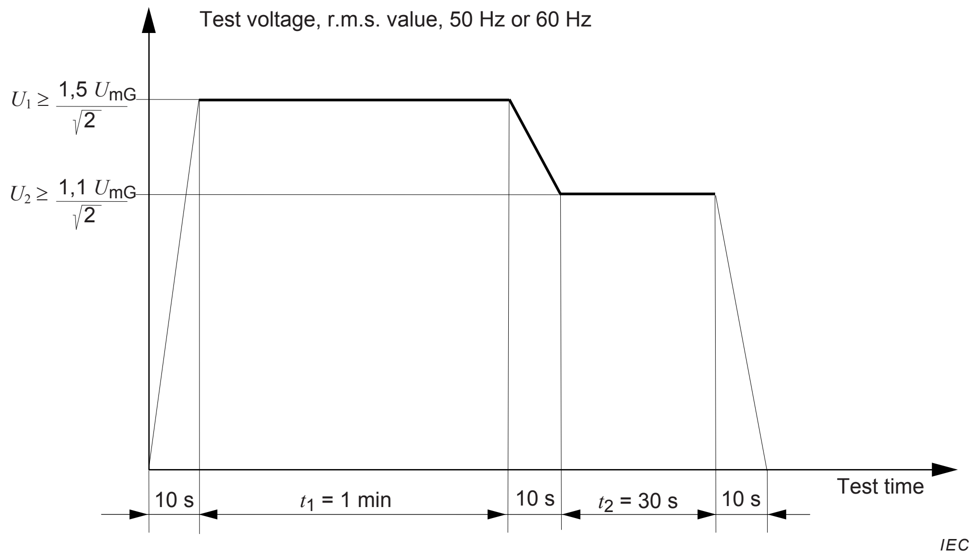


Figure 4 – Partial discharge test: voltage versus time

Table 9 – Partial discharge measurements

	Measure	Condition	Comment	Type or investigation test	Routine test
1	Q_{BG}	-	$Q_{BG} << Q_{MAX}$	X	X
2	U_i	at Q_{MAX}	$> U_2$	X	
3	Q_1	at U_1	-	X	X
4	U_e	at Q_{MAX}	$\geq U_2$	X	
5	Q_2	at U_2	$\leq Q_{MAX}$ and no continuing rising tendency during t_2.	X	X
6	$U_{e\text{-tot}}$	at Q_{BG}	-	X	

he sequence is as follows:

a) Before starting the test, the partial discharge background noise Q_{BG} is measured. The background noise should be considerably lower than the criterion Q_{MAX} in order to permit a sufficiently sensitive and accurate measurement of the inception and extinction voltage levels, and of the maximum permissible partial discharge magnitude Q_{MAX}.

   The voltage is ramped up to U_1 in 10 s and is maintained for t_1 = 1 min (see Figure 4). During this time t_1, some partial discharges may be observed.

   U_1 shall be taken equal to 1,5 $U_{mG}/\sqrt{2}$ minimum wherein U_{mG} is the highest recurring peak voltage across the insulation being tested.

b) When raising the voltage:
   - the inception voltage (U_i at which Q reaches or exceeds Q_{MAX}) shall be recorded;
   - the discharge level Q_1 at U_1 shall be recorded.

c) After t_1, the voltage is decreased to U_2 in 10 s and maintained for t_2 = 30 s. During the last 5 s of t_2, the level of partial discharge Q_2 is measured.

   U_2 shall be taken equal to 1,1 $U_{mG}/\sqrt{2}$ minimum.

d) When decreasing the voltage:

- the extinction voltage (U_e at which Q drops below Q_{MAX}) shall be recorded;
- the discharge level Q_2 at U_2 shall be recorded.

If significant discharges are still observed at U_2, the test voltage shall be further decreased until $U_{e\text{-tot}}$ when discharges disappear (down to background noise Q_{BG}).

Acceptance criteria – The test is successful if:

- no collapse of the test voltage occurs;
- the partial discharge behaviour at U_2 does not show a continuing rising tendency;
- the continuous level of apparent charge Q at U_2 during the last 5 s does not exceed the permissible level Q_{MAX}, to be agreed between purchaser and manufacturer.

  For example for dry-type components, Q_{MAX} is usually chosen between 10 pC and 50 pC. The value of Q_{MAX} is less important if the extinction is sharp.

For type or investigation test, if no significant discharges are observed at U_1, the test voltage shall be increased until either discharges reach the discharge limit Q_{MAX} or until the voltage reaches the separate source withstand test voltage or the induced test voltage.

The type test should be carried out both in hot (e.g. see D.4.1) and cold (e.g. ambient temperature) conditions.

It may happen that partial discharge inception and extinction voltages are lower in hot conditions. If the routine test is carried out in cold conditions, the upper and lower test voltages (U_1, U_2) shall be agreed between purchaser and manufacturer (however, U_1 shall never exceed U_a).

13.2.15 Short-circuit withstand test (optional type test)

13.2.15.1 General

When required by the purchaser, this test shall be requested in the tender specifications and agreed between purchaser and manufacturer upon order and shall be in accordance with IEC 60076-5.

The transformer/inductor together with all equipment and accessories shall be designed and constructed to withstand without damage the thermal and dynamic effects of external short circuits. The presence of an impedance and/or of protective devices (fuses, switches, etc.) in the corresponding circuits shall be taken into account. The short-circuit apparent power of the system at the transformer/inductor location shall be specified by the purchaser in his enquiry in order to obtain the short-circuit current to be used for the design and tests.

The thermal design shall be in accordance with IEC 60076-5.

The maximum value of short-circuit power available at the vehicle input shall be specified by the purchaser to the manufacturer.

The voltage to be taken into account is the maximum (U_{max1}) value of the traction system, as specified in IEC 60850.

For transformers, the test current peak value and the value of the symmetrical short-circuit current shall be calculated according IEC 60076-5.

Short-circuit currents for inductors shall be defined by the purchaser.

Unless otherwise agreed, the tests shall be carried out with protection accessories (pressure-relief device, etc.).

If the windings are provided with tappings, the reactance/inductance and, if required, also the resistance shall be measured for the tapping positions at which short-circuit tests will be carried out.

All the reactance/inductance measurements shall be to a repeatability of better than ± 0,2 %. A report containing the result of the routine tests shall be available at the beginning of short-circuit tests.

13.2.15.2 Testing

To obtain the initial peak value of the current in the phase winding under test, the moment of switching on shall be adjusted by means of a synchronous switch. In order to check the values of the test currents, oscillographic records shall always be taken. In order to obtain the maximum asymmetry of the current in the phase winding, the switching-on shall occur at the moment the voltage applied to this winding passes through zero.

For single-phase transformers/inductors the number of tests shall be three, for three-phase transformers/inductors the number of tests shall be nine.

The duration of each test shall be 0,25 s with a tolerance of ± 10 %.

During each test, oscillographic recordings shall be taken of the applied voltages and the currents.

After each test, the oscillograms taken during test shall be checked.

13.2.15.3 Detection of faults and evaluation of test results

After completion the test, the external parts of the transformer/inductor shall be inspected. The results of the short-circuit reactance/inductance measurements and the oscillograms taken during the different stages of the tests shall be examined for any indication of possible anomalies during the tests, especially any indications of change in the short-circuit reactance/inductance.

Different procedures are followed at this stage for transformers/inductors. Unless otherwise agreed, the active part shall be removed from the tank (liquid immersed transformers/inductors only) for inspection of the core and windings and compared with its state before the test, in order to reveal possible apparent defects such as changes in lead position, displacements, etc., which, in spite of successful routine tests, might endanger the safe operation of the transformer/inductor.

Visual inspection of the supporting structure shall give no indication that there has been any change in mechanical condition that will impair the function of the transformer/inductor. If after the short-circuit test program the winding clamping system has deteriorated, or surface cracks have increased significantly in number or dimension, the transformer/inductor 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 transformer/inductor shall be considered to have failed the test. If conditions stabilize after one or two extra short-circuit test and coupled with successful routine tests after short-circuit tests, the transformer/inductor shall be considered to have passed the short-circuit test.

All the routine tests, including dielectric tests at 80 % of the prescribed test value shall be repeated. If a lightning impulse test is specified, it shall be performed at this stage.

