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Introduction

This draft standard is based on national and international discussions. Your comments on this draft are invited and will assist in the preparation of the consequent standard.

For international standards, comments will be reviewed by the relevant UK national committee before sending the consensus UK vote and comments to the international committee, which will then decide appropriate action. If the international standard is approved, it is usual for the text to be published as a British Standard.

For national standards, comments will be reviewed by the relevant UK national committee and the resulting standards published as a British Standard.

UK Vote

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Template for comments and secretariat observations

Date: xx/xx/20xx	Document: ISO/DIS xxxx
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1	2	(3)	4	5	(6)	7
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/Figure/ Table/Note	Type of comment	Commend (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	



14/1079/CD

COMMITTEE DRAFT (CD)

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DATE OF CIRCULATION: 2021-12-17	CLOSING DATE FOR COMMENTS: 2022-03-11
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IEC TC 14 : POWER TRANSFORMERS	
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OF INTEREST TO THE FOLLOWING COMMITTEES:	PROPOSED HORIZONTAL STANDARD: ☐ Other TC/SCs are requested to indicate their interest, if any, in this CD to the secretary.
FUNCTIONS CONCERNED: ☐ EMC ☐ ENVIRONMENT ☐ QUALITY ASSURANCE ☐ SAFETY	

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TITLE: Power transformers - Part 5: Ability to withstand short circuit
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS

Part 5: Ability to withstand short-circuit

FOREWORD

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IEC 60076-5 has been prepared by Maintenance Team MT60076-5 ABILITY TO WITHSTAND SHORT-CIRCUIT, of IEC technical committee 14: POWER TRANSFORMERS. It is an International Standard.

This fourth edition cancels and replaces the third edition published in 2006. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- a) Inclusion of definitions of transformer parts
- b) Inclusion of standard short-circuit current calculation formulae
- c) Updated network short-circuit power
- d) Clarified mechanical withstand test procedure and pass-fail criteria
- e) Revision of thermal withstand formula
- f) Revised proof of withstand by calculation procedure.

289 The text of this International Standard is based on the following documents:

Draft	Report on voting
XX/XX/FDIS	XX/XX/RVD

290
291 Full information on the voting for its approval can be found in the report on voting indicated in
292 the above table.

293 The language used for the development of this international Standard is English.

294 This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in
295 accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available
296 at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are
297 described in greater detail at www.iec.ch/standardsdev/publications.

298 The committee has decided that the contents of this document will remain unchanged until the
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300 specific document. At this date, the document will be

- 301 • reconfirmed,
302 • withdrawn,
303 • replaced by a revised edition, or
304 • amended.

305

INTRODUCTION

Short-circuit withstand capability is an important characteristic of transformers. This standards defines the requirements for proving this capability.

The proof of withstand is based on the current which may flow in the transformer during an external short-circuit event, therefore a normative annex on calculation of the current with standardized formulae is given.

Short-circuit withstand consists of a thermal and mechanical capability.

The formula for the thermal withstand capability has been corrected in this edition.

For the mechanical withstand capability the test procedure and pass-fail criteria have been revised. The boundaries of transformer categories have been updated to reflect the current technology.

The proof of withstand capability by calculation has been completely revised as the criteria of similarity specified in the previous edition were hard to achieve. The new concept relies on the idea that no transformer should be more severely stressed than a tested object. The tested object can be within certain limits either a set of actual transformers, or transformer models.

In addition construction and components of transformer have been defined to provide a common understanding during design review as well as after tests.

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POWER TRANSFORMERS

Part 5: Ability to withstand short-circuit

1 Scope

This part of IEC 60076 establishes the requirements for power transformers to sustain without damage the effects of short-circuit currents resulting from external short-circuits. It describes the calculation procedures used to demonstrate the thermal ability of a power transformer to withstand such short-circuit currents and both the special test and the theoretical evaluation method used to demonstrate the ability to withstand the relevant dynamic effects. The requirements apply to transformers as defined in the scope of IEC 60076-1.

Note 1: The calculation and tests assumes that the transformer will be already energized at the time of short-circuit. The design calculation usually considers that there is a perfect balance of ampere-turns between the two windings. This may not be always the case during tests and under short-circuit conditions in the network. For particular designs of transformers energized from an inner winding or with axially split windings this may be significant and needs to be considered because the transformer may not be strong enough to survive a pre-applied fault.

Note 2: The currents resulting from out-of-phase synchronization are not considered.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

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

IEC 60076-8: Power transformers – Part 8: Application guide

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

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60076-1 and IEC 60076-3 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp>

3.1 Current

3.1.1

Symmetrical Short-circuit current

I

the rms value of the sinusoidal steady state symmetrical current appearing during a short-circuit.

Note 1 to entry: This definition does not means that the symmetrical current is the same in all three phase.

3.1.2

Short-circuit current peak value

$\hat{I}$

the value of the highest peak current occurring during a short-circuit.

3.2

Minimum expected short-circuit impedance

the impedance defined by the manufacturer which form the basis for the design calculation of a transformer.

Note 1 to entry: The minimum expected short-circuit impedance will be equal or greater than the minimum impedance guaranteed.

3.3 Structural Parts for core form transformers

3.3.1

Stick

A piece of insulating material creating a space between turns or windings parallel to the core axis and providing support for radial forces.

Note 1 to entry: This definitions includes clack bands and sticks that do not extend for the full length of the winding.

3.3.2

Spacer

A piece of insulating material creating a space between turns or windings perpendicular to the core axis and providing support for axial forces.

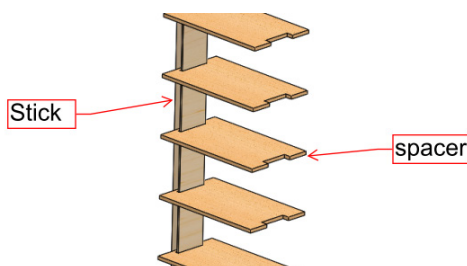


Figure 1 – Stick and spacer sketch

3.3.3

Static ring

An element with a conducting surface electrically connected to an adjacent turn and suitably shaped to reduce the dielectric stress in the area it is placed.

3.3.4

Washer

A piece of insulating material used to create a zigzag flow or used as a spacing element placed between spacers and windings to provide mechanical stability and increased creepage path.

3.3.5

Winding support blocks

Part of the end winding support, which supports part of the winding circumference thereby allowing liquid circulation between the winding and the common press plate and transmitting the axial forces.

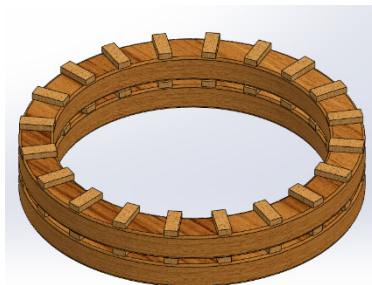


Figure 2 – Example of winding support including blocks and rings

3.3.6

End winding support

an insulating structure placed on the extremity of a winding supporting and transmitting the axial forces of the winding.

3.3.7

Common press plate

a structure used outside the winding supports to link two or more winding assemblies to the clamping structure.

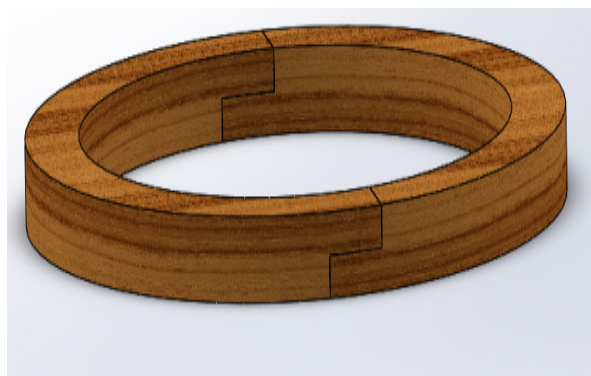


Figure 3 – Example of common press plate sketch

3.3.8

Insulating supports

Pieces of insulating material inserted between the common press plate and the clamping structure to transmit forces.

3.3.9

Dowel

Pieces of insulating material inserted between inner winding and the core to provide support of the inner winding.

Note 1 to entry: Due to the mechanical tolerances in large power transformers dowels may not be effective at providing radial support over the whole length of the winding, this should be considered during the design review.

Note 2 to entry: The word dowel does not necessarily imply a circular cross section.

3.3.10

Tie rods

parts in tension placed outside the winding used to apply a clamping force on the windings.

3.3.11

Flitch plates

parts in tension placed inside the winding along the core used to apply a clamping force on the windings.

3.3.12

General description of structural parts

the following sketches shows the different structural part in position either with flitch plate or tie rod technology.

