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(पहला पुनरीक्षण)

Indian Standard

POWER TRANSFORMERS

PART 5 ABILITY TO WITHSTAND SHORT CIRCUIT

(First Revision)

ICS 29.180

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B U R E A U O F I N D I A N S T A N D A R D S
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December 2011 **Price Group 8**

Power Transformers Sectional Committee, ETD 16

FOREWORD

This Indian Standard (Part 5) (First Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Power Transformers Sectional Committee had been approved by the Electrotechnical Division Council.

In the formulation of this standard considerable assistance has been derived from IEC pub 76-3-1 : 1987 'Power transformer: Part 3 Insulation levels and dielectric tests external clearances in air' issued by the International Electrotechnical Commission (IEC).

This standard is based on IEC 60076-5 : 2006 'Power transformers — Part 5: Ability to withstand short circuit test' with the modification of the temperature requirements at the beginning of short circuit test.

In this revision the requirements for power transformers are covered in various parts as given below:

Part 1 General
Part 2 Temperature rise
Part 3 Insulation levels, dielectric tests and external clearances in air
Part 4 Terminal markings, tappings and connections
Part 7 Loading guide for oil-immersed power transformers
Part 8 Application guide
Part 10 Determination of sound levels

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test or analysis shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value shall be the same as that of the specified value in this standard.

Indian Standard

POWER TRANSFORMERS

PART 5 ABILITY TO WITHSTAND SHORT CIRCUIT

(First Revision)

1 SCOPE

This standard (Part 5) 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 IS 2026 (Part 1).

2 REFERENCES

The following standards are necessary adjuncts to this standard:

IS No.	*Title*
2026	Power transformers:
(Part 1) : 2011	General (*second revision*)
(Part 2) : 2008	Temperature rise (*first revision)*
(Part 3) : 2009	Insulation levels, dielectric tests and external clearances in air (*third revision*)
(Part 8) : 2009	Application guide
10561 : 1983	Application guide for power transformers
11171 : 1985	Specification for 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.

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:

a) Regulating transformers with very low impedance that depend on the impedance of directly connected apparatus to limit overcurrents;
b) Unit generator transformers susceptible to high overcurrents produced by connection of the generator to the system out of synchronism;
c) 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;
d) Special transformers and transformers installed in systems characterized by high fault rates (*see* **3.2.6**); and
e) 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:

a) *Category I*: 25 kVA to 2 500 kVA;
b) *Category II*: 2 501 kVA to 100 000 kVA; and
c) *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 percent 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

Sl No.	Short Circuit Impedance at Rated Current	
	Rated Power kVA	Minimum Short Circuit Impedance, Percent
(1)	(2)	(3)
i)	25-630	4.0
ii)	631-1 250	5.0
iii)	1 251-2 500	6.0
iv)	2 501-6 300	7.0
v)	6 301-25 000	8.0
vi)	25 001-40 000	10.0
vii)	40 001-63 000	11.0
viii)	63 001-100 000	12.5
ix)	Above 100 000	12.5

NOTES

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

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

Sl No.	Highest Voltage for Equipment, *U*m kV	Short Circuit Apparent Power MVA	
		Current European Practice	Current North American Practice
(1)	(2)	(3)	(4)
i)	7.2; 12; 17.5 and 24	500	500
ii)	36	1 000	1 500
iii)	52 and 72.5	3 000	5 000
iv)	100 and 123	6 000	15 000
v)	145 and 170	10 000	15 000
vi)	245	20 000	25 000
vii)	300	30 000	30 000
viii)	362	35 000	35 000
ix)	420	40 000	40 000
x)	525	60 000	60 000
xi)	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* IS 2026 (Part 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 IS 2026 (Part 1) and IS 2026 (Part 2), 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:

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

where

Z_s = short-circuit impedance of the system.

$$Z_s = \frac{U_s^2}{S}, \text{ in ohm } (\Omega) \text{ per phase} \qquad \ldots(2)$$

(equivalent star connection)

where

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

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

U and Z_t = defined as follows:

a) for the principal tapping:

U = rated voltage U_r of the winding under consideration, in kilovolts (kV);

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

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

(equivalent star connection)

where

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

S_r = rated power of the transformer, in megavoltamperes (MVA).

b) for tappings other than the principal tapping:

U = unless otherwise specified, the tapping voltage of the winding under consideration, in kilovolts (kV);

Z_t = 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.

NOTES

1 Here symbols Z_t and z_t are used instead of Z and z, respectively, adopted for the same quantities in IS 2026 (Part 1), for the sake of clarity in connection with the content of **4.2.3**.

2 For the definition of tapping voltage [*see* **5.2** of IS 2026 (Part 1)].

3 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.

Table 3 Maximum Permissible Values of the Average Temperature of Each Winding After Short Circuit

Sl No.	Trans-former Type	Insulation System Temperature (Thermal Class in Brackets) °C	Maximum Value of Temperature °C	
			Copper	Aluminium
(1)	(2)	(3)	(4)	(5)
i)		105 (A)	180	180
		120 (E)	250	200
		130 (B)	350	200
ii)	Dry	155 (F)	350	200
		180 (H)	350	200
		200	350	200
		220	350	200

NOTES

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.