In order to consider the transformer/inductor as having passed the short-circuit test, the following conditions shall be fulfilled:

- the results of the short-circuit tests and the measurements and checks performed during tests do not reveal any conditions of faults;
- the routine tests have been successfully repeated, the lightning impulse test, if specified, and the wet dielectric tests for dry-type transformers/inductors, if specified successfully performed;
- if frequency response analysis (FRA) is required to evaluate the mechanical state of the windings, the results of measurements before and after short-circuit test shall be discussed between the manufacturer and purchaser. The method shall be according to IEC 60076-18 or the one defined in 13.2.20;
- the out-of-tank inspection does not reveal any defects such as displacements, shift of laminations, deformation of windings, connections of supporting structures, so significant that they might endanger the safe operation of the transformer/inductor;
- no traces of internal electrical discharge are found;
- the short-circuit reactance values, in ohms or the inductance in mH evaluated for each phase at the end of the tests, do not differ from the original values by more than:
  - 2 % for transformers/inductors with circular concentric coils and sandwich non-circular coils;
  - 7,5 % for transformers/inductors with non-circular concentric coils having a short-circuit impedance of 3 % or more. The value of 7,5 % may be reduced by agreement between manufacturer and purchaser but not below 4 %.

In addition, for dry-type transformers, wet dielectric tests may be required according to Annex D (informative).

13.2.16 Shock and vibration test (optional type test)

13.2.16.1 General

When required by the purchaser, this test shall be requested in tender specifications and agreed between purchaser and manufacturer upon order and shall be in accordance with IEC 61373.

The test is intended to highlight any weakness/error which may result in problems as a consequence of operation under environments where vibrations and shocks are known to occur in service of a railway vehicle. This is not intended to represent a full life test. However, the test conditions are sufficient to provide some reasonable degree of confidence that the equipment will survive the specified life under service conditions. The following tests are mandatory for compliance with standard IEC 61373:

- functional random test:

  not required for transformer and inductor;
- simulated long-life test:

  this test is aimed at establishing the mechanical integrity of the equipment at increased service levels. It is not necessary to demonstrate ability to function under these conditions;
- shock testing:

  shock testing is aimed at simulating rare service events. It is not necessary to demonstrate functionality during this test. It will be however be necessary to demonstrate that no change in operational state occurs, that there is no visual deformation and that mechanical integrity has not changed. These points shall be clearly demonstrated in the final test report.

Before and after the test, the mechanical transfer function shall be established in order to verify the mechanical integrity and the resonance modes.

13.2.16.2 Testing

13.2.16.2.1 Simulated long-life testing at increased random vibration levels

Equipment shall be subjected to a total conditioning time of 15 h. This shall be normally divided into periods of 5 h conditioning in each of three mutually perpendicular axes.

If multi-axis testing is used, total duration is 5 h.

It is recommended to perform the test without resilient transformer/inductor fixation.

If during the course of testing overheating of equipment is felt to be a problem, it is possible to stop the test for a period of time in order to allow the equipment to recover. However, the total duration of 5 h vibration shall be achieved. If tests are stopped this fact shall be stated in the report. Tests shall be carried out during the long-life tests according to IEC 61373:2010 for category 1 class A or B to be specified by the purchaser.

13.2.16.2.2 Shock test

Equipment under test shall be subjected to a sequence of single half sine pulses tests according to IEC 61373:2010 for category 1 class A or B to be specified by the purchaser.

If for practical reasons the 5 g cannot be met it is allowed to reduce the value but not less than 3 g provided that the velocity change rate is respected.

13.2.16.2.3 Detection of faults and evaluation of test results

A visual inspection of the transformer/inductor shall give no indication that there has been any damage. Tightening torques shall be checked for mechanical and electrical fastenings. For a liquid type transformer/inductor the active parts shall be visually inspected. Any movable parts (paddles, oil level sensors, pump, fans, etc.) associated with the transformer/inductor shall be functionally tested.

The performance tests to be repeated after the shock and vibration tests, unless otherwise agreed between purchaser and manufacturer shall be:

For transformers:

a) measurement of winding resistance;
b) measurement of no-load current and losses;
c) measurement of impedance voltage;
d) induced voltage and/or separate source voltage withstand test;
e) in addition, for dry-type transformers, wet dielectric tests may be required by the purchaser according to Annex D (informative).

For inductors:

f) measurement of winding resistance;
g) measurement of inductance;
h) measurement of losses;
i) separate source voltage withstand test;
j) in addition, for dry-type inductors, wet dielectric tests may be required by the purchaser according to Annex D (informative).

If the results of the tests in items a) b) c) and/or f) g) h) in 13.2.16.2.3 show a difference of less than 2 % in respect to the values measured during original tests, the transformer/inductor is considered to have been satisfactorily tested for shock and vibration withstand. For the test in items d), e), i) and j) the test voltage shall be 80 % of the values used for the original test. If a frequency response analysis is required to evaluate the mechanical state of the windings, the results of measurements before and after shock and vibration test shall be discussed between the manufacturer and purchaser. The method shall be according to IEC 60076-18 or the one defined in 13.2.20.

13.2.17 Voltage transmission ratio – VTR (optional type test)

The purpose of this test is to evaluate the highest capacitively transmitted voltage between primary and adjacent windings and to check if those windings are in the correct rated insulation voltage (U_{Nm}) class. Information about transmitted voltages can be found in IEC 60076-3.

An impulse or a.c. square wave low voltage source (e.g. 10 V; 1 A) and a maximum rise time of maximum 1,5 μs is applied to the primary between the HV terminal and the other terminal connected to ground.

The relevant configuration (I, II, III) is chosen according to purchaser's connections scheme and the relevant secondary winding voltages are measured.

The first peak voltage extrapolated by the VTR factor to U_{Ni} for the primary should be lower than rated impulse voltage (U_{Ni}) of the secondary or the value specified by the purchaser.

The typical winding terminal configurations and the VTR test (grounded, capacitively maintained or highly resistive grounded) are summarized in Figure 5:

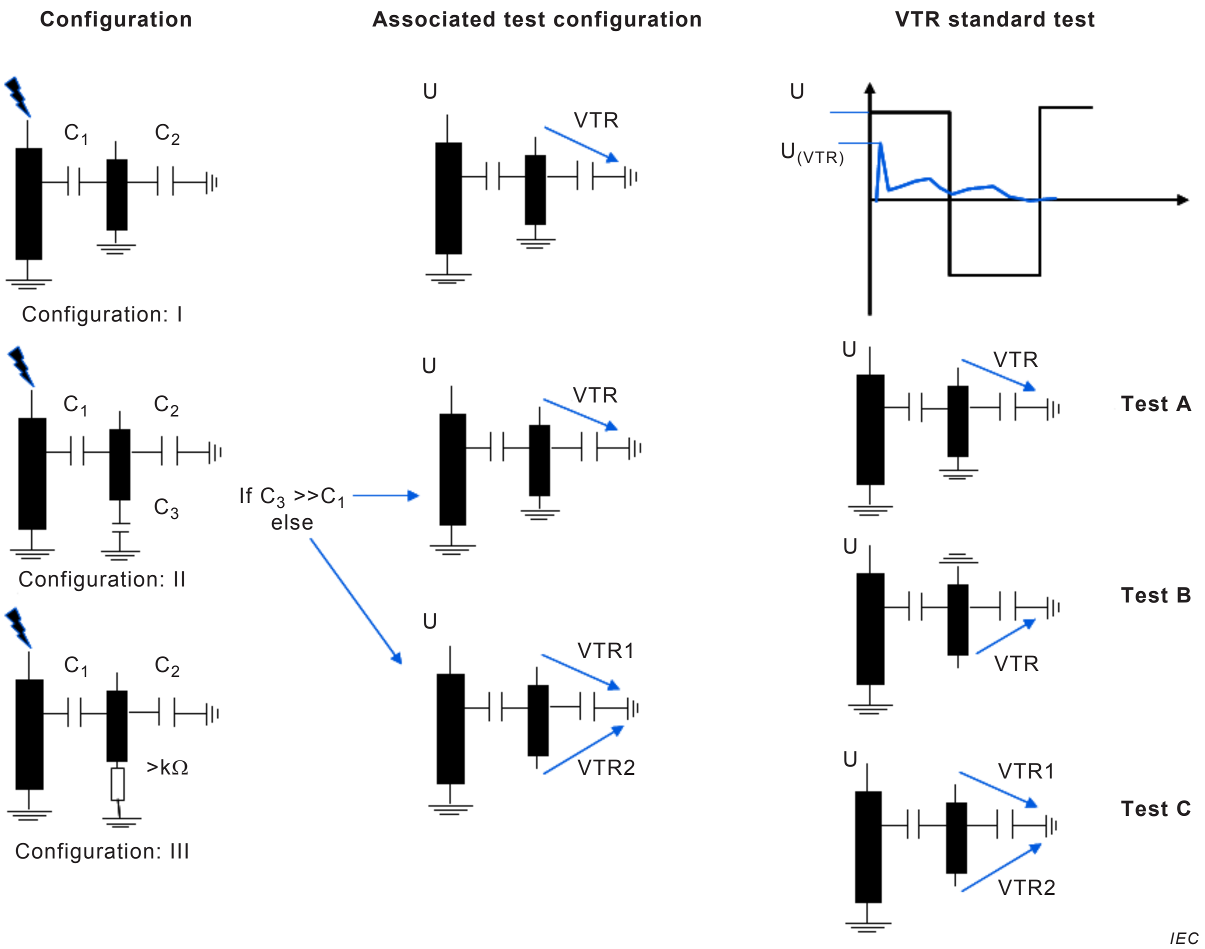


Figure 5 – Configurations for VTR test

13.2.18 Noise measurement (type test)

Noise level measurement shall be carried out according to IEC 60076-10 and specified cooling conditions.

