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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Power transformers –
Part 12: Loading guide for dry-type power transformers

Transformateurs de puissance –
Partie 12: Guide de charge pour transformateurs de puissance de type sec

IEC 60076-12:2008

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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 60076-12 has been prepared by IEC technical committee 14: Power transformers.

This standards cancels and replaces IEC 60905 (1987). This first edition constitutes a technical revision.

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

FDIS	Report on voting
14/584/FDIS	14/590/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.

A list of all parts of IEC 60076 series, under the general title *Power transformers,* can be found on the IEC website.

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- withdrawn: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.

INTRODUCTION

This part of IEC 60076 provides guidance for the specification and loading of dry type power transformers from the point of view of operating temperatures and thermal ageing. It provides the consequence of loading above the nameplate rating and guidance for the planner to choose appropriate rated quantities and loading conditions for new installations.

IEC 60076-11 is the basis for contractual agreements and it contains the requirements and tests relating to temperature-rise figures for dry type power transformers during continuous rated loading. It should be noted that IEC 60076-11 refers to the average winding temperature rise while this part of IEC 60076 refers mainly to the hot-spot temperature and the latter stated values are provided only for guidance.

This part of IEC 60076 gives mathematical models for judging the consequence of different loading, with different temperatures of the cooling medium, and with transient or cyclical variation with time. The models provide for the calculation of operating temperatures in the transformer, particularly the temperature of the hottest part of the winding. This hot-spot temperature is used for estimation of the number of hours of life time consumed during a particular time period.

This part of IEC 60076 further presents recommendations for limitations of permissible loading according to the results of temperature calculations or measurements. These recommendations refer to different types of loading duty – continuous loading, short-time and long time emergency loading. An explanation of ageing fundamentals is given in Annex A.

POWER TRANSFORMERS –

Part 12: Loading guide for dry-type power transformers

1 Scope

This part of IEC 60076 is applicable to dry-type transformers according to the scope of IEC 60076-11. It provides the means to estimate ageing rate and consumption of lifetime of the transformer insulation as a function of the operating temperature, time and the loading of the transformer.

NOTE For special applications such as wind turbine application transformers, furnace transformers, welding machine transformers, and others, the manufacturer should be consulted regarding the particular loading profile.

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

IEC 60216-1, *Electrical insulating materials – Properties of thermal endurance – Part 1: Ageing procedures and evaluation of test results*

IEC 61378-1:1997, *Convertor transformers – Part 1: Transformers for industrial applications*

3 Terms and definitions

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

3.1
long-time emergency loading
loading resulting from the prolonged outage of some system elements that will not be reconnected before the transformer reaches a new and higher steady state temperature

3.2
short-time emergency loading
unusually heavy loading of a transient nature (less than one time constant of the coil) due to the occurrence of one or more unlikely events which seriously disturb normal system loading

3.3
hot-spot
if not specifically defined, “hot-spot” means the hottest-spot of the winding

3.4
relative thermal ageing rate
for a given hot-spot temperature, the rate at which transformer insulation ageing is reduced or accelerated compared with the ageing rate at a reference hot-spot temperature

3.5
transformer insulation life time
the total time between the initial state for which the normal transformer insulation life time is considered new and the final state when due to thermal ageing, dielectric stress, short-circuit stress, or mechanical movement, which could occur in normal service and result in a high risk of electrical failure

3.6
AN cooling
cooling by natural air ventilation

3.7
AF cooling
method of cooling to increase the rated power of the transformer with fan cooling

4 Effect of loading beyond nameplate rating

4.1 General

Normal life expectancy is a conventional reference basis for continuous duty under design ambient temperature and rated operating conditions. The application of a load in excess of nameplate rating and/or an ambient temperature higher than specified ambient temperatures involves a degree of risk and accelerated ageing. It is the purpose of this part of IEC 60076 to identify such risks and to indicate how, within limitations, transformers may be loaded in excess of the nameplate rating.

4.2 General consequences

The consequences of loading a transformer beyond its nameplate rating are as follows:

– the temperatures of windings, terminals, leads, tap changer and insulation increase, and can reach unacceptable levels;
– enclosure cooling is more sensitive to overload leading to a more rapid increase in insulation temperature to unacceptable levels;
– as a consequence, there will be a risk of premature failure associated with the increased currents and temperatures. This risk may be of an immediate short-term character or may come from the cumulative effect of thermal ageing of the insulation in the transformer over many years.

