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colour inside

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

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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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This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

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.

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. ~~It should be noted that IEC 60076-2 refers to the average winding temperature rise while this part of IEC 60076 refers mainly to the hot-spot temperature and the stated values are provided only for guidance.~~

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 IEC 60354:1991 is the increased use of fibre optic temperature sensors in transformers. This has radically increased the possibilities of obtaining a proper thermal modelling of power transformers, especially at step changes in the load current. These possibilities have also yielded some differences between the "oil exponent x" and the "winding exponent y" used in this part of IEC 60076 and in IEC 60076-2:1993, for power transformers:~~

- ~~x = 0,9 in IEC 60076-2, and x = 0,8 in this part of IEC 60076 at ON cooling.~~
- ~~y = 1,6 in IEC 60076-2, and y = 1,3 in this part of IEC 60076 at ON and OF cooling.~~

~~For distribution transformers, the same x and y values are used in this part of IEC 60076 as in IEC 60076-2.~~

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 ~~should be~~ 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~~:1993~~, *Power transformers – Part 2: Temperature rise for liquid-immersed transformers*

~~IEC 60076-4:2002, *Power transformers – Part 4: Guide to the lightning impulse and switching impulse testing – Power transformers and reactors*~~

~~IEC 60076-5:2000, *power transformers – Part 5: Ability to withstand short circuit*~~

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**~~
~~**distribution transformer**~~
~~power transformer with a maximum rating of 2 500 kVA three-phase or 833 kVA single-phase~~

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 ~~exceeding the limits specified in 3.2~~ 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 ~~when~~ 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 ~~result in~~ 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:

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

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.

~~NOTE This definition was approved by the IEEE Transformers Committee Task Force for the Definition of Thermally Upgraded Paper on 7 October 2003.~~

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

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

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	
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	~~Number of~~ Principal tapping position	
tap_{r+1}	~~Number of~~ Tapping position $r + 1$	
tap_{min}	~~Number of~~ Minimum tapping position	
tap_{max}	~~Number of~~ 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)	

Symbol	Meaning	Units
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~~:1993~~	°C
θ_o	Top-oil temperature (in the tank) at the load considered	°C
θ_{ya}	Yearly average temperature, according to IEC 60076-2~~:1993~~	°C
τ_o	~~Average~~ 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
$\Delta\theta_h$	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 ~~Introduction~~ 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.

Voltages on both sides of the loaded transformer ~~should~~, therefore, ~~be~~ are observed during loading beyond the nameplate rating. As long as voltages at the energized side of a loaded transformer remain below the limits stated in IEC 60076-1:2011 [5], Clause 4, no excitation restrictions are needed during the loading beyond nameplate rating. When higher excitations occur to keep the loaded voltage in emergency conditions in an area where the network can still be kept upright, then the magnetic flux densities in core parts ~~should~~ never exceed values where straying of the core flux outside the core can occur (for cold-rolled grain-oriented steel these saturation effects start rapidly above 1,9 T). ~~In no time at all,~~ Stray fluxes may ~~then~~ cause unpredictably high temperatures at the core surface and in nearby metallic parts such as winding clamps or even in the windings, due to the presence of high-frequency components in the stray flux. They may jeopardize the transformer. In general, in all cases, the short overload times dictated by windings are sufficiently short not to overheat the core at overexcitation. This is prevented by the long thermal time constant of the core.

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 come from the cumulative effect of thermal ageing of the insulation in the transformer over many years.

5.3 Effects and hazards of short-time emergency loading

Short-time increased loading will result in a service condition having an increased risk of failure. Short-time emergency overloading causes the conductor hot-spot to reach a level likely to result in a temporary reduction in the dielectric strength. However, acceptance of this condition for a short time may be preferable to loss of supply. This type of loading is expected to occur rarely, and it should be rapidly reduced or the transformer disconnected within a short time in order to avoid its failure. The permissible duration of this load is shorter than the thermal time constant of the whole transformer and depends on the operating temperature before the increase in loading; typically, it would be less than half-an-hour.

The main risk for short-time failures is the reduction in dielectric strength due to the possible presence of gas bubbles in a region of high electrical stress, that is the windings and leads. These bubbles are likely to occur when the hot-spot temperature exceeds 140 °C for a transformer with a winding insulation moisture content of about 2 %. This critical temperature will decrease as the moisture concentration increases.

NOTE Concerning the bubble generation, see also IEC 60076-14.

a) Gas bubbles can also develop (either in oil or in solid insulation) at the surfaces of heavy metallic parts heated by the leakage flux or be produced by super-saturation of the oil. However, such bubbles usually develop in regions of low electric stress and have to circulate in regions where the stress is higher before any significant reduction in the dielectric strength occurs.

   Bare metallic parts, except windings, which are not in direct thermal contact with cellulosic insulation but are in contact with non-cellulosic insulation (for example, aramid paper, glass fibre) and the oil in the transformer, may rapidly rise to high temperatures. A temperature of 180 °C should not be exceeded.

b) Temporary deterioration of the mechanical properties at higher temperatures could reduce the short-circuit strength.

c) Pressure build-up in the bushings may result in a failure due to oil leakage. Gassing in condenser type bushings may also occur if the temperature of the insulation exceeds about 140 °C.

d) The expansion of the oil could cause overflow of the oil in the conservator.

e) Breaking of excessively high currents in the tap-changer could be hazardous.

The limitations on the maximum hot-spot temperatures in windings, core and structural parts are based on considerations of short-term risks (see Clause 7).

The short-term risks normally disappear after the load is reduced to normal level, but they need to be clearly identified and accepted by all parties involved, e.g. planners, asset owners and operators.

5.4 Effects of long-time emergency loading

This is not a normal operating condition and its occurrence is expected to be rare but it may persist for weeks or even months and can lead to considerable ageing.

a) Deterioration of the mechanical properties of the conductor insulation will accelerate at higher temperatures. If this deterioration proceeds far enough, it may reduce the effective life of the transformer, particularly if the latter is subjected to system short circuits or transportation events.

b) Other insulation parts, especially parts sustaining the axial pressure of the winding block, could also suffer increased ageing rates at higher temperature.

c) The contact resistance of the tap-changers could increase at elevated currents and temperatures and, in severe cases, thermal runaway could take place.

d) The gasket materials in the transformer may become more brittle as a result of elevated temperatures.

The calculation rules for the relative ageing rate and per cent loss of life are based on considerations of long-term risks.

5.5 Transformer size

The sensitivity of transformers to loading beyond nameplate rating usually depends on their size. As the size increases, the tendency is that:

- the leakage flux density increases;
- the short-circuit forces increase;
- the mass of insulation, which is subjected to a high electric stress, is increased;
- the hot-spot temperatures are more difficult to determine.

Thus, a large transformer could be more vulnerable to loading beyond nameplate rating than a smaller one. In addition, the consequences of a transformer failure are more severe for larger sizes than for smaller units.

Therefore, in order to apply a reasonable degree of risk for the expected duties, this part of IEC 60076 considers three categories:

a) ~~Distribution~~ small transformers, for which only the hot-spot temperatures in the windings and thermal deterioration ~~shall~~ should be considered;

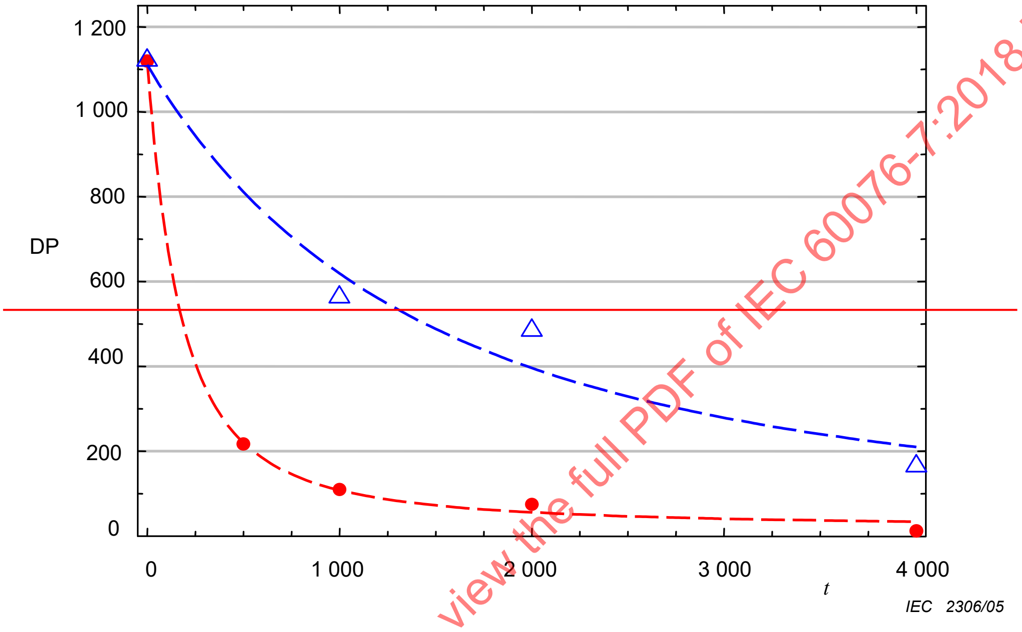
b) medium power transformers where the variations in the cooling modes ~~shall~~ should be considered;

c) large power transformers, where also the effects of stray leakage flux are significant and the consequences of failure are severe.

For hermetically sealed transformers without pressure relief devices the over pressure should be considered to avoid permanent tank deformation during loading beyond nameplate rating.

~~5.6 Non-thermally and thermally upgraded insulation paper~~

~~The purpose of thermally upgrading insulation paper is to neutralize the production of acids caused by the hydrolysis (thermal degradation) of the material over the lifetime of the transformer. This hydrolysis is even more active at elevated temperatures, and published research results indicate that thermally upgraded insulation papers retain a much higher percentage of their tensile and bursting strength than untreated papers when exposed to elevated temperatures [4], [5]. The same references also show the change of DP over time of non-thermally and thermally upgraded paper exposed to a temperature of 150 °C (see Figure 1).~~



~~**Key**~~

~~DP Degree of polymerization~~

~~*t* Time (h)~~

~~Δ Values for thermally upgraded paper~~

~~● Values for non-thermally upgraded paper~~

~~**Figure 1 – Sealed tube accelerated ageing in mineral oil at 150 °C**~~

~~Another reference [6] illustrates the influence of temperature and moisture content, as shown in Table 1.~~

~~**Table 1 – Life of paper under various conditions**~~

~~Paper type/ageing temperature~~		~~Life~~ ~~years~~	
		~~Dry and free from air~~	~~With air and 2 % moisture~~
~~Wood pulp at~~	~~80 °C~~	~~118~~	~~5,7~~
	~~90 °C~~	~~38~~	~~1,9~~
	~~98 °C~~	~~15~~	~~0,8~~
~~Upgraded wood pulp at~~	~~80 °C~~	~~72~~	~~76~~
	~~90 °C~~	~~34~~	~~27~~
	~~98 °C~~	~~18~~	~~12~~

~~The illustrated difference in thermal ageing behaviour has been taken into account in industrial standards as follows.~~

- ~~The relative ageing rate V = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and to 110 °C for thermally upgraded paper.~~

~~NOTE The results in Figure 1 and Table 1 are not intended to be used as such for ageing calculations and life estimations. They have been included in this document only to demonstrate that there is a difference in ageing behaviour between non-thermally and thermally upgraded insulation paper.~~

6 Relative ageing rate and transformer insulation life

6.1 General

~~There is no simple and unique end-of-life criterion that can be used to quantify the remaining life of a transformer. However, such a criterion is useful for transformer users, hence it seems appropriate to focus on the ageing process and condition of transformer insulation.~~

For the manufacture of paper and pressboard for electrical insulation, mainly unbleached softwood kraft pulp is used. The cellulose is refined from the tree by the so-called “sulphate” or “kraft” process. After processing, the typical composition of unbleached kraft pulp is 78 % to 80 % cellulose, 10 % to 20 % hemicellulose and 2 % to 6 % lignin.

Cellulose is a linear condensation polymer consisting of anhydroglucose joined together by glycosidic bonds, Figure 1.

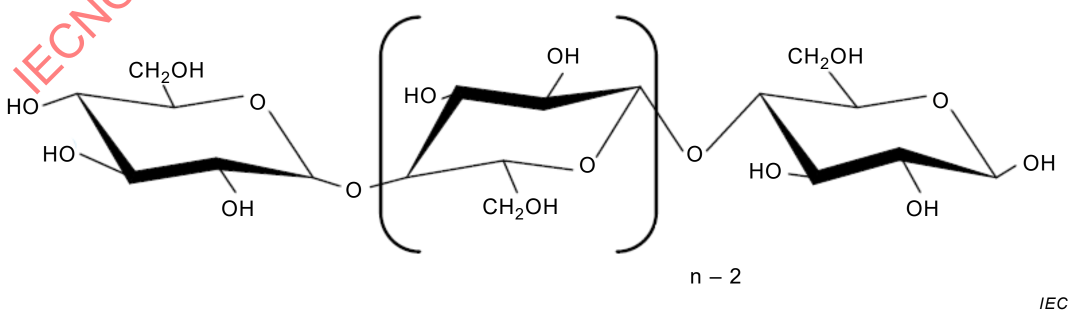


Figure 1 – Structural formula of cellulose

From kraft pulp various types of paper and pressboard having varying density are made. By adding various nitrogen containing compounds the ageing characteristics of the cellulose may be improved. Typical values for nitrogen content of thermally upgraded papers are between 1 % and 4 %. The purpose of thermally upgrading insulation paper is to neutralize the production of acids caused by the hydrolysis (thermal degradation) of the material over the lifetime of the transformer.

6.2 Insulation life

~~Reference [7] suggests four different end-of-life criteria, i.e. four different lifetimes for thermally upgraded paper as shown in Table 3.~~

~~Table 3 – Normal insulation life of a well-dried, oxygen-free thermally upgraded insulation system at the reference temperature of 110 °C~~

~~Basis~~	~~Normal insulation life~~	
	~~Hours~~	~~Years~~
~~50 % retained tensile strength of insulation~~	~~65 000~~	~~7,42~~
~~25 % retained tensile strength of insulation~~	~~135 000~~	~~15,41~~
~~200 retained degree of polymerization in insulation~~	~~150 000~~	~~17,12~~
~~Interpretation of distribution transformer functional life test data~~	~~180 000~~	~~20,55~~

~~The lifetimes in Table 3 are for reference purposes only, since most power transformers will operate at well below full load most of their actual lifetime. 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 transformer insulation being several times, for example, 180 000 h.~~

~~NOTE For GSU transformers connected to base load generators and other transformers supplying constant load or operating at relatively constant ambient temperatures, the actual lifetime needs special consideration.~~

In recent years, extensive work on paper degradation has been carried out and published in references [9] to [15], indicating that cellulose ageing may be described by combination of the three processes, i.e. oxidation, hydrolysis and pyrolysis.

The oxidation is a process possibly dominant at lower temperature. The oxidizing agent in this environment is oxygen from air ingress, and as the ultimate end product of the process appears water. The hydrolysis of cellulose is a catalytically governed process where the rate of chain scissions depends on carboxylic acids dissociated in water. As both water and carboxylic acids are produced during ageing of cellulose this process is auto accelerating. The pyrolysis is a process that can take place without access to water and/or oxygen, or any other agent to initiate the decomposition. At normal operating or overload temperatures, (i.e. < 140 °C), such processes are considered to be of little relevance.

In a real transformer all these processes – hydrolysis, oxidation and pyrolysis – act simultaneously. This hampers the application of one model describing the full complexity of the degradation processes. Which process will dominate depends on the temperature and the condition (i.e. oxygen, water and acid content).

Different parameters might be used to characterize cellulose degradation process during ageing. In reality it is the mechanical strength that is important for the winding paper to resist the shear stresses occurring during short circuits. However, due to the folded geometry of paper in a transformer, it is not possible to analyse tensile strength of paper sampled from used transformers. Hence, it is more convenient to characterize the degree of polymerization (DP) in order to describe the state of an insulation paper. Figure 2 shows a typical correlation between tensile strength and DP value (see [11]), the same correlation is valid for the thermally upgraded and non-thermally upgraded paper.

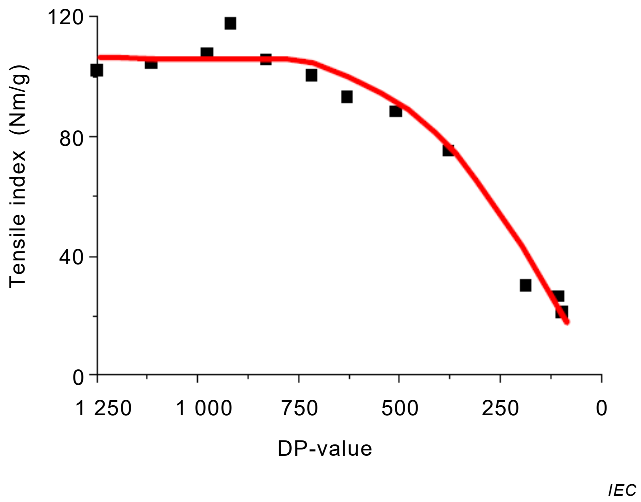


Figure 2 – Correlation between tensile strength and DP value

The degree of polymerization (DP) is the average number (n) of glycosidic rings in a cellulose macromolecule, which ranges between 1 100 and 1 400 for unbleached soft wood kraft before processing. Depending on the transformer drying process, the DP value may be reduced further to a lesser or higher degree. During ageing, the lengths of these polymeric cellulose molecules are reduced due to breakage of the covalent bonds between the anhydrous-β-glucose monomers. The change of DP over time of non-thermally and thermally upgraded paper exposed to a temperature of 140 °C, oxygen of < 6 000 ppm and water of 0,5 % is shown in Figure 3 (see [15]). The nitrogen content of the thermally upgraded paper used in this experiment was 1,8 %.

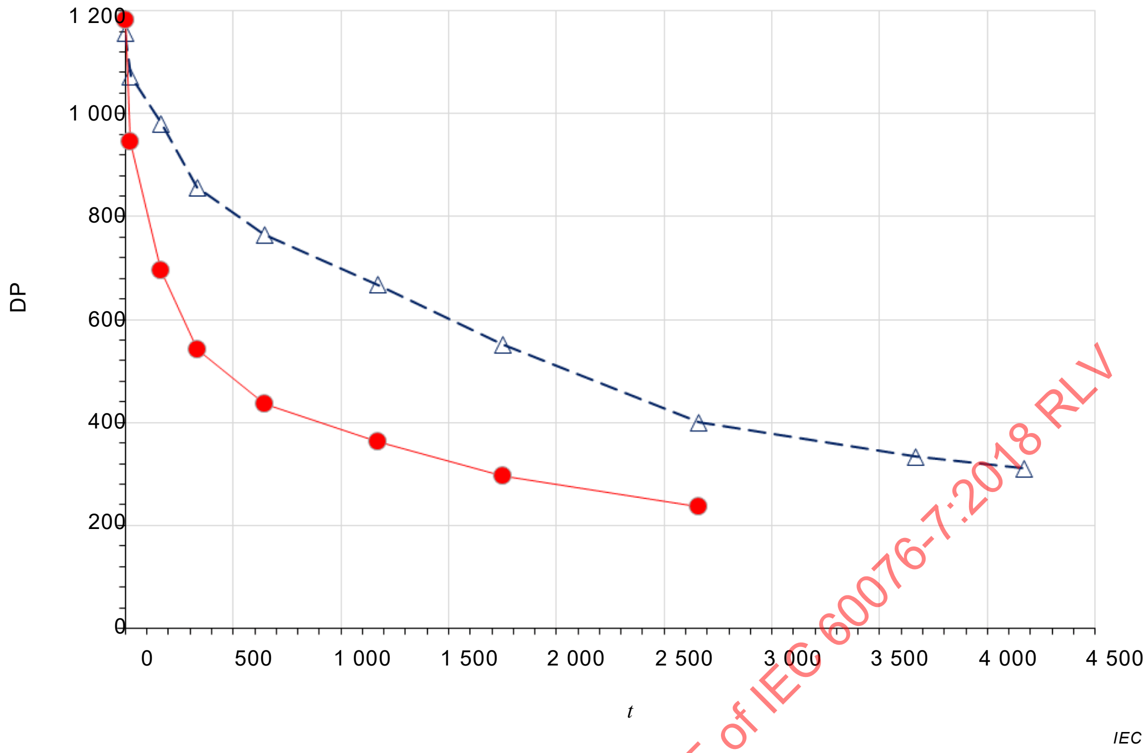
When the DP is reduced to 200 % or 35 % retained tensile strength, the quality of the paper (i.e. the mechanical strength) is normally considered so poor that this defines the "end of life" for such insulating material (see [11]), although the insulating material dielectric strength may be still at an acceptable level.

Annex A gives further elaboration of the paper ageing theory providing a mathematical methodology for estimation of the expected insulation life considering different ageing factors such as moisture, oxygen and temperature. The corresponding results for the non-thermally and thermally upgraded paper are presented in Figure 4 and Figure 5, respectively.

The illustrated difference in thermal ageing behaviour has been taken into account in industrial standards as follows:

- The relative ageing rate V = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and 110 °C for thermally upgraded paper.

NOTE 1 Disagreement between laboratory tests could come from testing procedures. It is difficult to reproduce the same ageing process with accelerated ageing often at quite elevated temperatures compared to service conditions. The values given in Table A.2, Figure 4 and Figure 5 are considered as unconfirmed and can be disputable. However, the numbers give a user the possibility to simulate different ageing scenarios.



Key

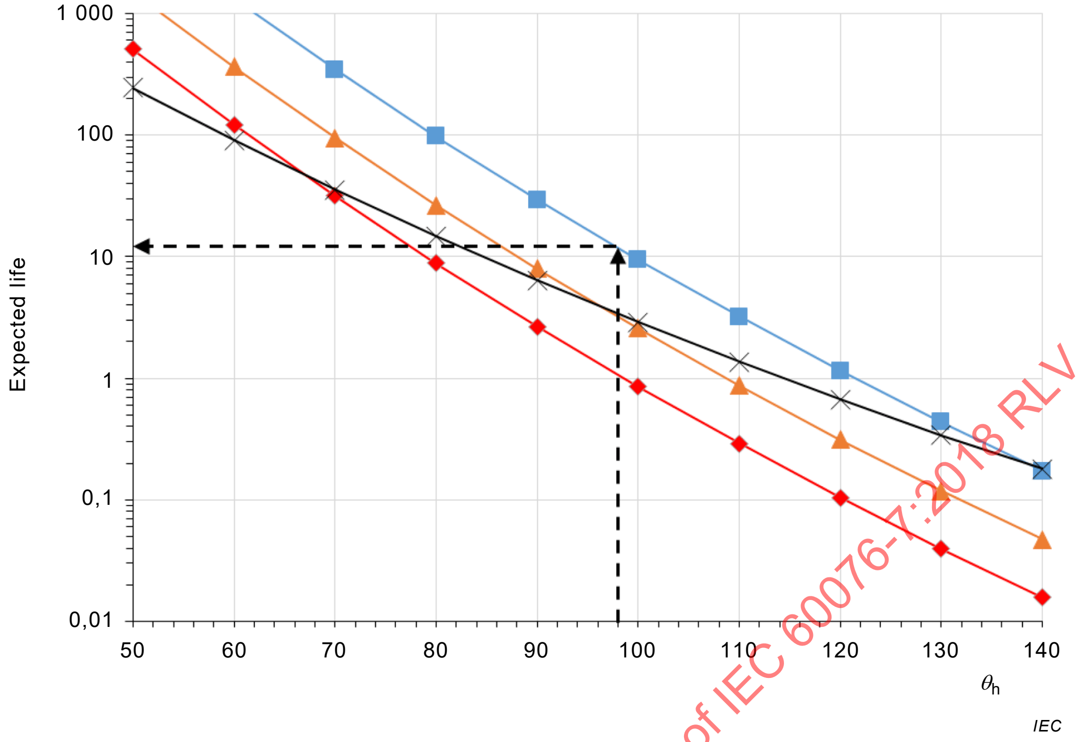
DP degree of polymerization

t time (h)

Δ values for thermally upgraded paper

• values for non-thermally upgraded paper

Figure 3 – Accelerated ageing in mineral oil at 140 °C, oxygen and moisture contents maintained at < 6000 ppm and 0,5 %, respectively



Key

expected life (years)

θ_h hot-spot temperature (°C)

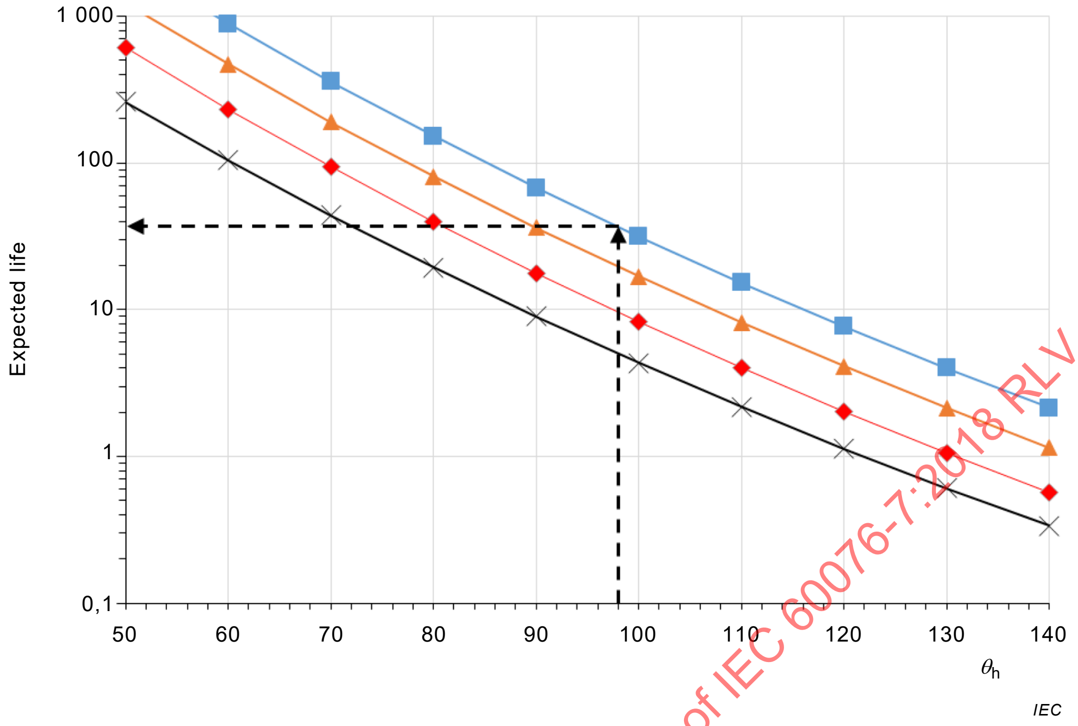
□ 0,5 % moisture, low oxygen

Δ 1,5 % moisture, low oxygen

◊ 3,5 % moisture, low oxygen

× 0,5 % moisture, high oxygen

Figure 4 – Expected life for non-thermally upgraded paper and its dependence upon moisture, oxygen and temperature



Key

expected life (years)

θ_h hot-spot temperature (°C)

□ 0,5 % moisture, low oxygen

Δ 1,5 % moisture, low oxygen

◊ 3,5 % moisture, low oxygen

× 0,5 % moisture, high oxygen

Figure 5 – Expected life for thermally upgraded paper and its dependence upon moisture, oxygen and temperature

NOTE 2 Figure 4 and Figure 5 indicate expected life values that are based on residual DP value of 200, and that are derived under the laboratory controlled condition as given in text above, (e.g. constant moisture content, constant and homogenous temperature, etc.). However, to evaluate the expected life of a transformer the real service conditions are considered (e.g. loading history and prediction, ambient temperature, insulation material and insulation moisture contamination). The moisture contamination estimate is usually based on the corresponding equilibrium curves for moisture partition between oil and paper, (e.g. WCO vs WCP or RH vs WCP).