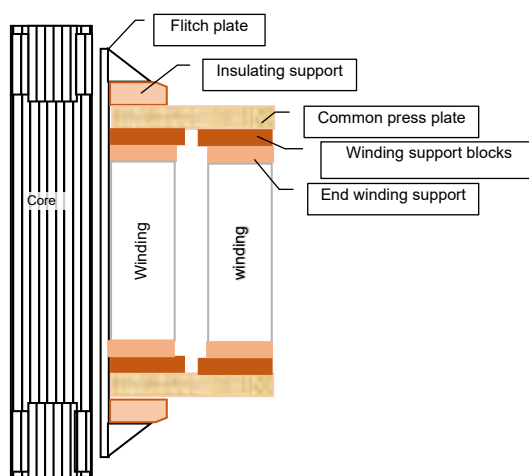


Figure 4 – Cross section of structural parts of a flitch plate core type transformer

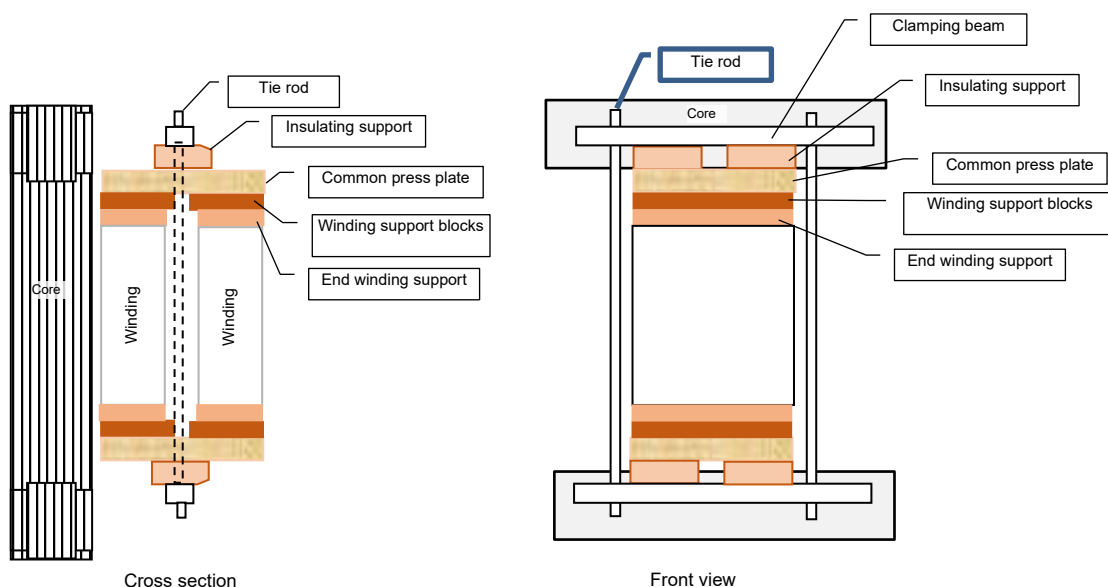


Figure 5 – Structural parts of a tie rod core type transformer

3.4 Structural Parts for shell type transformers

3.4.1

Spacer

a piece of insulating material stuck on insulated material screen providing support of turns against axial forces, electric distance between coils and oil channel for coil cooling.

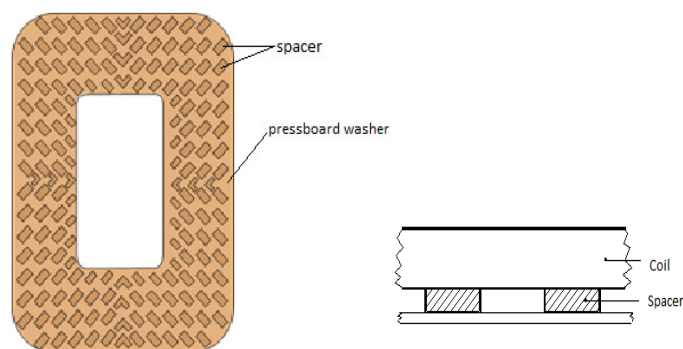


Figure 6 – Shell type spacer sketch

3.4.2

Pancake Coil ends

part of the pancake coil outside the magnetic circuit.

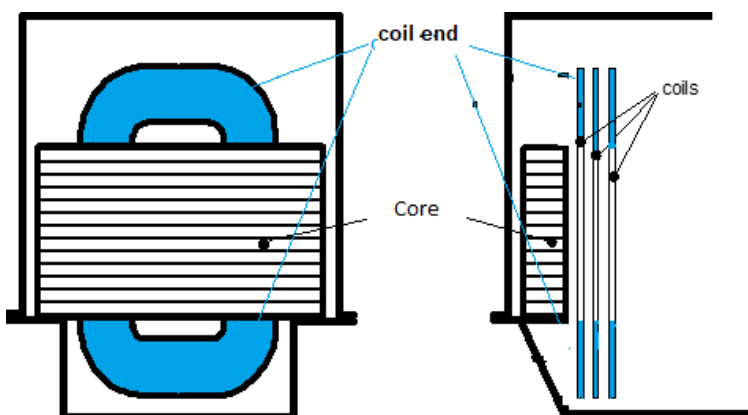


Figure 7 – Shell type coil end sketch

3.4.3

End wedge

an insulating structure placed between top or bottom coil heads and tank supporting the phases and transmitting the axial forces to the tank.

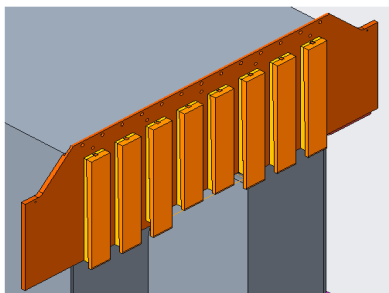


Figure 8 – End wedge of shell type transformer example

3.4.4

Inter-phase wedge

an insulating structure placed between top and bottom coil heads of the middle phase and extreme phases of a three-phase transformer and transmitting the axial forces.

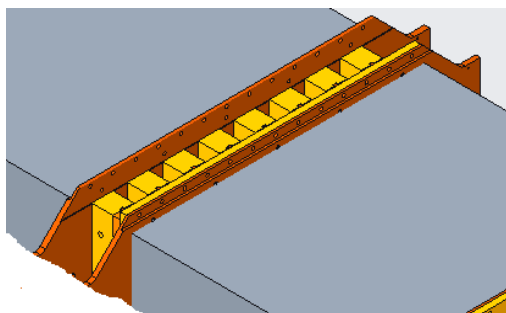


Figure 9 – interphase wedge of shell type transformer example

Note 1 to entry: This is only applicable when phases are coaxial.

3.4.5

Wedging panel

a flat piece of insulating material providing support and/or guidance for end and inter-phases wedges.

3.4.6

Core wedge

a piece of steel material or insulating material inserted between the top of the core and the phases providing radial tightening.

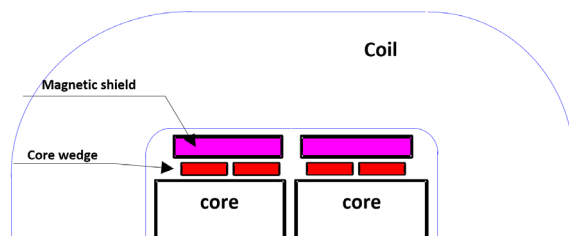


Figure 10 – Core wedge of shell type transformer example

Note 1 to entry: The magnetic shield may not be present.

3.4.7

Core tightening system

device placed at the joints of the magnetic circuit exerting a pressure normal to the plane of the core laminations.

Note 1 to entry: This could consist of a spring or a jack or any other mechanisms.

3.4.8

Short-circuit reinforcement structure

structural reinforcement providing to the base and bell tank the necessary mechanical rigidity for sustaining total axial forces.

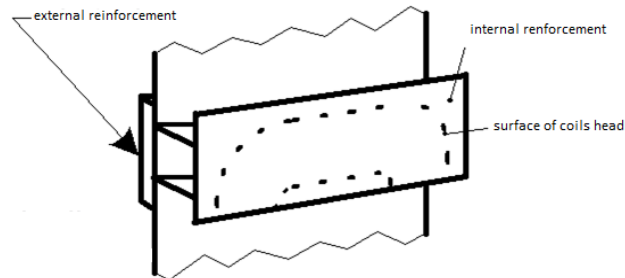


Figure 11 – example of a tank reinforcing structure of a shell type transformer

Note 1 to entry: the short-circuit reinforcement structure may also be used to compress the magnetic circuit.

Note 2 to entry: the short-circuit reinforcement structure may be internal to the tank or part of the tank.

3.4.9

T beam

a piece in shape of a T, made of steel, supporting the weight of the core and winding, fixed at both extremities of the base tank flanges providing supplementary rigidity to the tank base against axial forces.

3.4.10

General description of structural parts

the following sketches shows the different structural part in position.



Figure 12 – Structural parts of a shell type transformer

3.5 Forces, stresses

3.5.1

Electromagnetic force

the force resulting from the vector product of a magnetic field and a current.

3.6 Winding assembly failure modes

3.6.1

Radial Buckling

loss of radial stability of cylinder due to radial forces.

3.6.2

Radial forced Buckling

deformation between sticks due to radial forces.

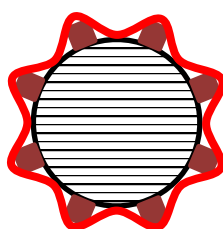


Figure 13 – Radial forced Buckling sketch

Note 1 to entry: The drawing is indicating only the shape of the failure and are not related to any detailed winding construction.

3.6.3

Radial free Buckling

deformation of a cylindrical winding due radial forces resulting in tangential compressive stress.

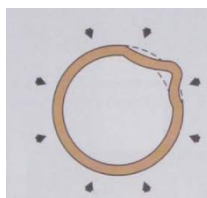


Figure 14 – Radial free Buckling sketch

Note 1 to entry: The drawing is indicating only the shape of the failure and are not related to any detailed winding construction.

3.6.4

Bending of a conductor

permanent deformation due to a force on a conductor between two fixed supports either sticks for radial bending or spacer for axial bending.

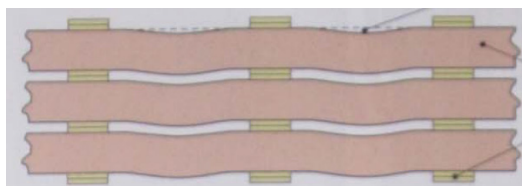


Figure 15 – Bending of a conductor sketch

3.6.5**Tilting of a conductor**

loss of axial stability of a strand or conductor where the conductor(s) tilt(s).