For the sound intensity method ISO 9614-1 or ISO 9614-2 (when the setup of the test bench allows the presence of operator around the equipment) applies. For the sound pressure method ISO 3746 applies. The number of microphones may be increased to achieve the accuracy grade specified by the purchaser. In case the parallelepiped method is adopted measurement shall be performed on five surfaces:

– step 1 – the noise test shall be performed in the factory of the manufacturer, in the conditions defined in the IEC 60076-10 with sinusoidal supply, unless the manufacturer is able to reproduce the specified waveforms;
– step 2 – if step 1 has not been performed with the specified waveforms, an additional test shall be performed on a test bench or on the rolling stock with the associated converter.

13.2.19 Leakage magnetic flux density measurement (optional type test)

The leakage magnetic flux density shall be measured in specified points by applying specified current and checked against the specified limits.

Measuring points and limits shall be agreed between purchaser and manufacturer.

13.2.20 Electrical Frequency Response Analysis FRA (investigation test)

FRA may be used for diagnostic purposes and to estimate the current harmonics injected from secondaries linked to electronic converters into the primary.

The preferred FRA function is the ratio of the primary current divided by the secondary voltage which is applied to the transformer. The voltage shall be applied between secondary terminals and also between the secondary terminal shorted and earth. The measurement shall be performed over a frequency range up at least to 500 kHz.

The detailed measurement method shall be agreed between the purchaser and manufacturer.

13.2.21 Inrush current measurement (optional type test)

Inrush current is the transient magnetizing current flowing after connecting a transformer to the a.c. system. This current is highly asymmetric and depends on the remanent flux just before switch on and on the instant of switching the transformer. This current may be limited by a network requirement.

The measurement of inrush current needs precision on recording and a source of sufficient energy with a controlled switching off and switching on system.

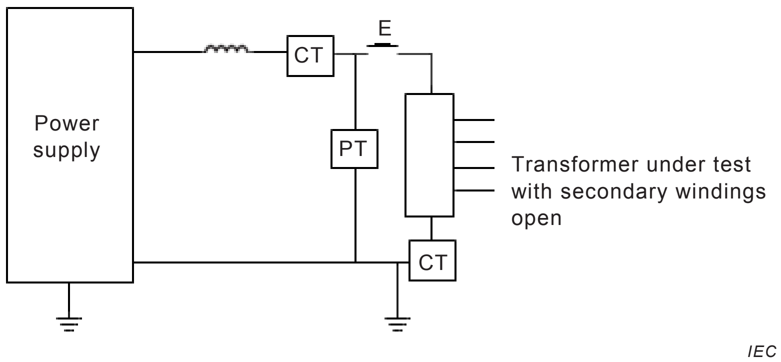
Following are the different stages for the measurement:

a) create a remanent flux in the transformer core by suitable switching off at a precise point of the voltage wave;
b) switch on the transformer at a voltage level U_{max1}, precisely at the point of zero voltage crossing;
c) record the primary peak current and the supply voltage;
d) measurement will be carried out for several times to obtain maximum current with a definite interval to allow the transients to diminish.

Acceptance criteria of primary inrush current shall be agreed between purchaser and manufacturer.

Example of test circuit (see Figure 6):

e) the power supply should have enough capacity to obtain correct inrush current;
f) the secondary windings are open.



Key
CT Current transformer
PT Potential transformer
E Synchronised switch

Figure 6 – Example of test circuit

13.3 Tests on inductors

13.3.1 List of tests

The checks, measurements and tests to be made on inductors are indicated in Table 10 below which also stipulates the kind of test and the clauses to which reference should be made.

Table 10 – List of checks and tests to be made on inductors

Nature of test	Clause or Subclause		
	Type	Routine	Investigation
Visual checks	13.3.3	13.3.3	-
Mass	13.3.4	13.3.4 (optional)	-
Measurement of winding resistance	13.3.5	13.3.5	-
Determination of losses	13.3.6	-	-
Measurement of inductance	13.3.7	13.3.7	-
Temperature-rise test	13.3.8	-	-
Insulation resistance test	13.3.9 (optional)	13.3.9 (optional)	-
Wet dielectric tests	13.3.10.1 dry-type only (optional)	13.3.10.1 dry-type only (optional)	13.3.10.1 dry-type only (optional)
Separate source voltage withstand test	13.3.10.2	13.3.10.2	-
Lightning impulse voltage withstand test	13.3.10.3	-	-
Voltage between terminals withstand test	13.3.10.4	13.3.10.4	-
Partial discharge test	13.3.11 dry-type only	13.3.11 dry-type only (optional)	-
Short-circuit withstand test	13.3.12 (optional)	-	-
Shock and vibration test	13.3.13 (optional)	-	-
Vibration test with current flowing	-	-	13.3.14
Noise measurement	13.3.15	-	-
Leakage magnetic flux density measurement	13.3.16 (optional)	-	-

13.3.2 Tolerances

Table 11 gives tolerances applicable to certain rated quantities and to other quantities when they are the subject of manufacturer's guarantees referring to this standard.

When a tolerance in one direction is omitted, there is no limit on the value in that direction.

Table 11 – Tolerances

Quantity	Subclause	Tolerances
1. Winding resistance	13.3.5	≤ 10 %[a)]
2. Losses	13.3.6	+10 % of the total losses +15 % of each component loss provided that the tolerance on total losses is not exceeded
3. Inductance	13.3.7	±10 % of the declared inductance. Identical inductors shall not deviate more than 3 % from the average value, unless otherwise agreed between purchaser and manufacturer [b)]
4. Mass	13.3.4	Type test: ±10 % (total mass < 100 kg) ±5 % (1 000 kg > total mass ≥ 100 kg) ±3 % (total mass ≥ 1 000 kg) Series production: ±3 %

a) For series production a lower tolerance is expected and shall be provided by the manufacturer depending on wire size and winding tolerances.

b) Smaller tolerance shall be subject to agreement between purchaser and manufacturer e.g. for the tuned filter inductor.

NOTE The impacts of tolerances shall be considered in the design phase and when evaluating the type test results.

For other values, if any, the tolerances shall be in accordance with IEC 60076-6.

13.3.3 Visual checks (type and routine test)

Visual checks shall be carried out according to 13.2.3.

13.3.4 Mass (type and optional routine test)

The inductor shall be weighed with all accessories included in the scope of supply.

13.3.5 Measurement of winding resistance (type and routine test)

The resistance of the winding(s) shall be measured with a direct current at ambient temperature, taking the usual care to minimize self-inductive effects. The temperature at which the measurement is made shall be recorded. The results shall be corrected to the reference temperature (see 13.2.5 and Table 7).

13.3.6 Determination of losses (type test)

The losses of alternating and pulsating current inductors shall be measured with a power frequency alternating current equivalent to the working current. The equivalent current shall be a r.m.s. value derived from the harmonic content or wave shape specified by the purchaser and shall take into account the estimated effect on the losses of the difference between the test and service condition.

The losses of direct current inductors shall be measured with direct current. Calculation of the losses in the magnetic core shall also be declared.

For inductors with a magnetic core or shield, the losses shall, whenever possible and unless otherwise agreed, be measured with a frequency and/or wave shape as close as practicable to the service.