6.3 Relative ageing rate

Although ageing or deterioration of insulation is a time function of temperature, moisture content, oxygen content and acid content, the model presented in this document is based only on the insulation temperature as the controlling parameter.

An example of how all ageing parameters can be taken into account is given in Annex A.

Since the temperature distribution is not uniform, the part that is operating at the highest temperature will normally undergo the greatest deterioration. Therefore, the rate of ageing is referred to the winding hot-spot temperature. In this case, the relative ageing rate V is defined according to Equation (2) for non-thermally upgraded paper and to Equation (3) for thermally upgraded paper (see [27]).

$$V = 2^{(\theta_h - 98)/6} \tag{2}$$

$$V = e^{\left(\frac{15\ 000}{110+273} - \frac{15\ 000}{\theta_h + 273}\right)} \tag{3}$$

where

θ_h is the hot-spot temperature in °C.

Equations (2) and (3) imply that V is very sensitive to the hot-spot temperature as can be seen in Table 1.

Table 1 – Relative ageing rates due to hot-spot temperature

θ_h °C	**Non-upgraded paper insulation** V	**Upgraded paper insulation** V
80	0,125	0,036
86	0,25	0,073
92	0,5	0,145
98	**1,0**	0,282
104	2,0	0,536
110	4,0	**1,0**
116	8,0	1,83
122	16,0	3,29
128	32,0	5,8
134	64,0	10,1
140	128,0	17,2
The indicated relative ageing rate V = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and 110 °C for thermally upgraded paper.		

6.4 Loss-of-life calculation

The loss of life L over a certain period of time is equal to

$$L = \int_{t_1}^{t_2} V\,\mathrm{d}t \quad \text{or} \quad L \approx \sum_{n=1}^{N} V_n \times t_n \tag{4}$$

where

V_n is the relative ageing rate during interval n, according to Equation (2) or (3);

t_n is the nth time interval;

n is the number of each time interval;

N is the total number of intervals during the period considered.

The maximum time interval should be less than half the smallest time constant, τ_w, in Equation (4) for an accurate solution.

7 Limitations

7.1 ~~Current and~~ Temperature limitations

With loading values beyond the nameplate rating, ~~all~~ none of the individual limits stated in Table ~~4~~ 2 should ~~not~~ be exceeded and account should be taken of the specific limitations given in 7.3 to 7.5.

~~Table 4 – Current and temperature limits applicable to loading beyond nameplate rating~~

~~Types of loading~~	~~Distribution transformers (see Note)~~	~~Medium power transformers (see Note)~~	~~Large power transformers (see Note)~~
~~Normal cyclic loading~~			
~~Current (p.u.)~~	~~1,5~~	~~1,5~~	~~1,3~~
~~Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)~~	~~120~~	~~120~~	~~120~~
~~Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)~~	~~140~~	~~140~~	~~140~~
~~Top-oil temperature (°C)~~	~~105~~	~~105~~	~~105~~
~~Long-time emergency loading~~			
~~Current (p.u.)~~	~~1,8~~	~~1,5~~	~~1,3~~
~~Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)~~	~~140~~	~~140~~	~~140~~
~~Other metallic hot-spot temperature (in contact with oil, aramid paper, glass-fibre materials) (°C)~~	~~160~~	~~160~~	~~160~~
~~Top-oil temperature (°C)~~	~~115~~	~~115~~	~~115~~
~~Short-time emergency loading~~			
~~Current (p.u.)~~	~~2,0~~	~~1,8~~	~~1,5~~
~~Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)~~	~~See 7.2.1~~	~~160~~	~~160~~
~~Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)~~	~~See 7.2.1~~	~~180~~	~~180~~
~~Top-oil temperature (°C)~~	~~See 7.2.1~~	~~115~~	~~115~~
~~NOTE The temperature and current limits are not intended to be valid simultaneously. The current may be limited to a lower value than that shown in order to meet the temperature limitation requirement. Conversely, the temperature may be limited to a lower value than that shown in order to meet the current limitation requirement.~~			

The limits given in Table 2 are applicable to transformers specified to have temperature rise requirements according to IEC 60076-2. For transformers specified according to IEC 60076-14, with a higher thermal class insulation materials, the limits given in IEC 60076-14 apply.

Table 2 – Maximum permissible temperature limits applicable to loading beyond nameplate rating

Types of loading	Small transformers	Large and medium power transformers
Normal cyclic loading		
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	120	120
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)	140	140
Inner core hot-spot temperature (°C)	130	130
Top-oil temperature, in tank (°C)	105	105
Long-time emergency loading		
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	140	140
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass-fibre materials) (°C)	160	160
Inner core hot-spot temperature (°C)	140	140
Top-oil temperature, in tank (°C)	115	115
Short-time emergency loading		
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	See 7.3.1	160
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)	See 7.3.1	180
Inner core hot-spot temperature (°C)	See 7.3.1	160
Top-oil temperature, in tank (°C)	See 7.3.1	115
NOTE For more information on the core temperature, see Annex B.		

7.2 Current limitations

There are limitations on current carrying capability of transformer other than temperature limits given in Table 2, and these are described in 7.3 to 7.5. Therefore, it is recommended that the current limits given in Table 3 are not exceeded even if the circumstances of the overload mean that the temperatures in Table 2 are not exceeded. Specific examples would be in cases of low ambient temperature, low levels of preload or high thermal capacity of the winding. The purchaser can specify higher current limits if required, but it should be recognized that this could lead to a special transformer design. The recommended current limits given in Table 3 should not apply to very short duration overloads, i.e. less than 10 s.

NOTE 1 The breaking capacity of tap-changers is limited to twice the rated current according to IEC 60214-1 [3].

Table 3 – Recommended current limits applicable to loading beyond nameplate rating

Types of loading	Small transformers	Medium power transformers	Large power transformers
Normal cyclic loading			
Current (p.u.)	1,5	1,5	1,3
Long-time emergency loading			
Current (p.u.)	1,8	1,5	1,3
Short-time emergency loading			
Current (p.u.)	2,0	1,8	1,5

NOTE 2 For specification beyond rated power, see Annex C.

7.3 Specific limitations for ~~distribution~~ small transformers

7.3.1 Current and temperature limitations

The limits on load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than windings and leads stated in ~~Table 4~~ Table 2 and Table 3 should not be exceeded. No limit is set for the top-oil, core and winding hot-spot temperature under short-time emergency loading for distribution transformers because it is usually impracticable to control the duration of emergency loading in this case. It should be noted that when the hot-spot temperature exceeds 140 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 5.3).

7.3.2 Accessory and other considerations

Apart from the windings, other parts of the transformer, such as bushings, cable-end connections, tap-changing devices and leads may restrict the operation when loaded above 1,5 times the rated current. Oil expansion and oil pressure could also impose restrictions.

7.3.3 Indoor transformers

When transformers are used indoors, a correction should be made to the rated top-oil temperature rise to take account of the enclosure. Preferably, this extra temperature rise will be determined by a test (see 8.3.2).

7.3.4 Outdoor ambient conditions

Wind, sunshine and rain may affect the loading capacity of distribution transformers, but their unpredictable nature makes it impracticable to take these factors into account.

7.4 Specific limitations for medium power transformers

7.4.1 Current and temperature limitations

The load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than windings and leads should not exceed the limits stated in ~~Table 4~~ Table 2 and Table 3. Moreover, it should be noted that, when the hot-spot temperature exceeds 140 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 5.3).

7.4.2 Accessory, associated equipment and other considerations

Apart from the windings, other parts of the transformer, such as bushings, cable-end connections, tap-changing devices and leads, may restrict the operation when loaded above

1,5 times the rated current. Oil expansion and oil pressure could also impose restrictions. Consideration may also have to be given to associated equipment such as cables, circuit breakers, current transformers, etc.

7.4.3 Short-circuit withstand requirements

During or directly after operation at load beyond nameplate rating, transformers ~~may~~ can not conform to the thermal short-circuit requirements, as specified in IEC 60076-5 [67], which are based on a short-circuit duration of 2 s. However, the duration of short-circuit currents in service is shorter than 2 s in most cases.

7.4.4 Voltage limitations

Unless other limitations for variable flux voltage variations are known (see IEC ~~60076-4~~ 60076-1), the applied voltage should not exceed 1,05 times either the rated voltage (principal tapping) or the tapping voltage (other tappings) on any winding of the transformer.

7.5 Specific limitations for large power transformers

7.5.1 General

For large power transformers, additional limitations, mainly associated with the leakage flux, ~~shall~~ should be taken into consideration. It is therefore advisable in this case to specify, at the time of enquiry or order, the amount of loading capability needed in specific applications.

As far as thermal deterioration of insulation is concerned, the same calculation method applies to all transformers.

According to present knowledge, the importance of the high reliability of large units in view of the consequences of failure, together with the following considerations, make it advisable to adopt a more conservative, more individual approach here than for smaller units.

- The combination of leakage flux and main flux in the limbs or yokes of the magnetic circuit (see 5.2) makes large transformers more vulnerable to overexcitation than smaller transformers, especially when loaded above nameplate rating. Increased leakage flux may also cause additional eddy-current heating of other metallic parts.
- The consequences of degradation of the mechanical properties of insulation as a function of temperature and time, including wear due to thermal expansion, may be more severe for large transformers than for smaller ones.
- Hot-spot temperatures outside the windings cannot be obtained from a normal temperature-rise test. Even if such a test at a rated current indicates no abnormalities, it is not possible to draw any conclusions for higher currents since this extrapolation may not have been taken into account at the design stage.
- Calculation of the winding hot-spot temperature rise at higher than rated currents, based on the results of a temperature-rise test at rated current, may be less reliable for large units than for smaller ones.

7.5.2 Current and temperature limitations

The load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than windings and leads but nevertheless in contact with solid insulating material should not exceed the limits stated in ~~Table 4~~ Table 2 and Table 3. Moreover, it should be noted that, when the hot-spot temperature exceeds 140 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 5.3).

7.5.3 Accessory, equipment and other considerations

Refer to 7.4.2.

7.5.4 Short-circuit withstand requirements

Refer to 7.4.3.

7.5.5 Voltage limitations

Refer to 7.4.4.

8 Determination of temperatures

8.1 Hot-spot temperature rise in steady state

8.1.1 General

To be strictly accurate, the hot-spot temperature should be referred to the adjacent oil temperature. This is assumed to be the top-oil temperature inside the winding. Measurements have shown that the top-oil temperature inside a winding might be, dependent on the cooling, up to 15 K higher than the mixed top-oil temperature inside the tank.

For most transformers in service, the top-oil temperature inside a winding is not precisely known. On the other hand, for most of these units, the top-oil temperature at the top of the tank is well known, either by measurement or by calculation.

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

- $\Delta\theta_{or}$, the top-oil temperature rise in the tank above ambient temperature at rated losses [K];
- $\Delta\theta_{hr}$, the hot-spot temperature rise above top-oil temperature in the tank at rated current [K].

The parameter $\Delta\theta_{hr}$ can be defined either by direct measurement during a heat-run test or by a calculation method validated by direct measurements.

NOTE The methods, principles and calculation procedures given in 8.1.2, 8.1.3, 8.1.4 and Annex D are ultimately valid for the converter transformers for HVDC application, however, with the necessary consideration of the effect of harmonics on the transformer thermal performance with a reference to a specific converter operating point and specific system conditions.

8.1.2 Calculation of hot-spot temperature rise from normal heat-run test data

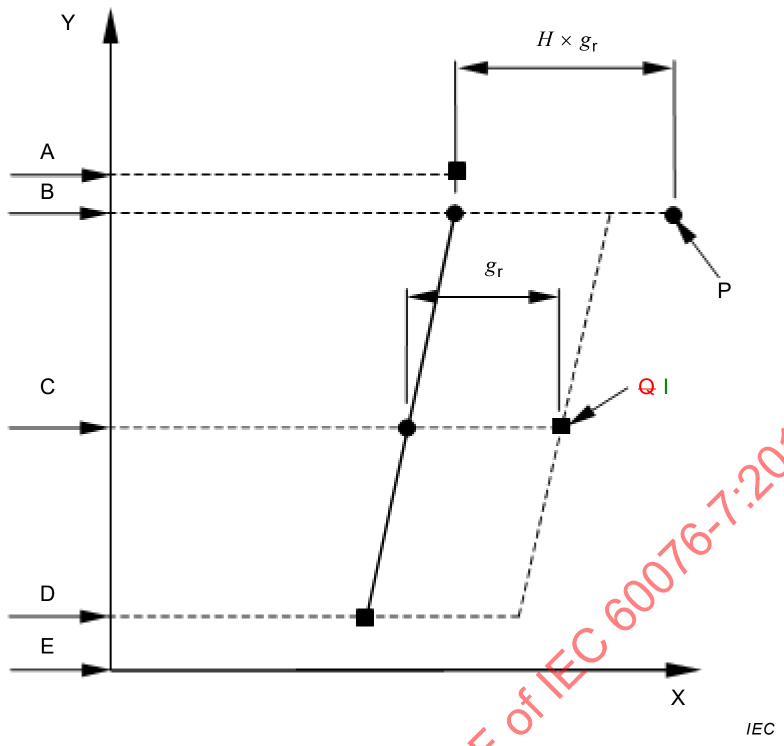
A thermal diagram is assumed, as shown in Figure 6, on the understanding that such a diagram is the simplification of a more complex distribution. The assumptions made in this simplification are as follows.

a) The oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode.

b) As a first approximation, the temperature rise of the conductor at any position up the winding is assumed to increase linearly, parallel to the oil temperature rise, with a constant difference g_r between the two straight lines (g_r being the difference between the winding average temperature rise by resistance and the average oil temperature rise in the tank).

c) The hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding as described in 8.1.2 b), because allowance has to be made for the increase in stray losses, for differences in local oil flows and for possible additional paper on the conductor. To take into account these non-linearities, the difference in temperature between the hot-spot and the top-oil in tank is made equal to $H \times g_r$, that is, $\Delta\theta_{hr} = H \times g_r$.

   NOTE In many cases, it has been observed that the temperature of the tank outlet oil is higher than that of the oil in the oil pocket. In such cases, the temperature of the tank outlet oil ~~should be~~ is used for loading.



Key

A Top-oil temperature derived as the average of the tank outlet oil temperature and the tank oil pocket temperature

B Mixed oil temperature in the tank at the top of the winding (often assumed to be the same temperature as A)

C Temperature of the average oil in the tank

D Oil temperature the inlet of the tank (assumed to be the same as at the bottom of the winding)

E Bottom of the tank

g_r Average winding to average oil (in tank) temperature gradient at rated current

H Hot-spot factor

P Hot-spot temperature

~~Q~~ I Average winding temperature determined by resistance measurement

x-axis Temperature

y-axis Relative positions

■ measured point; ● calculated point

Figure 6 – Thermal diagram

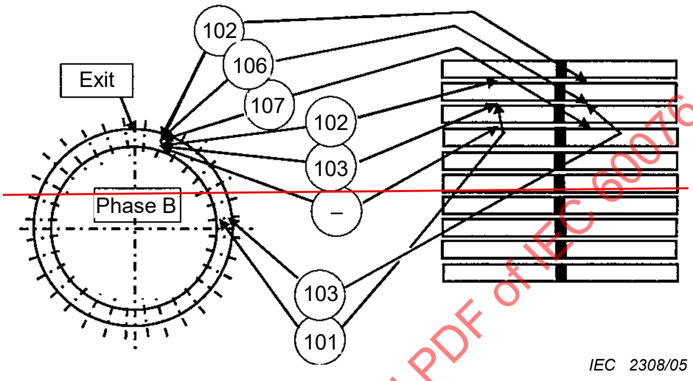
8.1.3 Direct measurement of hot-spot temperature rise

~~Direct measurement with fibre optic probes became available in the middle of the 1980s and has been practised ever since on selected transformers.~~

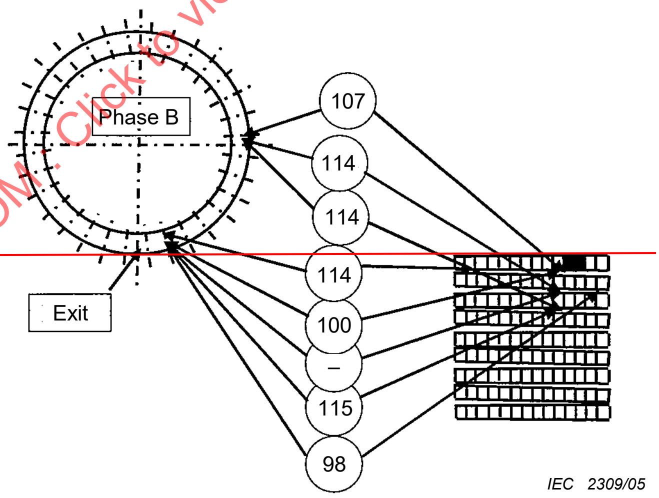
~~Experience has shown that there might be gradients of more than 10 K between different locations in the top of a normal transformer winding [8]. Hence, it is unlikely that the insertion of, for example, one to three sensors will detect the real hot-spot. A compromise is necessary between the necessity of inserting a large number of probes to find the optimum location, and the additional efforts and costs caused by fibre optic probes. It is recommended that sensors be installed in each winding for which direct hot-spot measurements are required.~~

~~Usually, the conductors near the top of the winding experience the maximum leakage field and the highest surrounding oil temperature. It would, therefore, be natural to consider that the top conductors contain the hottest spot. However, measurements have shown that the hottest spot might be moved to lower conductors. It is therefore recommended that the sensors be distributed among the first few conductors, seen from the top of a winding [8]. The manufacturer shall define the locations of the sensors by separate loss/thermal calculations.~~

~~Examples of the temperature variations in the top of a winding are shown in Figures 3 and 4 [8]. The installation of fibre optic probes was made in a 400 MVA, ONAF-cooled transformer. The values shown are the steady-state values at the end of a 15 h overload test. The values 107 K and 115 K were taken as the hot-spot temperature rises of the respective windings. The top-oil temperature rise at the end of the test was 79 K, i.e.~~ $\cancel{\Delta\theta_{hr} = 28}$ ~~K for the 120 kV winding and~~ $\cancel{\Delta\theta_{hr} = 36}$ ~~K for the 410 kV winding.~~



~~**Figure 3 – Local temperature rises above air temperature in a 120 kV winding at a load factor of 1,6**~~



~~**Figure 4 – Local temperature rises above air temperature in a 410 kV winding at a load factor of 1,6**~~

~~The sensors were inserted in slots in the radial spacers in such a way that there was only the conductor insulation and an additional thin paper layer between the sensor and the conductor metal (see Figure 5). Calibrations have shown that a reasonable accuracy is obtained in this way [9].~~

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~~**Figure 5 – Two fibre optic sensors installed in a spacer before the spacer was installed in the 120 kV winding**~~

~~The hot-spot factor H is taken as the ratio of the gradient $\Delta\theta_{hr}$ for the hottest probe and the average winding-to-average oil gradient g_r. In the example measurement, the g-values were 23 K for the 120 kV winding and 30 K for the 410 kV winding. This means that the H-values were 1,22 and 1,20 respectively.~~

Fibre optic probes are installed in windings to measure the hot-spot temperature rise. Although local loss densities and oil circulation speeds are calculated, it is very difficult to know where the hot-spot is exactly located. Thus, a certain minimum number of sensors should be installed in a winding. The sensors are inserted in slots in the radial spacers in such a way that there is only the conductor insulation and an additional thin paper layer between the sensor and the conductor metal. Calibrations have shown that a reasonable accuracy is obtained in this way (see [16]).

This minimum number of sensors is selected in such a way that the maximum measured temperature rise is close enough to the real hot-spot temperature rise for a safe operation of the winding. This maximum measured temperature is at the same time considered as the hot-spot of the winding.

In core type transformers the hot-spot is generally located at the top of the windings. If the winding is cooled by axial oil circulation, the most probable location is disc number 1 or 2 seen from the top. At zig-zag cooling one of the first 3 top discs is the most probable location. If the winding has tapping discs at its upper half, the hot-spot is probably located in the first current carrying disc above the currentless tapping discs in the (-) tap position. Therefore, it should be noted that the hot-spot location is transformer specific and highly affected by the transformer design. As such, this predetermined location should be discussed during design review.

Experience has shown that there might be gradients of more than 10 K between different sensors in the top of a normal transformer winding. Hence, it is not self-evident that the insertion of, for example, one or two sensors will detect a relevant temperature rise. An example of this is shown in Figure 7 [17]. The relative local loss densities compared to the average loss of the winding (which corresponded to the average winding gradient g) were 156 %, 133 %, etc. The figures indicated in the discs at the right (114 %, 142 %, 156 %, etc.) are the relative local loss densities in per cent of the average loss density of the whole winding that is the total loss of the winding divided by the number of discs. It should be noted that the highest temperature rise of 23,2 K was measured at the relative loss density 117 %, which was far from the highest value 156 %.

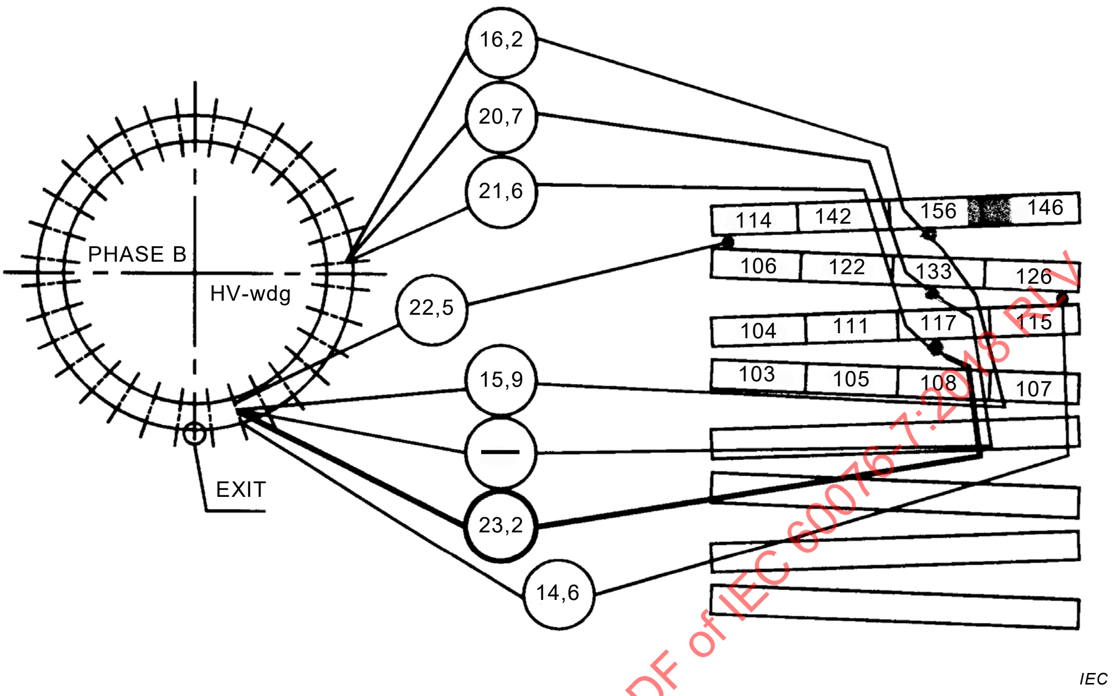


Figure 7 – Temperature rises above top-oil temperature (in tank) 65,8 °C of the zig-zag cooled HV-winding of a 400 MVA ONAF cooled 3-phase transformer, load current 1,0 p.u., tap position (-)

For the temperature rise test, the recommended number of sensors to be installed in one phase of ON-, OF-, OD-cooled core type transformers are as follows:

a) for transformers with a leakage flux ≥ 400 mWb/phase at the rated current, the number of sensors should be 8 per winding with full rating;

b) for transformers with a leakage flux between 150 mWb/phase and 400 mWb/phase at the rated current, the number of sensors should be 6 per winding;

c) for transformers with a leakage flux below 150 mWb/phase at the rated current, the number of sensors should be 4 per winding.

The sensors should be installed in the phase for which the warm resistance curve is recorded. However, each user should decide how accurate the hot-spot measurement needs to be for a particular transformer application (loaded tertiary winding, small transformers, etc.), and based on this should decide on the total sensor number per winding and per phase.

NOTE By leakage flux is here meant the maximum unidirectional flux (crest value), which is the integral of the absolute values of the axial flux densities between two intersections with the x-axis. A transformer might have several such integrals and in this case the maximum of these integrals is considered. An approximate formula for this maximum leakage flux is $1{,}8 \times Z \times S^{0{,}5}$ [18], where Z is the short-circuit impedance in per cent and S is the intrinsic rated power per wound limb in MVA. For auto-connected transformers, Z and S refer to the intrinsic MVA value and not to the MVA transformed. S is therefore equal to the nameplate rated power, multiplied by α, i.e. the auto factor. The auto factor, α, is equal to: (primary voltage – secondary voltage) / primary voltage. Z is equal to the nameplate short-circuit impedance divided by the auto factor.