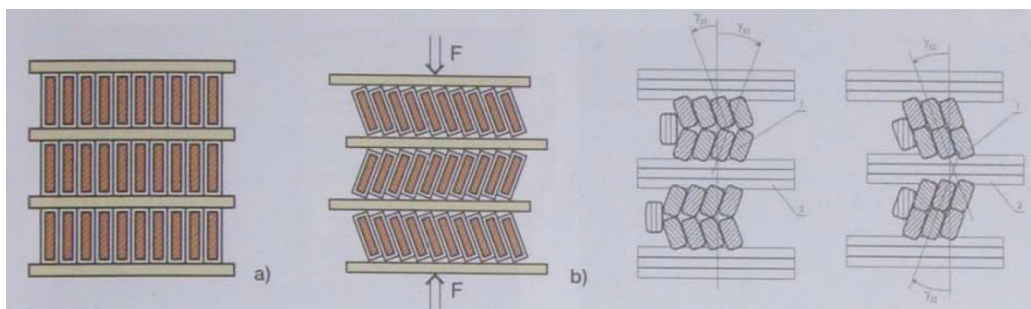


Figure 16 – Tilting of a conductor sketch

Note 1 to entry: This happens to conductors where the axial dimension is larger than the radial one either with or without spacer. Tilting may result in broken conductor insulation, magnified forces originated by conductor displacements as well as internal short-circuits between conductors. This failure modes usually gives an axial zigzag pattern of the failed coil or conductor.

3.6.6**Telescoping of turns**

a loss of axial stability of a winding resulting from the overlapping of turns wound on the same diameter not separated by spacers

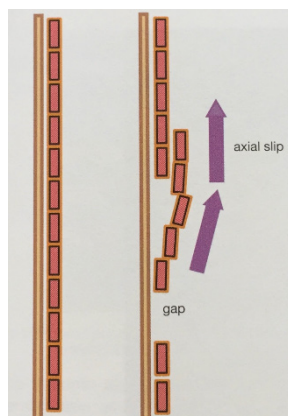


Figure 17 – telescoping of turns sketch

Note 1 to entry: Usually, telescoping results in destroyed conductor insulation and turn-to-turn fault.

3.6.7

Spiralling

Spiralling

either tightening or unwinding of a winding due to forces on the turns of a winding resulting in spacer circumferential displacement, leads deformation or loss or disruption of the axial support structure.

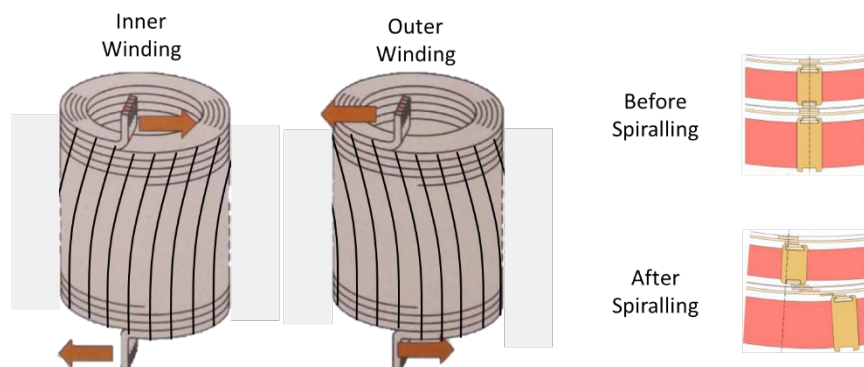


Figure 18 – Spiralling sketch

Note 1 to entry: This phenomenon can be due to the fact that the winding are not rotationally symmetric.

3.6.8

End insulation collapse

failure of the end winding support or common press plate to continue support or clamp the winding.

3.6.9

Axial insulation collapse

failure of the spacers or conductor insulation in the winding.

Note 1 to entry: This failure maybe be due to plastic deformation of spacers or damage of the paper

3.7 Winding types

3.7.1

Non-circular winding

a winding intentionally wound in a non-circular shape

Note 1 to entry: This usually includes square, rectangular and oval shapes and are mainly used for small transformers

3.7.2

Circular winding

a winding wound on a circular former even if there might be local deviations from the cylindrical shape such as for example because of the presence of exit leads in foil windings. If the ratio of the maximum diameter to the minimum one is lower than 1.1 then the winding is considered as circular shape.

3.7.3

Foil type winding

A winding in which the turns of the winding consist of a foil conductor.

3.7.4

Sandwich windings

A winding arrangement in which the different windings, e.g. LV and HV are interleaved along the axis of the magnetic circuit.

3.7.5**Layer type winding**

A winding in which the turns are wound joined to each other along the core axis and arranged one or more successive layers.

3.7.6**Helical type winding**

a winding similar to a layer winding where the turns or parallel conductors (if applicable) are separated from each other by either an axial and/or radial duct.

3.7.7**Radial duct disk type winding**

a winding where the turns are wound in the form of a disk perpendicular to the core axis alternately from inner diameter to outer and vice versa. Between disks there is spacer to create a cooling channel perpendicular to the core axis.

3.7.8**Axial duct disk type winding**

a winding where sticks or clack bands are used to create axial cooling channels parallel to the core axis.

3.7.9**Pancake coil winding**

a winding type used in shell type transformers where the turns are wound in a form to fit a rectangular core almost perpendicular to the core axis and where the cooling channels are made of spacer placed on an insulating material inserted between two adjacent pancakes.

3.7.10**Random technology winding**

a winding technology based on disk winding technology where the turns are randomly distributed.

Note 1 to entry: This type of winding is mostly used for dry type cast resin transformers

3.8**Physical winding**

the winding or part of a winding that forms a cohesive mechanical construction for the purposes of calculating mechanical stresses.

Note 1 to entry: For example a double concentric winding usually consists of at least two physical windings. A physical winding is normally made in one process on a winding machine. But more than one physical winding may be made in one process if axial or radial barriers are included.

4 Common requirements

4.1 General

Transformers together with all equipment and accessories shall be designed and constructed to withstand without damage the thermal and dynamic effects of external short-circuits under the conditions specified in 4.2

A transformer that has been successfully short-circuit tested shall be suitable for intended normal service conditions including short-circuit.

External short-circuits are not restricted to three-phase short-circuits; they include line-to-line, double-earth and line-to-earth faults. The currents resulting from these conditions in the windings are designated as short-circuit currents in this part of IEC 60076.

4.2 Short-circuit current conditions

4.2.1 Short-circuit current values

The short-circuit current shall be calculated as required in section 6.1.4 for all possible fault cases with the most unfavourable combination of positive, negative and zero sequence network impedance.

Unless otherwise specified the current in all windings for each of the following fault cases occurring on each of the windings where terminals are brought out shall be calculated:

- Three phase fault
- Single phase to ground fault
- Two phases and two phases to ground fault

Annex A gives the calculation method for the common cases with and without grounding impedance.

From the above calculation the “worst case” for the current in each winding will then be selected for testing.

If specified, the phase to phase or double phase to ground faults may not have to be considered in the calculations for windings where mechanical construction make this fault impossible. As for instance, for transformers directly connected to a generator where the connection between the generator and the transformer is constructed in such a way which prevents such faults.

4.2.2 General considerations

4.2.2.1 Application conditions requiring special consideration

The following situations affecting short-circuit current magnitude, duration, or frequency of occurrence require special consideration and shall be clearly identified in transformer specifications:

- regulating transformers with very low impedance that depend on the impedance of directly connected apparatus to limit short-circuit currents;
- unit generator transformers susceptible to high short-circuit currents produced by connection of the generator to the system out of synchronism;
- transformers directly connected to rotating machines, such as motors or synchronous capacitors, that can act as generators to feed current into the transformer under system fault conditions;

- special transformers and transformers installed in systems characterized by either a high fault level and/or a high fault frequency of occurrence which might lead to conditions exceeding those covered by the short-circuit test as described in this document.

4.2.2.2 Current limitations concerning series transformers

When the combined impedance of the series transformer and the system results in short-circuit current levels for which the transformer cannot feasibly or economically be designed to withstand, the manufacturer and the purchaser shall mutually agree on the maximum allowed short-circuit current. In this case, provision should be made by the purchaser to limit the short-circuit current to the maximum value determined by the manufacturer and stated on the rating plate. The ability of any tap changer inserted in the line shall be carefully evaluated particularly for phase shifting transformers where at zero phase angle shift the only element in series could be the tap changer.

4.2.3 Components

4.2.3.1 Tap-changing equipment

Where fitted, tap-changing equipment shall be capable of carrying the same short-circuit currents due to short-circuits as the windings. However, the on-load tap-changer is not required to be capable of switching the short-circuit current.

4.2.3.2 Neutral terminal

The neutral terminal of windings with star or zigzag connection shall be designed for the highest short-circuit current that can flow through this terminal.

4.2.4 Transformers categories

For the purpose of this standard, three categories for the rated power of three-phase transformers or three-phase banks are recognized:

- category I: up to and including 3 150 kVA;
- category II: above 3 150 kVA up to and including 31 500 kVA;
- category III: above 31 500 kVA.

The categories are used to define the pass-fail criteria and test procedure.

Transformers may be assigned to a higher category by agreement between purchaser and manufacturer.

Note 1: For example transformer with unusual combination of voltage and power such as 30 000 kVA at 420 kV could be assigned to category III, or single phase transformer in single phase application such as 10 MVA railway feeder transformer could be assigned as category III.

Note 2: For autotransformer, phase shifting transformers and series transformers the rated power is the throughput power as per IEC 60076-1.

4.2.5 Symmetrical short-circuit current

4.2.5.1 Two separate winding transformers

For transformers with two separate windings, normally only the three-phase short-circuit is to be considered, as the current of this case is substantially higher than the one occurring during the other possible types of fault

If due to the installation 3 phases fault are unlikely to occur, then their effect can be disregarded if allowed by the purchaser.

Note 1: In the case of winding in zigzag connection, the single-line-to-earth fault current may reach values higher than the three-phase short-circuit current. However, these high values are limited, in the two limbs concerned, to a half of the coil and furthermore the currents in the other star-connected winding are lower than for a three-phase short-circuit. Electrodynamical hazard to the winding assembly may be higher either at three- or single-phase short-circuit depending on the winding design. The manufacturer and the purchaser should agree which kind of short-circuit is to be considered.