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:

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

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

where

θ_0 = initial winding temperature, in °C;

J = short circuit current density, based on the r.m.s. value of the symmetrical short circuit current, in A/mm^2; and

t = duration, in s.

NOTE — Equations (1), (2), (3), (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;

a) by tests; or
b) 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 IS 2026 (Part 1)] and it shall be specified prior to placing the order. The test shall be carried out in accordance with the requirements given 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 IS 2026 (Part 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 percent.

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 50°C [*see* **10.1** of IS 2026 (Part 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 î 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:

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

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 = reactances of the transformer and the system ($X_t + X_s$), in ohms (Ω); and

R = 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 IS 2026 (Part 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.

NOTE — 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 = base of natural logarithm; and

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

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

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 = reactive component of z_t, in per cent (percent);

r_t = resistance component, at reference temperature, of z_t, in per cent (percent);

z_t = short circuit impedance of the transformer, at reference temperature, in per cent (percent).

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

$1.8 \times \sqrt{2} = 255$ 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*

If the duration of the short circuit test is sufficiently long, the asymmetrical current having first peak amplitude $\hat{\imath}$ will change into the symmetrical current having r.m.s. value *I* (*see* **4.1.2**).

The peak value of the current obtained in testing shall not deviate by more than 5 percent and the symmetrical current by more than 10 percent 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 (*see* Note 2).

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 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.

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.

NOTES

1 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.

2 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.

4.2.5.2 To obtain the initial peak value of the 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.

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.

NOTES

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.

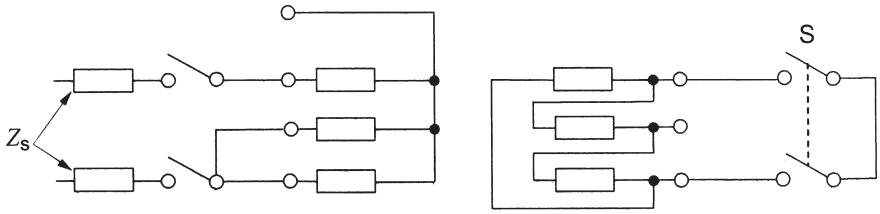
2 For transformers with star-zigzag connection belonging to Category I and with constant flux voltage variation having value for $x_t/r_t \leq 3$ (*see* **4.2.3**), the three phases are switched on simultaneously without the use of a synchronous switch. For other transformers with star-zigzag connection, 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 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 Fig. 1 and Fig. 2.

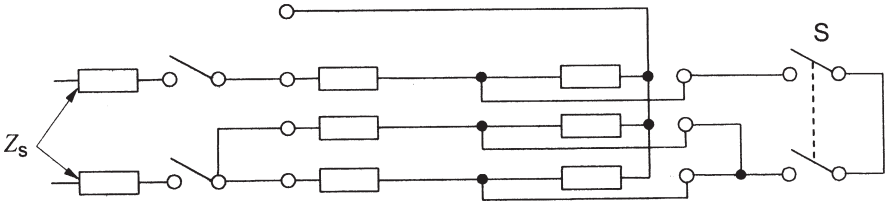


Components

Z_s = test system impedance; and

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

FIG. 1 STAR/DELTA CONNECTED TRANSFORMER



Components

Z_s = test system impedance; and

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

NOTES

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.

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.

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 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.

FIG. 2 STAR/STAR AUTO-TRANSFORMER

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 percent 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.

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, that is 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, that is 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, that is 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:

a) for single-phase transformers: 3; and
b) for three-phase transformers : 9.

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:

a) 0.5 s for transformers of Category I, and
b) 0.25 s for transformers of Categories II and III, with a tolerance of ±10 percent.

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 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.

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,

a) applied voltages; and
b) currents (*see* **4.2.5.2**).

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

NOTES

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.

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.

3 Temporary sparks across 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.

NOTES

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.

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.

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.

NOTES

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.

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.

Different procedures are followed at this stage for transformers of Categories I, II and III. These procedures and reactance limits are given below:

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 percent of the prescribed test value [*see* IS 2026 (Part 3)], 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
   i) 2 percent for transformers with circular concentric coils (*see* Note 3) 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 percent, are acceptable for transformers with a short circuit impedance of 3 percent or more. If the short circuit impedance is less than 3 percent, the above limit of 4 percent is subject to agreement between the manufacturer and the purchaser;
   ii) 7.5 percent for transformers with non-circular concentric coils having a short-circuit impedance of 3 percent or more. The value of 7.5 percent may be reduced by agreement between the manufacturer and the purchaser, but not below 4 percent.

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

NOTES

1 For transformers with non-circular concentric coils having a short circuit impedance below 3 percent, 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 $(22.5 - 5.0\ Z_t)$, Z_t being the short circuit impedance in per cent.

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.

3 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.

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 percent of the prescribed test value [*see* IS 2026 (Part 3)], 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 percent.

If the reactance variation is in the range 1 percent to 2 percent, 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 be applied (*see* Notes 1 to 3 **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 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

(*Clause* 4.2.1)

THEORETICAL EVALUATION OF THE ABILITY TO WITHSTAND THE DYNAMIC EFFECTS OF SHORT CIRCUIT

A-1 GENERAL

This Annex gives guidelines for the theoretical evaluation of the ability of a power transformer to withstand the dynamic effects of short circuit, based on calculation and consideration of the design characteristics and manufacturing practices.