NOTE Another consequence of overload is an increased voltage drop in the transformer.

4.3 Effects and hazards of short-time emergency loading

The main risks, for short-time emergency loading over the specified limits, are

– critical mechanical stresses due to increased temperature, which can reach an unacceptable level causing cracks in the insulation of a cast resin transformer;
– mechanical damage in the winding due to short and repetitive current above rated current;
– mechanical damage in the winding due to short and repetitive current combined with ambient temperature higher than specified;
– deterioration of mechanical properties at higher temperature could reduce the short-circuit strength;
– reduction of dielectric strength due to elevated temperature.

As a result the maximum overcurrent is limited to 50 % over the rated nominal current.

The agreement of the manufacturer is necessary in case of overloading in excess of 50 % to assess the consequences of such overloading. In any case the duration of such overloading should be kept as short as possible.

4.4 Effects of long-time emergency loading

The effects of long-time emergency loading are the following:

– cumulative thermal deterioration of the mechanical and dielectric properties of the conductor insulation will accelerate at higher temperatures. If this deterioration proceeds far enough, it reduces the lifetime of the transformer, particularly if the apparatus is subjected to system short-circuits;

– other insulation materials, as well as structural parts and the conductors, suffer increased ageing rate at higher temperature;

– the calculation rules for ageing rate and consumption of lifetime are based on considerations of loading.

5 Ageing and transformer insulation lifetime

5.1 General

Experience indicates that the normal lifetime of a transformer is some tens of years. It cannot be stated more precisely, because it may vary even between identical units, owing in particular to operating factors, which may differ from one transformer to another. With few exceptions a transformer rarely operates at 100 % of rated current throughout its lifetime. Other heating factors such as insufficient cooling, harmonics, over fluxing and/or unusual conditions as described in 60076-11 could also affect the life of the transformer.

When heat, which is mainly due to the transformer losses, is transferred to the insulation system, a chemical process begins. This process changes the molecular structure of the materials which form the insulation system. The ageing rate increases with the amount of heat transferred to the system. This process is cumulative and irreversible, which means that the materials do not regain their original molecular structure when the heat supply stops and the temperature decreases. The thermal index of the insulation system is stated in the manufacturer's documentation and is also written on the rating plate. It is assumed that failing insulation due to ageing is one of the causes of end of lifetime of the transformer.

Further it is assumed that the ageing rate varies with temperature according to the Arrhenius' equation. See Annex A for additional background information. The two constants in Arrhenius' equation should ideally be determined by means of thermal endurance testing. In cases where data from such testing is missing, this guide provides estimated constants, which are calculated on the basis of the following assumptions:

– a temperature increase of 6 K doubles the ageing rate. 6 K is an estimated value for the whole winding linked with the value of specific materials used in the winding;

– another value for this doubling rate should be used when supported by thermal endurance tests on the complete electrical insulation system (EIS), according to IEC 60216-1;

– insulation failures are the cause of end of life of the transformer.

5.2 Lifetime

The expected lifetime L of a transformer at a constant hot-spot thermodynamic temperature T in Kelvin (K) can be calculated by means of the equation:

$$L = a \times e^{\frac{b}{T}} \qquad (1)$$

This equation can be written more conveniently as:

$$L = a \times \exp(\frac{b}{T}) \quad (2)$$

Although any time unit may be used in these formulas, the hour is used in this guide. The constant a, given in Table 1 for the different insulation system temperatures, is based on this time unit.

NOTE 1 The expected lifetime calculated according to this equation should not be perceived in a too literal sense. The ability of the transformer to withstand high over-currents due to short-circuits in the power system and over-voltages is, after this theoretically calculated lifetime, certainly weakened compared to a new transformer. In the absence of such disturbances the transformer may still operate satisfactorily for many years. Taking precaution to avoid short-circuit and installing adequate over-voltage protection may extend the transformer lifetime.