Note 2: in some cases the single phase current may be higher than the three phase short-circuit current. The manufacturer and the purchaser should agree which kind of short-circuit is to be considered.

4.2.5.2 Transformers with more than two windings and auto-transformers

The short-circuit currents in the windings, including stabilizing windings and auxiliary windings, shall be determined from the impedances of the transformer and the system(s). Account shall be taken of the different forms of system faults that can arise in service, for example, line-to-earth faults and line-to-line faults associated with the relevant system and transformer earthing conditions (see IEC 60076-8). The characteristics of each system (at least the short-circuit apparent power level and the range of the ratio between zero-sequence impedance and positive-sequence impedance) shall be specified by the purchaser in his enquiry.

Delta-connected windings of three-phase transformers shall be capable of withstanding the short-circuit currents resulting from different forms of system faults that can arise in service associated with relevant system earthing conditions, including circulating current induced by unbalanced faults on the other windings.

Three phase transformers shall be capable of withstanding faults at the delta winding terminals if more than one corner of the delta is brought out, unless the purchaser specifies that special precautions will be taken to avoid the risk of line-to-line short-circuits.

Single-phase transformers connected to form a three-phase bank, shall be capable of withstanding faults on the terminals of any delta-connected windings, unless the purchaser specifies that special precautions will be taken to avoid the risk of line-to-line short-circuits.

Note: It may not be economical to design auxiliary windings to withstand short-circuits on their terminals. In such cases, the short-circuit current level should be limited by appropriate means, such as series reactors, phase separators avoiding phase to phase fault or, in some instances, fuses. Care should be taken to guard against faults in the zone between the transformer and the protective apparatus. The purchaser will have to take special care to avoid the possibility of earthing or test leads applied during maintenance not being removed prior to energization. There have been instances where fire protection caused a three phase fault.

4.2.5.3 Transformers directly associated with other apparatus

Where a transformer is directly associated with an apparatus, the impedance of which would limit the short-circuit current, the sum of the impedance of the transformer, the system and the directly associated apparatus may, by agreement between the manufacturer and the purchaser, be taken into account if no external fault can reasonably occur between the transformer and the associated apparatus.

This applies, for example, to unit generator transformers if the connection between generator and transformer is constructed in such a way that the possibility of line-to-line or double-earth faults in this region is negligible, or to transformers connected to series reactors or any short-circuit current limiting device, or a directly connected regulating transformer for instance as commonly used for rectifier transformers.

4.2.5.4 Special transformers and transformers to be installed in systems characterized by a high number of short-circuit currents

4.2.5.4.1 General consideration

The ability of the transformer to withstand frequent short-circuit currents, arising from the particular application (for example, arc furnace transformers and stationary transformers for traction systems), or the condition of operation (for example, high number of short-circuit currents occurring in the connected system(s)), shall be subjected to special agreement between the manufacturer and the purchaser.

For transformers expected to experience frequent short-circuit currents, the operating conditions shall be stated as clearly as possible at the tender stage.

Note: stating a normal number of short-circuit for a usual network transformer is a very complex exercise. Usually network transformers experience relatively low number of short-circuit and the values of the short-circuit current are usually lower than the maximum short-circuit current calculated for the design. In some networks the number of short-circuit events and/or the magnitude of the short-circuit current can be of significant importance. Examples that may influence the number of short-circuit are vandalism, vegetation overgrowth, wild life, extreme climatic events and so on.

Arc furnace and stationary traction transformers are expected to experience and withstand short-circuit currents between weekly and several times a day. Such transformers shall be clearly identified at the tender stage.

4.2.5.4.2 Arc furnace transformers

Normal operation of arc furnace transformers includes load cycles and frequent short-circuits at the electrodes in the furnace. Usually the overall impedance of the circuit is higher than the impedance of the transformer itself and the total fault impedance will limit the short-circuit current to only a few times the rated current.

The main point for life expectancy of those transformer is not only the peak short-circuit current but also the repeated effect of this current.

It must be recognized that the short-circuit test as defined in this standard may not covers the effect of repeated short-circuit if the design of the transformer is not adequate to guarantee that the transformer will fully recover after each shot. The short-circuit test procedure and pass fail criteria must be agreed between purchaser and manufacturer.

4.2.5.4.3 Rectifier transformers for industrial applications

For transformers according to IEC 61378-1 possible faults are short-circuit on the DC side of the rectifier and very rarely internal rectifier fault. The short-circuit current is not limited by the transformer short-circuit impedance only.

Typical values of short-circuit current are in the order of two to three times the rated current.

Those transformers shall be tested with the actual fault current calculated taking into account all limiting impedance.

4.2.5.4.4 Stationary transformers for traction systems

Trackside transformers are used to supply power to railways networks by feeding catenaries and feeders lines. Short-circuits on railways lines can happen on a daily or weekly basis with various short-circuit current amplitudes and most often between catenary and ground.

Note: It is common practice for railway companies to perform a site commissioning test by shorting the catenaries to ground and energizing the transformer at full voltage.

4.2.6 Usual impedance and network short-circuit power

4.2.6.1 Transformer impedance

Typical minimum values of impedance on rated tap position and at rated power are provided for guidance purposes in Table 4-1 below. Specified values below those given in the table shall not prevent the application of this standard but it should be recognised that the transformer may be difficult to design and not be economically viable. If after considering the network impedance (where applicable) the calculated symmetrical short-circuit current is more than 25 times rated current the purchaser should consider carefully the necessity for such low specified values of impedance.

Table 4-1 – Recognized minimum values of short-circuit impedance for transformers with two separate windings

Short-circuit impedance at rated power			
Rated power kVA			Minimum rated short-circuit impedance %
25	to	630	4,0
631	to	1 250	5,0
1 251	to	2 500	6,0
2 501	to	6 300	7,0
6 301	to	25 000	8,0
25 001	to	40 000	10,0
40 001	to	63 000	11,0
63 001	to	100 000	12,5
above		10 000	> 12,5
Note 1: Values for rated power greater than 100 000 kVA are generally subject to agreement between manufacturer and purchaser. Note 2: In the case of single-phase units connected to form a three-phase bank, the value of rated power applies to three-phase bank rating. Note 3: In the case of single phase transformer not intended to form a 3 phase bank then 3x rated power shall be used for reading the table.			

4.2.6.2 Network short-circuit power

4.2.6.2.1 General considerations

If the short-circuit apparent power is different from the one stated in Table 4-2, then the short-circuit apparent power or current of the system at the transformer location should be specified by the purchaser in his enquiry in order to obtain the value of the symmetrical short-circuit current to be used for the design and tests.,

If the short-circuit apparent power or current of the system is not specified, then the values given in Table 4-2 shall be used. Except in the case of category I transformer where infinite short-circuit apparent power shall be considered.

If the short-circuit current is specified it shall be considered as supplied under a voltage equal to U_m of each winding independently of the rated tapping voltage.

For the calculation of the single phase to earth and double phase to earth short-circuit current, if the ratio of zero-sequence to positive-sequence impedance of the system is not specified by the purchaser, then a value of 1 shall be considered.

Table 4-2 – Short-circuit apparent power of the system for category II and III transformers

Highest voltage for equipment, U_m kV	Short-circuit data	
	Current kA	Power MVA
7,2	63	785,7
12	63	1 309,5
17,5	63	1 909,6
24	63	2 618,9
36	63	3 928,3
52	63	5 674
72,5	63	7 910
100	80	13 856
123	80	17 043
145	80	20 090
170	80	23 556
245	80	33 948
300	80	41 569
362	80	50 160
420	80	58 197
550	80	76 210
800	80	110 850
1100	63	120 031
1200	63	130 943
Note: The above values are based on the breaking capacity of the circuit breakers in the network		

4.2.6.2.2 Transformers with auxiliary winding

Unless otherwise specified by the purchaser, the following criteria shall be considered

- If the auxiliary winding is connected to a networks including other sources of short-circuit current, then the short-circuit power of the system indicated in the standard (Table 4-2) shall be used unless otherwise specified.
- If the auxiliary winding is used to feed local auxiliary services devices or for stabilization purposes only then no short-circuit power in-feed shall be considered at its terminals.
- If the auxiliary winding is used to connect reactive compensation or energy storage equipment capable of supplying fault currents then it should be considered in the calculation using the level specified by the purchaser if not specified then no short-circuit power in-feed shall be considered at its terminals.

4.2.6.2.3 Transformer with winding connected to a generator

For generator step up transformers the short-circuit power supplied to the winding S_{sc} , connected to the generator depends on the sub-transient reactance of the generator as follows:

$$S_{sc} = \frac{100 \times S_r}{Z_G} \quad (1)$$

where

S_r is the low voltage winding rated power expressed in MVA;

Z_G is the generator sub-transient impedance based on the Low Voltage winding rated power and rated voltage, expressed in %.