13.3.7 Measurement of inductance (type and routine tests)

13.3.7.1 General

As a general rule, the type tests shall be carried out with a current appropriate to the type of inductor, whereas the routine tests may be made with an alternating current only or superimposed on a d.c. current. The value of the inductance specified or measured under these different conditions may not be the same and the manufacturer and purchaser shall agree the value to be used for the routine tests based on the results from the type test.

For coupled inductors, measurement of the mutual inductance (see IEC 60076-6) may be required as a type test.

The purchaser may require as additional type tests:

– the measurement of inductance variation with frequency;
– the measurement of inductance variation with temperature (e.g. for ferrite cores).

13.3.7.2 Measurement~~s~~ of a.c. inductance

13.3.7.2.1 General

These tests basically apply to inductors carrying alternating current with low harmonic contents. This test method may also be used for routine testing of other type of inductors.

The relevant inductance to measure is the a.c. inductance derived from the reactance where the voltage and the current are both given as r.m.s. values and where the voltage is sinusoidal: see IEC 60076-6 for reference.

The measurement shall be performed quickly so that the temperature-rise does not cause significant error. The d.c. resistance of the windings shall be indirectly measured if possible, from the measurement of losses during the record or measured directly before (for reference) and immediately after the record has been made.

13.3.7.2.2 Type test

The inductor shall be fed by an a.c. source (single or three phases as appropriate) at rated frequency; impedance or inductance curves shall be plotted as a function of the current over the whole range of utilisation of the inductor. If the purchaser requires, the saturation curve shall be agreed between the purchaser and the manufacturer before series production is started.

For air-cored inductors, the test shall be made only at rated current and maximum current.

For some inductors, the determination of the Q factor (see IEC 60076-6:2007, 9.4.11) may be required.

13.3.7.2.3 Routine test

The a.c. impedance shall be measured at rated current and at a frequency to be agreed between purchaser and manufacturer.

13.3.7.3 Measurement of incremental inductance

13.3.7.3.1 General

These tests basically apply to saturable inductors carrying d.c. current with low or significant harmonic contents (pulsating current).

The relevant inductance to measure is the incremental inductance derived from a record of the terminal voltage when a specified pulsating current is passing through the inductor: see IEC 60076-6 for reference.

The measurement shall be performed quickly so that the temperature-rise does not cause significant error referring to 13.3.2. The d.c. resistance of the windings shall be indirectly measured, if possible, from the measurement of losses during the record or measured directly before (for reference) and immediately after the record has been made.

13.3.7.3.2 Type test

The incremental inductance shall be measured at the specified harmonic frequency with a representative value of current superimposed on different d.c. currents within the specified current range.

NOTE 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.

Alternatively, the differential inductance may be used in lieu of the incremental inductance, subject to agreement between manufacturer and purchaser.

Curves of the incremental inductance shall be plotted as a function of the current over the whole range of utilisation of the inductor.

In case the routine test is to be performed with the a.c. impedance, on the inductor which has successfully passed the above type test, the impedance and inductance with alternating current at an agreed industrial frequency shall be recorded for several values of the current such that the voltage cannot reach dangerous values. The purchaser and manufacturer shall then agree on the choice of a certain point on the impedance curve so plotted; this point shall be adopted as a basis for the subsequent routine tests.

For air-cored inductors, the test shall be made only at rated and maximum current.

13.3.7.3.3 Routine test

Upon agreement between purchaser and manufacturer, the routine test may be performed either by measuring the incremental inductance in a single point (d.c. current and ripple current) or by measuring the a.c. impedance in the single point defined above.

13.3.7.4 Measurement of differential inductance

13.3.7.4.1 General

These tests basically apply to saturable inductors carrying a.c. or d.c. current with pulsating current (high harmonic contents).

This method may be used for air-cored inductors.

The relevant inductance to measure is the differential inductance derived from a digital record of instantaneous voltage and current in the inductor:

$$L_d(i) = \frac{d\psi(i)}{di} = \frac{u(t) - R \times i(t)}{di/dt}$$

NOTE This definition has the widest scope of application and describes best the magnetic characteristic of a saturable inductor. The other definitions of inductance can be derived from this characteristic.

In order to get accurate results:

a) The voltage shall be adjusted in order to generate a peak current which is higher than the current range specified for L_d and to cause saturation.

b) The measurements shall be performed quickly or with low energy so that temperature rises do not cause significant errors referring to 13.3.2. The d.c. resistance of the windings shall be indirectly measured, if possible, from the measurement of losses during the record or measured directly before (for reference) and immediately after the record has been made.

c) The raw digital record shall be adequately filtered to generate the $L_d(i)$ characteristic.

13.3.7.4.2 Type test

The instantaneous voltage and current (in each phase for three phase inductors) shall be recorded in a digital recorder. For every current value within the specified range, the differential inductance shall be calculated according to the above formula.

The test method shall further be agreed between purchaser and manufacturer. Suggested methods are as follows:

Method 1: a.c. voltage.

A single (or three) phase alternative voltage is applied to the inductor terminals at a frequency such that the peak current is higher than the range specified for L_d and to cause saturation, but such that the voltage does not exceed the maximum operating voltage.

For methods 2 to 5, in case of three phase inductors, the current shall be injected in turn in each phase. Depending on the connection diagram, the current shall be increased by the appropriate factor to take into account the contribution of the other phases in normal, three phases, operation.

Method 2: single phase a.c. current injection with d.c. current polarization.

Basically, this method is the same as the measurement of incremental inductance in d.c. inductors, but based on instantaneous rather than r.m.s. values.

The differential inductance shall be measured at the specified harmonic frequency with a representative value of current superimposed on different d.c. currents within the specified current range.

Method 3: single phase oscillating capacitor discharge.

A capacitor is discharged in the inductor.

The advantages of this method are:

- a high current and power source is not required;
- negligible temperature-rise of the winding; it is sufficient to measure the d.c. resistance of the winding before (for reference) and just after the record.

Method 4: single phase d.c. voltage pulse.

A d.c. voltage pulse is applied to the inductor terminals. The voltage amplitude and/or pulse duration shall be adjusted to reach at least the specified maximum current.

The advantages of this method are similar to those of Method 3.

Method 5: d.c. current charging-discharging.

See IEC 60076-6:2007, Annex B: the test is carried out with direct current either by means of a sudden closing of the circuit or by a sudden short-circuiting of the inductor.

In case the routine test is to be performed with the a.c. impedance, on the inductor which has successfully passed the above type test, the impedance and inductance with alternating current at an agreed industrial frequency shall be measured for several values of the current such that the voltage cannot reach dangerous values. The purchaser and manufacturer shall then agree on the choice of a certain point on the impedance curve so plotted; this point shall be adopted as a basis for the subsequent routine tests.

13.3.7.4.3 Routine test

Upon agreement between purchaser and manufacturer, the routine test may be performed either by measuring the differential inductance in a single point or by measuring the a.c. impedance in the single point defined above.

13.3.8 Temperature-rise test (type tests)

The temperature-rise test shall be carried out according to 13.2.11.

13.3.9 Insulation resistance test (optional type and routine test)

Before dielectric test, insulation resistance test shall be carried out by a 1 000 V Megger between windings and between winding and the earth. The cooling medium temperature shall be recorded.

13.3.10 Dielectric tests (type and routine tests)

13.3.10.1 General

The dielectric tests on new types of inductors shall be carried out in the manufacturer's workshops with the inductors at room temperature and equipped with those accessories which could influence the tests.

Dielectric tests include:

– separate source voltage withstand test (see 13.3.10.2);
– in addition, for dry-type inductors, wet dielectric tests may be required by the purchaser according to Annex D (informative);
– lightning impulse voltage withstand test (see 13.3.10.3);
– voltage between terminals withstand test (see 13.3.10.4);
– partial discharge test (see 13.3.11).

All non-tested conductive parts such as core, frame, tank or casing of the inductor, temperature sensors, shall be connected to earth.

13.3.10.2 Separate source voltage withstand test (type and routine test)

The separate source voltage withstand test shall be carried out according to 13.2.13.3.

13.3.10.3 Lightning impulse voltage withstand test (type test)

The lightning impulse voltage withstand test shall be carried out according to 13.2.13.4.

13.3.10.4 Voltage between terminals withstand test (type and routine tests)

The main purpose of this test is to check insulation between turns and between tappings, especially for windings repeatedly subjected to steep front voltage waveforms.

This test is to be carried out on transformers/inductors which may be exposed to dielectric stress between terminals during normal service or failure conditions.