EXAMPLE For single-phase 550/230 kV auto-connected transformer with the throughput rating S = 334 MVA, the corresponding impedance Z = 15 %, and the auto factor α = (550 − 230)/550 = 0,58, the leakage flux is approximately $[1{,}8 \times (0{,}58 \times 334)^{0{,}5} \times (15/0{,}58)]$ = 650 mWb.

In shell type transformers, the fibre optic sensors should be located in the coil edges (Figure 8) and in the brazed connections between coils.

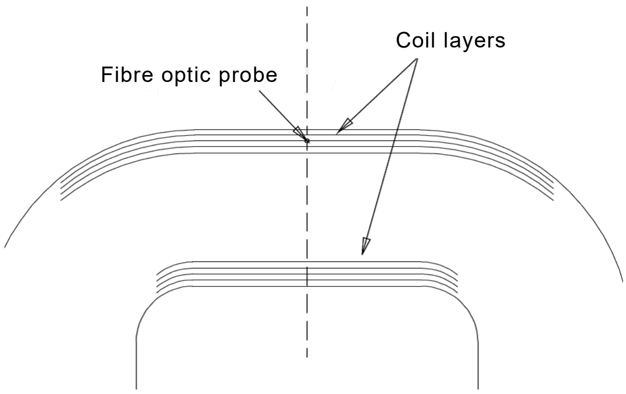


Figure 8 – Coil edges, where the sensors should be located in the edge with the higher calculated temperature rise

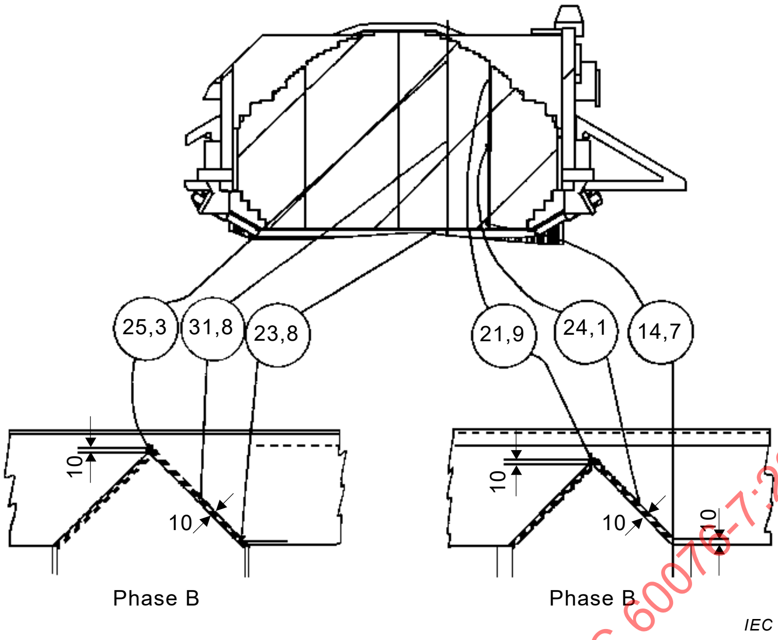
If it is not possible to install the fibre optic sensor in the expected hot-spot location, for example due to high voltage stress, then the installation can be made at a safer location. Consequently, the proposed alternative measuring location and the corresponding correction procedure should be further discussed between purchaser and manufacturer.

Although Table 2 comprises temperature limits for core and structural parts, such temperature rises are not measured in a normal temperature rise test. Those temperature rises are normally estimated by calculation. The manufacturers should install thermal sensors in these parts in selected transformers to calibrate their calculation methods. Manufacturers of fibre optic probes are producing insulation kits for this purpose, but also robust thermocouples or RTDs offer a good alternative. The thermocouples can be installed permanently in the transformer in such a way that they do not reduce the voltage strength and that they remain inside the transformer during its life. Thermocouples inside a transformer should be twisted to eliminate the effect of leakage flux impinging between the two thermocouple strands and causing an extra induced voltage between the two thermocouple metals. If specified such special test (i.e. the temperature rise of the core and structural part during the no-load test) should be discussed during the design review and the following parameters should be defined:

– cooling conditions;
– test duration;
– supply voltage;
– temperature limits.

Thermal sensors should particularly be installed in:

a) yoke clamp made of magnetic steel, e.g. winding supports, supports for exit leads, yoke clamp extensions at the end of cores with wound outer limbs, and in yoke clamps opposite to the centre line of a phase;
b) flitch-plates and outer core packets opposite to the top of the winding block;
c) in the top yoke, particularly at the top of the centre phase in a 3-phase transformer (Figure 9).



NOTE The three right-hand values are measured in the cooling duct.

Figure 9 – Temperature rises above top-oil temperature at the end of an 8 h thermal no-load test at 110 % supply voltage

Installation of sensors in the top yoke makes sense only if an extra thermal no-load test is done.

More details about the installation of thermal sensors are given in [18].

8.1.4 Hot-spot factor

The hot-spot factor H is winding-specific and should be determined on a case-by-case basis when required. Studies show that the factor H varies within the ranges 1,0 to 2,1 depending on the transformer size, its short-circuit impedance and winding design [19]. The factor H should be defined either by direct measurement (see 8.1.3 and Annex D) or by a calculation procedure based on fundamental loss and heat transfer principles, and substantiated by direct measurements on production or prototype transformers or windings. ~~For standard distribution transformers with a short-circuit impedance ≤ 8 % the value of H = 1,1 can be considered accurate enough for loading considerations. In the calculation examples in Annex E, it is assumed that H = 1,1 for distribution transformers and H = 1,3 for medium-power and large-power transformers.~~

A calculation procedure based on fundamental loss and heat transfer principles should consider the following [as given in Annex D, [18], and [20].

a) The fluid flow within the winding ducts, the heat transfer, flow rates and resulting fluid temperature should be modelled for each cooling duct.

b) The distribution of losses within the winding. One of the principal causes of extra local loss in the winding conductors is radial flux eddy loss at the winding ends, where the leakage flux intercepts the wide dimension of the conductors. The total losses in the subject conductors should be determined using the eddy and circulating current losses in addition to the DC resistance loss. Connections that are subject to leakage flux heating, such as coil-to-coil connections and some tap-to-winding brazes, should also be considered.

c) Conduction heat transfer effects within the winding caused by the various insulation thicknesses used throughout the winding.

d) Local design features or local fluid flow restrictions.

- Layer insulation may have a different thickness throughout a layer winding, and insulation next to the cooling duct affects the heat transfer.
- Flow-directing washers reduce the heat transfer into the fluid in the case of a zigzag-cooled winding (Figure 10).

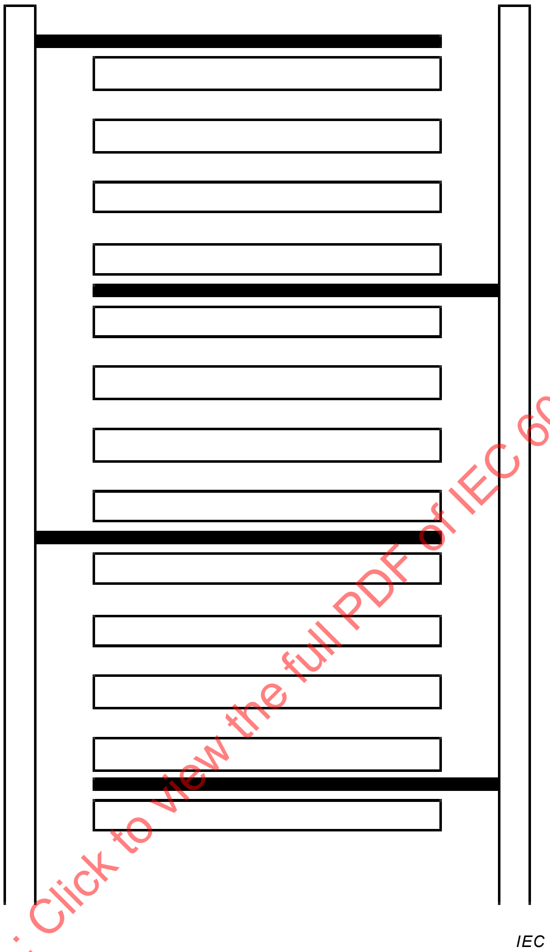


Figure 10 – Zigzag-cooled winding where the distance between all sections is the same and the flow-directing washer is installed in the space between sections

- Possible extra insulation on end turns and on winding conductors exiting through the end insulation.
- Not all cooling ducts extend completely around the winding in distribution transformers and small power transformers. Some cooling ducts are located only in the portion of the winding outside the core (see Figure 11). Such a “collapsed duct arrangement” causes a circumferential temperature gradient from the centre of the winding with no ducts under the yoke to the centre of the winding outside core where cooling ducts are located.

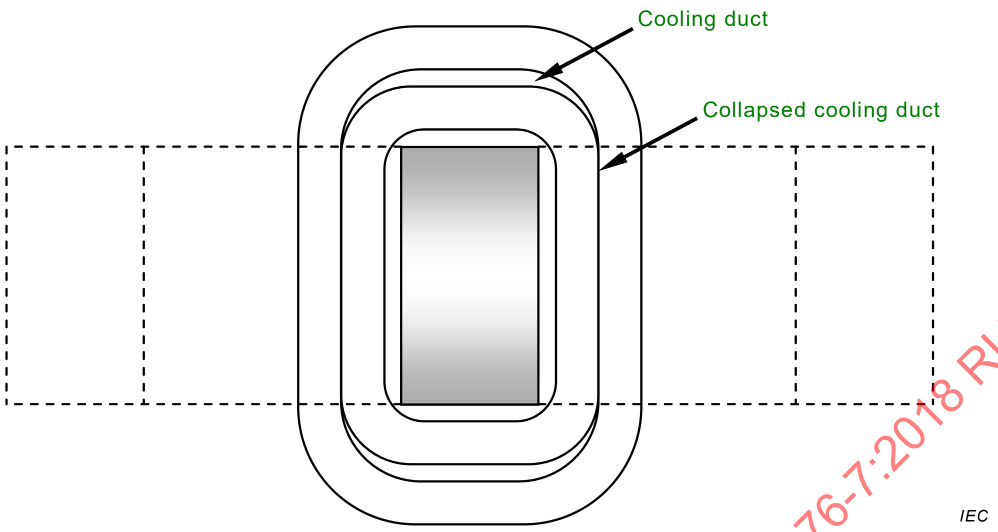


Figure 11 – Top view section of a rectangular winding with "collapsed cooling duct arrangement" under the yokes

8.2 Top-oil and hot-spot temperatures at varying ambient temperature and load conditions

8.2.1 General

Subclause 8.2 provides two alternative ways of describing the hot-spot temperature as a function of time, for varying load current and ambient temperature:

a) exponential equations solution [18], [21]~~, suitable for a load variation according to a step function. This method is particularly suited to determination of the heat transfer parameters by test, especially by manufacturers [12], and it yields proper results in the following cases.~~

- ~~Each of the increasing load steps is followed by a decreasing load step or vice versa.~~
- ~~In case of N successive increasing load steps ($N \geq 2$), each of the ($N - 1$) first steps has to be long enough for the hot-spot-to-top-oil gradient $\Delta\theta_h$ to obtain steady state. The same condition is valid in case of N successive decreasing load steps ($N \geq 2$).~~

b) difference equations solution [22]~~, suitable for arbitrarily time-varying load factor K and time-varying ambient temperature θ_a. This method is particularly applicable for on-line monitoring [13], especially as it does not have any restrictions concerning the load profile.~~

Both of these methods are suitable for arbitrarily time-varying load factor K and time-varying ambient temperature θ_a. The former method is particularly more suited to determination of the heat transfer parameters by test, especially by manufacturers, while the latter method is more suitable for on-line monitoring due to applied mathematical transformation. In principle, both methods yield the same results as they represent solution variation to the identical heat transfer differential equations.

The heat transfer differential equations are represented in block diagram form in Figure 12.

Observe in Figure 12 that the inputs are the load factor K, and the ambient temperature θ_a on the left. The output is the ~~desired~~ calculated hot-spot temperature θ_h on the right. The Laplace variable s is essentially the derivative operator d/dt.

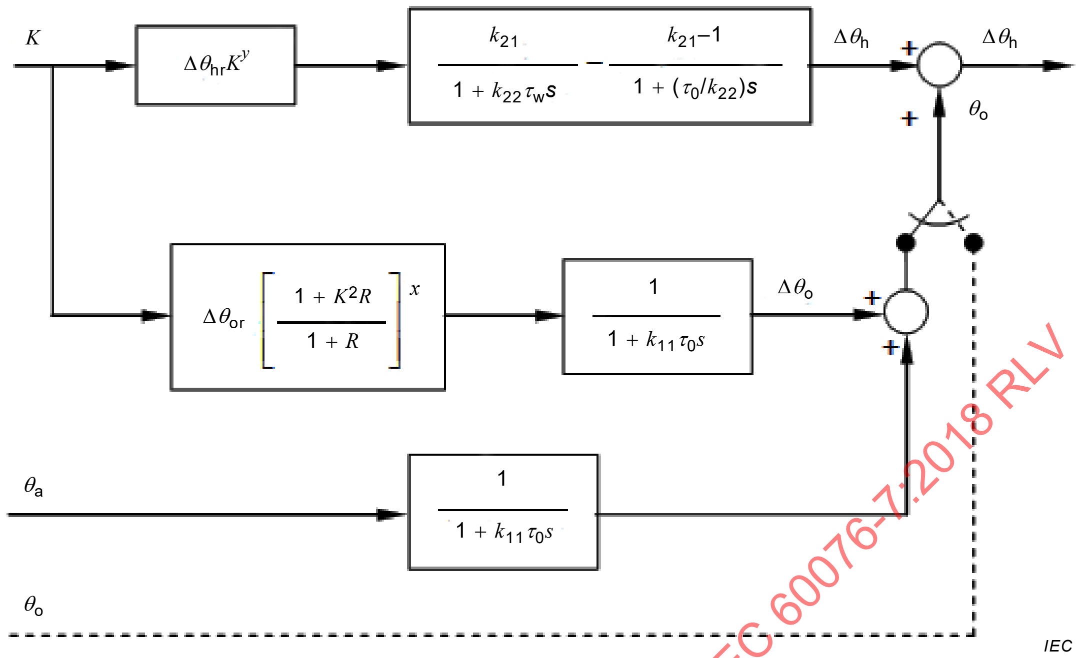


Figure 12 – Block diagram representation of the differential equations

In Figure 12, the second block in the uppermost path represents the hot-spot rise dynamics. The first term (with numerator k_{21}) represents the fundamental hot-spot temperature rise, before the effect of changing oil flow past the hot-spot is taken into account. The second term (with numerator $k_{21}-1$) represents the varying rate of oil flow past the hot-spot, a phenomenon which changes much more slowly. The combined effect of these two terms is to account for the fact that a sudden rise in load current may cause an otherwise unexpectedly high peak in the hot-spot temperature rise, very soon after the sudden load change. Values for k_{11}, k_{21}, k_{22} and the other parameters shown are discussed in 8.2.2 and suggested values given in Table 4.

~~The time step shall be less than one-half of the smallest time constant τ_w to obtain a reasonable accuracy. Additionally, τ_w and τ_o should not be set to zero.~~

If the top-oil temperature can be measured as an electrical signal into a computing device, then an alternative formulation is the dashed line path, with the switch in its right position; the top-oil calculation path (switch to the left) is not required. All of the parameters have been defined in 8.2.2.

The mathematical interpretation of the blocks in Figure 12 is given as follows:

The differential equation for top-oil temperature (inputs K, θ_a, output θ_o) is

$$\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) = k_{11}\tau_o \times \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \tag{5}$$

The differential equation for hot-spot temperature rise (input K, output $\Delta\theta_h$) is most easily solved as the sum of two differential equation solutions, where

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \tag{6}$$

The two equations are

$$k_{21} \times K^{y} \times (\Delta\theta_{hr}) = k_{22} \times \tau_{w} \times \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \quad (7)$$

and

$$(k_{21} - 1) \times K^{y} \times (\Delta\theta_{hr}) = (\tau_{o} / k_{22}) \times \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \quad (8)$$

the solutions of which are combined in accordance with Equation (6).

The final equation for the hot-spot temperature is

$$\theta_{h} = \theta_{o} + \Delta\theta_{h} \quad (9)$$

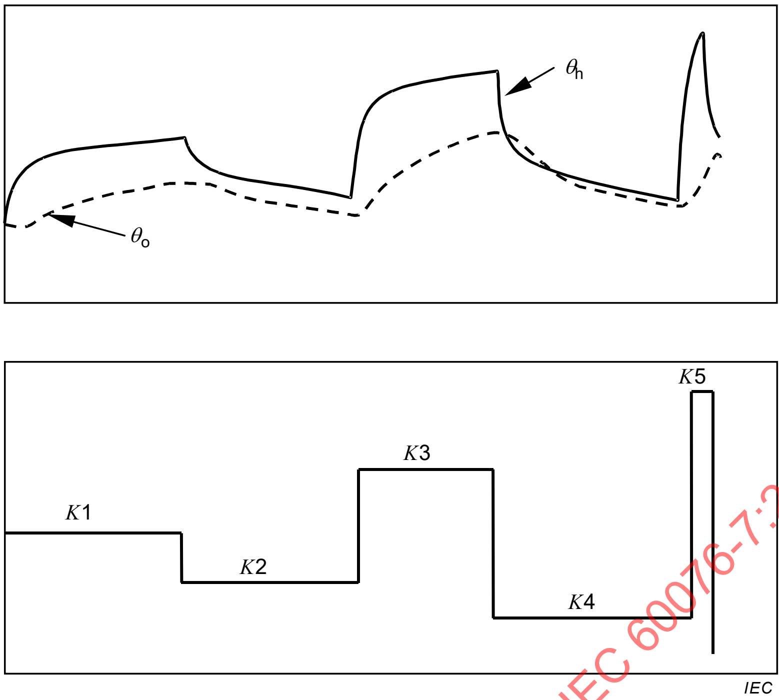
Regarding Equations (5) to (8), the complexity is in order to account for the fact that the oil-cooling medium has mechanical inertia in addition to thermal inertia. The effect is greatest for natural cooling (ON), somewhat less for non-directed-flow pumped-oil cooling (OF), and negligible for directed-flow pumped-oil cooling (OD), as regards power transformers. It is also negligible for small transformers (see 8.2.2).

NOTE For ON and OF cooling, the oil viscosity change counteracts the effect of the ohmic resistance variation of the conductors. In fact, the cooling effect of the oil viscosity change is stronger than the heating effect of the resistance change. This has been taken into account implicitly by the winding exponent of 1,3 in Table 5. For OD cooling, the influence of the oil viscosity on temperature rises is slight, and the effect of the ohmic resistance variation ~~should be~~ is considered. An approximate correction term (with its sign) for the hot-spot temperature rise at OD is 0,15 × $(\Delta\theta_{h} - \Delta\theta_{hr})$.

8.2.2 Exponential equations solution

Subclause 8.2.2 describes the exponential equation solution to the heat transfer differential Equations (5) to (8).

An example of a load variation according to a step function~~, where each of the increasing load steps is followed by a decreasing load step,~~ is shown in Figure 13 (the details of the example are given in Annex H).



735 min

Key

θ_h Winding hot-spot temperature

θ_o Top-oil temperature in tank

$K1$ is 1,0 $K2$ is 0,6 $K3$ is 1,5 $K4$ is 0,3 $K5$ is 2,1

Figure 13 – Temperature responses to step changes in the load current

The hot-spot temperature is equal to the sum of the ambient temperature, the top-oil temperature rise in the tank, and the temperature difference between the hot-spot and top-oil in the tank.

~~The temperature increase to a level corresponding to a load factor of K is given by:~~

$$\theta_h(t) = \theta_a + \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} \times f_1(t) + \Delta\theta_{hi} + \left\{ H g_r K^y - \Delta\theta_{hi} \right\} \times f_2(t) \tag{5}$$

~~Correspondingly, temperature decrease to a level corresponding to a load factor of K, is given by:~~

$$\theta_h(t) = \theta_a + \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x \right\} \times f_3(t) + H g_r K^y \tag{6}$$

~~The top-oil exponent x and the winding exponent y are given in Table 5 [14].~~

~~The function $f_1(t)$ describes the relative increase of the top-oil temperature rise according to the unit of the steady-state value:~~

~~$$f_1(t) = \left(1 - e^{(-t)/(k_{11} \times \tau_0)}\right) \tag{7}$$~~

~~where~~

~~k_{11} is a constant given in Table 5;~~

~~τ_0 is the average oil-time constant (min).~~

~~The function $f_2(t)$ describes the relative increase of the hot-spot-to-top-oil gradient according to the unit of the steady-state value. It models the fact that it takes some time before the oil circulation has adapted its speed to correspond to the increased load level:~~

~~$$f_2(t) = k_{21} \times \left(1 - e^{(-t)/(k_{22} \times \tau_w)}\right) - (k_{21} - 1) \times \left(1 - e^{(-t)/(\tau_0 / k_{22})}\right) \tag{8}$$~~

The top-oil temperature increase to a level corresponding to a load factor of K is given by:

$$\theta_o(t) = \theta_a + \Delta\theta_{oi} + \left\{\Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x - \Delta\theta_{oi}\right\} \times \left(1 - e^{(-t)/(k_{11} \times \tau_0)}\right) \tag{10}$$

Correspondingly, the top-oil temperature decrease to a level corresponding to a load factor of K is given by:

$$\theta_o(t) = \theta_a + \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x + \left\{\Delta\theta_{oi} - \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R}\right]^x\right\} \times e^{(-t)/(k_{11} \times \tau_0)} \tag{11}$$

The hot-spot to top-oil temperature gradient increase to a level corresponding to a load factor of K is given by:

$$\Delta\theta_h(t) = \Delta\theta_{h1}(t) - \Delta\theta_{h2}(t) \tag{12}$$

where two gradients are

$$\Delta\theta_{h1}(t) = \Delta\theta_{h1_i} + \left\{k_{21} H g_r K^y - \Delta\theta_{h1_i}\right\} \times \left(1 - e^{(-t)/(k_{22} \times \tau_w)}\right) \tag{13}$$

and

$$\Delta\theta_{h2}(t) = \Delta\theta_{h2_i} + \left\{(k_{21} - 1) H g_r K^y - \Delta\theta_{h2_i}\right\} \times \left(1 - e^{(-t)/(\tau_0 / k_{22})}\right) \tag{14}$$

Correspondingly, the hot-spot to top-oil temperature gradient decrease to a level corresponding to a load factor of K is given by:

$$\Delta\theta_{h1}(t) = k_{21} H g_r K^y + \left\{\Delta\theta_{h1_i} - k_{21} H g_r K^y\right\} \times e^{(-t)/(k_{22} \times \tau_w)} \tag{15}$$

and

$$\Delta\theta_{h2}(t) = (k_{21} - 1) H g_r K^y + \left\{\Delta\theta_{h2_i} - (k_{21} - 1) H g_r K^y\right\} \times e^{(-t)/(\tau_0 / k_{22})} \tag{16}$$

The final equation for the hot-spot temperature is:

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h(t) \tag{17}$$

where

τ_w is the winding time constant (min);

τ_0 is the oil-time constant (min).

The top-oil exponent x and the winding exponent y are given in Table 4 [23], [24].

The constants k_{11}, k_{21}, k_{22} and the time constants τ_w and τ_0 are transformer specific. They can be determined in a prolonged heat-run test during the "no-load loss + load loss" period, if the supplied losses and corresponding cooling conditions, for example AN or AF, are kept unchanged from the start until the steady state has been obtained (see Annex F). In this case, it is necessary to ensure that the heat-run test is started when the transformer is approximately at the ambient temperature. It is obvious that k_{21}, k_{22} and τ_w can be defined only if the transformer is equipped with fibre optic sensors. If τ_0 and τ_w are not defined in a prolonged heat-run test they can be defined by calculation (see Annex E). In the absence of transformer-specific values, the values in Table 4 are recommended. The corresponding graphs are shown in Figure 14.

NOTE 1 Unless the current and cooling conditions remain unchanged during the heating process long enough to project the tangent to the initial heating curve, the time constants cannot be determined from the heat-run test performed according to IEC practice.

NOTE 2 The ~~$f_2(t)$~~ $\Delta\theta_h(t)/\Delta\theta_{hr}$ graphs observed for ~~distribution~~ small transformers are similar to graph 7 in Figure 14, i.e. ~~distribution~~ small transformers do not show such a hot-spot "overshoot" at step increase in the load current as ON- and OF-cooled power transformers do.

NOTE 3 The background of the oil, x, and winding, y, exponents and corresponding determining procedure are given in Annex G.