4.2.6.2.4 Network short-circuit impedance Calculation

4.2.6.2.4.1 Three phase case

For three-phase transformers or 3 single phases transformers assembled in a three-phase bank the network impedance is calculated as follows:

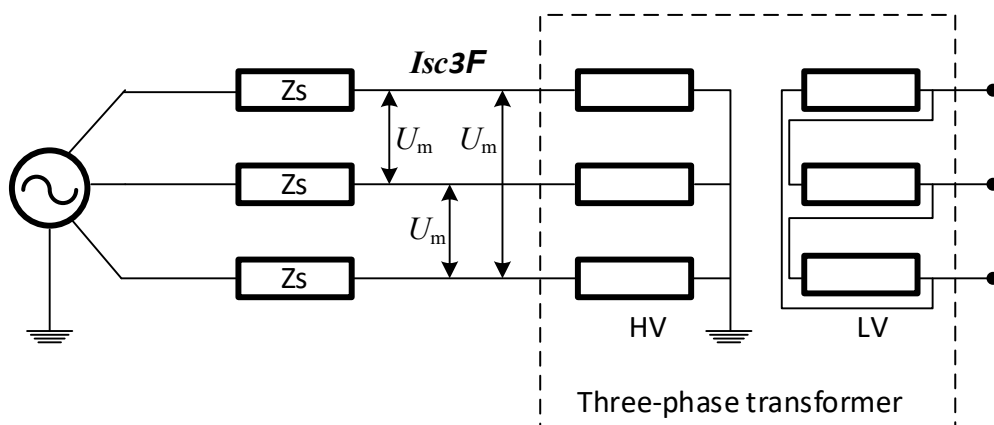


Figure 19 – three phase equivalent circuit

$$I_{sc3\phi} = \frac{U_m}{\sqrt{3} Z_s} \quad \text{and} \quad S_{3\phi} = 3 \cdot \frac{U_m}{\sqrt{3}} \cdot I_{sc3\phi} = \frac{U_m^2}{Z_s} \quad \text{i.e.} \quad Z_s = \frac{U_m^2}{S_{3\phi}} \quad (2)$$

where

Z_s is the short-circuit impedance of the network expressed in ohms (Ω) per phase,

U_m is the maximum system voltage expressed in kV,

S is the short-circuit apparent power of the network, expressed in MVA,

I_{sc} is the rms short-circuit current, expressed in kA.

4.2.6.2.4.2 Between phase case

For single-phase transformers connected between two phases of a three phase network for example railway track-side feeder transformers $Z_{s_{equivalent}}$ the equivalent short-circuit impedance of the network is calculated as follows:

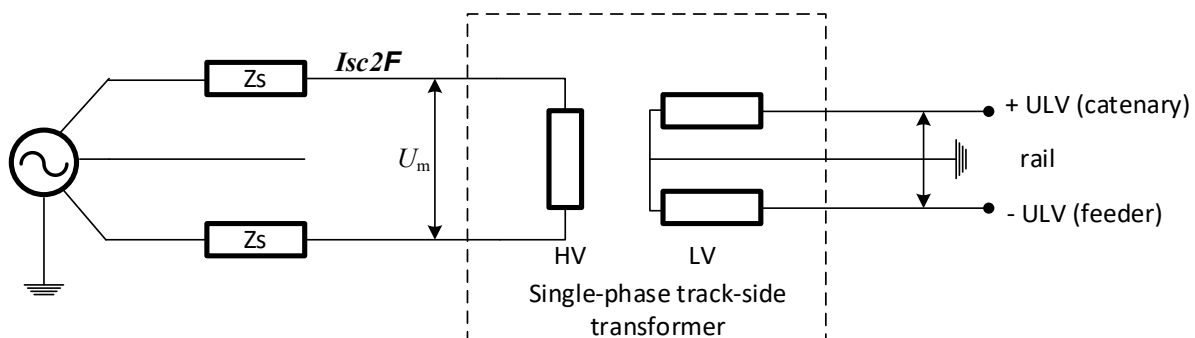


Figure 20 – Between phase equivalent circuit

$$I_{sc2\phi} = \frac{U_m}{2Z_s} \text{ and } S_{2\phi} = U_m \cdot I_{sc2\phi} = \frac{U_m^2}{2Z_s} \text{ i.e. } Z_{s_{equivalent}} = 2Z_s \quad (3)$$

where

Z_s is the short-circuit impedance per phase of the three-phase network, expressed in ohms (Ω) per phase;

U_m is the maximum system voltage expressed in kV,

S is the short-circuit apparent power of the network, expressed in MVA,

I_{sc} is the rms short-circuit current, expressed in kA.

4.2.7 Peak asymmetric current

The amplitude $\hat{i}$ of the first peak of the asymmetrical test current is calculated as follows:

$$\hat{i} = I \times k \times \sqrt{2} \quad (4)$$

where the symmetrical short-circuit current I is determined in accordance with 4.2.5

The factor k accounts for the initial offset of the test current and $\sqrt{2}$ accounts for the peak-to-r.m.s. value of a sinusoidal wave.

879 The factor k depends on the ratio X/R

880 where

881 X is the sum of the reactances of the transformer and the system ($X_t + X_s$), expressed in ohms
882 (Ω);

883 R is the sum of resistances of the transformer and the system ($R_t + R_s$), expressed in ohms
884 (Ω) with R_t at reference temperature (see IEC 60076-1)

885 When the short-circuit impedance of the system is included in the short-circuit current
886 calculation, the X_s/R_s ratio of the system shall be given by the purchaser at the enquiry stage,
887 if not specified, then it shall be taken to be equal to that of the transformer, the X_t/R_t ratio of the
888 transformer shall be the design value.

889 The asymmetry factor is calculated as follows:

$$k = 1 + \left(e^{-\left(\phi + \frac{\pi}{2}\right) \frac{R}{X}} \right) \sin \phi \quad (5)$$

890 where

891 e is the base of natural logarithm;

892 ϕ is the phase angle which is equal to $\tan^{-1}(X/R)$, expressed in radians;

893 X is the sum of the reactances of the transformer and the system ($X_t + X_s$), expressed in (Ω);

894 R is the sum of resistances of the transformer and the system ($R_t + R_s$), expressed in (Ω) with
895 R_t at reference temperature (see IEC 60076-1)

896 .Note: For example a value of X/R of 10 gives a $k\sqrt{2}$ of 2,46

897

5 Ability of transformers to withstand short-circuit

5.1 Ability of category I transformers to withstand short-circuit

5.1.1 Mechanical ability

Mechanical ability of category I transformers to withstand short-circuit shall be demonstrated by test according to clause 0 on the fully assembled transformer

5.1.2 Thermal ability

The transformer shall be able to withstand the short-circuit current during the prescribed duration given in 7.1 without exceeding the temperature limits given in 7.2

The demonstration of this ability is normally done by calculation according to 7.

5.2 Ability of category II and III transformers to withstand short-circuit

5.2.1 Mechanical ability

Ability of large power transformer to withstand short-circuit can be demonstrated by tests, or supported by calculation based on tested references and design and manufacture considerations.

The short-circuit test is the most comprehensive way of proving the ability of a transformer to withstand short-circuit.

Calculations according to 6.2 can support the assessment of the ability to withstand short-circuit.

5.2.2 Thermal ability

The transformer shall be able to withstand the short-circuit current during the prescribed duration given in 7.1 without exceeding the temperature limits given in 7.2

The demonstration of this ability is done by calculation according to section 7.3.

6 Mechanical withstand ability demonstration

6.1 Demonstration by test

6.1.1 Test requirements

6.1.1.1 Single unit

Unless otherwise specified, the symmetrical short-circuit current (for the r.m.s. value), shall be calculated using the measured short-circuit impedance of the transformer plus the minimum systems impedances.

If the transformer contains elements such as a non-linear series reactor where the impedance is lower at short-circuit current than at the measurement current than the short-circuit impedance at short-circuit current shall be used in the current calculation.

For transformers of category I, the contribution of the system impedance shall be neglected in the calculation of the short-circuit current.

6.1.1.2 Type tested unit of a series

Unless otherwise specified, the symmetrical short-circuit current (for the r.m.s. value), shall be calculated using the measured short-circuit impedance of the transformer plus the minimum systems impedances.

In order to be representative of the possible range of impedances expected over the series the customer can require the symmetrical short-circuit current (for the r.m.s. value), to be higher than the one based on the actual measured impedance to cover manufacturing tolerances as provided by the manufacturer.

Note: It is understood that in order to define the symmetrical short-circuit current (for the r.m.s. value), minimum expected short-circuit impedance over the whole series of transformers should be used as provided by the manufacturer.

If the transformer contains elements such as non-linear series reactor where the impedance is lower at short-circuit current than at the measurement current than the short-circuit impedance at short-circuit current shall be used in the current calculation.

For transformers of category I, the contribution of the system impedance shall be neglected in the calculation of the short-circuit current.

6.1.1.3 Tolerance on short-circuit current values

The tolerance is applicable to the actual current measured on the short-circuited winding.

The target value of the short-circuit peak asymmetrical current shall be 100 % of the value according to 6.1.1.1 and 6.1.1.2 as applicable.

The peak value of the short-circuit current obtained during tests shall be within -3 % and + 7 % of the target value. The symmetrical current shall not deviate by more than ± 10 % from the target value.

For a preset short-circuit test configuration, the current imbalance due to core saturation may increase the current of the energized winding, this can be reduced by preconditioning the core and maximum test deviation shall be agreed between manufacturer and testing laboratory.

6.1.1.4 Test frequency

The frequency of the test supply shall be, in principle, the rated frequency of the transformer. Nevertheless, if agreed between the purchaser and the manufacturer, it is permissible to test 60 Hz transformers with a 50 Hz power supply and 50 Hz transformers with a 60 Hz power supply provided that the prescribed test current values, as required in 4.2.7 and 6.1.1.3, are obtained.

6.1.1.5 Test voltage

This procedure requires that the voltage of the test supply is suitably adjusted with respect to the rated voltage of the object under test.

In order to obtain a test current according to the requirements the no-load voltage of the source may be higher than the rated voltage of the winding supplied. The short-circuiting of the winding may either follow (post-set short-circuit) or precede (pre-set short-circuit) the application of the voltage to the other winding of the transformer¹.

When the post-set short-circuit is used, if the test voltage exceed 1,1 times the rated tapping voltage of the winding over-fluxing of the core may occurs and potential saturation needs to be addressed by the manufacturer and the test laboratory.

6.1.1.6 Pre or post set short-circuit

Both pre and post set configurations are allowed.

If the pre-set short-circuit is used for a transformer with single-concentric windings, the supply should preferably be connected to the winding furthest from the core. The winding closer to the core is to be short-circuited in order to avoid saturation of the magnetic core which could lead to an excessive magnetizing current superimposed on the short-circuit current during the first few cycles.

If the short-circuit is pre-set, then both the short-circuit and the inrush magnetizing currents will flow in the supplied winding. This will make the ampere-turns unbalanced. Effective measures shall be taken during test to minimize the unbalance while using the preset configuration.