During the test, the tank and the windings other than the one under test shall be connected as in service.

Several methods are proposed below in order to address the service stress conditions for transformers/inductors. Selection of test method and test conditions shall be agreed between purchaser and manufacturer (see Table 12).

Table 12 – Test method of voltage between terminals withstand test

Service conditions / Test methods	Pulsed voltages (windings supplied with PWM voltage, chopper inductor, transient inductor, 3ph filter inductor, etc.)	Sinusoidal a.c. (tuned filter inductor, etc.)	Pure d.c. (line filter inductor, etc.)
Impulse test: to be selected according to Table 8 based on U_{Nm}	Performed 3 times at U_{Ni}		
Capacitor discharge oscillation[a)]	Performed 3 times at U_a		
Sinusoidal voltage with or without increased frequency[b)]	$T = 120 \times f_{assigned} / f_{test}$ at U_a (15 s minimum, 60 s maximum)		
Recurring voltage pulse generator with steep front ≥ 5 kV/μs[c)]	$U = 2 \times U_{mG}$ N ≥ 3 000 pulses	Not applicable	

a) Refer to IEC 60076-6:2007, Annex E (depending of the damping, number of cycles shall be agreed between purchaser and manufacturer).

b) For small inductance value, it may be required to increase the test frequency in order to keep the current sufficiently low for the source and the inductor.

T = test duration.

f = frequency.

c) dv/dt should not be less than the specified service conditions.

13.3.11 Partial discharge test (type or optional routine test for the dry-type)

The partial discharge test shall be carried out according to 13.2.14.

13.3.12 Short-circuit withstand test (optional type test)

The short-circuit test shall be carried out according to 13.2.15. For the short circuit test of d.c. line filter inductors, the zero crossing of the supply voltage is not relevant. The maximum short-circuit current and the duration shall be specified by purchaser.

By agreement between the purchaser and manufacturer short-circuit test may be realised by capacitor discharge.

13.3.13 Shock and vibration test (optional type test)

The shock and vibration test shall be carried out according to 13.2.16.

13.3.14 Vibration test with current flowing (investigation test)

Measurement of vibration characteristics during current flowing shall be carried out to measure amplitudes of acceleration and displacement by applying current to inductor alone. Test conditions shall be agreed between purchaser and manufacturer.

13.3.15 Noise measurement (type test)

The noise measurement test shall be carried out according to 13.2.18.

13.3.16 Leakage magnetic flux density measurement (optional type test)

The leakage magnetic flux density measurement shall be carried out according to 13.2.19.

Annex A
(informative)

List of items for which an agreement between purchaser and manufacturer is needed or for which further information or specifications shall be given by the purchaser or by the manufacturer

A.1 Items subject to agreement between purchaser and manufacturer

A.1.1 Transformer and inductors

1	Extension of the scope of the standard.
5	Special service conditions.
10.2	Other temperature limits of solid insulation.
10.4	Maximum temperature of tank surface.
11	Mechanical behaviour proved by FEA calculation (method, model calibration and fatigue limits).
11	Safety coefficient for mechanical design.
12	Items on rating plates.
13.1.3	Replacement of routine tests by sampling tests.
13.2.1	Tests as separate equipment for differential inductors associated with transformer.
13.2.11.1	Temperature-rise test: details of test conditions.
13.2.11.1	Temperature rise test in the overload conditions or any other condition.
13.2.11.1	Specific temperature tests.
13.2.11.3	Liquid-immersed type transformers/inductors: hot-spot winding temperatures determined by direct measurement.
13.2.11.3	Test with lower losses for liquid temperature–rise test.
13.2.11.3	Test in specified overload conditions for winding temperature-rise tests.
13.2.11.4	Dry-type transformers/inductors: position of temperature sensors.
13.2.11.4	Other steps for temperature-rise test.
13.2.11.4	Current injection test with lower losses.
13.2.11.6	Temperature-rise test criteria at rated power/current.
13.2.13	Arrangement of connections for dielectric test in each particular case.
13.2.13.4.1	Lightning impulse voltage withstand test: peak value of the applied voltage other than in Table 8.
13.2.13.4.1	Wider tolerances of the resulting impulse shape.
13.2.14	Partial discharge test: permissible level Q_{MAX}.

13.2.14	Partial discharge test in cold conditions: upper and lower test voltages (U_1, U_2).
13.2.15.3	Active part not being removed from the tank.
13.2.16.1	Check the behaviour of transformer with resilient fixation integrated on the vehicle.
13.2.16.2.3	Other performance tests after optional shock and vibration tests.
13.2.19	Measuring points and limits for leakage magnetic flux density measurement.
B.4.4	Position of temperature sensors inside the windings for a dry-type transformer/inductor.
D.2	Optional wet dielectric test 1 for dry-type transformers and inductors: soaking test on a sampling basis.
D.3	Optional wet test 2: duration of application of the wet separate source voltage.
D.4.2	Optional wet test 3: current injection conditions.
D.5	Optional wet dielectric tests: acceptance of a brief arc, non-recurrent at the same spot.
D.5	Value of insulation resistance criterion ($R_{\text{IS-DRY-24H}}$).
D.5	Maximum variation of the leakage current.
D.5	Minimum value of insulation resistance ($R_{\text{IS-WET-0}}$ and $R_{\text{IS-WET-1}}$).
D.5	Acceptance of any deviation to target criteria.

A.1.2 Transformers

7.1	Rated line-side voltage other than the nominal voltage of the traction system.
13.2.1	Table 5: list of tests to be performed.
13.2.2	Table 6: smaller tolerance on the impedance voltage for principal tapping.
13.2.3	Optional functional type and routine tests.
13.2.7.2	Other values of line-side voltages for the measurement of the no-load current and losses.
13.2.8.1	All the combinations in pairs of windings for impedance voltage measurement.
13.2.8.1	Additional measurements on other tapping or in other combinations of windings for impedance voltage measurement.
13.2.10	Any other method for harmonic losses calculation.
13.2.10	Losses associated with the train heating load.
13.2.11.3	Immersed-type transformers: temperature-rise test applying rated voltage and current by connection to a suitable load.
13.2.11.3	Back-to-back method for temperature-rise test.
13.2.11.4	Dry-type transformers: temperature-rise test applying rated voltage and current by connection to a suitable load.
13.2.11.4	Back-to-back method.

13.2.12 Minimum value of insulation resistance.

13.2.13 Table 8: dielectric test voltages for higher U_{Nm}.

13.2.13.1 Optional wet dielectric test.

13.2.13.2 Induced voltage withstand test: test voltages other than in Table 8.

13.2.13.3 Separate source voltage withstand test: test voltages other than in Table 8 for non-uniform insulation windings.

13.2.13.4.1 Lightning impulse voltage withstand test of low-voltage winding: tested with surges transferred from the high-voltage winding.

13.2.14 Optional partial discharge investigation tests for immersed type transformers.

13.2.15.1 Optional short-circuit withstand test.

13.2.15.3 Results of FRA measurements before and after short-circuit tests.

13.2.15.3 Reduced variation of short-circuit reactance below 7,5 % for non-circular concentric coils.

13.2.16.2.3 Results of FRA measurements before and after shock and vibration tests.

13.2.20 Electrical Frequency Response Analysis FRA: detailed measurement method.

13.2.21 Primary inrush current: acceptance criteria (optional).

A.1.3 Inductors

13.3.1 Table 10: list of tests to be performed.

13.3.2 Table 11: other tolerances on inductance.

13.3.6 Losses not being measured with a frequency and/or wave shape as close as practicable to the service.

13.3.7.1 Value of inductance to be used for the routine tests.

13.3.7.2.2 Measurement of a.c. inductance: saturation curve.

13.3.7.2.3 Frequency for the a.c. impedance measurement.

13.3.7.3.2 Measurement of incremental inductance: differential inductance being used in lieu of the incremental inductance.

13.3.7.3.2 Industrial frequency for impedance and inductance measurement with alternating current in type test.

13.3.7.3.2 Choice of a certain point on the impedance curve for type tests.

13.3.7.3.3 Routine test by measuring the incremental inductance in a single point or by measuring the a.c. impedance in the single point defined.

13.3.7.4.2 Measurement of differential inductance: test method for type test.

13.3.7.4.2 Industrial frequency for impedance and inductance measurement with alternating current in type test.

13.3.7.4.2 Choice of a certain point on the impedance curve for type tests.

13.3.7.4.3 Routine test by measuring the differential inductance in a single point or by measuring the a.c. impedance in the single point defined.

13.3.10.1	Optional wet dielectric test.
13.3.10.4	Voltage between terminals withstand test: selection of test method and test conditions.
13.3.12	Short circuit test by capacitor discharge.
13.3.14	Test conditions for vibration test with current flowing.

A.2 Information to be given by purchaser to manufacturer

A.2.1 Transformers and inductors

6.1	Load profile.
6.1	Current frequency spectrum.
6.2	Reference temperature for continuous load or temperature histogram.
8	Intermediate tappings.
9.2.3	Air flow for external air-forced or vehicle motion cooling.
13.1.2	Optional type tests.
13.1.4	Investigation tests.
13.1.4	Acceptance of the equipment after investigation tests.
13.2.11.1	Temperature of the cooling medium at the external interface of the transformer/inductor.
13.2.12	Repetition of insulation resistance test after test completion.
13.2.13	For all windings connected to a power converter generating steep voltage waves: recurring peak voltage amplitudes (U_{mT} and U_{mG}), d.c. link voltage, voltage rise rate and repetition frequency.
13.2.15.1	Optional requirement to measure the resistance for the tapping positions at which short-circuit test will be carried out.
13.2.15.3	Optional requirement of lightning impulse test after short-circuit test.
13.2.15.3	Optional requirement of wet dielectric test after short-circuit test.
13.2.16.2.1	Optional shock and vibration type test: specification of category 1 class A or B for simulated long-life testing at increased random vibration levels.
13.2.16.2.3	Optional requirement of wet dielectric tests for a dry-type transformer/inductor after shock and vibration tests.
13.2.18	Accuracy grade for noise measurement.
B.4.1	Current over time, i.e. load profiles, and current frequency spectrum.
B.4.2	Temperature histogram for the cooling medium at the external interface of a transformer/inductor. Or cooling medium reference temperature for lifetime calculations.
C.3.2	Operation conditions for thermal endurance calculations.
Annex E	Load profile: duration and frequency of overload operation.

A.2.2 Transformers

13.2.1	Table 5 – List of tests: requirement for optional or investigation tests.
13.2.7.2	Optional requirement to record the no-load voltage and current waveforms and to analyse their harmonic contents.
13.2.8.2	Optional requirement to measure the differential inductance for non-linear short-circuit inductance characteristics.
13.2.8.2	Optional requirement to measure the variation of impedance (resistance and inductance) with frequency.
13.2.10	Other conditions to calculate total losses for transformers other than traction transformers.
13.2.13.2	Test time at full test voltage other than 60 s.
13.2.13.2	Induced voltage other than $2 \times U_N$ (rated voltage) for auxiliary transformers.
13.2.14	Partial Discharge. Optional requirement for dry-type transformers as routine test. Optional requirement for immersed-type as investigation test.
13.2.15.1	Optional requirement for short-circuit withstand test as type test.
13.2.15.1	Short-circuit apparent power of the system.
13.2.15.1	Maximum value of short circuit power available at the vehicle input.
13.2.17	Connection scheme for choice of configuration for VTR tests.
13.2.17	Maximum value of VTR.

A.2.3 Inductors

13.2.15.1	Short-circuit current for inductors.
13.3.1	Table 10 – List of tests: requirement for optional or investigation tests.
13.3.6	Wave shape of the current for the determination of losses.
13.3.7.1	Optional requirement to measure mutual inductance as type test for coupled inductors.
13.3.7.1	Optional requirement of additional type tests: measurement of inductance variation with frequency and temperature.
13.3.7.2.2	Optional requirement to determine the Q factor.
13.3.11	Partial discharge. Optional requirement for dry-type inductors as routine test.
13.3.11	Optional requirement for short-circuit withstand test as type test.
13.3.12	Maximum short circuit current and duration.
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Annex B
(informative)

Thermal ageing and insulation life time

B.1 Insulation life time and thermal ageing

The insulation life time is defined as the total time between the initial state for which the normal component insulation is considered new and the final state when, due to many factors which are met or occur in normal service, there is a high risk of electrical failure.

The ageing factors are described in IEC 60505 (Evaluation and qualification of electrical insulation systems): thermal ageing, dielectric and mechanical stresses (vibration, thermal cycling, etc.), deleterious atmospheres and chemicals, moisture, dirt, radiation, etc.

As temperature is very often the dominating ageing factor, standards have introduced thermal classes (IEC 60085) and methods to characterize thermal endurance properties (IEC 60216-1).

Electrical Insulating Materials (EIM) or Systems (EIS) are characterised by thermal endurance properties (mechanical and dielectric strengths, thermal cycling resistance, sealing performance, etc.) which are described by two terms: Thermal Index (TI) and Halving Interval (HIC).

The thermal endurance of an EIM is always given for a specific property and end-point. If this is disregarded, any reference to thermal endurance properties ceases to be meaningful since the properties of a material subjected to thermal ageing may not all deteriorate at the same rate. Consequently, a material may be assigned more than one temperature index or halving interval derived, for example, from the measurement of different properties.

The description of a transformer/inductor as being of a particular thermal class does not mean, and shall not be taken to imply, that each EIM used in its construction is of the same thermal endurance.

- All parts of the transformer/inductor are not exposed to the same temperature and do not necessarily require materials of the same thermal class.
- The thermal class for an EIS may not be directly related to the thermal endurance of the individual EIM included in it.
- It should also not be assumed that the system thermal class would necessarily default to the lowest temperature class of the system's individual components. On the contrary, the thermal capability will often favour the highest temperature component. However, the individual component thermal class should provide guidance in the selection and positioning of the various materials within the insulation design.

The material deterioration rate is highest in high temperature areas. These areas will reach the end-point first and determine the service reliability of the whole transformer or inductor. Thermal endurance calculations are based on hot-spot temperatures.

B.2 Definitions of thermal endurance

For the purposes of this document, the following terms and definitions of thermal endurance characteristics of an insulating material or system apply.

B.2.1
thermal endurance
time taken for the deterioration of a selected property (electrical, mechanical, etc.) to reach a specified end-point at a given temperature. An end-point of 50 % of the initial value of the property is used (unless otherwise specified)

Note 1 to entry: An insulation material mainly ensures the electric performance (dielectric strength) of the conductor insulation, while the impregnation, casting, sealing, coating, etc., materials mainly ensure the mechanical performance of the windings (water tightness, resistance to thermal cycling and shock, resistance to vibration or shocks, thermal conduction, etc.).

B.2.2
Temperature Index
TI
numerical value of the temperature (in degrees Celsius) derived from the thermal endurance relationship at a time of 20 000 h (unless otherwise specified)

Note 1 to entry: TI is referring to the RTE (Relative Thermal Endurance) or ATE (Assessed Thermal Endurance) indexes used in IEC 60216-5.

B.2.3
Halving Interval
HIC
numerical value of the temperature interval (in Kelvins) which expresses the halving of the time to end-point taken at the temperature equal to TI

B.3 Thermal endurance calculations

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

NOTE As far as thermal endurance calculations are concerned, IEC 60076-12 provides an explanation of ageing fundamentals and the means to estimate ageing rate and consumption of lifetime of the transformer/inductor insulation as a function of operating temperature, time and loading. The hot-spot temperature is used to estimate the number of hours of life time consumed during a particular time period of loading.

B.3.1
thermal endurance in continuous operation
ECO
for a given hotspot temperature θ_{HS} (°C), the thermal endurance in continuous operation is derived from the simplified equation of the Arrhenius plot (based on TI and HIC) as follows:

$$ECO(h) = 20000 \times 2^{\frac{TI - \vartheta_{HS}}{HIC}}$$

this simplified formula is very convenient to understand the concept of TI and HIC. However, this formula yields slightly pessimistic results compared to the exact formula.

Whenever possible, the exact Arrhenius formula derived from the endurance graph (constants A and B) should be used, where E(h) is the thermal endurance and $T_{HS}(K) = \theta_{HS}$ (°C) + 273,15 is the thermodynamic (absolute) hot-spot temperature:

$$\log E(h) = \log A + \frac{B}{T_{HS}(K)}$$

which represents the thermal endurance graph, or

$$E(h) = a \times \exp\left(\frac{b}{T_{HS}}\right)$$

which expresses directly the thermal endurance value.

B.3.2
Actual Operating Time
AOT
actual time (in hours) the insulating system will operate at the given hotspot temperature

B.3.3
Consumed Endurance Potential
CEP

$$CEP(\%) = \frac{AOT}{ECO} \times 100$$

for a given hot-spot temperature

B.4 Special considerations for thermal design and test

B.4.1 General

For thermal endurance considerations, it is important to keep in mind the following.