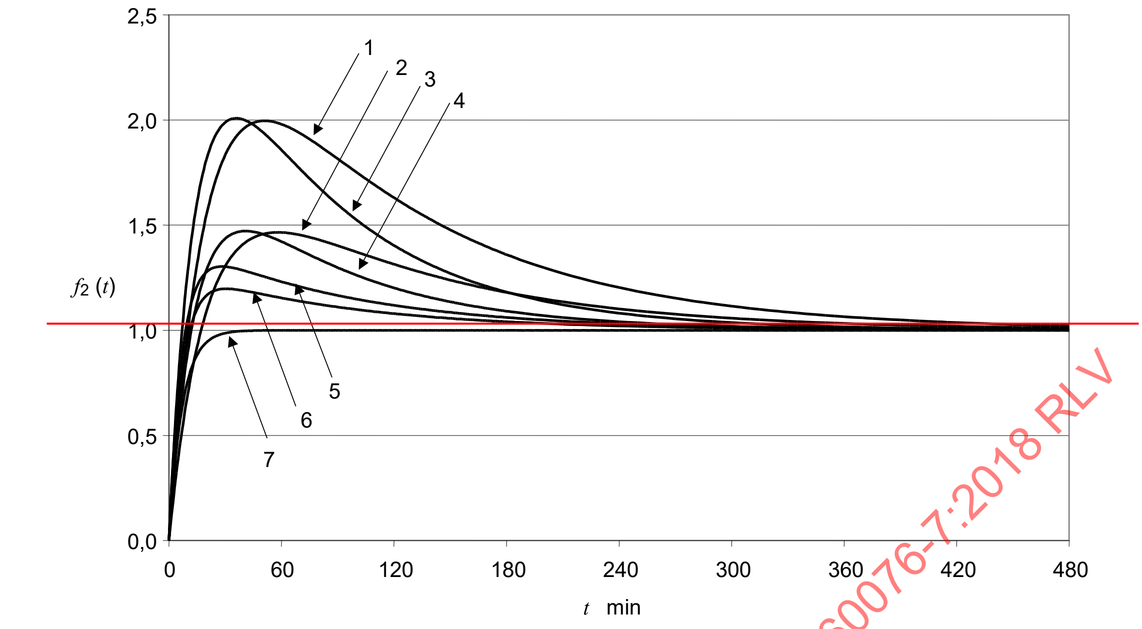
~~The function $f_3(t)$ describes the relative decrease of the top-oil-to-ambient gradient according to the unit of the total decrease:~~

$$\cancel{f_3(t) = e^{(-t)/(k_{11} \times \tau_0)}} \tag{9}$$

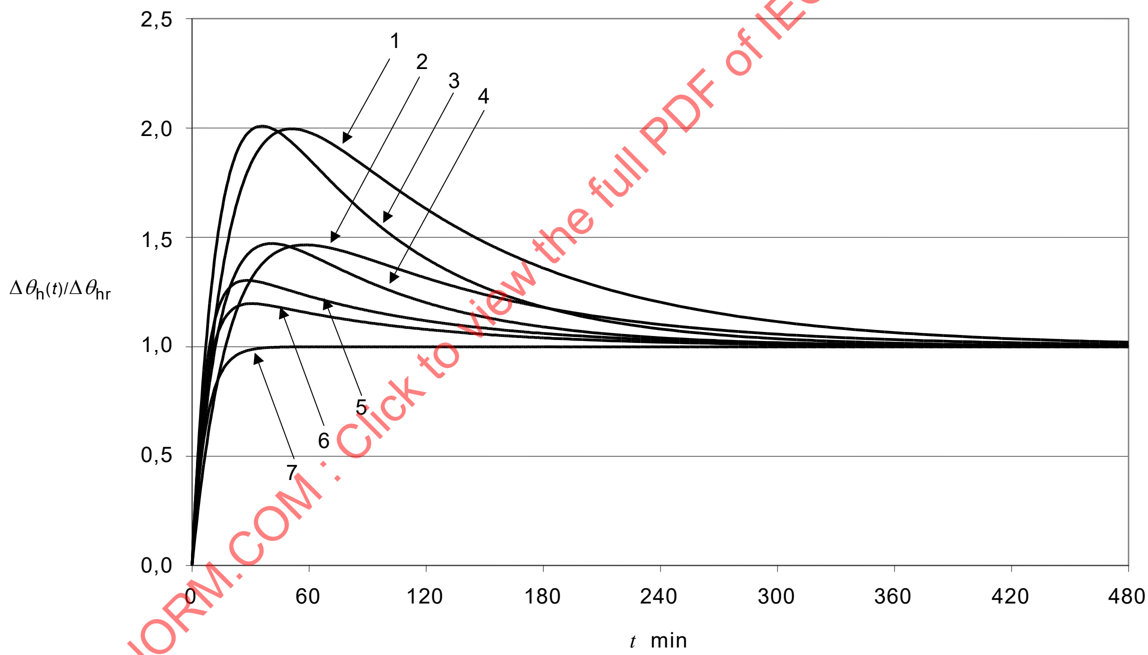
Table 4 – Recommended thermal characteristics for exponential equations

Characteristic	~~Distribution~~ Small transformers	Medium and large power transformers						
	ONAN	ONAN restricted[a]	ONAN	ONAF restricted[a]	ONAF	OF restricted[a]	OF	OD
Oil exponent x	0,8	0,8	0,8	0,8	0,8	1,0	1,0	1,0
Winding exponent y	1,6	1,3	1,3	1,3	1,3	1,3	1,3	2,0
Constant k_{11}	1,0	0,5	0,5	0,5	0,5	1,0	1,0	1,0
Constant k_{21}	1,0	3,0	2,0	3,0	2,0	1,45	1,3	1,0
Constant k_{22}	2,0	2,0	2,0	2,0	2,0	1,0	1,0	1,0
Time constant τ_0, min	180	210	210	150	150	90	90	90
Time constant τ_w, min	4	10	10	7	7	7	7	7

[a] If a winding of an ON- or OF-cooled transformer is zigzag-cooled, a radial spacer thickness of less than 3 mm might cause a restricted oil circulation, i.e. a higher maximum value of the function $\cancel{f_2(t)}$ $\Delta\theta_h(t)/\Delta\theta_{hr}$ than obtained by spacers ≥ 3 mm.



IEC 2314/05



IEC

Key

1 ONAN – restricted oil flow
2 ONAN
3 ONAF – restricted oil flow
4 ONAF
5 OF – restricted oil flow
6 OF
7 OD and ~~distribution~~ small power transformers

Figure 14 – The function ~~$f_2(t)$~~ $\Delta\theta_h(t)/\Delta\theta_{hr}$ generated by the values given in Table 4

An application example of the exponential equations solution is given in Annex H.

8.2.3 ~~Differential~~ Difference equations solution

~~This subclause describes the use of heat transfer differential equations, applicable for arbitrarily time-varying load factor K and time-varying ambient temperature θ_a. They are~~

~~intended to be the basis for the software to process data in order to define hot-spot temperature as a function of time and consequently the corresponding insulation life consumption.~~

~~The interpretation of the blocks in Figure 10 as convenient difference equations is described in detail in Annex C.~~

Subclause 8.2.3 describes the difference equation solution to the heat transfer differential equations, applicable for arbitrarily time-varying load factor K and time-varying ambient temperature θ_a.

If the differential equations are converted to difference equations, then the solution is quite straightforward, even on a simple spreadsheet.

The differential Equations (5) to (8) can be written as the following difference equations, where D stands for a difference over a small time step.

Equation (5) becomes:

$$D\theta_o = \frac{Dt}{k_{11}\tau_o}\left[\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) - [\theta_o - \theta_a]\right] \tag{18}$$

The “D” operator implies a difference in the associated variable that corresponds to each time step Dt. At each time step, the nth value of $D\theta_o$ is calculated from the $(n - 1)$th value using

$$\theta_{o(n)} = \theta_{o(n-1)} + D\theta_{o(n)} \tag{19}$$

Equations (7) and (8) become

$$D\Delta\theta_{h1} = \frac{Dt}{k_{22}\tau_w} \times \left[k_{21} \times \Delta\theta_{hr} K^y - \Delta\theta_{h1}\right] \tag{20}$$

and

$$D\Delta\theta_{h2} = \frac{Dt}{(1/k_{22})\tau_o} \times \left[(k_{21} - 1) \times \Delta\theta_{hr} K^y - \Delta\theta_{h2}\right] \tag{21}$$

The nth values of each of $\Delta\theta_{h1}$ and $\Delta\theta_{h2}$ are calculated in a way similar to Equation (19).

The total hot-spot temperature rise at the nth time step is given by:

$$\Delta\theta_{h(n)} = \Delta\theta_{h1(n)} - \Delta\theta_{h2(n)} \tag{22}$$

Finally, the hot-spot temperature at the nth time step is given by:

$$\theta_{h(n)} = \theta_{o(n)} + \Delta\theta_{h(n)} \tag{23}$$

For an accurate solution, the time step Dt should be as small as is practicable, certainly no greater than one-half of the smallest time constant in the thermal model. For example, if the time constant for the winding considered is 4 min, the time step should be no larger than 2 min. τ_w and τ_o should not be set to zero.

Also, there are theoretically more accurate numerical analysis solution methods than the simple one used in Equations (18) to (21), for example trapezoidal or Runge-Kutta methods. However, the increased complexity is not warranted here considering the imprecision of the input data.

The loss of life of cellulose insulation differential equations of 6.4 can also be converted to difference equations. The fundamental differential equation is

$$\frac{dL}{dt} = V \qquad (24)$$

implying

$$DL_{(n)} = V_{(n)} \times Dt \qquad (25)$$

and

$$L_{(n)} = L_{(n-1)} + DL_{(n)} \qquad (26)$$

An application example of the difference equations solution is given in Annex I.

8.3 Ambient temperature

8.3.1 Outdoor air-cooled transformers

For dynamic considerations, such as monitoring or short-time emergency loading, the actual temperature profile should be used directly.

For design and test considerations, the following equivalent temperatures are taken as ambient temperature:

a) the yearly weighted ambient temperature is used for thermal ageing calculation;
b) the monthly average temperature of the hottest month is used for the maximum hot-spot temperature calculation.

NOTE Concerning the ambient temperature, see also IEC 60076-2~~:1993~~.

If the ambient temperature varies appreciably during the load cycle, then the weighted ambient temperature is a constant, fictitious ambient temperature which causes the same ageing as the variable temperature acting during that time. For a case where a temperature increase of 6 K doubles the ageing rate and the ambient temperature can be assumed to vary sinusoidally, the yearly weighted ambient temperature, θ_E, is equal to

$$\theta_E = \theta_{ya} + 0{,}01 \times \left[2\left(\theta_{ma\text{-}max} - \theta_{ya}\right)\right]^{1{,}85} \qquad (27)$$

where

$\theta_{ma\text{-}max}$ is the monthly average temperature of the hottest month (which is equal to the sum of the average daily maxima and the average daily minima, measured in °C, during that month, over 10 or more years, divided by 2);

θ_{ya} is the yearly average temperature (which is equal to the sum of the monthly average temperatures, measured in °C, divided by 12).

EXAMPLE Using monthly average values (more accurately using monthly weighted values) for θ_a:

$$\left.\begin{array}{l}\theta_{ma\text{-}max} = 30\ °C \text{ for 2 months}\\ \theta_{ma} = 20\ °C \text{ for 4 months}\\ \theta_{ma} = 10\ °C \text{ for 4 months}\\ \theta_{ma} = 0\ °C \text{ for 2 months}\end{array}\right\}\quad \begin{array}{l}\text{Average } \theta_{ya} = 15{,}0\ °C\\ \text{Weighted average } \theta_E = 20{,}4\ °C\end{array}$$

The ambient temperature used in the calculation examples in Annex J is 20 °C.

8.3.2 Correction of ambient temperature for transformer enclosure

A transformer operating in an enclosure experiences an extra temperature rise which is about half the temperature rise of the air in that enclosure.

For transformers installed in a metal or concrete enclosure, $\Delta\theta_{or}$ in Equations (10) and (11) should be replaced by $\Delta\theta'_{or}$ as follows:

$$\Delta\theta'_{or} = \Delta\theta_{or} + \Delta(\Delta\theta_{or}) \tag{28}$$

where

$\Delta(\Delta\theta_{or})$ is the extra top-oil temperature rise under rated load.

It is strongly recommended that this extra temperature rise be determined by tests, but when such test results are not available, the values given in Table 5 for different types of enclosure may be used. These values should be divided by two to obtain the approximate extra top-oil temperature rise.

NOTE When the enclosure does not affect the coolers, no correction is necessary according to Equation (28).

Table 5 – Correction for increase in ambient temperature due to enclosure

Type of enclosure	Number of transformers installed	Correction to be added to weighted ambient temperature K			
		Transformer size kVA			
		250	500	750	1 000
Underground vaults with natural ventilation	1	11	12	13	14
	2	12	13	14	16
	3	14	17	19	22
Basements and buildings with poor natural ventilation	1	7	8	9	10
	2	8	9	10	12
	3	10	13	15	17
Buildings with good natural ventilation and underground vaults and basements with forced ventilation	1	3	4	5	6
	2	4	5	6	7
	3	6	9	10	13
Kiosks[a]	1	10	15	20	–

NOTE The above temperature correction figures have been estimated for typical substation loading conditions using representative values of transformer losses. They are based on the results of a series of natural and forced cooling tests in underground vaults and substations and on random measurements in substations and kiosks.

[a] This correction for kiosk enclosures is not necessary when the temperature rise test has been carried out on the transformer in the enclosure as one complete unit.

8.3.3 Water-cooled transformers

For water-cooled transformers, the ambient temperature is the temperature of the incoming water, which shows less variation in time than air.

9 Influence of tap-changers

9.1 General

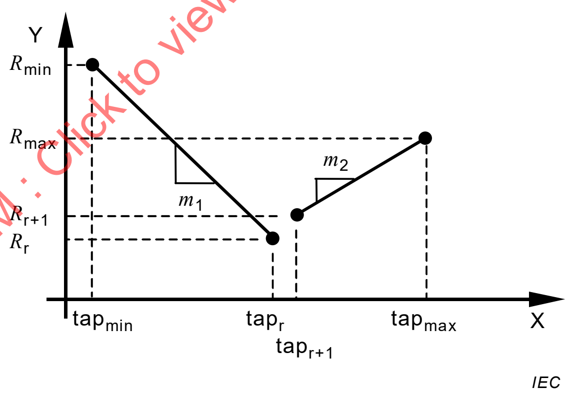
All quantities used in Equations (10), (11), (13), (14), (15), (16) and (17) have to be appropriate for the tap at which the transformer is operating.

For example, consider the case where the HV voltage is constant, and it is required to maintain a constant LV voltage for a given load. If this requires the transformer to be on a +15 % tap on the LV side, the rated oil temperature rise, losses and winding gradients have to be measured or calculated for that tap.

Consider also the case of an auto transformer with a line-end tap-changer – the series winding will have maximum current at one end of the tapping range whilst the common winding will have maximum current at the other end of the tapping range.

9.2 ~~Short-circuit losses~~ Load loss

The transformer's short-circuit loss is a function of the tap position. Several different connections of the tapped windings and the main winding can be realized. A universal approach to calculate the transformer's ratio of losses as a function of the tap position is shown in Figure 15. A linear function is calculated between the rated tap position and the minimum and maximum position. Figure 15 can be changed according to regulating winding arrangement regarding tapping method selected.



$$m_1 = \frac{R_r - R_{min}}{tap_r - tap_{min}} \qquad m_2 = \frac{R_{max} - R_{r+1}}{tap_{max} - tap_{r+1}}$$

Key

X Tap position

Y Ratio of losses

Figure 15 – Principle of losses as a function of the tap position

9.3 Ratio of losses

The transformer's top-oil temperature rise is a function of the loss ratio R. The no-load losses are assumed to be constant. Using a linear approximation, R can be determined as a function of the tap position.

For tap positions beyond the rated tap-changer position (from tap_{r+1} to tap_{max}):

$$R(\text{tap}) = R_{r+1} + (\text{tap} - \text{tap}_{r+1}) \times m_2 \tag{29}$$

For tap positions below the rated tap position (from tap_{min} to tap_r):

$$R(\text{tap}) = R_r + (\text{tap} - \text{tap}_r) \times m_1 \tag{30}$$

9.4 Load factor

The winding-to-oil temperature rise mainly depends on the load factor. K is not dependent on the tap position.

Annex A
(informative)

Insulation life expectancy and relative ageing rate considering oxygen and water effect

A.1 Insulation life expectancy

Ageing or change of polymerization of paper insulation is often described as a first order process that can be described by the following Arrhenius equation:

$$\frac{1}{DP_{\mathrm{end}}}-\frac{1}{DP_{\mathrm{start}}}=A\times t\times e^{-\frac{E_{\mathrm{A}}}{R\times(\theta_{\mathrm{h}}+273)}} \qquad \text{(A.1)}$$

where

DP_{end} is the insulation DP value at the moment of the sampling or the end of life criterion;

DP_{start} is the initial insulation DP value;

A is the pre-exponential factor in 1/h;

E_{A} is the activation energy in kJ/mol;

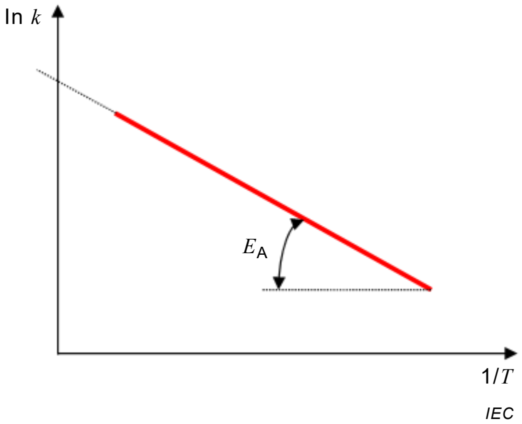
t is the life time of a transformer in h;

R is the gas constant in J/(K·mol);

θ_{h} is the hot-spot temperature, °C.

Arrhenius extrapolations assume that a chemical degradation process is controlled by a reaction rate k proportional to exp($-E_{\mathrm{A}}/RT$), where E_{A} is the Arrhenius activation energy, R the gas constant (8,314 J/(K·mol), T the absolute temperature and A the pre-exponential factor. The pre-exponent value A is a constant depending on the chemical environment. In an Arrhenius plot, the natural logarithm of the ageing rate (ln k) is plotted against the inverse absolute temperature (1/T) and a straight line is obtained as shown in Figure A.1 – illustrating how the ageing rate depends on temperature. The condition for achieving a straight line is that it is the same ageing process over the whole temperature range. The activation energy describes how much the reaction rates depend on temperature; if the ageing process is independent of temperature the activation energy is zero and the line becomes parallel with the x-axis, while if it increases fast with increasing temperature the line falls quickly. One should bear in mind that A and E_{A} values come in pairs. In principle, E_{A} is the slope of the line in Figure A.1, and the A-value is the value of interception with a virtual y-axis from 0, the higher the value the higher the location of the curve above the abscissa and the ageing is faster. The point is that a small change in slope will influence the A-value significantly.

NOTE The temperature and moisture values used in the transformer life estimation always refer to the same location.



Key

1/T inverse absolute hot-spot temperature

ln k logarithm of the ageing rate

Figure A.1 – Arrhenius plot for an ageing process

Knowing the end-of-life (EOL) criterion we can rearrange the Equation (A.1) to express life expectancy, t_{exp}, as a function of hot-spot temperature θ_h, and the parameters E_A and A:

$$t_{exp} = \frac{\frac{1}{DP_{end}} - \frac{1}{DP_{start}}}{A \times 24 \times 365} \times e^{\frac{E_A}{R \times (\theta_h + 273)}} \quad \text{(years)} \tag{A.2}$$

The feasibility of this procedure depends on a valid selection of E_A and A values. As main result of extensive research work (see references [9] to [15]), the activation energy over the range from 70 °C to 160 °C was calculated and an A value was estimated for each single case based on the first order ageing models. The corresponding coefficients applicable to the power transformers, where oil is separated from and in contact with air, are provided in Table A.1.

Table A.1 – Activation energy (E_A) and environment factor (A) for oxidation, hydrolysis

Paper type/ageing parameters		Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
Non-thermally upgraded paper	A (h^{-1})	$4,1 \times 10^{10}$	$1,5 \times 10^{11}$	$4,5 \times 10^{11}$	$4,6 \times 10^{5}$
	E_A (kJ/mol)	128	128	128	89
Thermally upgraded paper	A (h^{-1})	$1,6 \times 10^{4}$	$3,0 \times 10^{4}$	$6,1 \times 10^{4}$	$3,2 \times 10^{4}$
	E_A (kJ/mol)	86	86	86	82

The results of the expected life based on coefficients given in Table A.1, and starting with a DP of 1 000 and ending with a DP of 200, i.e. as "end of life criteria", for a range of hot-spot temperatures are shown in Table A.2. The corresponding graphical illustration considering the influence of temperature, oxygen and moisture content is shown in Figure 4 and Figure 5.

Table A.2 – Expected life of paper under various conditions

Paper type/ageing temperature		Expected life years			
		Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
Non-thermally upgraded paper at	80 °C	97,3	26,6	8,9	14,7
	90 °C	29,3	8	2,7	6,4
	98 °C	11,7	3,2	1,1	3,4
	110 °C	3,2	0,9	0,3	1,4
Thermally upgraded paper at	80 °C	151,9	81	39,9	19,4
	90 °C	67,8	36,1	17,8	9
	98 °C	36,7	19,6	9,6	5
	110 °C	15,3	9,6	4	2,2

A.2 Relative ageing rate considering oxygen and water effect

In 6.3, the rate of ageing of the interturn insulation of transformers under the effect of time and temperature is referred to a hot-spot temperature of 98 °C and 110 °C for the non-thermally and thermally upgraded paper, respectively. Further, the relative ageing rate V is defined according to Equations (2) and (3). These equations are based on the life expectancy formula of Montsinger [25], and Dakin's ageing rate formula [26], which are a simplification of the more general Arrhenius relation given in Equation (A.1), and valid only in a limited temperature range. On the other hand, the IEEE Loading Guide [27], recommends Equation (3), which is an equivalent to the acceleration ageing factor, F_{AA}, for a wide range of temperatures. Further, Equations (2) and (3) imply that the ageing rate is only dependent on the hot-spot temperature and do not consider different insulation conditions, which are defined in references [9] to [15].

Therefore, if the ageing rate of the paper insulation is given as follows:

$$k = A \times e^{-\frac{E}{R \times (\theta_h + 273)}} \tag{A.3}$$

and if an ageing rate at a certain temperature and at an insulation condition is chosen to be the rated one, k_r, then the ageing rate, k, determined for any temperature and insulation condition can be related to this rated rate, k_r, by a new relative ageing rate, V, given as their ratio [28]:

$$V = \frac{k}{k_r} = \frac{A}{A_r} e^{\frac{1}{R} \times \left(\frac{E_r}{\theta_{h,r} + 273} - \frac{E}{\theta_h + 273} \right)} \tag{A.4}$$

where

the subscript r stands for the rated condition.

The chosen rated insulation condition for both the non-thermally and thermally upgraded paper is "free from air and 0,5 % moisture" taken from Table A.1. Also, similar to the approach given in Clause 6, the rated relative ageing rate V = 1,0 at this condition corresponds to a temperature of 98 °C for non-thermally upgraded paper and to 110 °C for thermally upgraded paper.

The calculated relative ageing rates for different temperatures and insulation contamination conditions are compared with values given in Table 1. The results are summarized in Table A.3 and Table A.4.

The same could be applied to improve the IEEE equations for the ageing acceleration factor, F_{AA}, and the equivalent ageing factor, F_{EQA}.

It is obvious from the tables that the dominant ageing factor at higher temperatures for the kraft paper is the moisture. However, at lower temperatures the oxygen influence will prevail, Table A.3. On the other hand, the main factor responsible for the thermally upgraded paper ageing over the range of the temperatures is oxygen, Table A.4. This is in line with the conclusions in [13].

Table A.3 – Relative ageing rates due to hot-spot temperature, oxygen and moisture for non-upgraded paper insulation

Temperature °C	Relative ageing rate, V				
	Table 1	**Free from air and 0,5 % moisture**	**Free from air and 1,5 % moisture**	**Free from air and 3,5 % moisture**	**With air and 0,5 % moisture**
80	0,125	0,12	0,44	1,323	0,80
86	0,25	0,25	0,91	2,742	1,32
92	0,5	0,50	1,84	5,548	2,16
98	**1,0**	**1,00**	**3,66**	**10,976**	**3,47**
104	2	1,94	7,08	21,245	5,50
110	4	3,67	13,43	40,281	8,58
116	8	6,82	24,96	74,880	13,21
122	16	12,44	45,53	136,601	20,07
128	32	22,30	81,58	244,755	30,10
134	64	39,27	143,69	431,061	44,62
140	128	68,04	248,93	746,802	65,39

The relative ageing rates, V, for different ageing factors at temperature of 98 °C are indicated to be compared to the rated insulation condition, i.e. where the relative ageing rate is 1.

Table A.4 – Relative ageing rates due to hot-spot temperature, oxygen and moisture for upgraded paper insulation

Temperature °C	Relative ageing rate, V				
	Table 1	Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
80	0,036	0,10	0,19	0,38	0,79
86	0,073	0,16	0,31	0,63	1,25
92	0,145	0,26	0,5	1,00	1,97
98	0,282	0,42	0,78	1,59	3,05
104	0,536	0,65	1,22	2,48	4,66
110	**1,00**	**1,00**	**1,88**	**3,81**	**7,02**
116	1,83	1,52	2,84	5,78	10,45
122	3,29	2,27	4,26	8,66	15,36
128	5,8	3,36	6,30	12,82	22,32
134	10,07	4,91	9,22	18,74	32,07
140	17,2	7,11	13,33	27,12	45,60
The relative ageing rates, V, for different ageing factors at temperature of 110 °C are indicated to be compared to the rated insulation condition, i.e. where the relative ageing rate is 1.					

The loss of life, L, over certain period of time is calculated as given in 6.4.

Annex B
(informative)

Core temperature

B.1 General

In transformer cores, there are two different core hot-spots which, if not controlled, can cause insulation material degradation and subsequent gassing.

a) Core hot-spot inside the core, should be limited to 130 °C under conditions of highest core excitation, rated load and maximum ambient temperature. This is in order to prevent the core heating which results in the break-up of the thin oil film between core laminations, the consequence of which is the generation of mainly H_2 and CH_4, in addition to small quantities of other hydrocarbons [29], [30]. It is important to understand that any possible oil gas saturation should be prevented.
b) Core surface hot-spot, which is in contact with oil and solid insulation materials, should be limited according to Table 2.

B.2 Core hot-spot locations

The location of the internal core hot-spot depends largely on the core type and whether it is a shell form or a core form transformer. In the most common core type (three-phase, three-limb cores), this hot-spot is located in the middle of the top yoke between cooling ducts. In other core types, the location of the core hot-spot is typically at the top of the middle core limb [30].

The total core surface temperature rise is the sum of the following three components:

a) temperature rise due to the leakage flux impinging on the surface of the laminations of the outermost core step(s) – this value can vary from a few kelvins to several tens of kelvins over the adjacent oil depending on the transformer winding, core, and tank shielding design;
b) temperature rise due to the main flux in the core – this value can again vary from a few kelvins to several tens of kelvins over the adjacent oil depending on the transformer core design (diameter and number of cooling ducts), core induction, and core material;
c) temperature rise of the oil around the area of the surface hot-spot.

Therefore, in almost all cores, this core surface hot-spot is not located in the yoke but is located at the top of the middle core-limb, where the leakage flux enters the surface of the core laminations. Also, the relative magnitudes of the temperature rise due to the leakage flux versus the rise due to the core main flux depends wholly on the design of the transformer.

Consequently, the correct way to determine the core surface hot-spot is to determine the temperature increase at rated load (including temperature rise of adjacent oil) and add to it the temperature rise due to the highest core over-excitation. These temperatures are to be determined for the appropriate location of the core surface hot-spot in the core type evaluated.

Annex C
(informative)

Specification of loading beyond rated power

This document gives advice on the calculation of the capability of an existing transformer to be loaded beyond rated power. All transformers will have some overload capability. However since no specific loading requirements beyond rated power are specified in IEC 60076-1 [5] or IEC 60076-2 [52], it is up to the purchaser to specify any particular loading requirements (load, duration and ambient temperature).

Specification of loading beyond rated power can be done in the following ways.

a) Long time emergency loading

Since the hot-spot temperature limit in IEC 60076-2 is less than that given in Table 2, it is possible to have an increased loading available for emergency situations provided that the loss of life is accepted. The extent of this loading capability will depend on ambient temperature, while preload and the duration of loading are only relevant to loss of life.

The following need to be specified at the enquiry stage:

1) the ambient temperature at which the loading is required;
2) the load as per unit (p.u.) of rated current;
3) the winding(s) to which the loading is to be applied;
4) the tap position;
5) the cooling stage(s) in service.

If loading according to this document is specified, then the transformer should not exceed the temperatures and currents given in Table 2 and Table 3, respectively, under the following conditions:

- a yearly average ambient temperature (20 °C unless otherwise specified);
- current flowing in the highest rated winding is considered;
- the tap position that gives the rated voltage on the lower voltage side with rated voltage on the higher voltage side taking account of the voltage drop caused by the load for a unity power factor load;
- all normal cooling in service but with no standby cooling capacity.

b) Short time emergency loading

If the transformer is used at a load less than rated current, then there will be an additional short time loading capability caused by the thermal time constants of the oil and windings. If a specific short time loading capability is required then the following need to be specified:

1) the ambient temperature at which the loading is required;
2) the short time current that is required in p.u. of rated current;
3) the winding(s) to which the load will be applied;
4) the tap position;
5) the preload current applied before the short time emergency loading in p.u. of rated current;
6) the duration of the loading;
7) the cooling stage(s) in service.

If loading according to this document is specified, then the transformer should not exceed the temperatures and currents given in Table 2 and Table 3, respectively, and under the following conditions:

- a yearly average ambient temperature (20 °C unless otherwise specified);

- current flowing in the highest rated winding is considered;
- the tap position that gives the rated voltage on the lower voltage side with rated voltage on the higher voltage side taking account of the voltage drop caused by the preload for a unity power factor load;
- a preload of 0,75 p.u.;
- a duration of 15 min;
- all normal cooling in service appropriate to the preload condition but with no standby cooling capacity

c) Loading according to a specific cycle

Specify in detail the load and ambient temperature cycles.

Annex D
(informative)

Description of Q, S and H factors

IEC 60076-2 notes also that the hot-spot factor H is obtained by the product of the Q and S factors:

$$H = QS \tag{D.1}$$

The Q and S factors are dimensionless factors described in IEC 60076-2 as:

- Q is “a dimensionless factor to estimate the increase of the average winding gradient due to the local increase of additional loss.”
- S is “a dimensionless factor to estimate the local increase of the average winding gradient due to the variation in the oil flow stream.”

According these definitions, Q should be calculated by modelling the winding with the correct heat loss distribution, but with uniform oil velocity. The Q factor is then the ratio of the maximal winding to local oil gradient over the average winding to average oil gradient.

On the other hand, S should be calculated by modelling the winding with uniform heat losses and with the correct oil velocity inside the winding. The S factor is the ratio of the maximal winding to local oil gradient over the average winding to average oil gradient.

However after calculating Q and S in line with the IEC 60076-2 definition, the hot-spot factor H cannot be calculated directly as the product of Q and S factors, as mentioned in IEC 60076-2, because:

– discs with maximal Q factor and discs with maximal S factor can (and probably will) be different discs;

– when modelling the winding with correct heat loss distribution and oil flows, Q and S factors will not be independent from each other as explained later.

For the above reasons, CIGRE WG A2.38 [18] proposes more practical definitions of Q and S and H factors, as given below.

The H factor can be derived out of Figure 6 and is:

$$H = \frac{P - B}{I - \dfrac{B + D}{2}} \tag{D.2}$$

Equation (D.2) is different from the current IEC 60076-2 definition, because the hot-spot temperature is referenced to the mixed top-oil, while increase in local winding to oil gradient refers to local winding oil.

This formula for H has the following advantages:

– the H factor can be calculated directly from the calculation results (calculated with correct loss and oil flow distribution);

– this is the correct hot-spot factor to predict the hot-spot temperature out of the temperature rise results, obtained in the standard temperature rise test;

– this hot-spot factor can also be checked in case fibre optic measurements are made (the hot-spot temperature is known);

– the hot-spot is not always located at the top of the winding. However, this formulation is a practical solution to overcome this issue.

The Q factor is a dimensionless factor as a ratio of two losses, and in cylindrical coordinates can be defined as:

$$Q = Q(r, z, \varphi, T)/Q_{\text{ave}} \tag{D.3}$$

where

$Q(r, z, \varphi, T)$ is the local loss density at a location (W/m^3);

r is the radial position;

φ is the angle in circumferential position;

z is the axial position;

T is the local temperature at (r, z, φ), and

Q_{ave} is the average loss of the winding at average temperature.

For calculation purposes, one can redefine the Q factor for a disc winding in which each disc has several conductors in radial direction and consists of numerous discs in axial direction, as:

$$Q = Q(conductor\_number\_in\_disc, disk\_number, \varphi, T)/Q_{\text{ave}} \tag{D.4}$$

The Q factor is a scalar function and is based on the steady state condition of a defined loading at a defined tap position (if applicable).

It is important to note that the Q factor in this definition is not a ratio of temperatures but a ratio of losses.

Finally the S factor used in this document is defined as:

$$S = \frac{H}{Q} \tag{D.5}$$

which can be easily calculated as soon as H and Q are known.

This S factor is an indication of the local cooling inefficiency. Higher S factor means higher local temperature gradient thus worse cooling efficiency.

According to the current IEC 60076-2 calculation this S factor should be calculated as the ratio of local hot-spot gradient over winding gradient with constant heat losses. With this definition the S factor is proportional to the ratio of two thermal resistances, resulting in:

$$S \propto S(r, z, \varphi, T)/S_{\text{ave}} \tag{D.6}$$

where

$S(r, z, \varphi, T)$ is the local cooling resistance (K/W), and

S_{ave} is the average cooling resistance (K/W).

We should note that heat transfer can be in different directions. The (overall) local heat transfer consists of series and parallel parts, such as:

– the insulation between the neighbouring conductors, that are in direct contact with each other, in the radial direction.

– the insulation paper and oil boundary layer between conductor and the oil flow in axial direction. Note that heat transfer functions for the oil boundary layer are often function of q''.

– the copper (which almost can be neglected) in the tangential direction.

This implies that the Q and S factors are not fully independent, because they are linked by temperature, heat flux, etc. For example, if the local losses are higher, the local temperature will also increase and will influence the local flow stream and the local convection heat transfer coefficient from conductor to oil.

Remark 1 We should note that the size of one (paper insulated) conductor is the smallest element in which one calculates the losses. Inside each element there exists the same temperature, so thermal resistances inside the element are neglected. In the case one calculates the Q factor based on a number of conductors in one (or sometimes even 4) top discs, one increases in essence the element size to a large extent and one neglects the temperature distribution between conductors in the disc (and even between discs), which results in a too low estimate of the hot-spot. The approach of using one or more discs as smallest element results in a too low estimate of the hot-spot temperature and should be rejected.

Remark 2 In the case of a high Q factor in a transformer, one is able to limit the hot-spot factor by creating locally more cooling surface and so design for a low S factor at that location. This principle is easy to do by adding an axial cooling channel inside a radial spacer disc or by adding a radial spacer inside a winding with axial cooling channels. The location of the hot-spot does not necessarily have to correspond with the location of the maximum losses.

Annex E
(informative)

Calculation of winding and oil time constant

The winding time constant is as follows:

$$\tau_W = \frac{m_W \times c_W \times g}{60 \times P_W} \qquad \text{(E.1)}$$

where

τ_W is the winding time constant in min at the load considered;

g is the winding-to-oil gradient in K at the load considered;

m_W is the bare mass of the winding in kg;

c_W is the specific heat of the conductor material in Ws/(kg·K) (390 for Cu and 890 for Al);

P_W is the winding loss in W at the load considered.

Another form of Equation (E.1) is

$$\tau_W = 2{,}75 \times \frac{g}{(1+P_e) \times s^2} \quad \text{for Cu} \qquad \text{(E.2)}$$

$$\tau_W = 1{,}15 \times \frac{g}{(1+P_e) \times s^2} \quad \text{for Al} \qquad \text{(E.3)}$$

where

P_e is the relative winding eddy loss in p.u.;

s is the current density in A/mm² at the load considered.

The top-oil time constant is calculated according to the principles in references [27] and [31]. It means that the thermal capacity C for the ONAN, ONAF, OF and OD cooling modes is:

$$\cancel{C = 0{,}132 \times m_A + 0{,}0882 \times m_T + 0{,}400 \times m_O}$$

$$C = c_W \times m_W + c_{FE} \times m_{FE} + c_T \times m_T + k_O \times c_O \times m_O \qquad \text{(E.4)}$$

where

~~m_A is the mass of core and coil assembly in kilograms;~~

m_W is the mass of coil assembly in kg;

m_{FE} is the mass of core in kg;

m_T is the mass of the tank and fittings in kg (only those portions that are in contact with heated oil ~~shall~~ should be used, i.e. 2/3 of tank weight should be considered);

m_O is the mass of oil in kg;

c_W is the specific heat capacity of the winding material (390 for Cu and 890 for Al) in Ws/kgK;

c_{FE} is the specific heat capacity of the core (= 468) in Ws/kgK;

c_T is the specific heat capacity of the tank and fittings (= 468) in Ws/kgK;

c_O is the specific heat capacity of the oil (= 1800) in Ws/kgK;

k_O is the correction factor for the oil in the ONAF, ONAN, OF and OD cooling modes.

~~For the forced-oil cooling modes, either OF or OD, the thermal capacity is:~~

$$\cancel{C = 0{,}132 \times (m_A + m_T) + 0{,}580 \times m_O}$$

The correction factor for the oil, k_O, is the ratio of average to maximum top-oil temperature rise.

NOTE It is apparent that all the oil in a transformer is not heated to the same temperature as the top-oil. The ratio of average to maximum top-oil temperature rise ranges from 65 % to 95 % depending on design. If the corresponding temperature rises are not known then an average value of these figures, i.e. 80 %, is used as the oil correction factor for ONAN and ONAF cooling modes. For the forced-oil cooling modes, either OF or OD, and distribution transformer without external radiators the correction factor is 100 %.

The top-oil time constant at the load considered is given by the following:

$$\cancel{\tau_o = \frac{C \times \Delta\theta_{om} \times 60}{P}}$$

$$\tau_o = \frac{C_o \times \Delta\theta_o}{60 \times P} \tag{E.5}$$

where

τ_o is the ~~average~~ top-oil time constant in min;

$\Delta\theta_{o\cancel{m}}$ is the ~~average~~ top-oil temperature rise above ambient temperature in K at the load considered;

P is the supplied losses in W at the load considered.

Annex F
(informative)

Thermal model parameters

F.1 General

As defined in 8.2.3, the first gradient $\Delta\theta_{h1}$ (Equations (7) and (13) with thermal constants k_{21} and k_{22}) represents the fundamental hot-spot temperature rise, before the effect of changing oil flow past the hot-spot is taken into account. The second gradient $\Delta\theta_{h2}$ (Equations (8) and (14) with parameters k_{21} − 1 and k_{22}) represents the varying rate of oil flow past the hot-spot, a phenomenon which changes much more slowly. The combined effect of these two terms is to account for the fact that a sudden rise in load current may cause an otherwise unexpectedly high peak in the hot-spot temperature rise, very soon after the sudden load change. Similarly, thermal constant k_{11} in Equations (5) and (11) acts as a correction factor for the top-oil time constant, taking into account the fact that the time constant is being affected in a length of the time by the viscosity change.

The procedure to estimate these thermal constants from a prolonged heat-run test during the "no-load loss + load loss" period is defined in Clause F.2. The thermal constant estimation procedure from service data is defined in [18].

The model in this document represents the traditional way of modelling based on many years of experience [21], [31], [33]–[39], and it has been verified under different operational conditions [18], [21], providing satisfactory hot-spot temperature estimates. Being based on constant parameters the model provides exponential response for predefined thermal processes, and as such its further development in this form could be limited. However, due to extreme simplicity in application in the daily life of an engineer, it is still considered appropriate.

On the other hand, it is possible to provide complete analytical solution for these physical processes considering all system variables (oil viscosity, loss change with temperature, etc.), as is partly illustrated in Clause F.3. This approach would demand a certain change in modelling practice, for example deviation from traditional x and y exponents.

F.2 Thermal constant estimation: experimental approach

The thermal constant k_{11} should be estimated for the transient top-oil rise temperature curve obtained during the test period with total losses as follows (see [32]).

1) Define function $f_1(t)$, which describes the relative increase of the top-oil temperature rise according to the unit of the steady-state value:

$$f_1(t) = \left(1 - e^{(-t)/(k_{11} \times \tau_0)}\right) \tag{F.1}$$

2) Obtain measured relative increase of the top-oil temperature rise as per unit of the steady state value, Mf_{1j}, for the complete test period:

$$Mf_{1j} = \frac{M\theta_{oj} - M\theta_{aj}}{\Delta\theta_{or}} \tag{F.2}$$

3) Perform nonlinear regression by using the guess-error approach (alternatively curve fitting or optimization software also could be used) to find the constant to minimize the sum of squares of differences between f_{1j} and Mf_{1j}:

$$\text{minimize}: \sum_{j=1}^{N}\left[f_{1j}(z)-Mf_{1j}\right]^2 \tag{F.3}$$

where

M is a measured variable;

Z is a vector whose element is only k_{11} thermal time constant;

f_{1j} is the relative increase of the top-oil temperature rise as per unit of the steady state value as calculated from Equation (F.1);

Mf_{1j} is the measured relative increase of the top-oil temperature rise as per unit of the steady state value;

j is the index for each time step over the test period with the total losses.

The initial value for the k_{11} constant is taken from Table 4.

The oil time constant value to be set in the function $f_1(t)$ at the load considered is given in Annex E.

Similar to the top-oil thermal constant, k_{11}, estimation procedure, the thermal constants k_{21} and k_{22} for the hot-spot to top-oil thermal gradient are also obtained from the part of the temperature rise test with supplied total losses [32]. In general, this approach is acceptable due to fact that the shape of the thermal curve, $\Delta\theta_{\text{h}}(t)$, Figure 14, is not affected by the total supplied loss level [22], compared to when the unit is supplied with only rated load loss. Alternatively, a technically correct procedure would demand additional temperature tests, which would be run from the cold start until the corresponding steady state conditions would be observed at the rated current. The procedure specifies that the transformer winding is to be equipped with fibre optic sensors.

1) Define function $f_2(t)$, which describes the relative increase of the hot-spot-to-top-oil gradient according to the unit of the steady-state value:

$$f_2(t) = k_{21} \times \left(1 - e^{(-t)/(k_{22}\times\tau_{\text{w}})}\right) - \left(k_{21}-1\right) \times \left(1 - e^{(-t)/(\tau_0/k_{22})}\right) \tag{F.4}$$

2) obtain measured relative increase of the hot-spot to top-oil gradient, Mf_{2j}, as per unit of the steady state value for the complete test period:

$$Mf_{2j} = \frac{M\theta_{\text{h}j} - M\theta_{\text{o}j}}{\Delta\theta_{\text{hr}}} \tag{F.5}$$

3) perform nonlinear regression by using guess-error approach (alternatively curve fitting or optimization software could be used) to find the constant to minimize the sum of squares of differences between f_{2j} and Mf_{2j}

$$\text{minimize}: \sum_{j=1}^{N}\left[f_{2j}(z)-Mf_{2j}\right]^2 \tag{F.6}$$

where

M is a measured variable;

z is a vector whose elements are k_{21} and k_{22} constants;

f_{2j} is the relative increase of the hot-spot to top-oil gradient as per unit of the steady state value as calculated from Equation (F.4);

Mf_{2j} is the measured relative increase of the hot-spot to top-oil gradient as per unit of the steady state value;

j is the index for each step over the test period with total losses introduce the following constraint: maximum of f_{2j} is equal to maximum of Mf_{2j}.

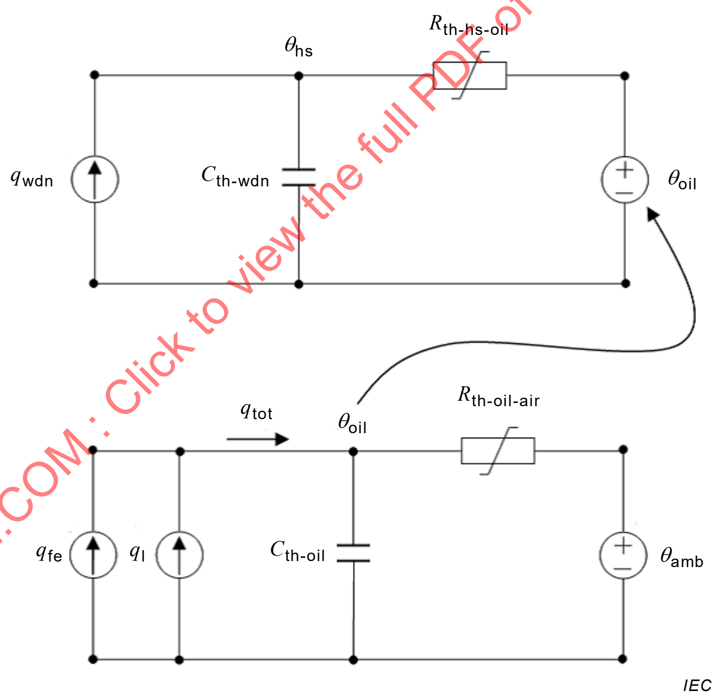
The initial values for the k_{21} and k_{22} constants are taken from Table 4.

The winding time constant value to be set in function f_{2j} is calculated according to procedure given in Annex E.

F.3 Dynamic thermal modelling: further development

Figure F.1 shows the final overall hot-spot and top-oil thermal model. It has the following features:

- it uses the "current source" concept as the copper loss and core loss heat source;
- it uses the "voltage source" concept as the ambient air heat source (or sink), and as the "ambient" oil heat source (or sink);
- the nonlinearities are included in an easily understood way;
- it is not a complicated equivalent circuit;
- it has been verified physically, as discussed in several papers [22], [40]–[44].



Key

q_{wdn}	heat generated by winding losses	$C_{th\text{-}wdn}$	thermal capacitance of the winding
θ_{hs}	hot-spot temperature	$R_{th\text{-}hs\text{-}oil}$	nonlinear winding to oil thermal resistance
θ_{oil}	top-oil temperature	q_{tot}	heat generated by total losses
q_{fe}	heat generated by no-load losses	q_{l}	heat generated by load losses
$C_{th\text{-}oil}$	equivalent thermal capacitance of the transformer oil	$R_{th\text{-}oil\text{-}air}$	non-linear oil to air thermal resistance
θ_{amb}	ambient temperature		

Figure F.1 – Hot-spot and top-oil overall model

Annex G
(informative)

Oil and winding exponents

G.1 General

The traditional oil exponent, x = 0,8, and winding exponent, y = 1,6, have been used since 1916 [33] in the transformer loading calculus. Consequently, the same values were adopted subsequently by the IEC 60076-2 [52] and IEC 60354 [4]. The background is further elaborated in Clause G.2. However, these exponents are transformer specific and any suggested values should be used only in absence of transformer-specific values. In addition, it has been found that the recommended winding exponent of 1,6 is quite conservative (see [23], [24] and [45]), and this has been accounted for in this document. This change is still included in this edition as given in Table 4.

Clauses G.2 and G.3 provide methods used to define the winding and oil exponents for specific transformer design.

G.2 Historical background

It was reported by Dulong and Petit in 1817 that the velocity of the cooling due solely to the contact of a gas is proportional to the excess of temperature in degrees centigrade raised to the power 1,233 [33]. Based on this, Swift [22] concluded: “It is fascinating that the reciprocal of 1.223 is approximately 0.8, a value of x commonly used to this day, for natural cooling conditions!”.

In 1881, Lorenz derived for convection of heat from vertical plane surface the following relation [33]:

$$P = 0{,}548 \times \sqrt[4]{\frac{c \times g \times k_{th}^{3}}{v \times L \times \theta_m}} \times \varrho^{0{,}5} \times \Delta\theta^{1{,}25} \quad (G.1)$$

where

P is the loss dissipated per cm^2,

c is the specific heat of gas at constant pressure,

k_{th} is the gas thermal conductivity,

v is the gas viscosity,

θ_{m} is the gas average temperature,

ρ is the gas average density,

g is the gravitational constant,

L is the height of plane, and

$\Delta\theta$ is the difference in temperature of plane surface and of the gas at a great distance from the plane.

For the given room temperature, known plate design and for standard atmospheric pressure, the equation is further reduced to:

$$P = C^{te} \times \Delta\theta^{1{,}25} \quad (G.2)$$

The result of the number of tests conducted by Montsinger [33], where most of the heat is dissipated by convection, was almost the same:

$$P = C^{te} \times \Delta\theta^{1,245} \tag{G.3}$$

where the constant C^{te} was determined empirically.

It was then concluded that the convection for vertical surface and within operational range of the temperatures can be expressed by Equation (G.3).

A simple equation rearrangement gives temperature rise variation with loss as follows:

$$\Delta\theta = \frac{1}{C^{te}} \times P^{1/1,25} = C_1^{te} \times P^{0,8} \tag{G.4}$$

It was found that Equation (G.4) holds for top-oil rise and for horizontal disc coils, but for the vertical/layer winding design the corresponding temperature rise over top-oil varies between 0,9 and the first power of the loss. Now the corresponding temperature rises at any load can be found from the following mathematical expression:

1) Top-oil temperature rise:

   Based on Equation (G.4), the temperature rise at rated load is expressed as follows:

$$\Delta\theta_{or} = C_{1,r}^{te} \times P_r^{0,8} \tag{G.5}$$

   If then Equation (G.4) is divided by Equation (G.5) the following ratio is obtained:

$$\frac{\Delta\theta_o}{\Delta\theta_{or}} = \frac{C_1^{te}}{C_{1,r}^{te}} \times \frac{P^{0,8}}{P_r^{0,8}} \tag{G.6}$$

   Also, if for given design and operating temperature range the following is defined:

$$C^{te}{}_{1,r} = C^{te}{}_1 \tag{G.7}$$

   then Equation (G.6) becomes:

$$\Delta\theta_o = \Delta\theta_{or} \times \left(\frac{P}{P_r}\right)^{0,8} \tag{G.8}$$

   It is also known that P represents the total losses when considering the top-oil temperature rise, which are equal to the sum of the load loss, P_l, and no-load loss, P_{fe}:

$$P = P_l + P_{fe} \tag{G.9}$$

   Further, if the loss ratio is defined as:

$$R = \frac{P_{lr}}{P_{fer}} \tag{G.10}$$

   and the following correlations are valid:

$$P_{fer} = P_{fe} \tag{G.11}$$

$$K^2 = \frac{P_l}{P_{lr}} \tag{G.12}$$

   the final equation for temperature rise is:

$$\Delta\theta_o = \left(\frac{1+R\times K^2}{1+R}\right)^{0,8} \times \Delta\theta_{or} \tag{G.13}$$

This expression is equivalent to the equation suggested by loading guide where "0,8" refers to the top-oil exponent "x" giving the final equation for the final top-oil temperature rise at any load as follows:

$$\Delta\theta_o = \left(\frac{1+R\times K^2}{1+R}\right)^x \times \Delta\theta_{or} \quad \text{(G.14)}$$

2) The hot-spot to top-oil temperature rise

By following the same procedure as above for the top-oil temperature rise and knowing that in this case the loss, P, represents only the load loss, P_l, the following formula is derived:

$$\Delta\theta_{hs-o} = \Delta\theta_{hs-or} \times K^{1,6} \quad \text{(G.15)}$$

Again, this is the same as the general form suggested in the loading guide where "1,6" refers to the winding exponent "y", giving the final equation for the final hot-spot temperature rise over top-oil temperature at any load as follows:

$$\Delta\theta_{hs-o} = \Delta\theta_{hs-or} \times K^y \quad \text{(G.16)}$$

G.3 Theoretical approach

Based on heat transfer theory, the natural convection oil flow around vertical, inclined and horizontal plates and cylinders the temperature rise and the average winding to average oil gradient can be obtained from the following empirical correlation (see references [46] to [50]):

$$N_u = C \times [G_r \times P_r]^n \quad \text{(G.17)}$$

where

$$N_u = \frac{h\times l}{\lambda} \quad \text{(G.18)}$$

$$P_r = \frac{\rho\times\nu\times c}{\lambda} \quad \text{(G.19)}$$

$$G_r = \frac{\beta\times\Delta\theta\times g\times l^3}{\nu^2} \quad \text{(G.20)}$$

where

N_u, G_r, P_r are Nusselt, Grashof and Prandtl numbers, respectively,

C and n are empirical constants affected by oil flow,

h is the heat transfer coefficient,

l is the dimension of the heated surface in the direction of flow,

λ is the thermal conductivity,

ρ is the oil density,

ν is the oil kinematic viscosity,

β is the coefficient of thermal cubic expansion,

g is the gravitational constant, and

$\Delta\theta$ is the corresponding surface drop, i.e. temperature gradient.

