INTERNATIONAL STANDARD

IEC 60076-5

Second edition
2000-07

Power transformers –

Part 5: Ability to withstand short circuit

*This **English-language** version is derived from the original **bilingual** publication by leaving out all French-language pages. Missing page numbers correspond to the French-language pages.*

Reference number
IEC 60076-5:2000(E)

Publication numbering

As from 1 January 1997 all IEC publications are issued with a designation in the 60000 series. For example, IEC 34-1 is now referred to as IEC 60034-1.

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Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

PRICE CODE S

For price, see current catalogue

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

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FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 60076-5 has been prepared by IEC technical committee 14: Power transformers.

This second edition cancels and replaces the first edition published in 1976 and amendment 2 (1994). This second edition constitutes a technical revision.

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

FDIS	Report on voting
14/346/FDIS	14/353/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 3.

Annex A is for information only.

Annex B forms an integral part of this standard.

The committee has decided that this publication remains valid until 2004. At this date, in accordance with the committee’s decision, the publication will be

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

POWER TRANSFORMERS –

Part 5: Ability to withstand short circuit

1 Scope

This part of IEC 60076 identifies the requirements for power transformers to sustain without damage the effects of overcurrents originated by external short circuits. It describes the calculation procedures used to demonstrate the thermal ability of a power transformer to withstand such overcurrents and both the special test and the calculation method used to demonstrate its ability to withstand the relevant dynamic effects. The requirements apply to transformers as defined in the scope of IEC 60076-1.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 60076. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of IEC 60076 are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60076-1:1993, *Power transformers – Part 1: General*

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

IEC 60726:1982, *Dry-type power transformers*

3 Requirements with regard to ability to withstand short circuit

3.1 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 3.2.

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 ‘overcurrents’ in this part of IEC 60076.

3.2 Overcurrent conditions

3.2.1 General considerations

3.2.1.1 Application conditions requiring special consideration

The following situations affecting overcurrent 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 overcurrents;
- unit generator transformers susceptible to high overcurrents produced by connection of the generator to the system out of synchronism;
- transformers directly connected to rotating machines, such as motors or synchronous condensers, that can act as generators to feed current into the transformer under system fault conditions;
- special transformers and transformers installed in systems characterized by high fault rates; see 3.2.6;
- operating voltage higher than rated maintained at the unfaulted terminal(s) during a fault condition.

3.2.1.2 Current limitations concerning booster transformers

When the combined impedance of the booster transformer and the system result 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 overcurrent. In this case, provision should be made by the purchaser to limit the overcurrent to the maximum value determined by the manufacturer and stated on the rating plate.

3.2.2 Transformers with two separate windings

3.2.2.1 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 2 500 kVA;
- category II: 2 501 kVA to 100 000 kVA;
- category III: above 100 000 kVA.

3.2.2.2 In the absence of other specifications, the symmetrical short-circuit current (r.m.s. value, see 4.1.2) shall be calculated using the measured short-circuit impedance of the transformer plus the system impedance.

For transformers of category I, the contribution of the system impedance shall be neglected in the calculation of the short-circuit current if this impedance is equal to or less than 5 % of the short-circuit impedance of the transformer.

The peak value of the short-circuit current shall be calculated in accordance with 4.2.3.

3.2.2.3 Commonly recognized minimum values for the short-circuit impedance of transformers at rated current (principal tapping) are given in table 1. If lower values are required, the ability of the transformer to withstand short circuit shall be subject to agreement between the manufacturer and the purchaser.

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

Short-circuit impedance at rated current	
Rated power kVA	**Minimum short-circuit impedance** %
Up 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 100 000	>12,5

NOTE 1 Values for rated power greater than 100 000 kVA are generally subjected to agreement between manufacturer and purchaser.

NOTE 2 In case of single-phase units connected to form a three-phase bank, the value of rated power applies to three-phase bank rating.

3.2.2.4 The short-circuit apparent power 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 of the system is not specified, the values given in table 2 shall be used.

Table 2 – Short-circuit apparent power of the system

Highest voltage for equipment, U_m kV	**Short-circuit apparent power** MVA	
	Current European practice	**Current North American practice**
7,2; 12; 17,5 and 24	500	500
36	1 000	1 500
52 and 72,5	3 000	5 000
100 and 123	6 000	15 000
145 and 170	10 000	15 000
245	20 000	25 000
300	30 000	30 000
362	35 000	35 000
420	40 000	40 000
525	60 000	60 000
765	83 500	83 500

NOTE If not specified, a value between 1 and 3 should be considered for the ratio of zero-sequence to positive-sequence impedance of the system.