A-2 DESIGN REVIEW

The theoretical evaluation of the ability of a power transformer to withstand the dynamic effects of short circuit consists of a design review covering the main mechanical strength aspects of the transformer. The documentation needed for the purpose includes all necessary technical data, such as electromagnetic design data sheets, calculations of short circuit currents, electromagnetic forces and mechanical stresses, supplemented by drawings, material specifications, manufacturing practices and process instructions, etc, either produced for the specific purpose of the

electromagnetic and mechanical design of the transformer or as part of the manufacturer's technology documentation.

The design review should check the most critical mechanical force and stress values appearing in the design as a consequence of the fault conditions specified. Such values should either be compared with the corresponding ones relating to a reference transformer successfully short circuit tested, on condition that the transformer under consideration is similar (*see* Note) or be checked against the manufacturer's design rules for short circuit strength. The winding support structure and overall clamping arrangement, as well as the manufacturing practices are also matter for consideration in the design review.

NOTE — As regards the definition of similar transformer (*see* Annex B).

The design review described in this Annex mainly applies to transformers of Categories II and III.

For transformers of Category I, which are normally classified as units that are purchased in bulk, the evaluation procedure consisting in carrying out a short circuit withstand test on one or two units should be preferred. Short circuit testing of one or two of units of a bulk order is normally considered as the quickest and cheapest way to verify conformance. Nevertheless, for these transformers it is also possible to adopt the evaluation procedure consisting of a design review.

With regard to transformers of Categories II and III, it is acknowledged that sometimes it turns out to be difficult for the manufacturer to find in his files a reference transformer fit for the purpose of comparison, with respect to similarity. In this case, for the purpose of evaluation the transformer may be simultaneously compared with a limited number of successfully short circuit tested transformers on condition that each of its characteristics, as listed in Annex B, equals the corresponding one on at least one of the transformers selected for reference.

For example, the evaluation of the design of a three-phase autotransformer provided with a delta-connected tertiary winding at reduced capacity can be split into two parts, namely:

a) As regards the series and common windings: comparison with the design data relevant to a three-phase autotransformer with no tertiary winding; and
b) As regards the tertiary winding: comparison with a three-phase transformer with a tertiary winding at reduced capacity, on which the tertiary winding has also been tested.

A-3 GUIDELINES FOR CONDUCTING THE DESIGN REVIEW

A-3.1 General

The design review should consist of the following steps:

a) Examination of the transformer based on pertinent technical documentation.
b) Evaluation of the transformer either:
   1) by comparison with a reference transformer which has passed the short-circuit test successfully, or
   2) by check against the manufacturer's design rules for short-circuit strength.
c) Result of the design review and formal acknowledgement of the transformer.

A-3.2 Information Relating to the Transformer to be Evaluated

The evidence to be presented by the manufacturer for the purpose of the design review should include the following items:

a) Electromagnetic design data sheets as needed for calculation.
b) Drawings or sketches of the complete winding and insulation arrangement within the core window with indication of the types of material.
c) Calculation of the short circuit current values (both peak and symmetrical r.m.s. values) affecting each single winding as a result of the service duty requirements specified and types of fault taken into consideration, with also due regard to the tapping positions in case of winding(s) provided with taps.
d) Calculation of the main short circuit forces (peak values occurring at the highest peak of the respective current), with reference to the fault cases, tapping positions and geometrical and relative positions of windings considered for design purposes. Full information has to be given, if any simplified geometrical configurations have been adopted for the windings, core and tank for the purpose of magnetic leakage field and electromagnetic force calculations.

Axial short circuit forces with core-type transformers and radial short circuit forces with shell-type transformers, respectively, are very sensitive to the relative positions of the windings holding m.m.fs of opposite sign. The manufacturer should specify which are the amounts of displacement due to workshop tolerances he has considered as well as the winding

configurations (planes of symmetry and boundary conditions) he has assumed for the purpose of short circuit force calculations.

The following electromagnetic forces should be considered:

a) *With core-type transformers*

1) radial inward or outward force on each physical winding;
2) maximum axial compression force on each physical winding (F^*_c) (*see* Note 1);
3) maximum axial end thrust force (up/down) on each physical winding;
4) maximum axial force-per-limb on common press ring (or plate), if used, and core clamps; and
5) thrust force acting on the lead exits of each main low-voltage winding (T^*_f) (*see* Note 2).

b) *With shell-type transformers*

1) axial forces acting on each coil and on winding groups at the inside and the outside of the core window;
2) radial forces acting on pancake coils;
3) total force on inter-phase wedges and press blocks against the core and tank reinforcement structures;
4) total force on core laminations; and
5) total force on tank reinforcement structures.

For each physical winding, the most severe force condition resulting from the fault cases and tapping positions considered in design has to be identified. As regards the whole structure of the transformer, one has to consider the forces resulting from the fault case involving the highest amount of reactive power drawn from the system(s).