When available testing facilities require the supply to be connected to the inner winding, special precautions shall be taken, for example, pre-magnetization of the core, to prevent the inrush of magnetizing current.

For transformers with sandwich windings, axial split windings or double-concentric windings, the pre-set short-circuit method shall be used only after agreement between the manufacturer and the purchaser.

Note 1: This standard does not cover the effects of unbalanced ampere-turns due to the exceptional cases of energization on an existing fault. If such a performance is required this has to be clearly specified, and pre-set method maybe used for demonstrating the withstand ability.

Note 2: The test circuit should comply with the internal winding and lead layout of the transformer under test to avoid undesirable magnetization effects of the core such as half turn effect. The manufacturer should inform the test laboratory of the basic design of the transformer such as type of core (free or forced flux) and presence of half turn in order to choose the most suitable test set up.

¹ Another testing procedure consists of applying simultaneously two opposite-phase voltages to the two windings under test. The two windings can be supplied either from the same power source or from two separate and synchronized power sources. The method is advantageous in preventing any saturation of the core and will reduce the power requirement of the supply.

6.1.1.7 Test current intervals

In order to avoid injurious overheating, an appropriate time interval shall occur between successive short-circuit current applications. This time shall be defined by agreement between the manufacturer and the purchaser.

Note: When testing transformers of category I, it might be necessary to consider the change of X/R factor caused by the temperature increase during the test and provide for its compensation in the test circuit.

6.1.1.8 Common test procedure.

6.1.1.8.1 Number of tests

6.1.1.8.1.1 General

In the absence of any particular specification, the number of tests on three-phase and single-phase transformers is determined as follows, not including preliminary adjustment tests carried out at less than 70 % of the specified current to check the proper functioning of the test set-up with regard to the moment of switching on, the current setting, the damping and the duration.

6.1.1.8.1.2 Categories I and II

- For categories I and II single-phase transformers, the number of tests shall be three.

Unless otherwise specified, the three tests on a single-phase transformer with tapings are made in a different position of the tap-changer, i.e. one test in the position corresponding to the highest voltage ratio, one test on the principal tapping or if the tapping range is asymmetrical, in the middle of the tapping range, and one test in the position corresponding to the lowest voltage ratio.

- For categories I and II three-phase transformers, the total number of tests shall be nine, i.e. three tests on each phase.

Unless otherwise specified, the nine tests on a three-phase transformer with tapings are made in different positions of the tap changer, i.e. three tests in the position corresponding to the highest voltage ratio on one of the outer phases, three tests on the principal tapping on the middle phase and three tests in the position corresponding to the lowest voltage ratio on the other outer phase.

Unless otherwise specified the phase which will be tested with the highest current in the tap leads is the phase with the longest connection between the winding and the tap changer.

6.1.1.8.1.3 Category III

For transformers of category III, an agreement between the manufacturer and the purchaser is always needed with regard to the number of tests and the position of the tap-changer. However, in order to simulate as closely as possible the effects of repetitive short-circuit events likely to occur in service, to allow a better monitoring of the behavior of the unit under test and to permit a meaningful judgment in connection with possible variations of the measured short-circuit impedance, it is recommended that the number of tests is as follows:

- for single-phase transformers: three;
- for three-phase transformers: nine.

With regard to tap-changer position and test sequence, the same procedure as described for transformers of categories I and II shall be applied unless otherwise agreed.

If the test is not failed according to the pass-fail criteria and the short-circuit reactance variation did not show a diminishing trend at the end of the specified number of short-circuit tests, then additional shots may be performed at the manufacturer's choice to determine if a diminishing trend can be established. Trend shall be considered only if compared on the same limb, same tap for the same winding pair, and measured with the same measuring system.

1044 For single phase transformers determining a trend of the reactance variation may not always
1045 be possible because of the test being performed on different tap positions.

1046 If variation between two consecutive shots is lower than 0,3 % then no trend can be determined.

1047 **6.1.1.8.2 Test duration**

1048 The duration of each test shall be

- 1049 • 0,5 s for transformers of category I,
- 1050 • 0,25 s for transformers of categories II and III,

1051 with a tolerance of ± 10 %.

1052 **6.1.2 Condition of the object before the short-circuit tests**

1053 **6.1.2.1 Object subject to test**

1054 Depending on the type of the tested object and on the specification, the tests shall be carried
1055 out on a new object ready for service with protection devices, including gas-and-oil-actuated
1056 relay, pressure-relief devices, visual indicators and all tank mounted devices capable of tripping
1057 the transformer, mounted for the test.

1058 For liquid immersed transformer the static pressure of the liquid at the pressure relief device
1059 during the test shall be equivalent to that obtained when the transformer is fully assembled and
1060 ready for operation.

1061 The mounting of accessories having no influence on behavior during short-circuit (for example,
1062 detachable cooling equipment) is not required.

1063 **6.1.2.2 Temperature of the tested object**

1064 At the beginning of short-circuit tests, the average temperature of the winding or for liquid
1065 immersed transformer that of the liquid shall be 10 °C or above.

1066 Note: During the tests, winding temperature is likely to increase owing to the circulation of the short-circuit current.
1067 For transformers of category I, the test circuit might need to be adjusted to take this into account during the test
1068 sequence.

1069 **6.1.3 Element to be recorded during tests**

1070 Before the short-circuit test, measurements and tests shall be carried out according to 6.1.5
1071 and the gas-and-oil actuated relay (if any) inspected. These measurements and tests serve as
1072 references for the detection of faults.

1073 During each test (including preliminary tests), oscillographic recordings of the following shall
1074 be taken:

- 1075 • the applied voltages;
- 1076 • the line currents
- 1077 • the current between tank and earth
- 1078 • the current through the grounded terminals

1079 The action of protective devices such as pressure relief device, gas and liquid actuated relay,
1080 sudden pressure relay shall be recorded.

1081 Furthermore, the outside of the transformer under test shall be observed visually and
1082 continuously video recorded.

1083 Note 1: Additional means of detection may be used to obtain information and improve the evaluation of the test event,
1084 such as recordings of noise and vibrations, recordings of oil pressure variations occurring at different locations inside
1085 the tank during short-circuit current flow, etc.

1086 After each test, the oscillograms taken during the test shall be checked, the gas-and-oil-
1087 actuated relay inspected and the short-circuit reactance measured. For three-phase
1088 transformers, the measured reactance shall be evaluated on a 'per-phase' basis, by direct
1089 measurement of the phase-to-neutral reactance in case of a star-connected winding with neutral
1090 or derived from three phase to phase measurements by a suitable method if no neutral is
1091 available.

1092 Note 1: Additional means of evaluation may be used to judge the result of the test, such as winding resistance
1093 measurements, low-voltage impulse testing techniques (for comparison between the oscillograms obtained in the
1094 original state and those after the test), analysis of frequency response spectrum, transfer function analysis, no-load
1095 current measurements and comparison of dissolved gas analysis results before and after test.

1096 Note 2: Any differences between the results of measurements made before and after the test may be used as a
1097 criterion for determining possible defects. It is particularly important to observe, during successive tests, possible
1098 changes in the short-circuit reactance measured after each test, which may be progressive or tending to vanish.

1099 Note 3: In order to detect turn-to-turn faults, it is advisable to perform short-circuit reactance measurements from the
1100 HV

1101 **6.1.4 Test and calculation short-circuit current**

1102 The test shall be performed with current holding maximum asymmetry as regards the phase
1103 under test.

1104 For test of the transformer the minimum current which shall be applied during the test sequence
1105 is equal to the highest value of the calculated peak current for each winding.

1106 For calculation of the stresses and the forces the current to be considered is the highest
1107 calculated value of the short-circuit current for all short-circuit cases in all windings.

1108 **6.1.5 Test sequence**

1109 **6.1.5.1 General test sequence**

1110 **6.1.5.1.1 Common consideration**

1111 The sequence of transformer test shall be as follow, the pass-fail criteria are listed in 6.1.8

1112 Other test may be added provided the following list and sequence is respected

1113 **6.1.5.1.2 Category I Transformers**

- 1114 • Routine tests according to IEC 60076-1
- 1115 • Short-circuit current application according to the present document
- 1116 • Routine tests according to IEC 60076-1 and dielectric type test according IEC 60076-3
- 1117 • Untanking and visual inspection according to 6.1.8

1118

6.1.5.1.3 Category II and III Transformers**6.1.5.1.3.1 Sequence choice**

Two alternative sequences can be performed upon specification.

6.1.5.1.3.2 Sequence 1 with dielectric test before visual inspection

- a) Transformer routine test according to IEC 60076-1
- b) Frequency response measurement according to IEC 60076-18
- c) Short-circuit current application according to the present document.
- d) Systematic verification
at least the following measurement shall be performed according to IEC 60076-1
 - Measurement of winding resistance.
 - Measurement of voltage ratio and check of phase displacement.
 - Check of core and frame insulation for liquid immersed transformers with core or frame insulation.
 - Repeat frequency response measurement according to IEC 60076-18.
 - Verification for transformers with $U_m > 72,5$ kV:
 - Measurement of D.C. insulation resistance between each winding to earth and between windings.
 - Measurement of dissipation factor ($\tan \delta$) of the insulation system capacitances.
 - Measurement of dissolved gasses in dielectric liquid from each separate oil compartment except diverter switch compartment.
 - For transformer drained for transport:
the two following points are not in any specific order.
 - routine and type dielectric tests according to IEC 60076-3 shall be performed.
 - Internal inspection at disassembly facility through available access.
 - For transformer transported fully assembled:
 - routine and type dielectric tests according to IEC 60076-3 shall be performed.
- e) Visual inspection of the active part according to 6.1.8.3
- f) Transformer routine test according to IEC 60076-1 except dielectric routine and type tests according to IEC 60076-3.
If all pass-fail criteria are met, then the transformer passed the short-circuit withstand test at this stage.
- g) Routine dielectric tests according to IEC 60076-3 .
- h) Type and special prescribed tests other than dielectric shall be performed at this stage.