3.2.2.5 For transformers with two separate windings, normally only the three-phase short circuit is taken into account, as the consideration of this case is substantially adequate to cover also the other possible types of fault (exception is made in the special case considered in the note to 3.2.5).

NOTE 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. Electrodynamic 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.

3.2.3 Transformers with more than two windings and auto-transformers

The overcurrents 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 stabilizing windings of three-phase transformers shall be capable of withstanding the overcurrents resulting from different forms of system faults that can arise in service associated with relevant system earthing conditions.

In the case of single-phase transformers connected to form a three-phase bank, the stabilizing winding shall be capable of withstanding a short-circuit on its terminals, 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 overcurrent level must be limited by appropriate means, such as series reactors or, in some instances, fuses. Care must be taken to guard against faults in the zone between the transformer and the protective apparatus.

3.2.4 Booster transformers

The impedance of booster transformers can be very low and, therefore, the overcurrents in the windings are determined mainly by the characteristics of the system at the location of the transformer. These characteristics shall be specified by the purchaser in his enquiry.

If a booster transformer is directly associated to a transformer for the purpose of voltage amplitude and/or phase variation, it shall be capable of withstanding the overcurrents resulting from the combined impedance of the two machines.

3.2.5 Transformers directly associated with other apparatus

Where a transformer is directly associated with other apparatus, the impedance of which would limit the short-circuit current, the sum of impedance of the transformer, the system and the directly associated apparatus may, by agreement between the manufacturer and the purchaser, be taken into account.

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.

NOTE If the connection between generator and transformer is constructed in this way, the most severe short-circuit conditions may occur, in the case of a star/delta-connected unit generator transformer with earthed neutral, when a line-to-earth fault occurs on the system connected to the star-connected winding, or in the case of out-of-phase synchronization.

3.2.6 Special transformers and transformers to be installed in systems characterized by high fault rates

The ability of the transformer to withstand frequent overcurrents, 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 faults occurring in the connected system(s)), shall be subjected to special agreement between the manufacturer and the purchaser. Notice of any abnormal operation conditions expected in the system(s) shall be given by the purchaser to the manufacturer in advance.

3.2.7 Tap-changing equipment

Where fitted, tap changing equipment shall be capable of carrying the same overcurrents 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.

3.2.8 Neutral terminal

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

4 Demonstration of ability to withstand short circuit

The requirements of this clause apply to both oil-immersed and dry-type transformers as specified in IEC 60076-1 and IEC 60726, respectively.

4.1 Thermal ability to withstand short circuit

4.1.1 General

According to this standard, the thermal ability to withstand short circuit shall be demonstrated by calculation. This calculation shall be carried out in accordance with the requirements of 4.1.2 to 4.1.5.

4.1.2 Value of symmetrical short-circuit current I

For three-phase transformers with two separate windings, the r.m.s. value of the symmetrical short-circuit current I shall be calculated as follows:

$$I = \frac{U}{\sqrt{3} \times (Z_t + Z_s)} \quad \text{(kA)} \tag{1}$$

where

Z_s is the short-circuit impedance of the system.

$$Z_s = \frac{U_s^2}{S}, \text{ in ohms per phase (equivalent star connection)} \tag{2}$$

where

U_s is the rated voltage of the system, in kilovolts (kV);

S is the short-circuit apparent power of the system, in megavoltamperes (MVA).

U and Z_t are defined as follows:

a) for the principal tapping:

U is the rated voltage U_r of the winding under consideration, in kilovolts;

Z_t is the short-circuit impedance of the transformer referred to the winding under consideration; it is calculated as follows:

$$Z_t = \frac{z_t \times U_r^2}{100 \times S_r}\text{, in ohms } (\Omega) \text{ per phase (equivalent star connection)}^{1)} \quad (3)$$

where

z_t is the measured short-circuit impedance at rated current and frequency at the principal tap and at reference temperature, as a percentage;

S_r is the rated power of the transformer, in megavoltamperes;

b) for tappings other than the principal tapping:

U is, unless otherwise specified, the tapping voltage[2)] of the winding under consideration, in kilovolts;

Z_t is the short-circuit impedance of the transformer referred to the winding and the tapping under consideration, in ohms per phase.

