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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Power transformers –
Part 5: Ability to withstand short circuit

Transformateurs de puissance –
Partie 5: Tenue au court-circuit

IEC 60076-5:2006

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Part 5: Ability to withstand short circuit

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of 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, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). 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. 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 third edition cancels and replaces the second edition published in 2000. This third edition constitutes a technical revision.

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

a) introduction of Annex A (informative) – "Theoretical evaluation of the ability to withstand the dynamic effects of short circuit", in place of previous Annex B (normative) – "Calculation method for the demonstration of the ability to withstand short circuit" (blank);
b) introduction of Annex B (informative) – "Definition of similar transformer", in place of previous Annex A (informative) – "Guidance for the identification of a similar transformer".

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

FDIS	Report on voting
14/518/FDIS	14/523/RVD

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

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

IEC 60076 consists of the following parts, under the general title *Power transformers*:

Part 1: General

Part 2: Temperature rise

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

Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors

Part 5: Ability to withstand short circuit

Part 6: Reactors [1]

Part 7: Loading guide for oil-immersed power transformers

Part 8: Application guide

Part 10: Determination of sound levels

Part 10-1: Determination of sound levels – Application guide

Part 11: Dry-type transformers

Part 12: Loading guide for dry-type power transformers[1]

Part 13: Self-protected liquid-filled transformers

Part 14: Design and application of liquid-immersed power transformers using high-temperature insulation materials

Part 15: Gas-filled-type power tranformers[1]

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

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

[1] Under consideration.

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 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.

2 Normative references

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

IEC 60076-1:1993, *Power transformers – Part 1: General*
Amendment 1 (1999)[2]

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

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

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

[2] There exists a consolidated edition 2.1 (2000) that includes edition 2.0 and its amendment.

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 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 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: 25 kVA 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 (for the 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 the 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** %
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 100 000	>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.	

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 should be limited by appropriate means, such as series reactors or, in some instances, fuses. Care should 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 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.

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 60076-11, 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:

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

where

Z_s is the short-circuit impedance of the system.

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

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 (kV);

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

$$Z_t = \frac{z_t \times U_r^2}{100 \times S_r}$$, in ohms (Ω) per phase (equivalent star connection)[3] (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 (MVA);

b) for tappings other than the principal tapping:

U is, unless otherwise specified, the tapping voltage[4] of the winding under consideration, in kilovolts (kV);

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

3 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.

4 For the definition of tapping voltage, see 5.2 of IEC 60076-1.

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.

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
	200	350	200
	220	350	200

NOTE 1 In the 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:

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

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

where

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

J is the short-circuit current density, based on the r.m.s. value of the symmetrical short-circuit current, in amperes per square millimetre (A/mm^2);

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)	0,022 4	0,035 5

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 and manufacture 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 demonstration based on calculation and design and manufacture considerations is selected, the guidelines given in Annex A shall be followed.

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 behaviour during short circuit (for example, detachable cooling equipment) 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, also the resistance shall 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:

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

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 (Ω);

R is the sum of resistances of the transformer and the system ($R_t + R_s$), in ohms (Ω), 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 to be 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 [5].

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 (%).

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

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5 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.