6.1.5.1.3.3 Sequence 2 with dielectric test after visual inspection

- a) Transformer routine test according to IEC 60076-1
- b) Frequency response measurement according to IEC 60076-18
- c) Short-circuit current application according to the present document.
- d) Systematic verification
at least the following measurement shall be performed according to IEC 60076-1
 - Measurement of winding resistance
 - Measurement of voltage ratio and check of phase displacement
 - Check of core and frame insulation for liquid immersed transformers with core or frame insulation
 - Repeat frequency response measurement according to IEC 60076-18
 - Verification for transformers with $U_m > 72,5$ kV
 - Measurement of D.C. insulation resistance between each winding to earth and between windings.
 - Measurement of dissipation factor ($\tan \delta$) of the insulation system capacitances.
 - Measurement of dissolved gasses in dielectric liquid from each separate oil compartment except diverter switch compartment
 - For transformer drained for transport :
 - Internal inspection at disassembly facility through available access
- e) Visual inspection of the active part out of tank according to 6.1.8.3. During this phase no repair nor modifications are allowed
- f) Transformer routine test according to IEC 60076-1 except dielectric routine and type tests according to IEC 6076-3. .
- g) Routine and type dielectric tests according to IEC 60076-3
the transformer shall pass the routine dielectric test according IEC 60076-3 and fulfill all pass-fail criteria to be considered as having passed the short-circuit withstand test.
- h) Type and special prescribed tests other than dielectric shall be performed at this stage.

6.1.5.2 Test of Transformers with two windings

To obtain the initial peak value of the current (see 4.2.7) 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 $\hat{i}$ and I of the test currents, oscillographic records shall always be taken.

In order to obtain the maximum asymmetry of the current in one of the phase windings, the switching-on shall occur at the moment the voltage applied to this winding passes through zero.

Note 1: For star-connected windings, the maximum asymmetry is obtained by switching on when the phase voltage passes through zero. The factor k of the peak value $\hat{i}$ can be determined from oscillograms of the line currents. For three-phase tests on delta-connected windings, this condition is obtained by switching on when the line-to-line voltage passes through zero. One of the methods of determining the factor k is by switching on during the preliminary adjustment tests at a maximum of the line-to-line voltage. In this case, the factor k is found from oscillograms of the line currents.

Another method for determining the phase current in a delta-connected winding is by suitably interconnecting the secondary windings of the current transformers measuring the line currents. The oscillograph can be set to record the phase currents.

Note 2: For transformers with star-zigzag connection belonging to category I and with constant flux voltage variation having value for $x_l/r_l \leq 3$ (see 4.2.7), the three phases are switched on simultaneously without the use of a synchronous switch. For other transformers with star-zigzag connection, the method of switching on is subject to agreement between the manufacturer and the purchaser.

For three-phase transformers, a three-phase supply should be used, as long as the requirements in 4.2.5 and 4.2.7 can be met. If this is not the case, a single-phase supply, as described below, may be used. For delta-connected windings, the single-phase supply is provided between two corners of the delta and the voltage during the test shall be the same as the voltage between phases during a three-phase test. For star-connected windings, the single-phase voltage is supplied between one line terminal and the other two line terminals connected together. The single-phase voltage during the test shall be equal to $\sqrt{3}/2$ times the voltage between phases during the three-phase test.

Examples of two possible single-phase test arrangements simulating the three-phase test are given in Figure 21 and Figure 22.

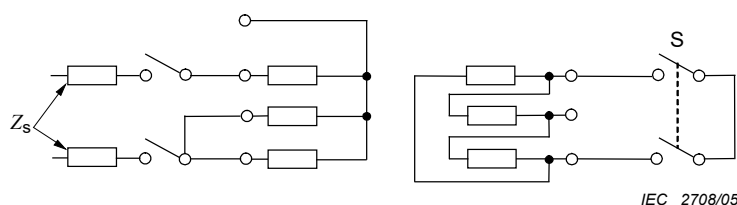


Figure 21 – Star/delta connected transformer

where

Z_s is the test system impedance;

S is the synchronous switch for a post-set short-circuit or rigid connection bar for a pre-set short-circuit

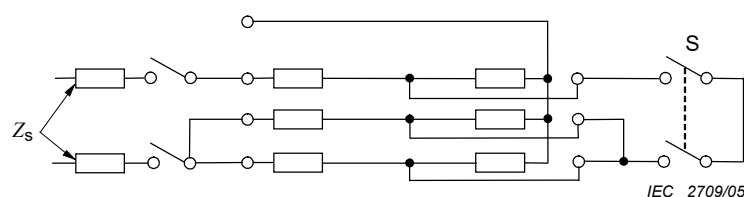


Figure 22 – Star/star auto-transformer

where

Z_s is the test system impedance;

S is the synchronous switch for a post-set short-circuit or rigid connection bar for a pre-set short-circuit

Note 1: The use of tests with single-phase supply applies mainly to transformers of category II or III and is seldom of interest for category I transformers.

Note 2: For star-connected windings with non-uniform insulation, it is necessary to check whether or not the insulation of the neutral is sufficient for single-phase testing.

Note 3: If, for star-connected windings, the power supply is insufficient for the single-phase testing described above and if the neutral is available, the manufacturer and the purchaser may agree upon the use of single-phase power supply between line terminal and the neutral, provided that the neutral is capable of carrying the relevant current. With this test arrangement, it might be convenient to mutually connect the corresponding terminals of the phases not submitted to test in order to better control their voltage, provided that this is feasible and the circuitry is correct.

6.1.6 Test of Transformers with more than two windings

6.1.6.1 General testing requirement

Transformer shall have all their winding tested during the mechanical withstand test. This may require more than one test set up.

Note 2: for more than two windings transformer the test laboratory limitation usually does not allow to supply from all the windings at the same time, and consequently the magnetic leakage field distribution will be different during test from actual in service.

6.1.6.2 Short-circuit consideration for transformers with more than two windings and auto-transformers

Various fault conditions may be considered for transformers with more than two windings and auto-transformers (see 4.2). In general, such conditions are of a more complex nature in comparison with the three-phase short-circuit which can be considered the reference case for two-winding transformers (see 4.2.5).

Special testing circuits are often necessary in order to reproduce some of the fault events by means of tests. The choice of the test duties to be performed should be made, as a rule, on the basis of the analysis of the results of calculations of electrodynamic forces occurring in all possible fault cases.

The testing arrangements, the current values, the sequence and the number of tests are always subject to agreement between the manufacturer and the purchaser.

It is recommended that the tolerance on the agreed test current values and the duration of the tests be in line with those prescribed for two-winding transformers and that the test sequence be selected according to the expected increase of electrodynamic forces.

6.1.6.3 3 windings transformers

6.1.6.3.1 Transformer with stabilizing winding

6.1.6.3.1.1 General consideration

If a transformer is fitted with a delta connected winding with not more than one corner of the delta brought out, even no short may occurs at its terminals, a current will flow in the delta during single phase and two phase faults of the main windings.

The tertiary shall be tested for this circulating current. The test circuit and procedure are subjected to agreement between the manufacturer and the user and the purchaser.

6.1.6.3.1.2 Examples of test circuits for three phase supply

Examples of test circuits are given in Figure 23 for three phase supply.

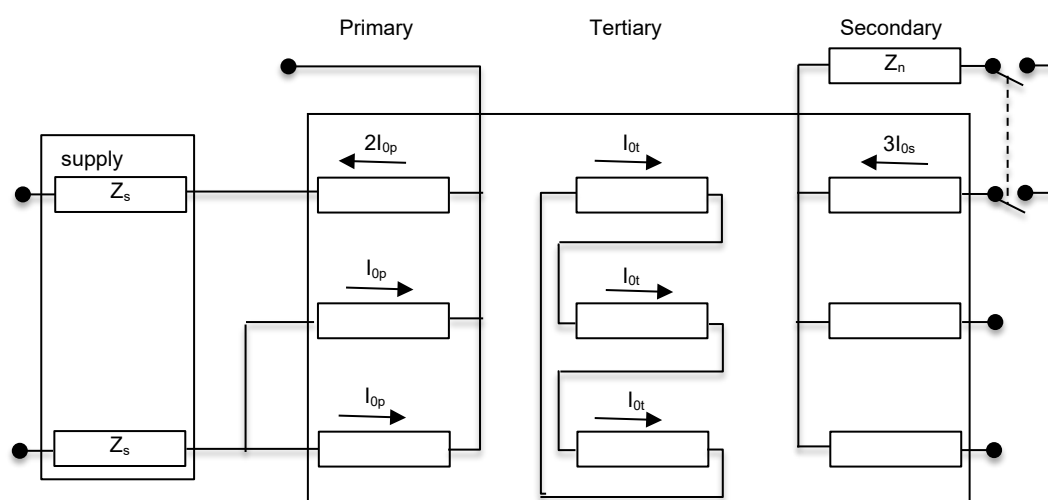


Figure 23 – Example of three phase supply circuit

where

Z_s is the test system impedance;

S is the synchronous switch for a post-set short-circuit or rigid connection bar for a pre-set short-circuit;

Z_n is the neutral impedance on secondary winding (if applicable);

I_{0p} is the zero sequence current in the primary winding;

I_{0s} is the zero sequence current in the secondary winding;

I_{0t} is the zero sequence current in the tertiary winding.

Note 1: The actual test current in the delta winding can be measured with temporary current sensors inserted in the delta for test purposes only. This could be made either with temporary bushings brought out or current sensor placed inside during manufacturing.

Note 2: If the three phase short-circuit is chosen, then special care might need to be taken to ensure that the actual test current will not exceed the calculated value of the main windings.