For transformers having more than two windings, auto-transformers, booster transformers and transformers directly associated with other apparatus, the overcurrents are calculated in accordance with 3.2.3, 3.2.4 or 3.2.5, as appropriate.

For all transformers, excluding the case given in 3.2.2.2, the effect of the short-circuit impedance of the system(s) shall be taken into consideration.

NOTE At the zigzag connected windings, the short-circuit current for a single-line-to-earth fault may reach considerably higher values than at the three-phase fault. This increase in current should be taken into consideration when calculating the temperature rise of the zigzag winding.

4.1.3 Duration of the symmetrical short-circuit current

The duration of the current I to be used for the calculation of the thermal ability to withstand short circuit shall be 2 s unless a different duration is specified.

NOTE For auto-transformers and for transformers with short-circuit current exceeding 25 times the rated current, a short-circuit current duration below 2 s may be adopted by agreement between the manufacturer and the purchaser.

4.1.4 Maximum permissible value of the average temperature of each winding

The average temperature θ_1 of each winding after loading with a symmetrical short-circuit current I of a value and duration as specified in 4.1.2 and 4.1.3, respectively, shall not exceed the maximum value stated in table 3 at any tapping position.

The initial winding temperature θ_0 to be used in equations (4) and (5) shall correspond to the sum of the maximum permissible ambient temperature and the temperature rise of the winding at rated conditions measured by resistance. If the measured winding temperature rise is not available, then the initial winding temperature θ_0 shall correspond to the sum of the maximum permissible ambient temperature and the temperature rise allowed for the winding insulation system.

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[1)] Here symbols Z_t and z_t are used instead of Z and z, respectively, adopted for the same quantities in IEC 60076-1, for the sake of clarity in connection with the content of 4.2.3.

[2)] For definition of "tapping voltage", see 5.2 of IEC 60076-1.

Table 3 – Maximum permissible values of the average temperature of each winding after short circuit

Transformer type	Insulation system temperature, °C (thermal class in brackets)	Maximum value of temperature, °C	
		Copper	**Aluminium**
Oil-immersed	105 (A)	250	200
Dry	105 (A)	180	180
	120 (E)	250	200
	130 (B)	350	200
	155 (F)	350	200
	180 (H)	350	200
	220	350	200

NOTE 1 In case of windings made of high tensile strength aluminium alloys, higher maximum values of temperature, but not exceeding those relevant to copper, may be allowed by agreement between the manufacturer and the purchaser.

NOTE 2 When insulation systems other than thermal class A are employed in oil-immersed transformers, different maximum values of temperature may be allowed by agreement between the manufacturer and the purchaser.

4.1.5 Calculation of temperature θ_1

The average temperature θ_1 attained by the winding after short circuit shall be calculated by the formula:

$$\theta_1 = \theta_0 + \frac{2 \times (\theta_0 + 235)}{\frac{106\,000}{J^2 \times t} - 1} \text{ for copper} \quad (4)$$

$$\theta_1 = \theta_0 + \frac{2 \times (\theta_0 + 225)}{\frac{45\,700}{J^2 \times t} - 1} \text{ for aluminium} \quad (5)$$

where

θ_0 is the initial winding temperature, in degrees Celsius (°C);

J is the short-circuit current density, in amperes per square millimetre, based on the r.m.s. value of the symmetrical short-circuit current;

t is the duration, in seconds (s).

NOTE Equations (4) and (5) are based on adiabatic conditions and are valid for only a short time duration, not exceeding 10 s. The coefficients are based on the following material properties:

	Copper	**Aluminium**
Specific heat at 100 °C [J/kg·°C]	398,4	928
Density at 100 °C [kg/m^3]	8 894	2 685
Resistivity at 100 °C [μΩ·m]	0,0224	0,0355
Source: Table of physical and chemical constants – Kay and Laby – 15th edition, Longmans, 1986.		

4.2 Ability to withstand the dynamic effects of short circuit

4.2.1 General

If required by the purchaser, the ability to withstand the dynamic effects of short circuit shall be demonstrated either

– by tests, or

– by calculation and design considerations.

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

When a short-circuit test is selected, it shall be regarded as a special test, (see 3.11.3 of IEC 60076-1) and it shall be specified prior to placing the order. The test shall be carried out in accordance with the requirements in 4.2.2 to 4.2.7.