By substituting Equations (G.18), (G.19) and (G.20) in Equation (G.17), the following expression is obtained:

$$\frac{h \times l}{\lambda} = C \times \left[\frac{\rho \times \nu \times c}{\lambda} \times \frac{\beta \times \Delta\theta \times g \times l^3}{\nu^2}\right]^n \tag{G.21}$$

If the temperature gradient is given as the heat loss to heat coefficient ratio:

$$\Delta\theta = \frac{P}{h} \tag{G.22}$$

and if Equation (G.21) is solved for heat transfer coefficient and substituted in Equation (G.22), the following is obtained:

$$\Delta\theta = \frac{P}{\frac{C \times \lambda}{l} \times \left[\frac{\rho \times \nu \times c}{\lambda} \times \frac{\beta \times \Delta\theta \times g \times l^3}{\nu^2}\right]^n} \tag{G.23}$$

Also, as for the range of the operating temperatures the physical properties of the oil in Equation (G.23) can be considered constant the following is valid:

$$\Delta\theta = C_1 \times P^{1/(1+n)} \tag{G.24}$$

where

$$C_1 = \frac{1}{\left[C \times \lambda^{n-1} \times \rho \times c \times \frac{\beta \times g \times l^{3-n}}{\nu}\right]^n} \tag{G.25}$$

Equation (G.24) is identical to Equation (G.4) and by following the same procedure as given above, it is possible to arrive at Equations (G.14) and (G.16) by defining correlation:

$$\frac{1}{1+n} (=) x \tag{G.26}$$

$$\frac{1}{1+n} (=) y \tag{G.27}$$

Apart of the oil physical parameters the accuracy of the equation depends also on accurately determined C and n empirical constants. This can be done according to the following procedure:

1) Obtain the hot-spot/average winding and oil temperatures from the extended temperature rise test.
2) Calculate average winding to average oil gradient.
3) Calculate mean boundary layer temperature between the heating surface and coolant:

$$\theta_m = \frac{\theta_h + \theta_o}{2} \tag{G.28}$$

4) Calculate average value of the heat transfer coefficient:

$$h = \frac{P}{\Delta\theta} \tag{G.29}$$

5) For calculated mean boundary layer temperature obtain the physical properties of the oil and calculate Nussel, Prandtl and Grashof numbers

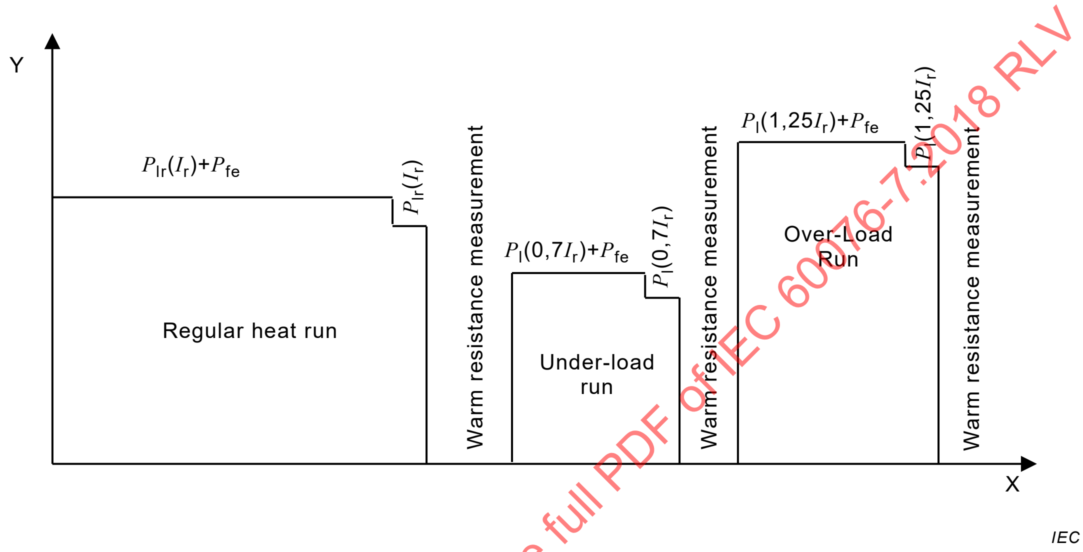
Plot the following graph in log-log system:

$$N_u = f(G_r \times P_r) \tag{G.30}$$

The line on the log-log chart that bests fits the plot is drawn and the lines that best fit the data points plotted using the least-square method should be used to estimate corresponding empirical coefficients n and C. The set of the empirical constants n and C is specific for a given design. This means that any change in design affects the estimated values.

G.4 Extended temperature rise test approach

The top-oil and winding exponents are obtained from an extended temperature rise test whose load profile is given on Figure G.1 [51]. However, shorter and less time consuming profiles are also available as defined in [13] and [52].



Key

x-axis losses in kW

y-axis time in h

Figure G.1 – Extended temperature rise test

The extended test consists of the three successive thermal runs:

1) Regular heat run:

This part of the test is the regular temperature rise test, i.e. the transformer is short-circuited and supplied with total losses. Once the oil temperature is stabilized and corresponding oil temperature rises recorded, the test immediately continues with the rated losses supplied for 1 h. This is followed with the transformer shut down in order to measure the warm resistance and to estimate the corresponding average winding to average oil gradient.

2) Under-load test

After the warm resistance measurements for the rated current are recorded, the test continues with the supplied losses produced by 70 % of the rated current plus the additional current to simulate the rated no-load losses. When the oil temperature is stabilized and the corresponding temperature rises are recorded, the test immediately continues with the losses produced by 70 % of the rated current for 1 h. This is followed with the transformer shut down in order to measure the warm resistance and to estimate the corresponding average winding to average oil gradient.

3) Over-load test

After the warm resistance measurements for the rated current are recorded, the test continues with the supplied losses produced by 125 % of the rated current plus the additional current to simulate the rated no-load losses. When the oil temperature is stabilized and the corresponding temperature rises are recorded, the test immediately continues with the losses produced by 125 % of the rated current for 1 h. This is followed with the transformer shut down in order to measure the warm resistance and to estimate the corresponding average winding to average oil gradient.

Based on the extended run test results the exponent x is obtained as the slope of the line on log-log chart that bests fits the plot of the top-oil temperature rise measured at the end of the three temperature tests (70 % + P_{fe}, 100 % + P_{fe} and 125 % + P_{fe}) versus the loss equation, Figure G.2 a. Correspondingly, exponent y is the slope of the line on log-log chart that best fits the plot of the average winding temperature rise above average top-oil temperature measured at the end of three temperature tests (70 %, 100 % and 125 %) versus the loading factor Figure G.2 b. This method assumes that the hot-spot rise over top-oil temperature is proportional to the average winding rise over average oil temperature.

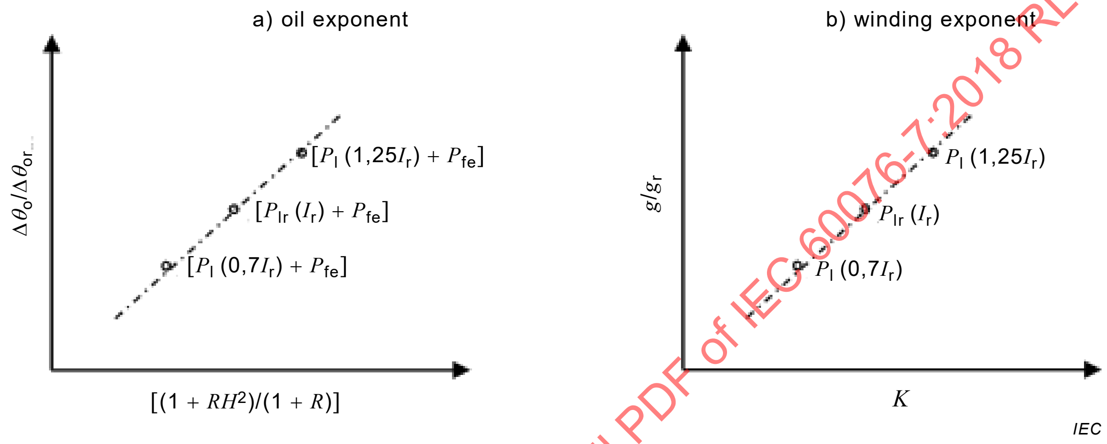


Figure G.2 – Transformer exponent estimation plots

The slopes should be determined by the slopes of the lines that best fit the data points plotted using the least-square method.

Annex H
(informative)

Practical example of the exponential equations method

H.1 ~~Introduction~~ General

The curves in Figure 14 are taken from an example in real life, and details of the case will be given in this annex. A 250 MVA, ONAF-cooled transformer was tested as follows. During each time period, the load current was kept constant, that is, the losses changed due to resistance change during each load step. The corresponding flowchart is in Annex J.

Table H.1 – Load steps of the 250 MVA transformer

Time period min	Load factor
0 to 190	1,0
190 to 365	0,6
365 to 500	1,5
500 to ~~710~~ 705	0,3
~~710 – 735~~ 705 to 730	2,1
~~735 – 750~~ 730 to 745	0,0

The two main windings were equipped with eight fibre optic sensors each. The hottest spot was found in the innermost main winding (118 kV). In this example the variation of the hottest spot temperature during time period 0 min to ~~750~~ 745 min will be defined according to the calculation method described in 8.2.2. A comparison with the measured curve will be made.

The characteristic data of the transformer, necessary for the calculation, are:

θ_a = 25,6 °C

$\Delta\theta_{or}$ = 38,3 K

R = 1 000 (because the test was made by the “short-circuit method”)

H = 1,4 (defined by measurement, see 8.1.3)

g_r = 14,5 K

τ_w = 4,6 min to 8,7 min (depending on the loading case. The value in Table 4, that is, 7 min, will be used in the calculation)

τ_o = 162 min to170 min (depending on the loading case. The value in Table 4, that is, 150, will be used in the calculation)

The winding is zigzag-cooled with a spacer separation ≥ 3 mm.

H.2 Time period 0 min to 190 min

~~$\Delta\theta_{oi}$ = 12,7 K~~ ~~(This test was started at 08:20 in the morning. The preceding evening an overloading test at 1,49 p.u. had been finished at 22:00)~~

~~K = 1,0~~

~~$\Delta\theta_{hi}$ = 0,0 K~~

~~The equations (5), (7) and (8) yield the hot-spot variation as a function of time, hence from equation (5):~~

$$\cancel{\theta_h(t) = 25{,}6 + 12{,}7 + \left\{38{,}3 \times \left[\frac{1+1\ 000 \times 1{,}0^2}{1+1\ 000}\right]^{0{,}8} - 12{,}7\right\} \times f_1(t) + 0{,}0 + \left\{1{,}4 \times 14{,}5 \times 1{,}0^{1{,}3} - 0{,}0\right\} \times f_2(t)}$$

~~From equation (7):~~

$$\cancel{f_1(t) = \left(1 - e^{(-t)/(0{,}5\times150)}\right)}$$

~~From equation (8):~~

$$\cancel{f_2(t) = 2{,}0 \times \left(1 - e^{(-t)/(2{,}0\times7)}\right) - (2{,}0 - 1{,}0) \times \left(1 - e^{(-t)/(150/2{,}0)}\right)}$$

The initial data for the time period 0 min to 190 min are as follows:

$\Delta\theta_{oi}$ = 12,7 K (This test was started at 08:20 in the morning. The preceding evening an overloading test at 1,49 p.u. had been finished at 22:00)

K = 1,0

$\Delta\theta_{hi}$ = 0,0 K

Equations (10), (12), (13), (14) and (17) yield the hot-spot variation as a function of time, hence from Equation (10):

$$\theta_o(t) = 25{,}6 + 12{,}7 + \left\{38{,}3 \times \left[\frac{1+1\ 000 \times 1{,}0^2}{1+1\ 000}\right]^{0{,}8} - 12{,}7\right\} \times \left(1 - e^{(-t)/(0{,}5\times150)}\right)$$

From Equation (13):

$$\Delta\theta_{h1}(t) = 0{,}0 + \left\{2{,}0 \times 1{,}4 \times 14{,}5 \times 1{,}0^{1{,}3} - 0{,}0\right\} \times \left(1 - e^{(-t)/(2{,}0\times7)}\right)$$

From Equation (14):

$$\Delta\theta_{h2}(t) = 0{,}0 + \left\{(2{,}0 - 1{,}0) \times 1{,}4 \times 14{,}5 \times 1{,}0^{1{,}3} - 0{,}0\right\} \times \left(1 - e^{(-t)/(150/2{,}0)}\right)$$

From Equation (12):

$$\Delta\theta_h(t) = \Delta\theta_{h1}(t) - \Delta\theta_{h2}(t)$$

From Equation (17):

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h(t)$$

H.3 Time period 190 min to 365 min

~~$\Delta\theta_{oi}$ = 36,2 K (calculated in B.2)~~

~~K = 0,6~~

~~$\Delta\theta_{hi}$ = 22,0 K (calculated in B.2)~~

~~The equations (6) and (9) yield the hot-spot variation as a function of time, hence from equation (6):~~

$$\cancel{\theta_h(t) = 25{,}6 + 38{,}3 \times \left[\frac{1 + 1\ 000 \times 0{,}6^2}{1 + 1\ 000}\right]^{0{,}8} + \left\{36{,}2 - 38{,}3 \times \left[\frac{1 + 1\ 000 \times 0{,}6^2}{1 + 1\ 000}\right]^{0{,}8}\right\} \times f_3(t) + 1{,}4 \times 14{,}5 \times 0{,}6^{1{,}3}}$$

~~From equation (9):~~

$$\cancel{f_3(t) = e^{(-t)/(0{,}5 \times 150)}}$$

The initial data for the time period 190 min to 365 min are as follows:

$\Delta\theta_{oi}$ = 36,2 K (calculated in H.2)

K = 0,6

$\Delta\theta_{hi1}$ = 40,6 K (calculated in H.2)

$\Delta\theta_{hi2}$ = 18,7 K (calculated in H.2)

Equations (11), (15), (16) and (17) yield the hot-spot variation as a function of time, hence from Equation (11):

$$\theta_o(t) = 25{,}6 + 38{,}3 \times \left[\frac{1 + 1\ 000 \times 0{,}6^2}{1 + 1\ 000}\right]^{0{,}8} + \left\{36{,}2 - 38{,}3 \times \left[\frac{1 + 1\ 000 \times 0{,}6^2}{1 + 1\ 000}\right]^{0{,}8}\right\} \times e^{(-t)/(0{,}5 \times 150)}$$

From Equation (15):

$$\Delta\theta_{h1}(t) = 2{,}0 \times 1{,}4 \times 14{,}5 \times 0{,}6^{1{,}3} + \left\{40{,}6 - 2{,}0 \times 1{,}4 \times 14{,}5 \times 0{,}6^{1{,}3}\right\} \times e^{(-t)/(2{,}0 \times 7)}$$

From Equation (16):

$$\Delta\theta_{h2}(t) = (2{,}0 - 1{,}0) \times 1{,}4 \times 14{,}5 \times 0{,}6^{1{,}3} + \left\{18{,}6 - (2{,}0 - 1{,}0) \times 1{,}4 \times 14{,}5 \times 0{,}6^{1{,}3}\right\} \times e^{(-t)/(0{,}5 \times 150)}$$

From Equation (17):

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h(t)$$

H.4 Time period 365 min to 500 min

~~$\Delta\theta_{oi}$ = 18,84 K (calculated in B.3)~~

~~K = 1,5~~

~~$\Delta\theta_{hi}$ = 10,45 K (calculated in B.3)~~

~~The calculation is identical to that one in B.2, when the following replacements are made in equation (5):~~

~~12,7 replaced by 18,84~~

~~1,0 replaced by 1,5~~

~~0,0 replaced by 10,45~~

The initial data for the time period 365 min to 500 min are as follows:

$\Delta\theta_{oi}$ = 18,8 K (calculated in H.3)

K = 1,5

$\Delta\theta_{hi1}$ = 20,9 K (calculated in H.3)

$\Delta\theta_{hi2}$ = 11,25 K (calculated in H.3)

The calculation is identical to the one in H.2, when the following replacements are made in Equation (10):

12,7 replaced by 18,8

1,0 replaced by 1,5

In Equation (13):

0,0 replaced by 20,9

1,0 replaced by 1,5

In Equation (14):

0,0 replaced by 11,25

1,0 replaced by 1,5

H.5 Time period 500 min to ~~710~~ 705 min

~~$\Delta\theta_{oi}$ = 64,1 K (calculated in B.4)~~

~~K = 0,3~~

~~$\Delta\theta_{hi}$ = 37,82 K (calculated in B.4)~~

~~The calculation is identical to the one in B.3, when the following replacements are made in equation (6):~~

~~36,2 replaced by 64,1~~

~~0,6 replaced by 0,3~~

~~22,0 replaced by 37,82~~

The initial data for the time period 500 min to 705 min are as follows:

$\Delta\theta_{oi}$ = 63,6 K (calculated in H.4)

K = 0,3

$\Delta\theta_{hi1}$ = 68,2 K (calculated in H.4)

$\Delta\theta_{hi2}$ = 30,3 K (calculated in H.4)

The calculation is identical to the one in H.3, when the following replacements are made in Equation (11):

36,2 replaced by 63,6

0,6 replaced by 0,3

In Equation (15):

40,6 replaced by 68,2

1,0 replaced by 1,5

In Equation (16):

18,6 replaced by 30,3

1,0 replaced by 1,5

H.6 Time period ~~710~~ 705 min to ~~735~~ 730 min

~~$\Delta\theta_{oi}$ = 9,65 K (calculated in B.5)~~

~~K = 2,1~~

~~$\Delta\theta_{hi}$ = 4,24 K (calculated in B.5)~~

~~The calculation is identical to the one in B.4, when the following replacements are made in equation (5):~~

~~18,84 replaced by 9,65~~

~~1,5 replaced by 2,1~~

~~10,45 replaced by 4,24~~

The initial data for the time period 705 min to 730 min are as follows:

$\Delta\theta_{oi}$ = 9,4 K (calculated in H.5)

K = 2,1

$\Delta\theta_{hi1}$ = 8,5 K (calculated in H.5)

$\Delta\theta_{hi2}$ = 6,0 K (calculated in H.5)

The calculation is identical to the one in H.4, when the following replacements are made in Equation (10):

18,8 replaced by 9,4

1,5 replaced by 2,1

In Equation (13):

20,9 replaced by 8,5

1,5 replaced by 2,1

In Equation (14):

11,25 replaced by 6,0

1,5 replaced by 2,1

H.7 Time period ~~735~~ 730 min to ~~750~~ 745 min

~~$\Delta\theta_{oi}$ = 41,36 K (calculated in B.6)~~

~~K = 0,0~~

~~$\Delta\theta_{hi}$ = 71,2 K (calculated in B.6)~~

~~The calculation is made in the same way as in B.3 and B.5.~~

The initial data for the time period 730 min to 745 min are as follows:

$\Delta\theta_{oi}$ = 42,3 K (calculated in H.6)

K = 0,0

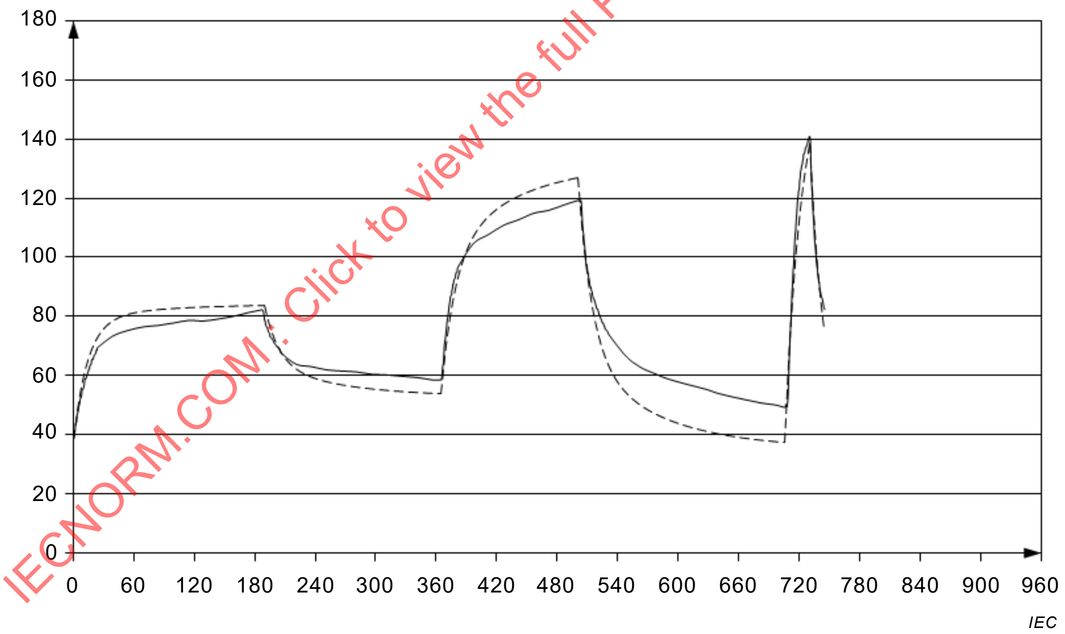
$\Delta\theta_{hi1}$ = 90,0 K (calculated in H.6)

$\Delta\theta_{hi2}$ = 19,4 K (calculated in H.6)

The calculation is made in the same way as in H.3 and H.5.

H.8 Comparison with measured values

The calculated and measured hot-spot temperature curves are shown in Figure H.1. The corresponding curves for the top-oil temperature are shown in Figure H.2. The numerical values at the end of each load step are shown in Table H.2.



Key

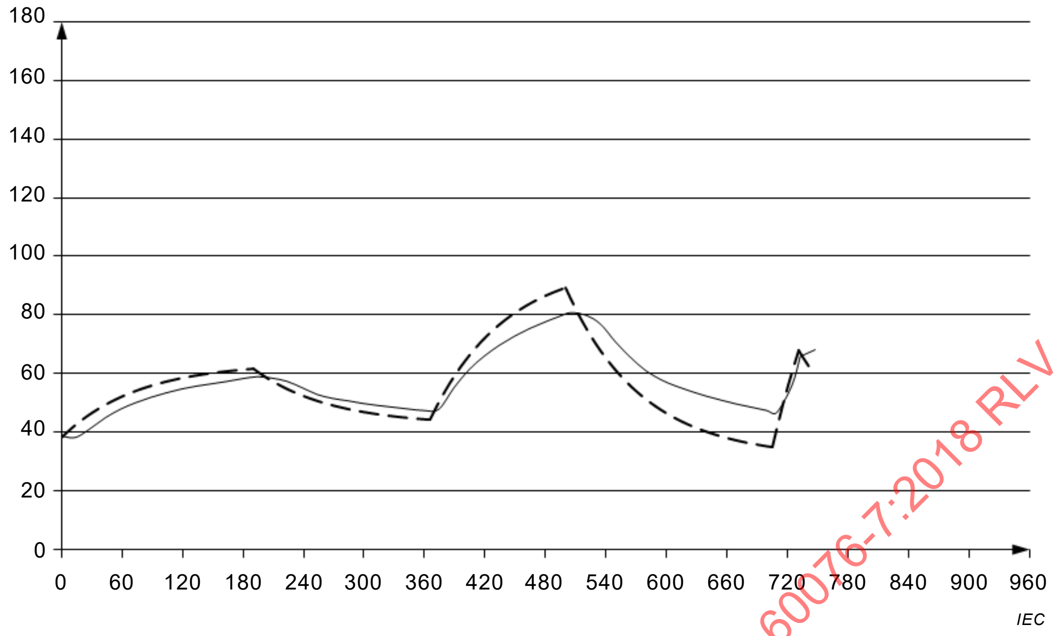
x-axis time t in minutes

y-axis temperature θ_h in °C

—— Measured values

---- Calculated values

Figure H.1 – Hot-spot temperature response to step changes in the load current



Key

x-axis time t in minutes

y-axis temperature θ_o in °C

—— Measured values

---- Calculated values

Figure H.2 – Top-oil temperature response to step changes in the load current

Table H.2 – Temperatures at the end of each load step

Time (min) / load factor	Top-oil temperature °C		Hot-spot temperature °C	
	Calculated	Measured	Calculated	Measured
190 / **1,0**	**~~61,8~~ 61,9**	**58,8**	**83,8**	**82,2**
365 / 0,6	44,4	47,8	~~54,9~~ 54,0	58,6
500 / **1,5**	**~~89,7~~ 89,2**	**80,8**	**~~127,5~~ 127,0**	**119,2**
~~710~~ 705 / 0,3	~~35,3~~ 35,0	46,8	~~39,5~~ 37,54	49,8
~~735~~ 730 / **2,1**	**~~67,0~~ 67,9**	**65,8**	**~~138,2~~ 138,6**	**140,7**
~~750~~ 745 / 0,0	~~59,5~~ 60,3	68,2	~~59,5~~ 75,3	82,4
NOTE Bold values indicate load increase.				

The calculation method in this document is intended to yield relevant values, especially at load increase (noted by bold entries in Table H.2).