Calculation of basic mechanical stresses on winding conductors and adjacent mechanically coupled structures originated by the short circuit forces. The following mechanical stresses should be considered.

c) *With core-type transformers*

1) mean hoop tensile stress on outer windings (σ^*_t) (*see* Note 3);
2) mean hoop compressive stress on disc-, helical-, single-layer-type inner windings (σ^*_c) (*see* Note 4);
3) equivalent mean hoop compressive stress on layer-type inner windings ($\sigma^*_{c,\,eq}$) (*see* Note 5);
4) stress due to radial bending on conductors in the span between axial sticks and between spacers used to build any axial cooling ducts within the winding radial width (σ^*_{br});
5) stress due to axial bending on conductors in the span between radial spacers with disc- and helical-type windings (σ^*_{ba});
6) compressive stress on radial spacers with disc- and helical-type windings (σ^*_{sp}) (*see* Note 6);
7) compressive stress on conductor paper insulation with layer-type windings (σ^*_{pi});
8) compressive stresses on end stack insulation structures (σ^*_{es}) and end rings (σ^*_{er});
9) compressive stress on common press rings (or plates), if used (σ^*_{pr}); and
10) tensile stress on tie rods (flitch plates) of the clamping structure (σ^*_{rod}).

d) *With shell-type transformers*

1) stress due to axial bending on conductors in the span between coil spacers (σ^*_{ba});
2) compressive stress on conductor paper insulation (σ^*_{pi}) and on spacers (σ^*_{sp}) in pancake coils;
3) compressive stress on inter-phase wedges (σ^*_{iw}) and on press blocks against the core and tank reinforcement structures (σ^*_{pb});
4) tensile and bending stress on core laminations (σ^*_{cl}); and
5) tensile and bending stress on tank reinforcement structures (σ^*_{tr}).

NOTES

1 See Note 2 after Table 6.

2 For the definition and calculation of the thrust force acting on the low-voltage winding lead exits (*see* **A-3.3.2.2**).

3 As regards mean hoop tensile stress calculation, disc- and helical-type windings provided with one or more cooling ducts within their radial width can be treated like solid rings with no ducts.

4 As regards mean hoop compressive stress calculation, disc- and helical-type windings provided with one or more cooling ducts within their radial width can be treated like solid rings with no ducts.

5 In the case of two equal layers the equivalent mean hoop compressive stress is equal to the arithmetic mean of the respective stresses. In the case of three or more layers, the above stress is assumed to be equal to 1.1 times the arithmetic mean of the compressive stresses calculated on the various layers.

6 Compressive stress on radial spacers is calculated by considering the area covered by the bare conductors and by neglecting any effect relating to their corner radius.

For each physical winding and structural component, the most severe stress condition originated by the short circuit forces should be considered.

a) Drawings, sketches, or computer outputs, concerning the winding support structure and core-and-coil clamping arrangement, such as

   1) *With core-type transformers*

      arrangement of the radial supports against the core limb, configuration of the end stack insulation structures, common press rings (or plates), if used, overall core-and-coil clamping arrangement, etc.

   2) *With shell-type transformers*

      i) axial clamping arrangement, press blocks, fillers, wedging arrangement for coil heads and between phases, insulation barriers between windings and core, etc.

      ii) supports of the core against the tank, arrangement of the springs to hold the core, tank reinforcement structures, other fastening provisions of the lamination stack, etc.

   3) *In general*

      i) means for securely fastening the winding lead exits and LV connection leads or bars to the bushings and lead runs to tap-changers, etc.

      ii) means for the application of any axial pre-load.

b) Instructions for quality assurance and quality control concerning both materials and manufacturing practices, with specific reference to manufacturing activities such as,

   1) winding of the conductors on the mandrel and control of the pulling force, sizing and elastic stabilizing of windings and coils, assembling within specified tolerances, drying and impregnation with oil, application of pre-load (clamping force), fastening/securing of winding supports, leads and clamping devices, etc.

   2) specifically for shell-type transformers: clamping and pressing of the coils at the inside and the outside of the core window by means of inter-phase wedges, press blocks for the purpose of clamping against the core and tank reinforcements, etc.

c) Checks concerning main transformer external components, in particular high-voltage bushings, especially in the case where they are slope-mounted on turrets, etc.

A-3.3 Evaluation of the Transformer

A-3.3.1 *General*

In the evaluation of the transformer, two alternative methods can be pursued, based either on the comparison with a reference transformer that has passed the short circuit test successfully (*see* **A-3.3.2**) or the check against documented design rules for short-circuit strength adopted by the manufacturer in regular production (*see* **A-3.3.3**).

These alternative methods are described below.

A-3.3.2 *Evaluation by Comparison with a Reference Transformer*

A-3.3.2.1 *Acknowledgement of the reference transformer*

The reference transformer is judged suitable for the purpose of comparison on condition that it fulfills the following requirements:

a) Its characteristics are such that the transformer on evaluation can be considered similar.

b) It has been designed by basically the same calculation methods and mechanical withstand criteria as those employed for the transformer under evaluation.

c) It has been manufactured according to basically the same practices, quality assurance and quality control instructions as those employed for the transformer under evaluation.

d) The validity range of the rules for short circuit strength adopted for design covers the characteristics of both transformers.