Table 1 – Constants for lifetime equation

Insulation system temperature (thermal class)	Arrhenius' equation constants		Rated hot spot winding temperature
	a	***b***	$\vartheta_{HS,r}$
°C	h	K	°C
105 (A)	3,10E-14	15 900	95
120 (E)	5,48E-15	17 212	110
130 (B)	1,72E-15	18 115	120
155 (F)	9,60E-17	20 475	145
180 (H)	5,35E-18	22 979	170
200	5,31E-19	25 086	190
220	5,26E-20	27 285	210

NOTE 2 The following formulas are used to determine the coefficients a and b for the rated hot-spot temperature in the winding:

$$\ln(180\ 000) = \frac{b}{\vartheta_{HS,r} + 273} + \ln(a)$$

$$\ln(90\ 000) = \frac{b}{\vartheta_{HS,r} + 6 + 273} + \ln(a)$$

$\vartheta_{HS,r}$ is the winding rated hot-spot temperature;

Ti is insulation system temperature (thermal index Ti).

The Table 1 is calculated by doubling the ageing for each 6 K.

NOTE 3 Most power transformers operate well below full load most of their actual lifetime. Since a hot-spot temperature of as little as 6 °C below rated values results in half the rated loss of life, the actual lifetime of a transformer typically exceeds 20 years. Accordingly, the constants in Table 1 were developed based on 180 000 h using a halving constant of 6 K.

5.3 Relation between constant continuous load and temperature

The constant hot-spot thermodynamic temperature T, in Kelvin (K), of the winding is given by:

$$T = 273 + \vartheta_a + \Delta\vartheta_{HSn} \quad (3)$$

where

ϑ_a is the ambient temperature in degrees Celsius (°C);

$\Delta\vartheta_{HSn}$ is the winding hot-spot temperature rise above the ambient temperature at the considered load.

Note that the ambient temperature may not be independent of the loading, but may be a function of the loading :

$$\vartheta_a = f(\text{current}) \qquad (4)$$

This function may vary from one site to another. Knowledge of this correlation for the particular site is necessary to make relevant estimates of the ageing rate and consumption of lifetime. The correlation may be found by measurement at the specific site. If no such information is available, indications regarding ageing rate and lifetime consumption can be obtained by making alternative calculations at different ambient temperatures, for example within the range 10 °C to 40 °C.

The formulas given in this standard consider eddy losses as ohmic losses in the windings. Test data indicates that the formulas show higher loss of lifetime than expected. If harmonic currents are present, the increased eddy losses during overloading may need additional consideration in accordance with Annex A of IEC 61378-1.

5.4 Ageing rate

The normal lifetime of a transformer is in practice at least 180 000 h. In order to express the ageing rate k as consumption of lifetime-hours per hour of operation time at a temperature T in Kelvins (K), 180 000 h is used as a conservative reference in the following equation:

$$k = 180\,000 \times a^{-1} \times \exp\left(\frac{-b}{T}\right) \qquad (5)$$

The relative ageing rate kr at constant hot-spot temperature T, in Kelvins (K), expressed as a percentage of the ageing rate that gives 180 000 h lifetime is calculated according to the equation:

$$kr = 100 \times t \times a^{-1} \times \exp\left(\frac{-b}{T}\right) \qquad (6)$$

a and b are be to taken from Table 1.

5.5 Lifetime consumption

The lifetime consumption L_c, expressed in hours (h), at a constant hot-spot temperature T, in Kelvins (K), during a time t in hours (h) is calculated according to the equation:

$$L_c = 180\,000 \times t \times a^{-1} \times \exp\left(\frac{-b}{T}\right) \qquad (7)$$

a and b are taken from Table 1.

5.6 Hot-spot temperature in steady state

For most transformers in service, the hot-spot temperature inside a winding is not precisely known. For most of these units, the hot-spot temperature can be assessed by calculation.

The calculation rules in this document are based on the following:

ϑ_{HS} is the hot-spot temperature, in degrees Celsius (°C), at rated conditions (rated current, rated ambient temperature, rated voltage, rated frequency…).

The parameter ϑ_{HS} can be found by calculation method or by test.

NOTE Although there is no standard test to determine the hot-spot temperature, if the manufacturer demonstrates other values by test, the manufacturer can use these values to carry out calculation of the life consumption of the transformer.