Annex I
(informative)

~~Illustration~~ Application of the ~~differential~~ difference equation~~s~~ solution method

~~C.1 Introduction~~

~~This annex provides more detailed information on the differential equations method described in 8.2.3 and how they are solved by conversion to difference equations. An example is provided.~~

~~C.2 General~~

~~The formulation of the heating equations as exponentials is particularly suited to determination of the heat-transfer parameters by test and for simplified scenarios. In the field, the determination of hot-spot temperature is more likely to be required for arbitrarily time-varying load factor~~ ~~K~~ ~~and time-varying ambient temperature~~ ~~θ_a.~~

~~For this application, the best approach is the use of the heat-transfer differential equations. Such equations are easily solved if converted to difference equations as shown later in this annex.~~

~~C.3 Differential equations~~

~~When heat-transfer principles are applied to the power transformer situation, the differential equations are only linear for directed-flow OD cooling. For the other forms of cooling, OF and ON, the cooling medium circulation rate depends on the coolant temperature itself. In other words, if there are no fans, the airflow rate in the radiator depends on its temperature, whereas if there are fans, it does not. Similarly, if there are no oil pumps or the oil flow is not 'directed', the oil flow rate depends on its own temperature, whereas if there are pumps and directed flow, it does not.~~

~~The consequence of this is that for ON and OF cooling, the differential equations are non-linear, implying that the response of either the top-oil temperature rise or the hot-spot temperature rise, to a step change in load current, is not a true exponential function [13].~~

~~However, to avoid undue complexity in this part of IEC 60076, an approximation is made, namely that the non-linear relationship affects only the final value of any temperature change that occurs, and that the time function is still exponential, whether ON, OF or OD cooling. It can be shown that the error is not great.~~

~~The result is that the differential equation for top-oil temperature (inputs~~ ~~K, θ_a,~~ ~~output~~ ~~θ_o)~~ ~~is~~

$$\cancel{\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) = k_{11}\tau_o \times \frac{d\theta_o}{dt} + [\theta_o - \theta_a]} \qquad \text{~~(C.1)~~}$$

~~All symbols for variables and parameters are defined earlier in this document.~~

~~The differential equation for hot-spot temperature rise (input~~ ~~K,~~ ~~output~~ ~~$\Delta\theta_h$)~~ ~~is most easily solved as the sum of two differential equations, where~~

$$\Delta\theta_{h} = \Delta\theta_{h1} - \Delta\theta_{h2} \qquad \text{~~(C.2)~~}$$

~~The two equations are~~

$$k_{21} \times K^{y} \times (\Delta\theta_{hr}) = k_{22} \times \tau_{w} \times \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \qquad \text{~~(C.3)~~}$$

~~and~~

$$(k_{21} - 1) \times K^{y} \times (\Delta\theta_{hr}) = (\tau_{o} / k_{22}) \times \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \qquad \text{~~(C.4)~~}$$

~~the solutions of which are combined in accordance with equation (C.2).~~

~~The final equation for the hot-spot temperature is~~

$$\theta_{h} = \theta_{o} + \Delta\theta_{h} \qquad \text{~~(C.5)~~}$$

~~Regarding equations (C.2) to (C.4), the complexity is in order to account for the fact that the oil-cooling medium has mechanical inertia in addition to thermal inertia. The effect is greatest for natural cooling (ON), somewhat less for non-directed-flow pumped-oil cooling (OF), and negligible for directed-flow pumped-oil cooling (OD), as regards power transformers. It is also negligible for distribution transformers (see 8.2.2).~~

~~The block diagram representation of these equations is shown in 8.2.3.~~

~~C.4 Conversion to difference equations~~

~~The foregoing differential equations cannot be solved for the output functions in terms of simple mathematical functions such as exponentials, unless the input functions are also simple: for example, pure step functions. For an installed transformer, load current and ambient temperature are not well-defined functions of time. If approximations are made, for example, approximating the load current as a series of step changes and holding the ambient temperature constant, then it follows that the results are also only approximate.~~

~~If the differential equations are converted to difference equations, then the solution is quite straightforward, even on a simple spreadsheet.~~

~~The differential equations of Clause C.3 can be written as the following difference equations, where D stands for a difference over a small time step.~~

~~Equation (C.1) becomes:~~

$$D\theta_{o} = \frac{Dt}{k_{11}\tau_{o}} \left[\left[\frac{1 + K^{2}R}{1 + R} \right]^{x} \times (\Delta\theta_{or}) - [\theta_{o} - \theta_{a}] \right] \qquad \text{~~(C.6)~~}$$

~~The "D" operator implies a difference in the associated variable that corresponds to each time step Dt. At each time step, the nth value of $D\theta_{o}$ is calculated from the $(n-1)$th value using~~

$$\theta_{o(n)} = \theta_{o(n-1)} + D\theta_{o(n)} \qquad \text{~~(C.7)~~}$$

~~Equations (C.3) and (C.4) become~~

$$\cancel{D\Delta\theta_{h1} = \frac{Dt}{k_{22}\tau_w} \times \left[k_{21} \times \Delta\theta_{hr} K^y - \Delta\theta_{h1}\right]} \quad \text{(C.8)}$$

~~and~~

$$\cancel{D\Delta\theta_{h2} = \frac{Dt}{(1/k_{22})\tau_o} \times \left[(k_{21}-1) \times \Delta\theta_{hr} K^y - \Delta\theta_{h2}\right]} \quad \text{(C.9)}$$

~~The nth values of each of $\Delta\theta_{h1}$ and $\Delta\theta_{h2}$ are calculated in a way similar to equation (C.7).~~

~~The total hot-spot temperature rise at the n^{th} time step is given by:~~

$$\cancel{\Delta\theta_{h(n)} = \Delta\theta_{h1(n)} - \Delta\theta_{h2(n)}} \quad \text{(C.10)}$$

~~Finally, the hot-spot temperature at the n^{th} time step is given by:~~

$$\cancel{\theta_{h(n)} = \theta_{o(n)} + \Delta\theta_{h(n)}} \quad \text{(C.11)}$$

~~For an accurate solution, the time step Dt should be as small as is practicable, certainly no greater than one-half of the smallest time constant in the thermal model. For example, if the time constant for the winding considered is 4 min, the time step should be no larger than 2 min.~~

~~NOTE τ_w and τ_o should not be set to zero.~~

~~Also, there are theoretically more accurate numerical analysis solution methods than the simple one used in equations (C.6) to (C.9), for example trapezoidal or Runge-Kutta methods. However, the increased complexity is not warranted here considering the imprecision of the input data.~~

~~The loss of life of cellulose insulation differential equations of subclause 6.3 can also be converted to difference equations. The fundamental differential equation is~~

$$\cancel{\frac{dL}{dt} = V} \quad \text{(C.12)}$$

~~implying~~

$$\cancel{DL_{(n)} = V_{(n)} \times Dt} \quad \text{(C.13)}$$

~~and~~

$$\cancel{L_{(n)} = L_{(n-1)} + DL_{(n)}} \quad \text{(C.14)}$$

I.1 General

Annex I provides an example of the application of difference equation method described in 8.2.3.

I.2 Example

Suppose the objective is that an on-line monitoring device is to generate hot-spot temperature and loss-of-life information. The steps in the solution are as follows:

1) establish the transformer parameters;
2) establish the input data;
3) calculate the initial conditions;
4) solve the differential equations;
5) tabulate the output data;
6) plot the output data.

The details are as follows.

1 – Establish the transformer parameters

The parameters used are chosen in such a way that the rated hot-spot temperature is 110 °C at an ambient temperature of 30 °C. Other parameters are typical.

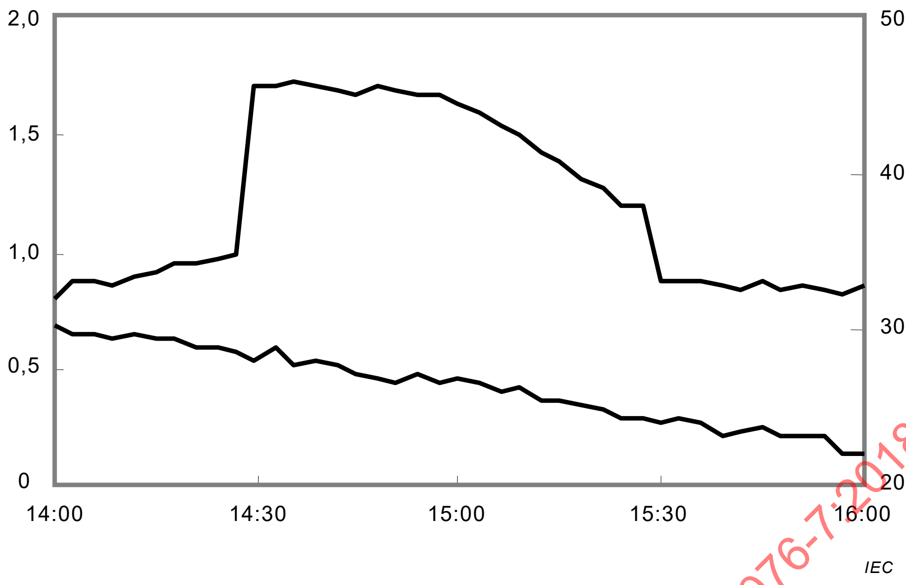
$\Delta\theta_{or}$ = 45 K	τ_o = 150 min	R = 8	y = 1,3	k_{21} = 2
$\Delta\theta_{hr}$ = 35 K	τ_w = 7 min	x = 0,8	k_{11} = 0,5	k_{22} = 2

2 – Establish the input data

The input data for this example are listed in Table I.1 and plotted in Figure I.1.

Table I.1 – Input data for example

Step	Time t min	Time of day h:min	Ambient temperature θ_a °C	Load factor K
0	0	14:00	30,3	0,81
1	3	14:03	29,9	0,87
2	6	14:06	29,8	0,88
3	9	14:09	29,5	0,86
4	12	14:12	29,6	0,90
5	15	14:15	29,5	0,92
6	18	14:18	29,5	0,95
7	21	14:21	28,9	0,96
8	24	14:24	29,0	0,97
9	27	14:27	28,6	1,00
10	30	14:30	28,0	1,70
11	33	14:33	28,7	1,70
12	36	14:36	27,8	1,73
13	39	14:39	28,1	1,72
14	42	14:42	27,9	1,69
15	45	14:45	27,1	1,68
16	48	14:48	26,9	1,71
17	51	14:51	26,7	1,69
18	54	14:54	27,2	1,67
19	57	14:57	26,7	1,68
20	60	15:00	26,9	1,63
21	63	15:03	26,5	1,59
22	66	15:06	26,2	1,53
23	69	15:09	26,3	1,49
24	72	15:12	25,4	1,41
25	75	15:15	25,6	1,38
26	78	15:18	25,3	1,32
27	81	15:21	24,8	1,28
28	84	15:24	24,5	1,21
29	87	15:27	24,3	1,19
30	90	15:30	24,1	0,87
31	93	15:33	24,3	0,88
32	96	15:36	24,1	0,87
33	99	15:39	23,4	0,86
34	102	15:42	23,6	0,85
35	105	15:45	23,8	0,87
36	108	15:48	23,1	0,83
37	111	15:51	23,3	0,86
38	114	15:54	23,1	0,85
39	117	15:57	22,3	0,82
40	120	16:00	22,2	0,86



Key

Load factor (upper curve, left axis)

Ambient temperature in °C (lower curve, right axis)

Time of day (y-axis)

Figure I.1 – Plotted input data for the example

Ambient temperatures and load factors are available at 3 min intervals. This is a maximum time step since it should be less than half the smallest time constant, τ_w, in the equations, for an accurate solution. Because τ_w = 7 min in this case, the time step $Dt = 3$ min.

3 – Calculate the initial conditions

Although the system may not strictly be in the steady state at the start of a calculation period, this is usually the best one can assume, and it has little effect on the result.

The initial conditions, then, are calculated by setting the time derivatives equal to zero in each of Equations (5), (7) and (8), resulting in the following values.

From Equation (5), the initial value of θ_o is $\theta_{o(0)} = \left[\dfrac{1+K^2R}{1+R}\right]^x \times \Delta\theta_{or} + \theta_a$ = 63,9 °C.

From Equation (7), the initial value of $\Delta\theta_{h1}$ is $\Delta\theta_{h1(0)} = k_{21} \times K^y \times \Delta\theta_{hr}$ = 53,2 K.

From Equation (8), the initial value of $\Delta\theta_{h2}$ is $\Delta\theta_{h2(0)} = (k_{21} - 1) \times K^y \times \Delta\theta_{hr}$ = 26,6 K.

Also, the initial condition for the loss of life, L, should be chosen. Assume here that the purpose of the calculation is to find out the loss of life for this particular overload occurrence. Therefore, the initial value of L is $L_{(0)}$ = 0.

4 – Solve the difference equations

At n = 0, t = 0, $\theta_{o(0)}$ = 63,9 (units are omitted; traditionally °C for temperatures and K for temperature differences)

$\Delta\theta_{h1(0)}$ = 53,2

$\Delta\theta_{h2(0)}$ = 26,6

$L_{(0)}$ = 0

At n = 1, t = 3 min, from Equations (18) and (19), the top-oil temperature changes as follows:

$$D\theta_{o(1)} = \frac{3}{0{,}5 \times 150}\left[\left[\frac{1+0{,}87^2 \times 8}{1+8}\right]^{0{,}8} \times 45 - [63{,}9 - 29{,}9]\right]$$ = 0,121 and

$$\theta_{o(1)} = \theta_{o(0)} + D\theta_{o(1)}$$ = 63,9 + 0,121 = 64,0

Similarly, from Equation (20), the hot-spot temperature rise first term changes as follows:

$$D\Delta\theta_{h1(1)} = \frac{3}{2{,}0 \times 7}\left(2{,}0 \times 35 \times 0{,}87^{1{,}3} - 53{,}2\right)$$ = 1,12 and

$$\Delta\theta_{h1(1)} = \Delta\theta_{h1(0)} + D\Delta\theta_{h1(1)}$$ = 53,2 + 1,12 = 54,3

Similarly, from Equation (21), the hot-spot temperature rise second term changes as follows:

$$D\Delta\theta_{h2(1)} = \frac{3}{(1/2{,}0) \times 150}\left((2{,}0-1) \times 35 \times 0{,}87^{1{,}3} - 26{,}6\right)$$ = 0,104 and

$$\Delta\theta_{h2(1)} = \Delta\theta_{h2(0)} + D\Delta\theta_{h2(1)}$$ = 26,6 + 0,104 = 26,7

Then the total hot-spot temperature rise, from Equation (22) is

$$\Delta\theta_{h(1)} = \Delta\theta_{h1(1)} - \Delta\theta_{h2(1)}$$ = 54,3 – 26,7 = 27,6

and, finally, the hot-spot temperature is, from Equation (23)

$$\theta_{h(1)} = \theta_{o(1)} + \Delta\theta_{h(1)}$$ = 64,0 + 27,6 = 91,6

The loss of life L over this time step is given by Equation (25):

$$DL_{(1)} = V_{(1)} \times Dt = \left[e^{\frac{15\,000}{110+273} - \frac{15\,000}{\theta_{h(1)}+273}}\right] \times 3$$ = 0,42 min

(Loss of life under rated conditions would have been 3 min.)

The total loss of life to this point is:

$L_{(1)} = L_{(0)} + DL_{(1)}$ = 0 + 0,42 min, or 0,000 29 days.

At n = 2, t = 6 min, the entire calculation is repeated, with all subscripts incremented by 1, that is, each variable $X_{(1)}$ becomes $X_{(2)}$. At n = 3, t = 9 min, each variable $X_{(2)}$ becomes $X_{(3)}$ and so on. Continue until n = 40, t = 120 min.

5 – Tabulate the output data

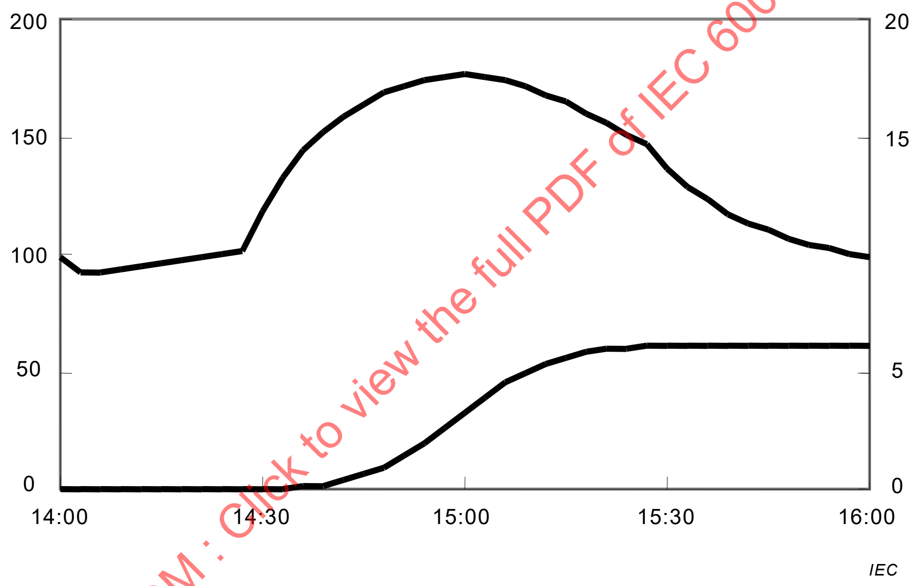
The results of the calculation are shown in Table I.2 and Figure I.2.

Table I.2 – Output data for the example

Step	Time t min	Time of day h:min	Hot-spot temperature θ_h °C	Loss of life L min	Loss of life L days
0	0	14:00	90,5	0	0
1	3	14:03	91,6	0	0,00
2	6	14:06	92,7	1	0,00
3	9	14:09	93,2	1	0,00
4	12	14:12	94,3	2	0,00
5	15	14:15	95,6	3	0,00
6	18	14:18	97,2	3	0,00
7	21	14:21	98,6	4	0,00
8	24	14:24	100,0	5	0,00
9	27	14:27	101,6	7	0,00
10	30	14:30	118,6	14	0,01
11	33	14:33	132,1	39	0,03
12	36	14:36	143,5	109	0,08
13	39	14:39	152,4	258	0,18
14	42	14:42	158,8	508	0,35
15	45	14:45	163,6	875	0,61
16	48	14:48	168,2	1 402	0,97
17	51	14:51	171,5	2 076	1,44
18	54	14:54	173,6	2 871	1,99
19	57	14:57	175,7	3 796	2,64
20	60	15:00	176,1	4 754	3,30
21	63	15:03	175,6	5 675	3,94
22	66	15:06	173,8	6 480	4,50
23	69	15:09	171,5	7 156	4,97
24	72	15:12	167,8	7 667	5,32
25	75	15:15	164,3	8 055	5,59
26	78	15:18	160,1	8 335	5,79
27	81	15:21	156,0	8 534	5,93
28	84	15:24	151,1	8 668	6,02
29	87	15:27	146,8	8 761	6,08
30	90	15:30	136,9	8 800	6,11
31	93	15:33	129,1	8 819	6,12

Step	Time t min	Time of day h:min	Hot-spot temperature θ_h °C	Loss of life L min	Loss of life L days
32	96	15:36	122,8	8 830	6,13
33	99	15:39	117,5	8 836	6,14
34	102	15:42	113,1	8 840	6,14
35	105	15:45	110,0	8 843	6,14
36	108	15:48	106,6	8 846	6,14
37	111	15:51	104,5	8 847	6,14
38	114	15:54	102,6	8 849	6,14
39	117	15:57	100,4	8 850	6,15
40	120	16:00	99,3	8 851	6,15

6 – Plot the output data



Key

Hot-spot temperature in °C (upper curve, left axis)

Loss of life in days (lower curve, right axis)

Time of day (x-axis)

Figure I.2 – Plotted output data for the example

Since the elapsed time of the plot is 2 h or 0,083 3 days, and the loss of life is 6,15 days, the relative loss of life during this overload is 6,15/0,083 3 = 74 times normal. This is not serious if there are otherwise long periods of time (usually the case) at relatively low hot-spot temperatures.

I.3 Use of measured top-oil temperature

If top-oil temperature is available as a measured quantity, for example as a 4 mA to 20 mA signal to the monitoring device, then the calculations become more accurate. Hot-spot temperature rise is calculated from difference Equations (20), (21) and (22) and added directly to the measured top-oil temperature data, at each time step. See the dashed line path in Figure 12.

Annex J
(informative)

Flowchart, based on the example in Annex H

START

↓

INPUT DATA

Cooling method: ONAF

The ambient temperature: θ_a = 25,6 °C

The top-oil temperature rise at the rated current: $\Delta\theta_{or}$ = 38,3 K

Ratio of load losses at rated current to no-load losses: R = 1 000

The hot-spot factor: H = 1,4

The winding-to-oil temperature difference: g_r = 14,5 K

The winding time constant: τ_w = 7 min

The average oil time constant: τ_o= 150 min

The oil temperature exponent: x = 0,8

The winding temperature exponent: y = 1,3

Thermal constants: k_{11} = 0,5; k_{21} = 2,0; k_{22} = 2,0

The number of intervals in load cycle: N = 6

Load factor for each interval:

$K(1)$ = 1,0; I(1) = (0 – 190) min

$K(2)$ = 0,6; I(2) = (190 – 365) min

$K(3)$ = 1,5; I(3) = (365 – 500) min

$K(4)$ = 0,3; I(4) = (500 – 705) min

$K(5)$ = 2,1; I(5) = (705 – 730) min

$K(6)$ = 0,0; I(6) = (730 – 745) min

Duration of each interval:

$D(1)$ = 190 min

$D(2)$ = 175 min

$D(3)$ = 135 min

$D(4)$ = 205 min

$D(5)$ = 25 min

$D(6)$ = 15 min

Spacer thickness ≥ 3 mm

↓

C = 1 (interval counter settings)

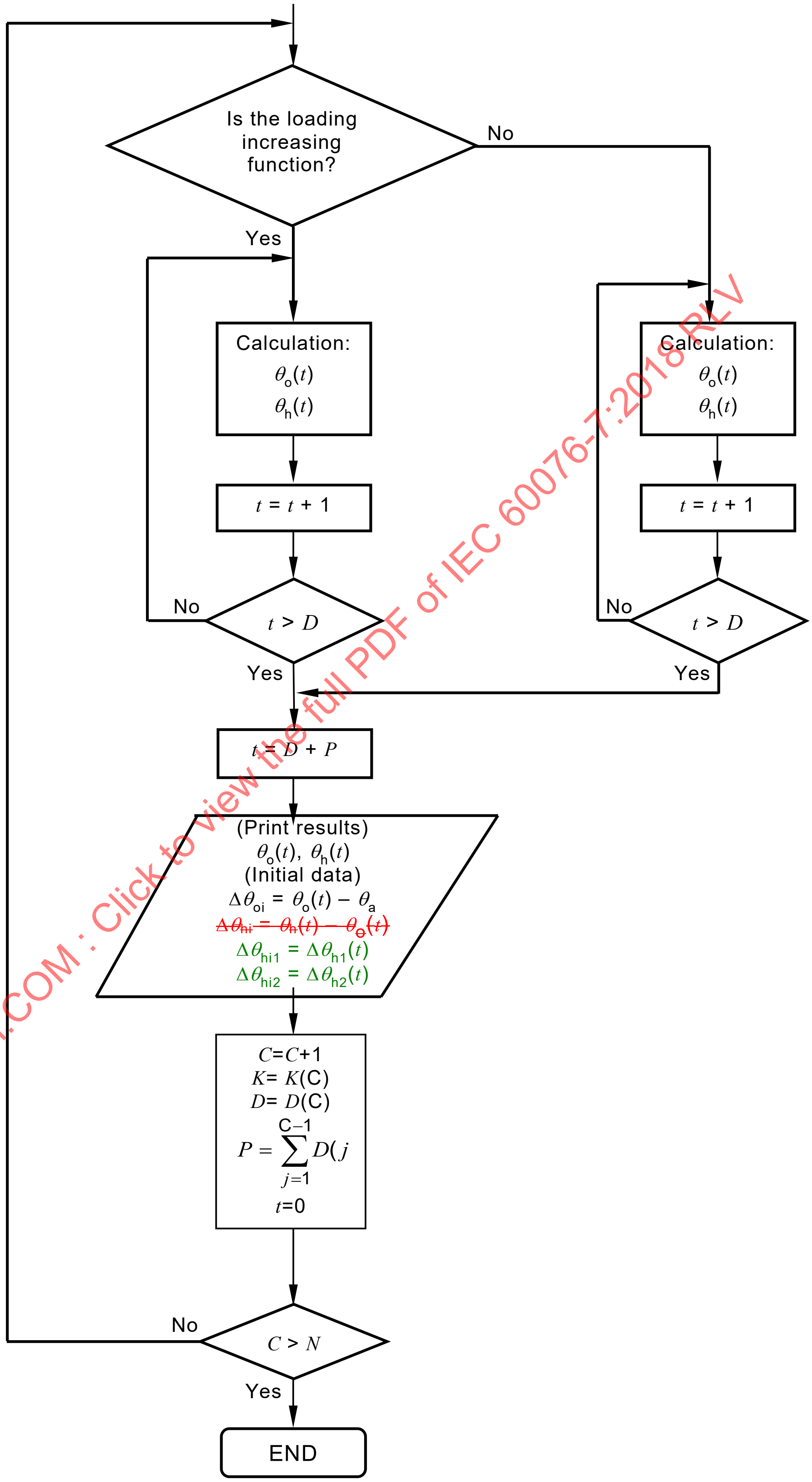
$K = K(1)$ $D = D(1)$

P = 0 t =0

(Initial data)

$\Delta\theta_{oi}$ = 12,7 K $\Delta\theta_{hi1}$ = 0,0 K

$\Delta\theta_{hi2}$ = 0,0 K


Is the loading increasing function?
No
Yes
Calculation:
θo(t)
θh(t)
t = t + 1
t > D
No
Yes
Calculation:
θo(t)
θh(t)
t = t + 1
t > D
No
Yes
t = D + P
(Print results)
θo(t), θh(t)
(Initial data)
Δθoi = θo(t) − θa
~~Δθhi = θh(t) − θo(t)~~
Δθhi1 = Δθh1(t)
Δθhi2 = Δθh2(t)
C=C+1
K= K(C)
D= D(C)
P = Σ D(j
t=0
C > N
No
Yes
END

Annex K
(informative)

Example of calculating and presenting overload data

Annex K contains an example of how to calculate and present the overload data with the equations presented in this document.

Table K.1 gives, as an example, some characteristics that might be used.

Table K.1 – Example characteristics related to the loadability of transformers

Characteristic		~~Distribution~~ Small transformers	Large and medium power transformers			
		ONAN	ONAN	ONAF	OF	OD
Oil exponent	x	0,8	0,8	0,8	1,0	1,0
Winding exponent	y	1,6	1,3	1,3	1,3	2,0
Loss ratio	R	5	6	6	6	6
Hot-spot factor	H	1,1	1,3	1,3	1,3	1,3
Oil time constant	τ_o	180	210	150	90	90
Winding time constant	τ_w	4	10	7	7	7
Ambient temperature	θ_a	20	20	20	20	20
Hot-spot temperature	θ_h	98	98	98	98	98
Hot-spot to top-oil (in tank) gradient at rated current	$\Delta\theta_{hr}$	23	26	26	22	29
Average oil temperature rise [a]	$\Delta\theta_{omr}$	44	43	43	46	46
Top-oil (in tank) temperature rise	$\Delta\theta_{or}$	55	52	52	56	49
Bottom oil temperature rise [a]	$\Delta\theta_{br}$	33	34	34	36	43
k_{11}		1,0	0,5	0,5	1,0	1,0
k_{21}		1,0	2,0	2,0	1,3	1,0
k_{22}		2,0	2,0	2,0	1,0	1,0

[a] Average oil temperature rise and bottom oil temperature rise are given for information only.

With a spreadsheet programme, a 24 h period is created, with the time-scale in minutes. Equations (10) to (17) are used to calculate for each minute the hot-spot temperature as a function of the load. The initial conditions for $\Delta\theta_{oi}$ and $\Delta\theta_{hi1}$, $\Delta\theta_{hi2}$ can be determined ~~with $f_1(t) = 0$, $f_2(t) = 0$ and $f_3(t) = 1$,~~ with $t \to \infty$.

When the hot-spot temperature is known, the relative ageing can be calculated with Equation (2). With Equation (4) the loss of life, expressed in “normal” days, can be calculated by dividing the sum of the relative ageing of each minute by 1 440.

For example, consider a case with a pre-load (K_1) of 0,8, then an overload K_2 = 1,4 during 30 min and return to K_1 = 0,8 for the time remaining (1 410 min). The transformer is OF cooled; therefore, the example characteristics of Table H.1 (OF) are used.