The reference transformer should have passed the short circuit test successfully.

The acknowledgement of the reference transformer(s) consists of the following steps:

a) A check that it is suitable for the purpose of comparison as described above.

b) Examination of the report(s) concerning the short circuit test(s).

c) Acknowledgement of the main electromagnetic design data, calculations performed and mechanical withstand criteria adopted for design.

d) Acknowledgement of the practices adopted for manufacture and quality assurance and quality control instructions.

A-3.3.2.2 *Comparative evaluation*

The comparative evaluation should start with the examination and comparison of the winding and main

insulation structures and clamping arrangement of the two transformers, especially in the light of their respective apparent mechanical withstand characteristics. From this comparative evaluation it should be possible to conclude that the transformer on evaluation is, in principle, as robust as the reference transformer with regard to its basic mechanical structure.

Corresponding force and stress values (*see* **A-3.2**) calculated on the two transformers are then to be compared. For this purpose, the use of Table 5 or Table 6 is recommended. Any force or stress figure relating to the actual transformer on evaluation and to the reference transformer should be entered into the corresponding cell in the columns marked "act." (actual) and "ref." (reference), respectively. The highest force or stress value resulting from the short circuit conditions considered in design should be used both for each physical winding and associated components and for the whole mechanical structure of the transformer.

As a result of the comparison, the transformer is considered able to withstand the dynamic effects of short circuit on condition that none of its force or stress figures to be filled in Table 5 or Table 6 exceeds 1.2 times the corresponding one calculated on the reference transformer, except for the following stresses and forces for which more stringent requirements are suggested to be applied for core-type transformers.

a) Mean hoop compressive stress on disc-helical- and single-layer-type windings;

$$\sigma^*_{c,\,act} \leq 1.1 \times \sigma^*_{c,\,ref}$$

b) Equivalent mean hoop compressive stress on multi-layer-type windings;

$$\sigma^*_{c,\,eq,\,act} \leq 1.1 \times \sigma^*_{c,\,eq,\,ref}$$

c) Thrust force acting on the low-voltage winding lead exits (*see* Note); and

$$T^*_{f,\,act} \leq 1.1 \times T^*_{f,\,ref}$$

NOTE — The thrust force acting on the low-voltage winding lead exits (kN) is assumed conventionally to be equal to the product of mean hoop compressive stress on the winding (kN/mm^2) and cross-sectional area of the lead exit (mm^2). The thrust force might deform the winding by tightening it up with a screwing pattern. In the rare case that the low-voltage winding is an outer winding, the stress is of a tensile nature and the winding might show a tendency to unwind.

A-3.3.3 *Evaluation by Check Against the Manufacturer's Design Rules for Short Circuit Strength*

A-3.3.3.1 *Acknowledgement of the manufacturer's design information for short circuit strength*

The rules for short circuit strength on which the manufacturer has based the design of the unit to be evaluated should possess a solid experimental basis. This means that these rules should stem from the analysis either of the results of a number of short circuit withstand tests performed on actual transformers or the outcome of tests performed on representative transformer models combined to any indirect supportive evidence based on a long duration, trouble-free operation of a number of transformers in the field as regards the short circuit performance, or both. The manufacturer should present the following information.

a) The list of transformers built by the manufacturer which have been subject to the short circuit test, including main transformer data, such as rated power, rated voltage, tapping range, and short circuit impedance.
b) The results of the tests performed on models, if any, and their impact on the design rules.
c) The contents of the technical standards for short circuit strength of power transformers used by the manufacturer in regular design and production activities.
d) Service records and in-field failure rates as regards short circuit performance.
e) The number of units produced and the number of service years of successfully operated transformers.

From the above information it should be proved that the manufacturer has adequate design rules for short circuit strength.

A-3.3.3.2 *Checking procedure*

The checking procedure should start with a preliminary examination of the winding and main insulation structures and clamping arrangement of the transformer. From this examination, it should result that both such structures and the clamping arrangement are consistent with the corresponding ones adopted by the manufacturer in his production of short circuit safe transformers.

The next step consists of comparing any force and stress values (*see* **A-3.2**) calculated on the transformer with the corresponding allowable or critical values that the manufacturer has adopted in his design practice (*see* Note 1). Such values could be different for different manufacturers. For this purpose, the use of Table 5 or Table 6 is recommended. Any force or stress figure relating to the transformer on evaluation should be entered into the appropriate cell in the column marked "act." (actual). Any

corresponding allowable or critical force or stress figure that the manufacturer has adopted as a design rule should be entered into the appropriate cell in the columns marked "all." (allowable) or "crit." (critical). The highest force or stress value resulting from the short circuit conditions considered in design should be used for each physical winding and associated components and for the whole structure, respectively.

As a result of the check, the transformer is considered to be able to withstand the dynamic effects of short circuit on condition that none of its force or stress figures filled in Table 5 or Table 6 exceeds the corresponding maximum allowable force or stress figure adopted by the manufacturer for design purposes and 0.8 times the corresponding critical stress value identified by the manufacturer.