5.7 Assumed hot-spot factor

For the following consideration, the assumed hot-spot factor Z is 1,25:

$$\Delta\vartheta_{HS,r} = Z \times \Delta\vartheta_{Wr} \quad (8)$$

where

$\Delta\vartheta_{HS,r}$ is the hot-spot temperature rise, in Kelvin (K);

$\Delta\vartheta_{Wr}$ is average winding temperature rise at rated load, in Kelvin (K).

5.8 Hot-spot temperature rises at varying ambient temperature and load conditions

The basic value required for calculating the life consumption is the temperature at the hot-spot. For this purpose, it is necessary to know the temperature rise at this position for each load condition as well as the ambient temperature.

$$\Delta\vartheta_{HSn} = Z \times \Delta\vartheta_{Wr} \times I_n^q \quad (9)$$

where

$\Delta\vartheta_{HSn}$ is the hot-spot temperature rise at the considered load;

I_n is the loading factor per unit;

q is equal to 1,6 for air natural cooling (AN) ; or
is equal to 2 for AF cooled transformers (AF);

Z is assumed to be 1,25.

Whenever possible it is preferable to use test results for $\Delta\vartheta_{Wr}$, to limit the uncertainty regarding the validity of the factor Z and the value of q. Experience shows that q and Z assume different values depending on the type of transformer and the level of the load current at which it operates.

NOTE With some types of winding constructions, determination of $\Delta\vartheta_{Wr}$ may be possible only on prototype transformers.

5.9 Loading equations

5.9.1 Continuous loading

The hot-spot temperature ϑ_{HS} as a function of load for steady-state conditions should be calculated by the following equations:

$$\vartheta_{HS} = \vartheta_a + \Delta\vartheta_{HS} \quad (10)$$

For AN cooling the following equation applies:

$$\Delta\vartheta_{HS} = \Delta\vartheta_{HS,r}[I]^{2m} \tag{11}$$

For AF cooling the following equation applies:

$$\Delta\vartheta_{HS} = \Delta\vartheta_{HS,r}\left[I^2 C_T\right]^X \tag{12}$$

$$C_T = \frac{T_k + \vartheta_{HS}}{T_k + \vartheta_{HS,r}} \tag{13}$$

where

$\Delta\vartheta_{HS}$ is the hot-spot temperature rise at per unit load I, in Kelvins (K);

$\vartheta_{HS,r}$ is the rated or tested hot-spot temperature at 1,0 per unit load, in degrees Celsius (°C) [tested values for self-cooled operation for use in Equation (11) may be different than tested values for fan-cooled operation for use in Equation (12)] ;

I is loading factor per unit (ratio between load current and rated current);

C_T is the temperature correction for resistance change with temperature;

m is an empirical constant, which is equal to 0,8 (suggested unless test data is available);

ϑ_a is the ambient temperature, in degrees Celsius (°C);

ϑ_{HS} is the hot-spot temperature at load I, in degrees Celsius (°C);

T_k is the temperature constant for conductor, which is 225 for aluminium and 235 for copper;

X is an empirical constant used in forced-air calculation, which is 1 (suggested unless test data available).

Test data indicates that the above equations should result in conservative predictions of the hot-spot temperature.

The m exponent of 0,8 for self-cooled operation and the X exponent of 1 for forced-air operation are derived from heat transfer correlation for natural and forced convection. Test data indicates that a temperature correction for resistance given by Equation (13) is required to predict hot-spot temperatures rise during forced-air loading due to the higher losses present at forced-cooled operation.

Equation (11) and Equation (12) ignore eddy losses in the windings, which vary inversely with temperature. The formula provides a conservative result since Eddy losses are usually low unless harmonic currents are present.

Equation (11) and Equation (12) require an iterative calculation procedure. Using the suggested exponents and considering the resistance change with temperature for fan-cooled operation should result in conservative calculations of the hot-spot temperature rise, even when eddy losses are ignored. If harmonic currents are present, the increased eddy losses during overloading may need consideration in accordance with Annex A of IEC 61378-1.

5.9.2 Transient loading

The hot-spot temperature rise due to transient overloading should be determined by the following equations: