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INTERNATIONAL STANDARD

colour inside

Power transformers –
Part 7: Loading guide for mineral-oil-immersed power transformers

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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 60076-7 has been prepared by IEC technical committee 14: Power transformers.

This second edition cancels and replaces the first edition published in 2005. It constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

a) title has been updated from "oil-immersed power transformers" to "mineral-oil-immersed power transformers";

b) insulation life is updated by considering latest research findings;

c) temperature limits have been reviewed and maximum core temperature is recommended;

d) number of fibre optic sensors is recommended for temperature rise test;

e) Q, S and H factors are considered;

f) thermal models are revised and rewritten in generally applicable mathematical form;

g) geomagnetic induced currents are briefly discussed and corresponding temperature limits are suggested;

h) extensive literature review has been performed and a number of references added to bibliography.

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

FDIS	Report on voting
14/933/FDIS	14/942/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 the 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 stability date indicated on the IEC website 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.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

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

IEC 60076-2 is the basis for contractual agreements and it contains the requirements and tests relating to temperature-rise figures for oil-immersed transformers during continuous rated loading.

This part of IEC 60076 gives mathematical models for judging the consequence of different loadings, 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, in turn, used for evaluation of a relative value for the rate of thermal ageing and the percentage of life consumed in a particular time period. The modelling refers to small transformers, here called distribution transformers, and to power transformers.

A major change from the previous edition is the extensive work on the paper degradation that has been carried out indicating that the ageing may be described by combination of the oxidation, hydrolysis and pyrolysis. Also, providing possibility to estimate the expected insulation life considering different ageing factors, i.e. moisture, oxygen and temperature, and more realistic service scenarios. The title has been updated from "oil-immersed power transformers" to "mineral-oil-immersed power transformers". The temperature and current limits are reviewed and the maximum core temperature is recommended. The use of fibre optic temperature sensors has become a standard practice, however, the number of installed sensors per transformer highly varies. This issue and the description of Q, S and H factors are now considered as well. The thermal models are revised and rewritten in generally applicable mathematical form. The geomagnetic induced currents are briefly discussed and corresponding temperature limits are suggested.

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, normal cyclic undisturbed loading or temporary emergency loading. The recommendations refer to distribution transformers, to medium power transformers and to large power transformers. Clauses 1 to 7 contain definitions, common background information and specific limitations for the operation of different categories of transformers.

Clause 8 contains the determination of temperatures, presents the mathematical models used to estimate the hot-spot temperature in steady state and transient conditions.

Clause 9 contains a short description of the influence of the tap position.

Application examples are given in Annexes A, B, C, D, E, F, G, H, I and K.

POWER TRANSFORMERS –

Part 7: Loading guide for mineral-oil-immersed power transformers

1 Scope

This part of IEC 60076 is applicable to mineral-oil-immersed transformers. It describes the effect of operation under various ambient temperatures and load conditions on transformer life.

NOTE For furnace transformers, the manufacturer is consulted in view of the peculiar loading profile.

2 Normative references

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

IEC 60076-2, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

IEC 60076-14, *Power transformers – Part 14: Liquid-immersed power transformers using high-temperature insulation materials*

3 Terms and definitions

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

3.1
small power transformer
power transformer without attached radiators, coolers or tubes including corrugated tank irrespective of rating

3.2
medium power transformer
power transformer with a maximum rating of 100 MVA three-phase or 33,3 MVA single-phase

3.3
large power transformer
power transformer with a maximum rating of greater than 100 MVA three-phase or greater than 33,3 MVA single-phase

3.4
cyclic loading
loading with cyclic variations (the duration of the cycle usually being 24 h) which is regarded in terms of the accumulated amount of ageing that occurs during the cycle

Note 1 to entry: The cyclic loading may either be a normal loading or a long-time emergency loading.

3.5
normal cyclic loading
loading in which a higher ambient temperature or a higher-than-rated load current is applied during part of the cycle, but which, from the point of view of relative thermal ageing rate (according to the mathematical model), is equivalent to the rated load at normal ambient temperature

Note 1 to entry: This is achieved by taking advantage of low ambient temperatures or low load currents during the rest of the load cycle. For planning purposes, this principle can be extended to provide for long periods of time whereby cycles with relative thermal ageing rates greater than unity are compensated for by cycles with thermal ageing rates less than unity.

3.6
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

3.7
short-time emergency loading
unusually heavy loading of a transient nature (less than 30 min) due to the occurrence of one or more unlikely events which seriously disturb normal system loading

3.8
hot-spot
if not specially defined, hottest spot of the windings

3.9
relative thermal ageing rate
for a given hot-spot temperature, rate at which transformer insulation ageing is reduced or accelerated compared with the ageing rate at a reference hot-spot temperature

3.10
transformer insulation life
total time between the initial state for which the insulation is considered new and the final state for which the insulation is considered deteriorated due to thermal ageing, dielectric stress, short-circuit stress, or mechanical movement (which could occur in normal service), and at which a high risk of electrical failure exists

3.11
per cent loss of life
equivalent ageing in hours over a time period (usually 24 h) times 100 divided by the expected transformer insulation life

Note 1 to entry: The equivalent ageing in hours is obtained by multiplying the relative ageing rate with the number of hours.

3.12
non-thermally upgraded paper
kraft paper produced from unbleached softwood pulp under the sulphate process without addition of stabilizers

3.13
thermally upgraded paper
cellulose-based paper which has been chemically modified to reduce the rate at which the paper decomposes

Note 1 to entry: Ageing effects are reduced either by partial elimination of water forming agents (as in cyanoethylation) or by inhibiting the formation of water through the use of stabilizing agents (as in amine addition, dicyandiamide). A paper is considered as thermally upgraded if it meets the life criteria defined in ANSI/IEEE C57.100 [1][1]; 50 % retention in tensile strength after 65 000 h in a sealed tube at 110 °C or any other time/temperature combination given by the equation:

$$\text{Time (h)} = e^{\left(\frac{15\,000}{(\theta_\text{h} + 273)} - 28{,}082\right)} \approx 65\,000 \times e^{\left(\frac{15\,000}{(\theta_\text{h} + 273)} - \frac{15\,000}{(110 + 273)}\right)} \quad (1)$$

Because the thermal upgrading chemicals used today contain nitrogen, which is not present in kraft pulp, the degree of chemical modification is determined by testing for the amount of nitrogen present in the treated paper. Typical values for nitrogen content of thermally upgraded papers are between 1 % and 4 % when measured in accordance with ASTM D-982 [2], but after the sealed tube test.

3.14
non-directed oil flow
OF
flow indicating that the pumped oil from heat exchangers or radiators flows freely inside the tank, and is not forced to flow through the windings

Note 1 to entry: The oil flow inside the windings can be either axial in vertical cooling ducts or radial in horizontal cooling ducts with or without zigzag flow.

3.15
non-directed oil flow
ON
flow indicating that the oil from the heat exchangers or radiators flows freely inside the tank and is not forced to flow through the windings

Note 1 to entry: The oil flow inside the windings can be either axial in vertical cooling ducts or radial in horizontal cooling ducts with or without zigzag flow.

3.16
directed oil flow
OD

flow indicating that the principal part of the pumped oil from heat exchangers or radiators is forced to flow through the windings

Note 1 to entry: The oil flow inside the windings can be either axial in vertical cooling ducts or zigzag in horizontal cooling ducts.

3.17
design ambient temperature
temperature at which the permissible average winding and top-oil and hot-spot temperature over ambient temperature are defined

4 Symbols and abbreviations

Symbol	Meaning	Units
C	Thermal capacity	Ws/K
c	Specific heat	Ws/(kg·K)
DP	Degree of polymerization	
D	Difference operator, in difference equations	
g_r	Average-winding-to-average-oil (in tank) temperature gradient at rated current	K
H	Hot-spot factor	
k_{11}	Thermal model constant	
k_{21}	Thermal model constant	

[1] Numbers in square brackets refer to the bibliography.