Large power transformers sometimes cannot be tested according to this standard due, for example, to testing limitations. In these cases, the testing conditions shall be agreed between the purchaser and the manufacturer.

When calculation and design consideration is selected, validation by comparison with a previously tested similar transformer or tests on representative models is required. Guidance for the identification of a similar transformer is given in annex A.

4.2.2 Condition of the transformer before the short-circuit tests

4.2.2.1 Unless otherwise agreed, the tests shall be carried out on a new transformer ready for service. Protection accessories, such as a gas-and-oil-actuated relay and pressure relief device, shall be mounted on the transformer during the test.

NOTE The mounting of accessories having no influence on the behaviour during short circuit (e.g. detachable cooling equipment), it is not required.

4.2.2.2 Prior to the short-circuit tests, the transformer shall be subjected to the routine tests which are specified in IEC 60076-1. However, the lightning impulse test is not required at this stage.

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

All the reactance 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.

4.2.2.3 At the beginning of short-circuit tests, the average temperature of the winding shall preferably be between 10 °C and 40 °C (see 10.1 of IEC 60076-1).

During the tests, winding temperature may increase owing to the circulation of the short-circuit current. This aspect shall be taken into consideration when arranging the test circuit for transformers of category I.

4.2.3 Test current peak value $\hat{\imath}$ for two-winding transformers

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

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

$$\hat{\imath} = I \times k \times \sqrt{2} \qquad (6)$$

where the symmetrical short-circuit current I is determined in accordance with 4.1.2.

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.

The factor $k \times \sqrt{2}$, or peak factor, depends on the ratio X/R

where

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

R is the sum of resistances of the transformer and the system ($R_t + R_s$), in ohms, where R_t is at reference temperature; see 10.1 of IEC 60076-1.

When the short-circuit impedance of the system is included in the short-circuit current calculation, the X/R ratio of the system, if not specified, shall be assumed equal to that of the transformer. Table 4 specifies the value for the peak factor as a function of the X/R ratio to be used for practical purposes [3].

Table 4 – Values for factor $k \times \sqrt{2}$

X/R	1	1,5	2	3	4	5	6	8	10	14
$k \times \sqrt{2}$	1,51	1,64	1,76	1,95	2,09	2,19	2,27	2,38	2,46	2,55
NOTE For other values of X/R between 1 and 14, the factor $k \times \sqrt{2}$ may be determined by linear interpolation.										

NOTE When $Z_s < 0,05\ Z_t$, instead of X_t and R_t (in ohms), x_t and r_t may be used for the principal tapping where

x_t is the reactive component of z_t, in per cent;

r_t is the resistance component, at reference temperature, of z_t, in per cent;

z_t is the short-circuit impedance of the transformer, at reference temperature, in per cent.

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[3] Table 4 is based on the following expression for the peak factor:

$k \times \sqrt{2} = (1+(e^{-(\phi+\pi/2)R/X})\sin\phi) \times \sqrt{2}$

where

e is the base of natural logarithm;

ϕ is the phase angle which is equal to arctan X/R, in radians.

If not otherwise specified, in the case X/R >14 the factor $k \times \sqrt{2}$ is assumed equal to

$1,8 \times \sqrt{2}$ = 2,55 for transformers of category II,

$1,9 \times \sqrt{2}$ = 2,69 for transformers of category III.

4.2.4 Tolerance on the asymmetrical peak and symmetrical r.m.s. value of the short-circuit test current

The asymmetrical current having first peak amplitude $\hat{\imath}$ (see 4.2.3) will change (if the duration of the short-circuit test current is sufficiently long) into the symmetrical current I (see 4.1.2).

The peak value of the current obtained in testing shall not deviate by more than 5 % and the symmetrical current by more than 10 % from the respective specified value.

4.2.5 Short-circuit testing procedure for transformers with two windings

4.2.5.1 In order to obtain a test current according to 4.2.4, 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 transformer[4)].

If the post-set short circuit is used, the voltage shall not exceed 1,15 times the rated voltage of the winding, unless otherwise agreed between the manufacturer and the purchaser.

If the pre-set short circuit is used for a transformer with single-concentric windings, the supply should preferably be connected to the winding further 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.

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

In order to avoid injurious overheating, an appropriate time interval shall occur between successive overcurrent 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.