The allowable force and stress limits which are given below for the purpose of guidance are based on past experience, under due consideration of the boundary conditions, such as material properties, tolerances, mechanical design details and production processes. Nevertheless, they are not to be considered as standard limits and may be exceeded in the design on condition that the manufacturer can demonstrate any solid and documented experience with higher values.

a) *With core-type transformers* (*see* Note 2)

1) Mean hoop tensile stress on disc- and helical-type windings and on each individual layer of multi-layer-type windings (*see* Note 3)

$$\sigma^*_{t,\,act} \leq 0.9 \times R_{p0.2}$$

2) Mean hoop compressive stress on disc-helical- and single-layer-type windings

i) with regular strands and non-bonded CTCs (*see* Note 4)

$$\sigma^*_{c,\,act} \leq 0.35 \times R_{p0.2}$$

ii) with resin-bonded strands and CTCs

$$\sigma^*_{c,\,act} \leq 0.6 \times R_{p0.2}$$

3) Equivalent mean hoop compressive stress on multi-layer-type windings

i) with regular strands and non-bonded CTCs

$$\sigma^*_{c,\,eq,\,act} \leq 0.35 \times R_{p0.2}$$

ii) with resin-bonded strands and CTCs

$$\sigma^*_{c,\,eq,\,act} \leq 0{,}6 \times R_{p0.2}$$

4) Stress due to radial bending on conductors in the span between axial sticks or spacers

$$\sigma^*_{br,\,act} \leq 0{,}9 \times R_{p0.2}$$

5) Stress due to axial bending on conductors in the span between radial spacers

$$\sigma^*_{ba,\,act} \leq 0.9 \times R_{p0.2}$$

6) Maximum axial compression force on each physical winding in relation to conductor tilting (*see* Note 5)

$$F^*_{c,\,act} \leq 0.8 \times F^*_{tilt}$$

7) Compressive stress on radial spacers (*see* Note 6)

i) in the presence of paper covering on conductors

$$\sigma^*_{sp,\,act} \leq 80 \text{ MPa}$$

ii) in the presence of pure enamel coating on conductors

$$\sigma^*_{sp,\,act} \leq 120 \text{ MPa}$$

8) Compressive stress on conductor paper insulation with layer-type windings

$$\sigma^*_{pi,\,act} \leq 35 \text{ MPa}$$

9) Compressive stress on pressboard end rings (wound-type)

$$\sigma^*_{er,\,act} \leq 40 \text{ MPa}$$

10) Compressive stress on pressboard end rings (stacked-type)

$$\sigma^*_{er,\,act} \leq 80 \text{ MPa}$$

11) Compressive stress on pressboard common press rings or press plates (if used)

$$\sigma^*_{pr,\,act} \leq 80 \text{ MPa}$$

12) Tensile stress on tie rods (flitch plates) of the clamping structure (*see* Note 7)

$$\sigma^*_{rod} \leq R_{eL}$$

b) *With shell-type transformers*

1) Stress due to axial bending on conductors in the span between coil spacers

$$\sigma^*_{ba,\,act} \leq 0.9 \times R_{p0,2}$$

2) Compressive stress on inter-phase wedges and press blocks made of pressboard

$$\sigma^*_{iw,\,act}\ \sigma^*_{pb,\,act} \leq 80 \text{ MPa}$$

3) Compressive stress on inter-phase wedges and press blocks made of fibre reinforced plastics or laminated wood

$$\sigma^*_{iw,\,act}\ \sigma^*_{pb,\,act} \leq 120 \text{ MPa}$$

4) Tensile and bending stress on core laminations

$$\sigma^*_{cl,\,act} \leq R_{eL}$$

5) Tensile and bending stress on tank reinforcement structures

$$\sigma^*_{tr,\,act} \leq R_{eL}$$

6) Pressure on the areas of the overlap of the laminations (*see* Note 8)

$$P_{act} \geq P$$

NOTES

1 Allowable value means any force or stress value that the structure can withstand without being impaired in its strength and function; critical value means any force or stress value which causes any permanent deformation, loss of stability or collapse on the structure.

2 In the case of core-type transformers, specific attention is drawn to the importance of hoop compressive stresses on the windings. Windings subjected to hoop compressive stresses may fail because of either inward over-bending of conductors in the spans between two consecutive supports (forced buckling) or loss of form stability resulting in heavy radial deformations of conductors at one or few locations on the winding circumference (free buckling).

Forced buckling typically occurs on windings provided with relatively stiff supports at their inner contour.

Free buckling is a more common pattern of collapse, which occurs suddenly as soon as the critical compressive stress value for the structure is attained.

Setting any critical compressive stress value for free buckling is a highly complex task, both because of the non-homogeneous nature of the windings and the influence resulting from the manufacturing processes.

For the reasons above, no specific formulas for critical hoop compressive stresses on windings have been given.

Additional information about buckling and other technical issues relating to the short-circuit capability of power transformers are given in Cigre Brochure 209, "The Short Circuit Performance of Power Transformers", August 2002.

3 The proof stress $R_{p0,2}$ is the tensile stress which produces, when the load is still applied, a non-proportional elongation equal to 0,2 percent of the gauge length.