Symbol	Meaning	Units
k_{22}	Thermal model constant	
K	Load factor (load current/rated current)	
L	Total ageing over the time period considered	h
m_A	Mass of core and coil assembly	kg
m_T	Mass of the tank and fittings	kg
m_O	Mass of oil	kg
m_W	Mass of winding	kg
n	Number of each time interval	
N	Total number of intervals during the time period considered	
OD	Either ODAN, ODAF or ODWF cooling	
OF	Either OFAN, OFAF or OFWF cooling	
ON	Either ONAN or ONAF cooling	
P	Supplied losses	W
P_e	Relative winding eddy loss	p.u.
P_W	Winding losses	W
R	Ratio of load losses at rated current to no-load losses at rated voltage	
R_r	Ratio of load losses to no-load loss at principal tapping	
R_{r+1}	Ratio of load losses to no-load loss at tapping $r + 1$	
R_{min}	Ratio of load losses to no-load loss at minimum tapping	
R_{max}	Ratio of load losses to no-load loss at maximum tapping	
RTD	Resistance Temperature Detector	
RH	Oil relative humidity	%
s	Laplace operator	
t	Time variable	min
tap_r	Principal tapping position	
tap_{r+1}	Tapping position $r + 1$	
tap_{min}	Minimum tapping position	
tap_{max}	Maximum tapping position	
V	Relative ageing rate	
V_n	Relative ageing rate during interval n	
WOP	Water content of oil	ppm
WCP	Water content of paper insulation	%
x	Exponential power of total losses versus top-oil (in tank) temperature rise (oil exponent)	
y	Exponential power of current versus winding temperature rise (winding exponent)	
θ_a	Ambient temperature	°C
θ_E	Yearly weighted ambient temperature	°C
θ_h	Winding hot-spot temperature	°C
θ_{ma}	Monthly average temperature	°C
$\theta_{ma\text{-}max}$	Monthly average temperature of the hottest month, according to IEC 60076-2	°C
θ_o	Top-oil temperature (in the tank) at the load considered	°C
θ_{ya}	Yearly average temperature, according to IEC 60076-2	°C
τ_o	Oil time constant	min
τ_W	Winding time constant	min
$\Delta\theta_{br}$	Bottom oil (in tank) temperature rise at rated load (no-load losses + load losses)	K

Symbol	Meaning	Units
$\Delta\theta_h$	Hot-spot-to-top-oil (in tank) gradient at the load considered	K
$\Delta\theta_{hi}$	Hot-spot-to-top-oil (in tank) gradient at start	K
$\Delta\theta_{hr}$	Hot-spot-to-top-oil (in tank) gradient at rated current	K
$\Delta\theta_o$	Top-oil (in tank) temperature rise at the load considered	K
$\Delta\theta_{oi}$	Top-oil (in tank) temperature rise at start	K
$\Delta\theta_{om}$	Average oil (in tank) temperature rise at the load considered	K
$\Delta\theta_{omr}$	Average oil (in tank) temperature rise at rated load (no-load losses + load losses)	K
$\Delta\theta_{or}$	Top-oil (in tank) temperature rise in steady state at rated losses (no-load losses + load losses)	K
$\Delta\theta'_{or}$	Corrected top-oil temperature rise (in tank) due to enclosure	K
$\Delta(\Delta\theta_{or})$	Extra top-oil temperature rise (in tank) due to enclosure	K

5 Effect of loading beyond nameplate rating

5.1 General

The 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 design ambient temperature 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. These risks can be reduced by the purchaser clearly specifying the maximum loading conditions and the supplier taking these into account in the transformer design.

5.2 General consequences

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

a) The temperatures of windings, cleats, leads, insulation and oil will increase and can reach unacceptable levels.

b) The leakage flux density outside the core increases, causing additional eddy-current heating in metallic parts linked by the leakage flux.

c) As the temperature changes, the moisture and gas content in the insulation and in the oil will change.

d) Bushings, tap-changers, cable-end connections and current transformers will also be exposed to higher stresses which encroach upon their design and application margins.

The combination of the main flux and increased leakage flux imposes restrictions on possible core overexcitation [6], [7], [8].

NOTE For loaded core-type transformers having an energy flow from the outer winding (usually HV) to the inner winding (usually LV), the maximum magnetic flux density in the core, which is the result of the combination of the main flux and the leakage flux, appears in the yokes.

As tests have indicated, this flux is less than or equal to the flux generated by the same applied voltage on the terminals of the outer winding at no-load of the transformer. The magnetic flux in the core legs of the loaded transformer is determined by the voltage on the terminals of the inner winding and almost equals the flux generated by the same voltage at no-load.

For core-type transformers with an energy flow from the inner winding, the maximum flux density is present in the core-legs. Its value is only slightly higher than that at the same applied voltage under no-load. The flux density in the yokes is then determined by the voltage on the outer winding.