6.1.6.3.1.3 Examples of test circuits for single phase supply

Examples of test circuits are given in Figure 24 for single phase supply.

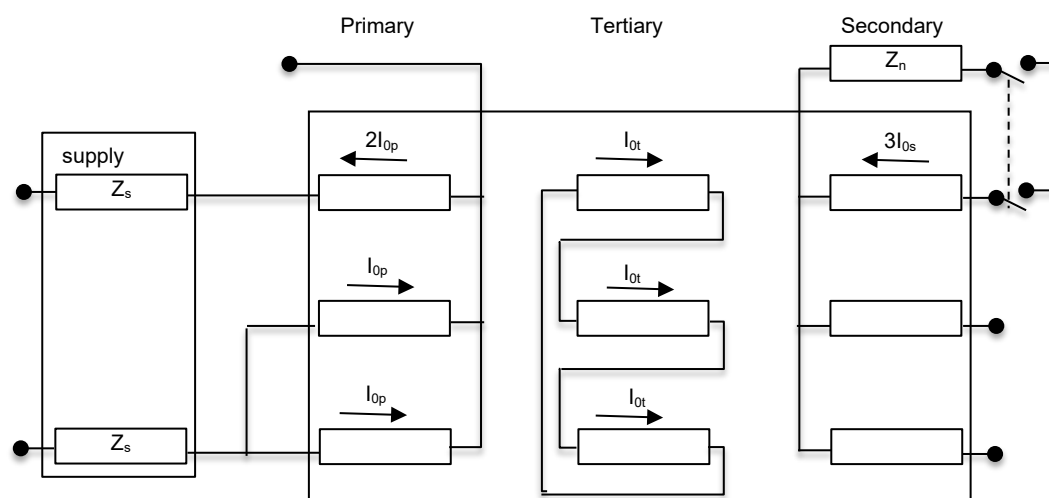


Figure 24 – Example of single phase supply circuit

where

Z_s is the test system impedance;

S is the synchronous switch for a post-set short-circuit or rigid connection bar for a pre-set short-circuit;

Z_n is the neutral impedance on secondary winding (if applicable);

I_{0p} is the zero sequence current in the primary winding;

I_{0s} is the zero sequence current in the secondary winding;

I_{0t} is the zero sequence current in the tertiary winding;

Note 1: The actual test current in the delta winding can be measured with temporary current sensors inserted in the delta for test purposes only. This could be made either with temporary bushings brought out or current sensor placed inside during manufacturing.

Note 2: If the three phase short-circuit is chosen, than special care might need to be taken to ensure that the actual test current will not exceed the calculated value of the main windings.

6.1.6.3.2 Transformer with auxiliary winding

The auxiliary winding shall be tested by using the same method as two windings transformers. The supply current shall be such as to simulate the actual short-circuit current for the auxiliary winding.

1303 6.1.6.3.3 Transformer with dual LV**1304 6.1.6.3.3.1 General**

1305 A transformer is considered as having two LV if one of the winding have a rated power equal to
1306 or within the order of magnitude of the sum of the two others,

1307 For transformers where two LV winding are present the test shall include all the short-circuit
1308 cases that may appear. The test shall include HV against the two LV shorted simultaneously,
1309 and HV again each of the LV shorted the other one being left open.

1310 6.1.6.3.3.2 Transformer with two axially stacked LV

1311 For transformers with two axially stacked LV windings and one HV winding made of two axially
1312 stacked parallel-connected branches and if there is no intermediate yoke, then special
1313 considerations are necessary when carrying out the short-circuit test with only one of the two
1314 LV shorted.

1315 Because the LV windings are loosely coupled, even when only one secondary is shorted,
1316 current will flow in both branches of the HV winding including the one facing the open LV. This
1317 will result in much higher axial forces than if the current was flowing only in the HV branch
1318 facing the shorted LV.

1319 Therefore, in order to carry out a proper verification of the short-circuit withstand capability, the
1320 manufacturer shall consider the currents flowing in both branches of the HV winding when
1321 calculating forces associated to the short-circuit of a single LV.

1322 If the LV windings are placed next to the core, when only one of the LV is shorted, the portion
1323 of core limb facing the open LV will be magnetized by the flux imposed by the HV winding.

1324 If the short-circuit is preset then effective measures shall be taken to minimize the effects of
1325 ampere-turns unbalance.

1326 6.1.6.4 Transformers with four or more windings

1327 For transformers with four or more windings the number of tests required to cover all the winding
1328 combinations may become excessive. In this circumstance the number of tested winding
1329 combinations may be reduced provided the highest stresses on individual windings taking into
1330 account the possible fault scenarios are covered.

1331 6.1.7 Large or Special transformers

1332 If due to testing laboratory limitation or other reason the test can't be performed according to
1333 this standard then the purchaser and the manufacturer shall agree on the tests parameters and
1334 procedure at the tender stage.

1335

6.1.8 Pass-fail criteria

6.1.8.1 General Pass-fail criteria

All the reactance measurements shall be to a repeatability of better than $\pm 0,2 \%$,

If different tap positions are used on one phase (either of a single or a three phase transformer) then the reactance shall be measured after each application of full test current, on all the tapping positions at which short-circuit tests will be carried out.

General principle is that the transformer should not trip under a short-circuit in service due to operation of protective device.

After completion of the short-circuit currents applications, the outside of the transformer and the gas-and-oil-actuated relay, if any, shall be inspected. The results of the short-circuit reactance 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.

Note 1: At the end of the tests, if the windings are provided with tapping, the reactance should be measured for all the tapping positions at which the short-circuit tests have been carried out.

Note 2: Generally, the short-circuit reactance variation should show a tendency to diminish in the course of the tests. There may also be a certain change of reactance with time after the tests. Hence, if there is a high variation of reactance exceeding the prescribed limits, based on measurements made immediately after the test, it may be prudent to repeat the measurements after an interval in order to check whether the variation is maintained. This last value of reactance is accepted as the final value when determining compliance with the requirements of the standard.

After short-circuit tests the following procedures shall be applied.

- All the routine tests, and dielectric type tests shall be performed. The dielectric test shall be performed at 100 % of the prescribed test value (see IEC 60076-3). Any special dielectric test specified by the purchaser shall also be performed after the short-circuit.
- In order to consider the transformer 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 the tests do not reveal any fault conditions.
 - The dielectric tests including lightning impulse test even for transformer with $U_m \leq 72,5 \text{ kV}$ and all other routine tests when applicable, have been successfully repeated.
 - The out-of-tank inspection does not reveal any defects such as displacements, shift of laminations, deformation of windings, connections or supporting structures, so significant that they might endanger the safe operation of the transformer.
 - No traces of internal electrical discharge or breakdown are found.
 - No operation of the pressure relief device or over pressure detection device, a leakage which did not cause the operation of either the visual indicator or the contact of the device is considered as acceptable.
 - No bushing failure occurs.
 - If gas collection device has operated: no significant combustible gases are detected either in oil or gas.
 - The short-circuit reactance values, in ohms, evaluated for each phase at the end of the tests, do not differ from the original values by more than the values prescribed in the following sections-

Due to the difference between the configuration during test and on site, the operation of the protective device may not mean that the test is failed but this shall be investigated and appropriate corrective action agreed.

1383 Temporary external sparks across metallic joints such as tank, tank cover, support structure,
1384 flanges etc...that are not intentionally insulated might occur due to induced current at the
1385 energizing and short-circuit stages.

1386 **6.1.8.2 Reactance variation**

1387 **6.1.8.2.1 Category I and II**

1388 The short-circuit reactance values, in ohms, evaluated for each phase at the end of the tests
1389 do not differ from the original values by more than the following values.

- 1390 • 2 % for transformers with circular concentric coils and sandwich non-circular coils.
- 1391 • 4 % for transformers with rated power up to 10 000 kVA and with a short-circuit impedance
1392 of 3 % or more, where at least one of the windings of the tested winding pair is a circular
1393 foil winding. If the short-circuit impedance is less than 3 %, the above limit of 4 % is subject
1394 to agreement between the manufacturer and the purchaser
- 1395 • 7,5 % for transformers with non-circular concentric coils, having a short-circuit impedance
1396 of 3 % or more. The value of 7,5 % may be reduced by agreement between the manufacturer
1397 and the purchaser, but not below 4 %.

1398 When a transformer falls into more than one of the above categories, then the highest reactance
1399 variation shall apply.

1400 Note 1: For transformers with non-circular concentric coils having a short-circuit impedance below 3 %, the maximum
1401 variation in reactance cannot be specified in a general manner. Practical knowledge of certain types of construction
1402 leads to the acceptance for such transformers of a variation equal to $(22,5 - 5,0 \cdot Z_t)$ %, Z_t being the short-circuit
1403 impedance in per cent.

1404 Note 2: Transformers falling in the upper range of category II and having highest voltage for equipment U_m not
1405 exceeding 52 kV deserve particular attention and may require an adjustment of the above reactance variation limit.

1406 Note 3: The variation of reactance after short-circuit may result in impedance value of a transformer not complying
1407 with the agreed guaranteed value.

1408 If any of the above conditions are not met, the unit shall be dismantled, as necessary, to
1409 establish the cause of the deviation.

1410 **6.1.8.2.2 Category III**

1411 The short-circuit reactance values, in ohms, evaluated for each phase at the end of the tests
1412 do not differ from the original values by more than 1 %.

1413 Note 1: In connection with the economic impact of the cost of a transformer of category III and the cost implication
1414 of any thorough visual inspection extended to the inner parts of the unit, it is recommended that a series of
1415 photographs be taken of the position of the winding leads, taps, alignment of spacers and configuration of the end-
1416 insulation components, etc. to allow accurate comparison of the parts before and after the tests. In this context, a
1417 check of the axial compression of the windings could be useful. By necessity, it is left to mutual agreement between
1418 the parties to accept the existence of small displacements and changes, provided that the service reliability of the
1419 transformer is not affected.

1420