– Lifetime is related to temperature by an inverse exponential function.

  Example: if HIC is 10 K, every increase of 10 °C temperature reduces lifetime by a factor 2.

– Winding temperature is directly affected by the cooling medium temperature at the external interface.
– The winding temperature rise is roughly proportional to load losses. Load losses are made of ohmic and additional losses. Ohmic losses directly proportional to the square of the current and to the d.c. resistance. Additional losses are related to the current frequency spectrum and inversely proportional to the d.c. resistance. The winding d.c. resistance is proportional to temperature.

The purchaser is able to specify the current over time, i.e. the load profile, including its frequency spectrum, and the temperature histogram at the external cooling interface.

But the losses and temperature rises in the transformer/inductor depend on the design of the manufacturer.

For the temperature rise tests, it is important to define correctly the cooling medium reference temperature and the continuous current rating of each winding in order to be able to check compliance with the specified lifetime.

B.4.2 Cooling medium temperature at the external interface

Cooling medium temperature histogram:

– a temperature histogram should be provided by the purchaser for the cooling medium at the external interface of the transformer/inductor. Otherwise, the purchaser shall provide directly the cooling medium reference temperature for lifetime calculations.

Cooling medium reference temperature for lifetime calculation:

– the reference temperature of the cooling medium at the external interface of the transformer/inductor, for the purpose of lifetime calculation, is the permanent temperature for which the effects on material ageing are equivalent to those of the specified temperature histogram during the lifetime;
– either this reference temperature shall be calculated by the manufacturer, or it shall be provided by the purchaser.

NOTE Thermal ageing is an exponential function of temperature, i.e. the reference temperature for lifetime calculation is an exponentially weighted average based on the winding temperature. It is higher than the arithmetic mean temperature.

B.4.3 Rated current

The rated current of a winding is the current this winding can sustain permanently, at the reference temperature of the cooling medium for lifetime calculation, for which the effects on material ageing are equivalent to those of the specified load profiles during lifetime.

NOTE The rated current is an exponentially weighted average based on the winding temperature.

B.4.4 Temperature rise test of a dry-type transformer/inductor

For direct measurement of the temperature, temperature sensors shall be fitted inside the windings in positions, to be agreed between manufacturer and purchaser, where the hot-spots are presumed to be located.

B.5 Thermal conformity of the insulation system

The suitability of the insulation system for the specified application should be demonstrated by the manufacturer by thermal endurance calculations based on the thermal endurance characteristics of the insulation system (Arrhenius plot and formula constants or, at least, ATE or RTE and HIC, according to IEC 60216-1 and IEC 60216-5) for the relevant performance (mechanical, electrical).

See an example of detailed calculations in Annex C (informative).

B.6 End of life criterion

Definition of end-points in IEC 60216-1 is mainly conventional and is not functional. The deterioration of the material happens gradually. The end-point represents no sharp limit between ‘life’ and ‘death’ of the component. In the thermal endurance experiments, the end-point is reached when half of the samples submitted to the test have failed the selected criterion (for example, 50 % of the initial a.c. breakdown voltage). It is up to manufacturer to take this reduction into account in design rules to achieve the specified life time with the specified reliability.

Under these conditions, a transformer or inductor is deemed acceptable from the thermal endurance point of view if the sum of Consumed Endurance Potential (CEP) for all service conditions and relevant electrical and mechanical properties is lower or roughly equal to 100 %. In case 100 % is exceeded, the manufacturer shall explain why this result may be acceptable.

Annex C
(informative)

Example of thermal endurance calculation to demonstrate the suitability of an insulation system for a specified application

C.1 Preliminary

The following are just examples for the purpose of understanding the calculation method set up in Annex B (informative).

They are based on purely indicative thermal endurance characteristics and should not been taken as reference for actual applications if not supported by actual thermal endurance test data.

For easy understanding, the simplified Arrhenius formula has been used.

C.2 Example 1 – Temperature limits for a dry-type transformer/inductor

In the examples of Table C.1, two insulation systems of different classes are considered which have a TI at the lower limit of their thermal class and with the shown HIC.

Table C.1 – Temperature limits and expected lifetime for a dry-type transformer or inductor (examples)

Thermal class	Thermal endurance characteristics for the examples		Short-time operation at maximum hot-spot temperature (NOTE 1)		Continuous operation (210 000 h) (NOTE 2)
	TI	HIC	Maximum hot-spot temperature °C	Expected lifetime h	Maximum hot-spot temperature °C
105 (A)	105	6	130	1 100	85
180 (H)	180	11	205	4 100	143

NOTE 1 Column 5 shows the expected lifetime if the insulation system is operated continuously at the maximum hot-spot temperature according to Table 3. The expected lifetime is calculated for 100 % CEP.

NOTE 2 Column 6 shows the maximum temperature for continuous operation of the insulation system for a specified lifetime of 210 000 h (i.e. 30 years 7 000 h per year).

C.3 Example 2 – Thermal endurance calculation

C.3.1 General

It is often possible to split the operation of a traction transformer or inductor into simple equivalent loading conditions thanks to their usually high thermal time constant compared with the running cycle of the railway vehicle. This process leads to simplified load cycle histograms and cooling medium temperature histograms.

This example considers a dry-type, d.c. line filter, air-cored inductor for a traction application, cooled by forced air ventilation.

C.3.2 Operating conditions to be provided by the purchaser

Total operation hours over lifetime: 180 000 h (30 years at 16 h per day).

Load cycle histogram.Two main electrical conditions define the temperature rise of the inductor by the current flowing into it: normal and overload conditions with the specified split of operating time over lifetime shown in Table C.2.

Table C.2 – Load cycle histogram

Load cycle	Current $A_{r.m.s.}$	Operation over lifetime	
		Split %	AOT h
Normal	425	90	162 000
Overload	495	10	18 000
Total		100	180 000

Cooling medium temperature histogram at the external interface. The temperature histogram of the cooling air at the inlet side of the inductor is given in Table C.3.

Table C.3 – Temperature histogram

$\theta_{COOL\ AIR}$ °C	Operation over lifetime	
	Split %	AOT h
20	50	90 000
30	35	63 000
40	15	27 000
Total	100	180 000

C.3.3 Thermal endurance characteristics to be provided by the manufacturer

– Information about the reference and actually used insulation system according to IEC 60216-5: generic type of materials, test certificates.

– Thermal class, endurance graph (Arrhenius formula constants, ATE or RTE, HIC). In the example, the ATE or RTE index is taken for TI in the calculations with the following values: TI = 180 °C and HIC = 11 K.

C.3.4 Temperature rise test results

Table C.4 shows the average and hot-spot temperatures and temperature rises, measured during the temperature rise test conducted at the indicated current and cooling air temperature ($\theta_{COOL\ AIR}$).

Table C.4 – Temperature rise test results

Load cycle	Current $A_{r.m.s.}$	Temperature rise		Temperature at $\theta_{COOL\ AIR}$ = 20 °C	
		Average K	Hot-spot K	Average °C	Hot-spot °C
Normal	425	52	97	72	117
Overload	495	78	140	98	160

NOTE 1 In this example, due to the design of the inductor, the temperature of the hot-spot is significantly higher than the average temperature of the winding.

NOTE 2 Due to the increase of the d.c. resistance of the winding with temperature, the temperature rise variation between normal and overload conditions is more than proportional to the square of the current.

C.3.5 Calculations

Table C.5 shows the effect of the cooling air temperature ($\theta_{COOL\ AIR}$) on the ageing of the inductor for both load cycles.

This table is derived from Table C.4 by calculation. The winding temperatures are extrapolated at other cooling air temperatures by applying the iterative method of 13.2.11.5 for cooling medium temperature correction.

Table C.5 – Thermal endurance calculation

Load cycle	$\theta_{COOL\ AIR}$ °C	Operation over lifetime		Temperature		Thermal endurance	
		Split % (NOTE 1)	AOT h	Average °C	Hot-spot °C	ECO h	CEP %
Normal	20	45,0	81 000	72	117	1 089 000	7,4
	30	31,5	56 700	85	130	456 000	12,4
	40	13,5	24 300	97	144	191 000	12,7
Subtotal		90,0	162 000				32,5
Overload	20	5,0	9 000	98	160	69 000	13,0
	30	3,5	6 300	112	176	25 900	24,3
	40	1,5	2 700	125	191	9 700	27,7
Subtotal		10,0	18 000				65,0
Grand total		100	180 000				97,5

NOTE 1 In this table, the operation split is the result of multiplying the split of the load cycle histogram (Table C.2) by the split of the temperature histogram (Table C.3).