4.2.5.2 To obtain the initial peak value of current (see 4.2.3) 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 $\hat{\imath}$ and I of the test currents, oscillographic records shall always be taken.

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4) 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.

In order to obtain the maximum asymmetry of the current in one of the phase windings, the switching on must 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 $\hat{\imath}$ 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.

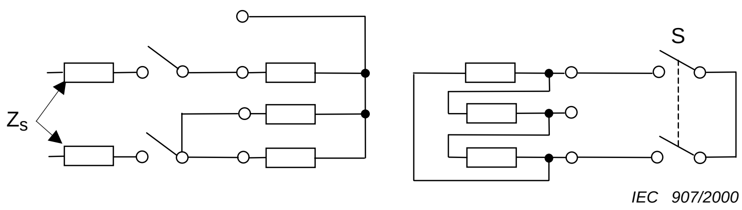
NOTE 2 For transformers with star-zigzag connection belonging to category I and with constant flux voltage variation having value for $x_t/r_t \leq 3$ (see 4.2.3), the three phases are switched on simultaneously without the use of a synchronous switch. For other transformers with star-zigzag connection, the method of switching on is subject to agreement between the manufacturer and the purchaser.

4.2.5.3 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 4.2.3 and 4.2.4, are obtained.

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

4.2.5.4 For three-phase transformers, a three-phase supply should be used, as long as the requirements in 4.2.4 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 has to 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 figures 1 and 2.

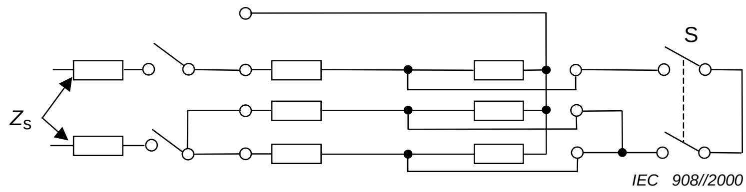


Components

Z_s test system impedance

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

Figure 1 – Star/delta connected transformer



Components

Z_s test system impedance

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

Figure 2 – Star/star auto-transformer

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 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 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 circuitry correct.

4.2.5.5 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 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.

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 tappings 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 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 tappings 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.

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 behaviour of the unit under test and to permit a meaningful judgement 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 is recommended.

The duration of each test shall be

– 0,5 s for transformers of category I,
– 0,25 s for transformers of categories II and III,

with a tolerance of ±10 %.

4.2.6 Short-circuit testing procedure 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 3.2.3). 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 3.2.2.5).

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 are in line with those prescribed for two-winding transformers and that the test sequence is selected according to the expected increase of electrodynamic forces.

4.2.7 Detection of faults and evaluation of test results

4.2.7.1 Before the short-circuit testing, measurements and tests shall be carried out according to 4.2.2 and the gas-and-oil actuated relay (if any) inspected. These measurements and tests serve as references for the detection of faults.

4.2.7.2 During each test (including preliminary tests), oscillographic recordings shall be taken of

– the applied voltages,
– the currents (see 4.2.5.2).

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

NOTE 1 Additional means of detection may be used to obtain information and improve the evaluation of the test event, such as recording of the current between the tank (insulated) and earth, recordings of noise and vibrations, recordings of oil pressure variations occurring at different locations inside the tank during short-circuit current flow, etc.

NOTE 2 Random gas-and-oil-actuated relay tripping may occur during the tests due to vibration. This circumstance is not significant for the ability of the transformer to withstand short-circuit unless combustible gas is found in the relay.

NOTE 3 Temporary sparks over tank joints may occur at the energizing stage and internal sparking at the frame joints at the energizing and short-circuit stages.

4.2.7.3 After each test, the oscillograms taken during the test shall be checked, the gas-and-oil-actuated relay inspected and the short-circuit reactance measured. For three-phase transformers, the measured reactance shall be evaluated on a ‘per phase’ basis, either by direct measurement of the phase-to-neutral reactance in case of a star-connected winding or derived from a delta winding configuration by a suitable method.

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

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

NOTE 3 In order to detect turn-to-turn faults, it is advisable to perform short-circuit reactance measurements from the HV as well as LV side.

4.2.7.4 After completion of the tests, 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 must 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 be also 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.

Different procedures are followed at this stage for transformers of categories I, II and III. These procedures and reactance limits are given in the following items a) and b).

a) Transformers of categories I and II

   Unless otherwise agreed, the active part shall be removed from the tank 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.