4 CTCs means continuously transposed conductors.

5 For F^*_{tilt}, *see* Note 2 after Table 6.

6 Valid for spacers made of pre-compressed pressboard.

7 R_{eL} is the lower yield stress of the material, practically equal to $R_{p0,2}$.

8 For *P*, *see* Note 3 after Table 6.

A-3.4 Result of the Design Review and Acknowledgement of the Transformer Under Evaluation

The result of the design review is positive if,

a) requirements of the specification have been checked to duly cover the actual system conditions;

b) design fully covers the specification;

c) design review has been performed according to **A-3.1** or **A-3.2** to identify all the resultant forces and stresses;

d) evaluation of the transformer under consideration has been performed according to **A-3.3.2** or **A-3.3.3** and the compliance with the short-circuit force and stress criteria listed in this Annex is evident from the content of Table 5 or Table 6; and

e) mechanical design and production/ manufacturing processes have been judged to adequately provide the required short circuit performance of the transformer.

The purchaser is requested to formally acknowledge that the design review of the transformer has been

Table 5 Comparison of Forces and Stresses in Core-Type Transformers
(*Clauses* A-3.3.3.2 *and* A-3.4)

Sl No.	Type of Force/ Stress	LV Winding				MV Winding				HV Winding				Tap Winding			
		act.	ref.	all.	crit	act.	ref.	all.	crit.	act.	ref.	all.	crit.	act.	ref.	all.	crit.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
i)	Mean hoop tensile stress on disc-, helical- and layer-type windings (MPa)																
ii)	Mean hoop compressive stress on disc-, helical-, single layer type windings (MPa)																
iii)	Equivalent mean hoop compressive stress on multi-layer-type windings (MPa)																
iv)	Stress due to radial bending of conductors between axial sticks and spacers (MPa)																

Table 5 — *Concluded*

Sl No.	Type of Force/ Stress	LV Winding				MV Winding				HV Winding				Tap Winding			
		act.	ref.	all.	crit	act.	ref.	all.	crit.	act.	ref.	all.	crit.	act.	ref.	all.	crit.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
v)	Stress due to axial bending of conductors between radial spacers (MPa)																
vi)	Thrust force acting on the low-voltage winding lead exits (kN)																
vii)	Maximum axial compression force on each physical winding (kN)																
Maximum axial compression force on winding compared to crit. force for tilting (kN)																	
Maximum end thrust force on physical winding: – up (kN) – down (kN)																	
Compressive stress on conductor paper insulation and radial spacers (MPa)																	
Compressive stress on end stack insulation structures and end ring (MPa)																	
Compressive stress on common press rings (or plates) (MPa)										act.		ref.	all.		crit.		
Tensile stress on tie rods (flitch plates) (MPa)										act.		ref.	all.		crit.		
Clamping force per limb (kN)										act.		ref.	all.				

act. = calculated force or stress value relating to the transformer under consideration.

ref. = calculated force or stress value relating to the reference transformer.

all. = allowable force or stress value (based on manufacturer's design rules).

crit. = critical force or stress value (based on manufacturer's design rules).

carried out with positive result by following the guidelines described in this Annex. In this light, an appropriate statement should be signed jointly by the purchaser and the manufacturer.

The purchaser's signature does not exempt the manufacturer from any of his obligations as regards absence of non-conformities and the ability of the transformer in question to withstand the dynamic effects of short circuit in connection with the service duty requirements specified.

The information released to the purchaser in the occasion of the design review remains the manufacturer's intellectual property and should be kept confidential.

Table 6 Comparison of Forces and Stresses in Shell-Type Transformers
(*Clauses* A-3.3.3.2 *and* A-3.4)

Sl No.	Type of Force/ Stress	LV Winding				MV Winding				HV Winding				Tap Winding			
		act.	ref.	all.	crit.	act.	ref.	all.	crit.	act.	ref.	all.	crit.	act.	ref.	all.	crit.
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)
i)	Stress due to axial bending on conductors in the span between coil spacers (MPa)																
ii)	Compressive stress on conductor paper insulation and spacer (MPa)																
iii)	Total force on inter-phase wedges and press blocks (kN)	act.				ref.				all.				crit.			
iv)	Total force on core laminations (kN)	act.				ref.				all.				crit.			
v)	Total force on tank reinforcement structure (kN)	act.				ref.				all.				crit.			
vi)	Compressive stress on inter- phase wedges and press blocks (MPa)	act.				ref.				all.				crit.			
vii)	Tensile / bending stress on core laminations due to radial forces (MPa)	act.				ref.				all.				crit.			
viii)	Tensile / bending stress on tank reinforcement structure due to axial forces (MPa)	act.				ref.				all.				crit.			
ix)	Pressure on the areas of the overlap of the laminations (MPa)	act.				ref.				all.				crit.			

Act = calculated force or stress value relating to the transformer under consideration.
ref. = calculated force or stress value relating to the reference transformer.
all = allowable force or stress value (based on manufacturer's design rules).
crit. = critical force or stress value (based on manufacturer's design rules).

NOTES

1 Symbol * (apex) has been used in this Annex to denote a physical quantity (force or stress) that relates to a condition of maximum peak of prospective short circuit current.