NOTE 2 Due to the design of the inductor chosen for this example, although the overload operation is limited to 10 % of the specified lifetime, it consumes 65 % of the lifetime potential of the insulation system.

The total Consumed Endurance Potential (CEP) is lower than 100 %: this inductor is acceptable from the thermal endurance point of view.

On the basis of Table C.5, it is possible to calculate an equivalent current and an equivalent temperature consuming the same potential of thermal endurance. This provides the rated current (I_{RATED}) and the reference temperature of the cooling medium for lifetime calculation ($\theta_{\mathrm{COOL\_AIR\_REF}}$): the results are shown in Table C.6.

Table C.6 is generated from Table C.5 in two steps:

– step 1 – a single temperature $\theta_{\mathrm{COOL\_AIR\_REF}}$ for both load cycles is determined which consumes the same overall CEP. This is performed by iterative calculations by using the same method as for Table C.5;
– step 2 – a single current I_{RATED} is then determined which consumes the same overall CEP at $\theta_{\mathrm{COOL\_AIR\_REF}}$. This is performed by applying the iterative method of 13.2.11.5 for power or current correction.

Table C.6 – Equivalent current and temperatures

I_{RATED} A$_{\mathrm{r.m.s.}}$	$\theta_{\mathrm{COOL\_AIR\_REF}}$ °C	Operation over lifetime		Temperature		Thermal endurance	
		Split %	AOT h	Average °C	Hot-spot °C	ECO h	CEP %
451	29,3	100	180 000	93	145	184 500	97,5

Annex D
(informative)

Wet dielectric tests for dry-type transformers and inductors

D.1 General

Dielectric failures of dry-type power wound components sometimes occur after a few years service in wet conditions, such as:

– misting (fine water droplets) on rainy days or during car wash operations;

– fine snow sucked by forced air and melting on winding;

– condensation e.g. entering tunnels in cold season, hot and wet weather following cold and dry days;

– cold winter with de-icing operations.

These failures occur although those wound components have successfully passed the dry dielectric tests.

The purpose of this annex is to propose optional tests based on return of experience to assess the ability to operate in wet conditions over the required lifetime.

The principle is to add separate source voltage withstand tests:

– in conditions generating or simulating water misting;

– before and after thermal shock;

– and after soaking in water.

The described wet dielectric tests 1 to 3 have an increasing severity level. The pollution degree according to IEC 62497-1 can be used as a guideline to require (or not) a wet test as investigation, type or routine test depending on the specified operation environment in terms of exposure to humidity and dust. If more than one test is required the tests shall be performed in sequence 1, 2 and 3.

Detailed procedures and criteria are given below.

Unless otherwise stated, the wound component under test, or the water used for testing shall be cold, i.e. at room ambient temperature.

The dielectric test voltage and the insulation resistance test are performed on the windings in a similar way as for the separate source voltages withstand tests at industrial frequency.

D.2 Wet test 1 (optional type test or optional routine test): short soaking

After the dry separate source voltage withstand test in 13.2.13.3, each cold wound component shall be totally immersed in cold tap water for the specified duration. Then, the wound component shall be taken out of the water, and submitted to the insulation resistance and wet separate source voltage tests, in the normal mounting position, and within less than 10 min overall. The voltage shall be applied for 1 min.

If required as a routine test, and if a high stability of the manufacturing process has been demonstrated by routine test after a few batches, this soaking test may be performed on a sampling basis, upon agreement.

D.3 Wet test 2 (investigation test or optional type test): misting

The cold wound component shall be placed in a ventilated enclosure, in the normal mounting position, and sprayed with water using a misting machine (nebulizer). This is not equivalent to spraying water directly on the wound component. For example, water is injected via a spraying nozzle placed between a fan and the wound component, in order to generate a fine water mist. This arrangement shall be left operating for minimum 2 h until the entire surface of the wound component is covered by a continuous layer of very fine water droplets. The fan and water injection shall then be stopped, and the wound component shall be submitted to the insulation resistance test and the wet separate source voltage shall be applied for a duration to be agreed between purchaser and manufacturer (minimum 1 min).

For investigation, partial discharge inception and extinction voltages should be measured according to 13.2.14 before and after the separate source voltage withstand test.

D.4 Wet test 3 (investigation test): thermal shock – long soaking – misting

D.4.1 General

This test is used to simulate the effects of thermal cycling combined with accumulation of dirt and moisture.

D.4.2 Temperature conditioning

The wound component is first heated up by current injection in conditions to be agreed (e.g. at twice the rated current according to IEC 60076-11 for thermal shock test). The average temperature of each winding shall be checked by measuring the d.c. resistance variation just before soaking for thermal shock. The average temperature of each winding shall be:

– either the temperature class minus 30 °C, with a tolerance of ±15 °C (e.g. 150 °C ±15 °C for a class 180 insulation system);

– or, if higher, the winding average temperature in actual service (± 15 °C), in rated conditions at cooling medium reference temperature for lifetime calculation.

D.4.3 Thermal shock

When hot, the component shall be immediately (within 15 min after the end of the heat run), abruptly and totally immersed in cold tap water. The tank shall contain a mass of water at least equal to half the mass of the wound component and a volume high enough to submerge it totally.

NOTE For example, for an iron close core component, both conditions are met if each dimension of the tank is at least 20 % larger than the corresponding one of the wound component, and if the tank is topped up with water.

D.4.4 Dielectric test

After the specified soaking duration, the cold wound component shall be taken out of the water and submitted to the misting test according to Clause D.3.

D.5 Common test procedure and criteria for wet dielectric tests

After taking the wound component out of the water, it is permitted to drain and tilt it for 1 min to eliminate the excess of water. However, it is not allowed to wipe out, nor dry, any part of it before proceeding with insulation resistance and wet separate source voltage tests or with the next wet test step.

The insulation resistance shall be measured, just before ($R_{\text{IS-WET-0}}$) and after ($R_{\text{IS-WET-1}}$) the wet separate source voltage test.

The leakage current shall be measured periodically (e.g. every 30 s) during the dielectric test: after the test voltage is established.

The wet separate source test voltage shall be 80 % of the dry test voltage.

Acceptance criteria:

– there shall not be visible or audible arcing during the dielectric test. However, a brief arc non-recurrent at the same spot, may be acceptable upon agreement of the purchaser.
– if $R_{\text{IS-WET-1}}$ is less than the criterion of $R_{\text{IS-DRY-24H}}$, to be agreed between purchaser and manufacturer, the insulation resistance shall be measured again, at regular intervals, until maximum 24 h of natural drying in ambient conditions. The part shall be rejected if the insulation resistance is still lower than the indicated criterion $R_{\text{IS-DRY-24H}}$.

Target criteria:

– the variation of the leakage current during the test or between parts should be lower than a value to be agreed between purchaser and manufacturer;
– the insulation resistances ($R_{\text{IS-WET-0}}$ and $R_{\text{IS-WET-1}}$) should be higher than a value to be agreed between purchaser and manufacturer.

If a target criterion is not met, the component shall not automatically be rejected. However, before acceptance can be decided, the manufacturer shall investigate and discuss the reasons of deviation and the following with the purchaser:

– the amplitude of variation of I_{LEAK} during each test and the spread of its average value $I_{\text{LEAK\_AVG}}$, within and between batches;
– the stability of $R_{\text{IS-WET-0}}$ and $R_{\text{IS-WET-1}}$, within and between batches.

Annex E
(informative)

Load profiles

The load profile should be specified considering the following operating conditions:

– normal load profiles are defined when all equipment are operating properly;

– overload profile. In case of a traction or auxiliary supply system providing redundancy, if a subsystem fails, the remaining one(s) will have to supply higher power/current than in normal conditions. The purchaser shall specify the duration and frequency of overload operation;

– peak transient (or surge) power/current. This surge capability is defined by a maximum short time current (e.g. compressor start) delivered both in normal and overload conditions. The purchaser shall specify the duration and frequency of transient operation;

– winter and summer current/power load profiles in relation with the corresponding cooling medium temperature range;

– air speed for AN transformers/inductors;

– fan management (variable speed or discontinuous operation) and maximum train speed for AF transformers/inductors.

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