   All the routine tests, including dielectric tests at 100 % of the prescribed test value, shall be repeated. If a lightning impulse test is specified, it shall be performed at this stage. However, for transformers of category I, the repetition of the routine tests with the exception of the dielectric tests may be omitted.

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

   1) the results of the short-circuit tests and the measurements and checks performed during tests do not reveal any condition of faults;
   2) the dielectric tests and other routine tests when applicable, have been successfully repeated and the lightning impulse test, if specified, successfully performed;
   3) 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;
   4) no traces of internal electrical discharge are found;

5) 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

   – 2 % for transformers with circular concentric coils [5] and sandwich non-circular coils. However, for transformers having metal foil as a conductor in the low-voltage winding and with rated power up to 10 000 kVA, higher values, not exceeding 4 %, are acceptable for transformers with a short-circuit impedance of 3 % or more. If the short-circuit impedance is less than 3 %, the above limit of 4 % is subject to agreement between the manufacturer and the purchaser;

   – 7,5 % for transformers 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 the manufacturer and the purchaser, but not below 4 %.

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

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

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

b) Transformers of category III

   The active part shall be made visible 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.

   All the routine tests, including dielectric tests at 100 % 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 as having passed the short-circuit tests, the following conditions shall be fulfilled:

   1) the results of the short-circuit tests and the measurements and checks performed during tests do not reveal any condition of faults;

   2) the routine tests have been successfully repeated and the lightning impulse test, if specified, successfully performed;

   3) 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;

   4) no traces of internal electrical discharge are found;

   5) 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 1 %.

———————

[5] Circular coils include all coils wound on a cylindrical form, even though, for example, because of the presence of the exit leads in metal foil windings, there might be local deviations from the cylindrical shape.

If the reactance variation is in the range 1 % to 2 %, the acceptance is subject to agreement between the purchaser and the manufacturer. In this case, a more detailed examination may be required, including a dismantling of the unit as necessary to establish the cause of the deviation. However, before dismantling, it is suggested that additional diagnostic means are applied (see note 1 of 4.2.7.3).

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

Annex A
(informative)

Guidance for the identification of a similar transformer

Transformers similar to a reference transformer can be identified by comparison using the following non-exclusive list of critical features:

– same type of operation, for example generator step-up unit, distribution, interconnection transformer as the reference unit;

– same conceptual design, for example dry-type, oil-immersed type, core type with concentric windings, sandwich type, shell type, circular coils, non-circular coils as the reference unit;

– same arrangement of main windings and geometrical sequence as the reference unit;

– same type of winding conductors, for example, aluminium, aluminium alloy, annealed or hardened copper, metal foil, wire, flat conductor, continuously transposed conductors and epoxy bonding, if used, as the reference unit;

– same type of main windings for example, helical, disc, layer, pancake, as the reference unit;

– absorbed power at short-circuit (rated power/per unit short-circuit impedance) between 30 % and 130 % of that of the reference unit;

– axial forces and relative winding stresses (ratio of actual stress to critical stress) at short-circuit not exceeding 110 % of those in the reference unit;

– same manufacturing processes as the reference unit;

– same clamping and supporting arrangement.

Annex B
(normative)

Calculation method for the demonstration of the ability to withstand the dynamic effects of short circuit

A standardized calculation method is under consideration.

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Q2 Please tell us in what capacity(ies) you bought the standard *(tick all that apply).* I am the/a:

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- design engineer ❑
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- marketing specialist ❑
- other...

Q3 I work for/in/as a: *(tick all that apply)*

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- product research ❑
- product design/development ❑
- specifications ❑
- tenders ❑
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- thesis ❑
- manufacturing ❑
- other...

Q5 This standard meets my needs: *(tick one)*

- not at all ❑
- nearly ❑
- fairly well ❑
- exactly ❑

Q6 If you ticked NOT AT ALL in Question 5 the reason is: *(tick all that apply)*

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- standard is incomplete ❑
- standard is too academic ❑
- standard is too superficial ❑
- title is misleading ❑
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Q7 Please assess the standard in the following categories, using the numbers:
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(2) below average,
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(4) above average,
(5) exceptional,
(6) not applicable

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ISBN 2-8318-5275-7

ICS 29.180

Typeset and printed by the IEC Central Office
GENEVA, SWITZERLAND