2 With core-type transformers, when a physical winding is subject to an excessive axial compression force, it may lose its capability to remain mechanically stable. In this case, the winding conductors "tilt": the whole set of adjacent conductors inside the radial width of the winding turn in the same direction, whereas the next axially adjacent set of conductors turns in the opposite direction. The result is a zigzag deformation pattern assumed by the winding conductors.

It is, therefore, required that the maximum axial compression force F^*_c acting on the winding be less than the critical force F^*_{tilt} that triggers a collapse by conductor tilting. There should also be an adequate safety margin between the two.

3 The pressure P which is necessary to apply on the areas of the overlap of the core laminations in order to hold the

magnetic circuit should be at least

$$P = \frac{F^* .10^3}{2.S.a.t.h} \text{ (MPa)}$$

where

F^* = short circuit force (peak value) exerted onto the end yoke in, kN;

S = area of the corner overlap of the core laminations in mm^2;

a = adherence factor in, p.u.;

t = number of sheets of core laminations per unit of height in, mm^{-1}; and

h = height of the magnetic circuit, in mm.

One has to distinguish between two cases:

a) with disc-, helical- and layer-type windings having conductors consisting of resin-bonded CTCs, there is no design constraint as regards the maximum axial compression force in relation with tilting. In fact, such conductors are extremely resistant to tilting, irrespective of the work hardening degree of the copper material. No check is therefore required; and

b) with disc-, helical- and layer-type windings having conductors consisting of strands or non-bonded CTCs, the corresponding critical force for tilting F^*_{tilt} should be calculated on the basis of the following equation:

$$F^*_{tilt} = \left[K_1 . E_0 . \frac{n . b_{eq} . h^2}{D_{mw}} + K_2 . \frac{n . X . b_{eq}^3 . \pi . D_{mw} . \gamma}{h} \right] . K_3 . K_4 . 10^{-3} \text{ (kN)}$$

where

E_0 = modulus of the elasticity of copper
= 1.1×10^5 MPa;

n = number of strands or twin conductors in the winding radial width, in the case of flat conductors, and is equal to $g \cdot (f - 1)/2$ in the case of a CTC;

where

g = number of CTCs in the winding radial width;

f = number of strands in a single CTC;

b_{eq} = radial width of the strand in the case of flat conductors, in mm;
= twice the radial width of a single conductor in the case of resin-bonded twin conductors, in mm;
= radial width of a single strand in the case of non-bonded CTC, in mm;

D_{mw} = average diameter of the winding (in mm);

$X = \frac{c . z}{\pi . D_{mw}}$ = spacer coverage factor for disc- and helical-type windings

where

c = radial spacer width (in the circumferential direction), in mm;

z = number of radial spacers on the circumference;

X = 1.0 for layer-type windings;

h = strand height if the conductor is a flat conductor, in mm;

is twice the height of a single strand if there are two parallel strands in the axial direction which are paper covered together (in mm);
= height of a single strand if the conductor is a CTC, in mm;

γ = constant for conductor shape;
= 1.0 for standard strand corner radius;
= 0.85 for fully rounded strands or conductors;

K_1 = coefficient for the twisting term = 0.5;

K_2 = coefficient for the bedding term (N/mm^3);
= 45 for single and twin conductors;
= 22 for non-bonded CTC;

K_3 = factor accounting for the copper work hardening degree (*see* Table 7);

K_4 = factor accounting for dynamic tilting (*see* Table 8).

Table 7 Values for Factor K_3
(*Clause* A-3.4)

$R_{p0.2}$ MPa	K_3
Annealed	1.0
150	1.1
180	1.2
230	1.3
>230	1.4

Table 8 Values for Factor K_4
(*Clause* A-3.4)

Conductor Type	Winding Type	
	Disc-helical	Layer
Strand or twin	1.2	1.1
Non-bonded CTC	1.7	1.3

It should be noted that the above equation to calculate F^*_{tilt} refers to dynamic tilting and is based on a semi-empirical approach. The actual critical value of the force also depends on the winding construction and the nature and thickness of the conductor insulation.

ANNEX B
(*Clause* A-2)
DEFINITION OF SIMILAR TRANSFORMER

B-1 A transformer is considered similar to another transformer taken as a reference if it has the following characteristics in common with the latter:

a) Same type of operation, for example generator step-up unit, distribution, interconnection transformer;
b) Same conceptual design, for example dry type, oil-immersed type, core type with concentric windings, sandwich type, shell type, circular coils, non-circular coils;
c) Same arrangement and geometrical sequence of the main windings;
d) Same type of winding conductors, for example aluminium, aluminium alloy, annealed or work-hardened copper, metal foil, wire, flat conductor, continuously transposed conductors and epoxy bonding, if used;
e) Same type of main windings, for example helical-, disc-, layer-type, pancake coils;
f) Absorbed power at short circuit (rated power/ per unit short-circuit impedance) between 30 percent and 130 percent of that relating to the reference transformer;
g) Axial forces and winding stresses occurring at short circuit not exceeding 120 percent of those relating to the reference transformer;
h) Same manufacturing processes; and
j) Same clamping and winding support arrangement.

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This Indian Standard has been developed from Doc No.: ETD 16 (6061).

Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected

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Published by BIS, New Delhi