The initial values, after a steady state pre-load are:

K_1 = 0,8

$\Delta\theta_{oi}$ = 38,7 K

~~$\Delta\theta_{hi}$ = 16,5 K~~

$\Delta\theta_{hi1}$ = 21,4 K

$\Delta\theta_{hi1}$ = 4,95 K

The values after t = 30 min from start:

K_2 = 1,4

~~$f_1(t{=}30)$ = 0,28, $f_2(t{=}30)$ = 1,20~~

$\theta_o(t = 30)$ = 76,7 °C

$\theta_h(t = 30)$ = 114,2 °C ~~(equation (5) of 8.2.2)~~

The values after t = 31 min from start:

K_1 = 0,8

~~$f_3(t = 1)$ = 0,99~~

$\theta_o(t = 1)$ = 76,5 °C

$\theta_h(t = 1)$ = 111 °C

~~$\theta_h(t = 1)$ = 92,9 °C (equation (6) of 8.2.2)~~

The values after t = 1 440 min from start:

K_1 = 0,8

~~$f_3(t{=}1410)$ = 1,6E – 07~~

$\theta_o(t = 1\,410)$ = 58,7 °C

$\theta_h(t = 1410)$ = 75,2 °C ~~(equation (6) of 8.2.2)~~

This results in a loss of life of 0,14 days and a maximum hot-spot temperature rise of 94 K.

The parameters used in the described method can be varied to obtain a table with the loss of life as a function of K_1 and K_2. When the overload time is changed, a complete set of tables can be obtained.

As an example, one table with an overload time of 30 min is presented in Table K.2.

Table K.2 – An example table with the permissible duties and corresponding daily loss of life (in "normal" days), and maximum hot-spot temperature rise during the load cycle

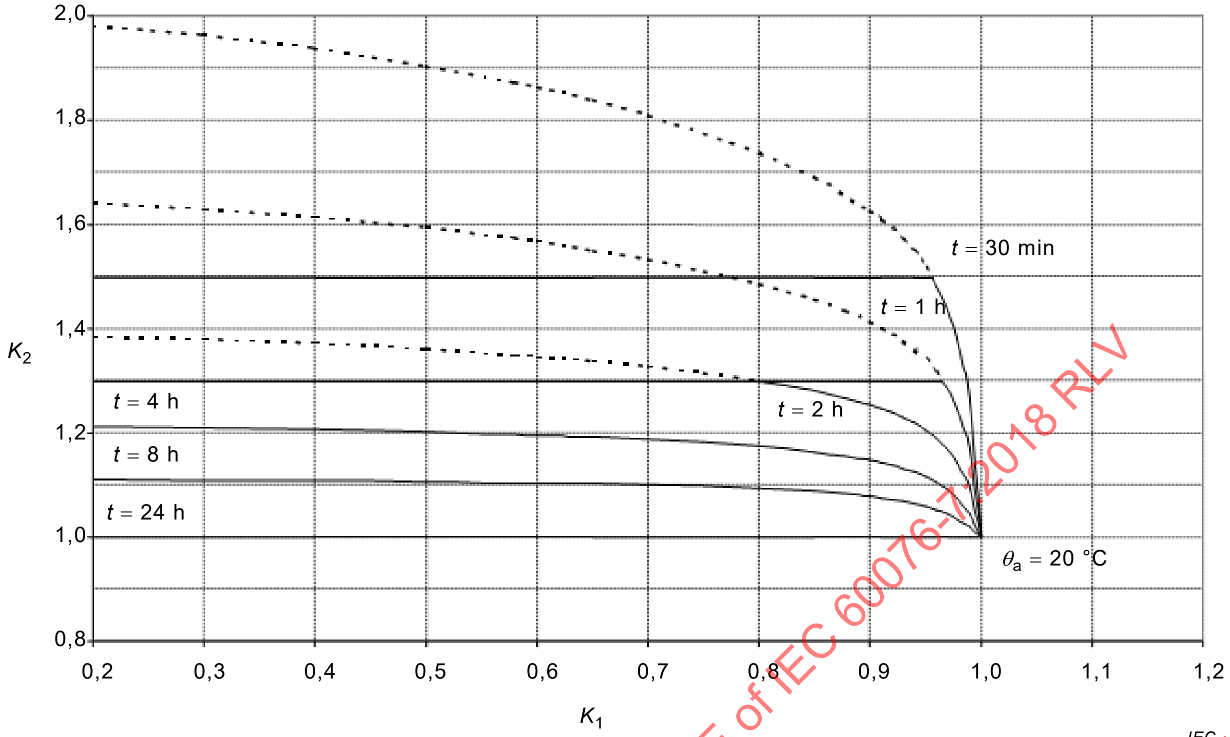
K_1	0,25	0,5	0,7	0,8	0,9	1,0	1,1	1,2	1,3	1,4	1,5
K_2											
0,7	0,001	0,004	0,02								
	33	38	45								
0,8	0,001	0,004	0,02	0,07							
	38	43	51	55							
0,9	0,001	0,004	0,03	0,07	0,25						
	43	49	56	61	66						
1,0	0,001	0,004	0,03	0,08	0,26	1,00					
	49	55	62	67	72	78					
1,1	0,001	0,01	0,03	0,08	0,27	1,04	4,48				
	56	61	68	73	78	84	91				
1,2	0,002	0,01	0,03	0,09	0,29	1,09	4,66	22,6			
	62	68	75	80	85	91	98	105			
1,3	0,004	0,01	0,04	0,11	0,33	1,19	4,94	23,6	128,9		
	69	75	82	87	92	98	105	112	120		
1,4	0,01	0,02	0,06	0,14	0,40	1,36	5,43	25,2	135,0	827,1	
	77	82	90	94	100	106	112	119	127	136	
1,5	0,01	0,03	0,10	0,21	0,55	1,71	6,34	28,0	144,9	868,7	5 975
	85	90	97	102	107	113	120	127	135	144	153
1,6	*0,03*	*0,06*	*0,18*	*0,37*	*0,87*	*2,44*	*8,19*	*33,3*	*162,7*	*938,3*	*6 297*
	93	*98*	*105*	*110*	*115*	*121*	*128*	*135*	*143*	*152*	*161*
1,7	*0,07*	*0,15*	*0,40*	*0,76*	*1,64*	*4,12*	*12,3*	*44,6*	*198,0*	*1 067*	*x*
	101	*107*	*114*	*119*	*124*	*130*	*137*	*144*	*152*	*161*	*x*
1,8	*0,18*	*0,37*	*0,94*	*1,73*	*3,55*	*8,24*	*22,1*	*70,5*	*275,2*	*x*	*x*
	110	*115*	*123*	*127*	*133*	*139*	*145*	*153*	*161*	*x*	*x*
1,9	*0,48*	*0,95*	*2,39*	*4,32*	*8,58*	*18,9*	*47,0*	*134,7*	*x*	*x*	*x*
	119	*125*	*132*	*137*	*142*	*148*	*154*	*162*	*x*	*x*	*x*
2,0	*1,34*	*2,61*	*6,45*	*11,5*	*22,5*	*48,1*	*x*	*x*	*x*	*x*	*x*
	129	*134*	*141*	*146*	*151*	*157*	*x*	*x*	*x*	*x*	*x*

Type of cooling OF, θ_a = 20 °C

Pre-load K_1, load K_2 during 30 min, load K_1 during 1410 min

NOTE The italic style values in Table K.2 show the results of the calculation, disregarding the limits from ~~Table 4~~ Table 2 and Table 3.

The data can also be presented in a graph. In Figure K.1, an example is given where K_2 is presented as a function of K_1 with a given overload time and unity loss of life.



NOTE The dotted lines show the results of the calculation, disregarding the limits from ~~Table 4~~ Table 2 and Table 3.

Figure K.1 – OF large power transformers: permissible duties for normal loss of life

Annex L
(informative)

Geomagnetic induced currents

L.1 Background

Transformers serve long distance lines and intermeshed power grids. In such systems geomagnetic induced currents (GIC) are possible as a consequence of solar magnetic disturbances like solar winds and sun spots. The varying geo-magnetic field causes a time varying DC current that flows from the grounded transformer neutral into the high voltage windings of the transformer, Figure L.1. The signature of this DC current depends on the magnitude and duration of the geo-magnetic field variation, the network topology and the earth conductivity. Moderate GIC levels in the range of several amperes which can last some days and high GIC peaks up to a few hundred amperes for only a few minutes are possible [53].

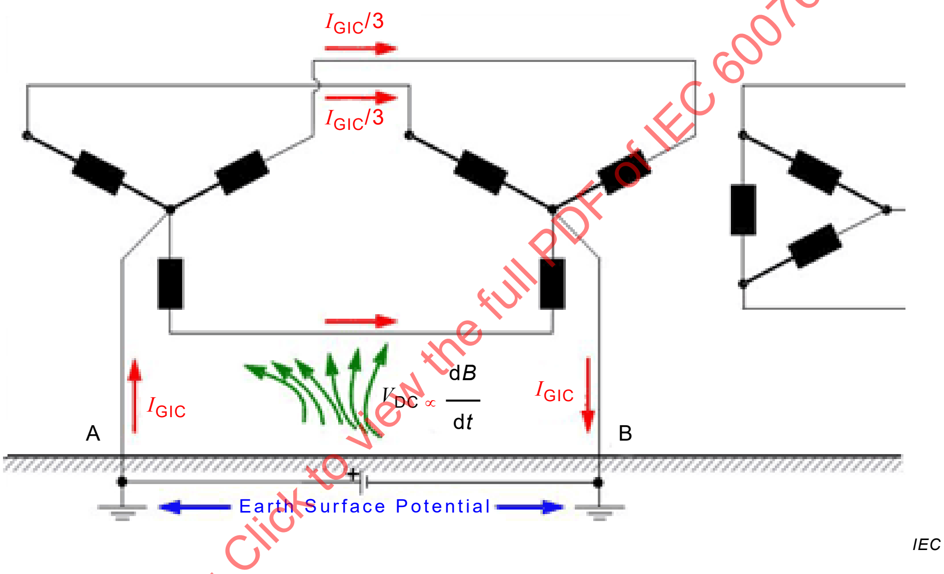


Figure L.1 – GIC flow into a power transformer

During the transformer operation the GIC causes a magnetic flux offset in addition to the alternating core flux. This leads to temporary unidirectional core saturation, once every exciting voltage cycle. The effects of this half cycle saturation are harmonics and additional reactive power consumption as well as increased transformer heating. This means that the transformer operates during a GIC event under an exceptional load condition.

L.2 GIC capability of power transformers [54], [55]

The capability of a power transformer to withstand GIC events depends on the transformer design. Single-phase units and transformers with 5-limb core designs are more vulnerable to DC currents whereas 3-limb core designs are less sensitive. The magnitude of the DC current is also not the sole influence parameter of the GIC sensitivity of a transformer. The number of DC-carrying transformer winding turns is very important. Therefore, the same DC magnitude can cause significantly different DC excitations in the core. Also, the core geometry and material have an influence. Measurements and calculations have shown that the location and magnitude of the hot-spot differ from the nominal loading condition of the transformer. Core-near structural parts like tie bars and clamping plates are most vulnerable to overheating and also the winding hot-spot temperature increase due to GIC. Therefore, the vendor should declare the behaviour of the transformer design under DC, if the unit is exposed to GIC in the power grid. To evaluate the thermal risk of the transformer design, the temperature limits of short and long time emergency loading in Table 2 can be used or if specified by customer different temperature limits can be applicable.

Annex M
(informative)

Alternative oils

Synthetic esters and natural esters have been used for some years now in power transformers [56] to [59]. There has been an attempt to use these oils at increasing voltages and power ratings, and there are some examples of these oils being used in high voltage and high power transformers. CIGRE Brochure 436 includes an overview of how these liquids are currently used, their properties, considerations that impinge on transformer designing and manufacturing, testing regimes, handling precautions and reliability [60]; however, this brochure was written in 2010 just as the market for alternative liquids was developing. Since the CIGRE Brochure 436 was published, IEC 62770:2013 [61] – a new standard for unused natural ester liquids for transformers – has been published. IEC 60076-14 further discusses the application of these oils in transformer design and considering among others their thermal characteristics and permissible temperatures, including suggested thermal limits when operated above nameplate rating. Moreover, a 50 MVA commercial transformer designed for mineral oil was comparatively tested by filling first with natural ester and then with mineral oil [62]. Some other ageing studies have been reported in references [63] to [65] and the corresponding bubbling phenomenon was presented in [66]. While inconclusive, these tests demonstrate the difference in the thermal performance that can be expected with these oils compared to mineral oil. Consequently, introduction of these oils in this document requires further continuous research activities to give reliable and prompt answers to their effect on the transformer design and service life.

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IEC 60076-7

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INTERNATIONAL STANDARD

colour inside

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

IEC 60076-7:2018-01(en)

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

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

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:

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

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	
$R_{\mathrm{r+1}}$	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
$\mathrm{tap}_{\mathrm{r}}$	Principal tapping position	
$\mathrm{tap}_{\mathrm{r+1}}$	Tapping position $r + 1$	
$\mathrm{tap}_{\mathrm{min}}$	Minimum tapping position	
$\mathrm{tap}_{\mathrm{max}}$	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
$\theta_{\mathrm{ma\text{-}max}}$	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
$\Delta\theta_{\mathrm{br}}$	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.

Voltages on both sides of the loaded transformer, therefore, are observed during loading beyond the nameplate rating. As long as voltages at the energized side of a loaded transformer remain below the limits stated in IEC 60076-1:2011 [5], Clause 4, no excitation restrictions are needed during the loading beyond nameplate rating. When higher excitations occur to keep the loaded voltage in emergency conditions in an area where the network can still be kept upright, then the magnetic flux densities in core parts never exceed values where straying of the core flux outside the core can occur (for cold-rolled grain-oriented steel these saturation effects start rapidly above 1,9 T). Stray fluxes may cause unpredictably high temperatures at the core surface and in nearby metallic parts such as winding clamps or even in the windings, due to the presence of high-frequency components in the stray flux. They may jeopardize the transformer. In general, in all cases, the short overload times dictated by windings are sufficiently short not to overheat the core at overexcitation. This is prevented by the long thermal time constant of the core.

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 come from the cumulative effect of thermal ageing of the insulation in the transformer over many years.

5.3 Effects and hazards of short-time emergency loading

Short-time increased loading will result in a service condition having an increased risk of failure. Short-time emergency overloading causes the conductor hot-spot to reach a level likely to result in a temporary reduction in the dielectric strength. However, acceptance of this condition for a short time may be preferable to loss of supply. This type of loading is expected to occur rarely, and it should be rapidly reduced or the transformer disconnected within a short time in order to avoid its failure. The permissible duration of this load is shorter than the thermal time constant of the whole transformer and depends on the operating temperature before the increase in loading; typically, it would be less than half-an-hour.

The main risk for short-time failures is the reduction in dielectric strength due to the possible presence of gas bubbles in a region of high electrical stress, that is the windings and leads. These bubbles are likely to occur when the hot-spot temperature exceeds 140 °C for a transformer with a winding insulation moisture content of about 2 %. This critical temperature will decrease as the moisture concentration increases.

NOTE Concerning the bubble generation, see also IEC 60076-14.

a) Gas bubbles can also develop (either in oil or in solid insulation) at the surfaces of heavy metallic parts heated by the leakage flux or be produced by super-saturation of the oil. However, such bubbles usually develop in regions of low electric stress and have to circulate in regions where the stress is higher before any significant reduction in the dielectric strength occurs.

   Bare metallic parts, except windings, which are not in direct thermal contact with cellulosic insulation but are in contact with non-cellulosic insulation (for example, aramid paper, glass fibre) and the oil in the transformer, may rapidly rise to high temperatures. A temperature of 180 °C should not be exceeded.

b) Temporary deterioration of the mechanical properties at higher temperatures could reduce the short-circuit strength.

c) Pressure build-up in the bushings may result in a failure due to oil leakage. Gassing in condenser type bushings may also occur if the temperature of the insulation exceeds about 140 °C.

d) The expansion of the oil could cause overflow of the oil in the conservator.

e) Breaking of excessively high currents in the tap-changer could be hazardous.

The limitations on the maximum hot-spot temperatures in windings, core and structural parts are based on considerations of short-term risks (see Clause 7).

The short-term risks normally disappear after the load is reduced to normal level, but they need to be clearly identified and accepted by all parties involved, e.g. planners, asset owners and operators.

5.4 Effects of long-time emergency loading

This is not a normal operating condition and its occurrence is expected to be rare but it may persist for weeks or even months and can lead to considerable ageing.

a) Deterioration of the mechanical properties of the conductor insulation will accelerate at higher temperatures. If this deterioration proceeds far enough, it may reduce the effective life of the transformer, particularly if the latter is subjected to system short circuits or transportation events.
b) Other insulation parts, especially parts sustaining the axial pressure of the winding block, could also suffer increased ageing rates at higher temperature.
c) The contact resistance of the tap-changers could increase at elevated currents and temperatures and, in severe cases, thermal runaway could take place.
d) The gasket materials in the transformer may become more brittle as a result of elevated temperatures.

The calculation rules for the relative ageing rate and per cent loss of life are based on considerations of long-term risks.

5.5 Transformer size

The sensitivity of transformers to loading beyond nameplate rating usually depends on their size. As the size increases, the tendency is that:

- the leakage flux density increases;
- the short-circuit forces increase;
- the mass of insulation, which is subjected to a high electric stress, is increased;
- the hot-spot temperatures are more difficult to determine.

Thus, a large transformer could be more vulnerable to loading beyond nameplate rating than a smaller one. In addition, the consequences of a transformer failure are more severe for larger sizes than for smaller units.

Therefore, in order to apply a reasonable degree of risk for the expected duties, this part of IEC 60076 considers three categories:

a) small transformers, for which only the hot-spot temperatures in the windings and thermal deterioration should be considered;
b) medium power transformers where the variations in the cooling modes should be considered;
c) large power transformers, where also the effects of stray leakage flux are significant and the consequences of failure are severe.

For hermetically sealed transformers without pressure relief devices the over pressure should be considered to avoid permanent tank deformation during loading beyond nameplate rating.

6 Relative ageing rate and transformer insulation life

6.1 General

For the manufacture of paper and pressboard for electrical insulation, mainly unbleached softwood kraft pulp is used. The cellulose is refined from the tree by the so-called “sulphate” or “kraft” process. After processing, the typical composition of unbleached kraft pulp is 78 % to 80 % cellulose, 10 % to 20 % hemicellulose and 2 % to 6 % lignin.

Cellulose is a linear condensation polymer consisting of anhydroglucose joined together by glycosidic bonds, Figure 1.

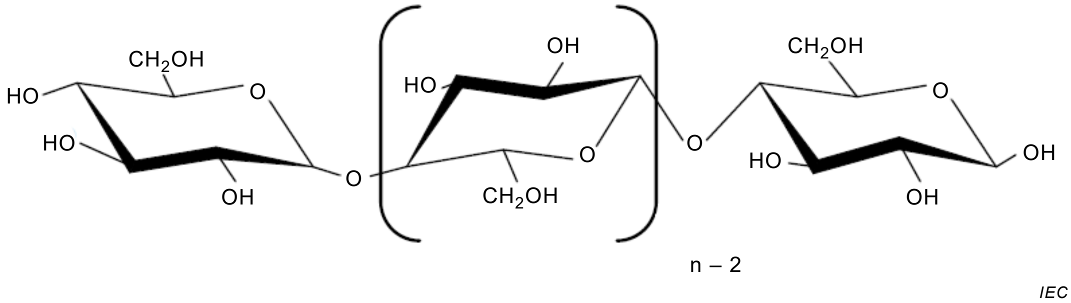


Figure 1 – Structural formula of cellulose

From kraft pulp various types of paper and pressboard having varying density are made. By adding various nitrogen containing compounds the ageing characteristics of the cellulose may be improved. Typical values for nitrogen content of thermally upgraded papers are between 1 % and 4 %. The purpose of thermally upgrading insulation paper is to neutralize the production of acids caused by the hydrolysis (thermal degradation) of the material over the lifetime of the transformer.

6.2 Insulation life

In recent years, extensive work on paper degradation has been carried out and published in references [9] to [15], indicating that cellulose ageing may be described by combination of the three processes, i.e. oxidation, hydrolysis and pyrolysis.

The oxidation is a process possibly dominant at lower temperature. The oxidizing agent in this environment is oxygen from air ingress, and as the ultimate end product of the process appears water. The hydrolysis of cellulose is a catalytically governed process where the rate of chain scissions depends on carboxylic acids dissociated in water. As both water and carboxylic acids are produced during ageing of cellulose this process is auto accelerating. The pyrolysis is a process that can take place without access to water and/or oxygen, or any other agent to initiate the decomposition. At normal operating or overload temperatures, (i.e. < 140 °C), such processes are considered to be of little relevance.

In a real transformer all these processes – hydrolysis, oxidation and pyrolysis – act simultaneously. This hampers the application of one model describing the full complexity of the degradation processes. Which process will dominate depends on the temperature and the condition (i.e. oxygen, water and acid content).

Different parameters might be used to characterize cellulose degradation process during ageing. In reality it is the mechanical strength that is important for the winding paper to resist the shear stresses occurring during short circuits. However, due to the folded geometry of paper in a transformer, it is not possible to analyse tensile strength of paper sampled from used transformers. Hence, it is more convenient to characterize the degree of polymerization (DP) in order to describe the state of an insulation paper. Figure 2 shows a typical correlation between tensile strength and DP value (see [11]), the same correlation is valid for the thermally upgraded and non-thermally upgraded paper.

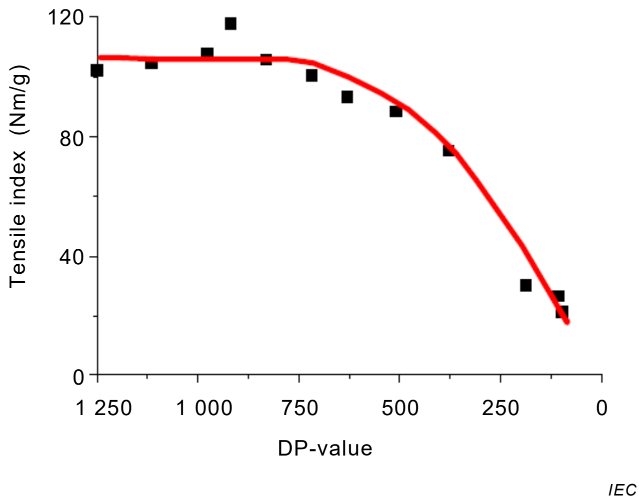


Figure 2 – Correlation between tensile strength and DP value

The degree of polymerization (DP) is the average number (n) of glycosidic rings in a cellulose macromolecule, which ranges between 1 100 and 1 400 for unbleached soft wood kraft before processing. Depending on the transformer drying process, the DP value may be reduced further to a lesser or higher degree. During ageing, the lengths of these polymeric cellulose molecules are reduced due to breakage of the covalent bonds between the anhydrous-β-glucose monomers. The change of DP over time of non-thermally and thermally upgraded paper exposed to a temperature of 140 °C, oxygen of $<$ 6 000 ppm and water of 0,5 % is shown in Figure 3 (see [15]). The nitrogen content of the thermally upgraded paper used in this experiment was 1,8 %.

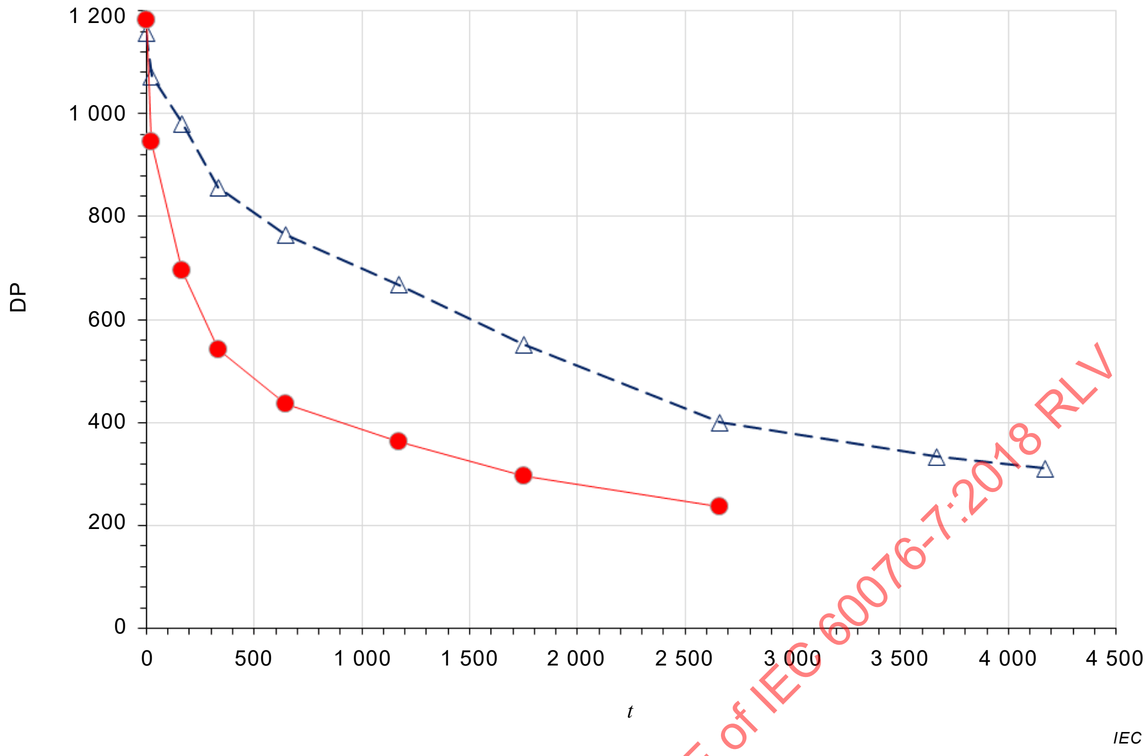
When the DP is reduced to 200 % or 35 % retained tensile strength, the quality of the paper (i.e. the mechanical strength) is normally considered so poor that this defines the "end of life" for such insulating material (see [11]), although the insulating material dielectric strength may be still at an acceptable level.

Annex A gives further elaboration of the paper ageing theory providing a mathematical methodology for estimation of the expected insulation life considering different ageing factors such as moisture, oxygen and temperature. The corresponding results for the non-thermally and thermally upgraded paper are presented in Figure 4 and Figure 5, respectively.

The illustrated difference in thermal ageing behaviour has been taken into account in industrial standards as follows:

- The relative ageing rate V = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and 110 °C for thermally upgraded paper.

NOTE 1 Disagreement between laboratory tests could come from testing procedures. It is difficult to reproduce the same ageing process with accelerated ageing often at quite elevated temperatures compared to service conditions. The values given in Table A.2, Figure 4 and Figure 5 are considered as unconfirmed and can be disputable. However, the numbers give a user the possibility to simulate different ageing scenarios.



Key

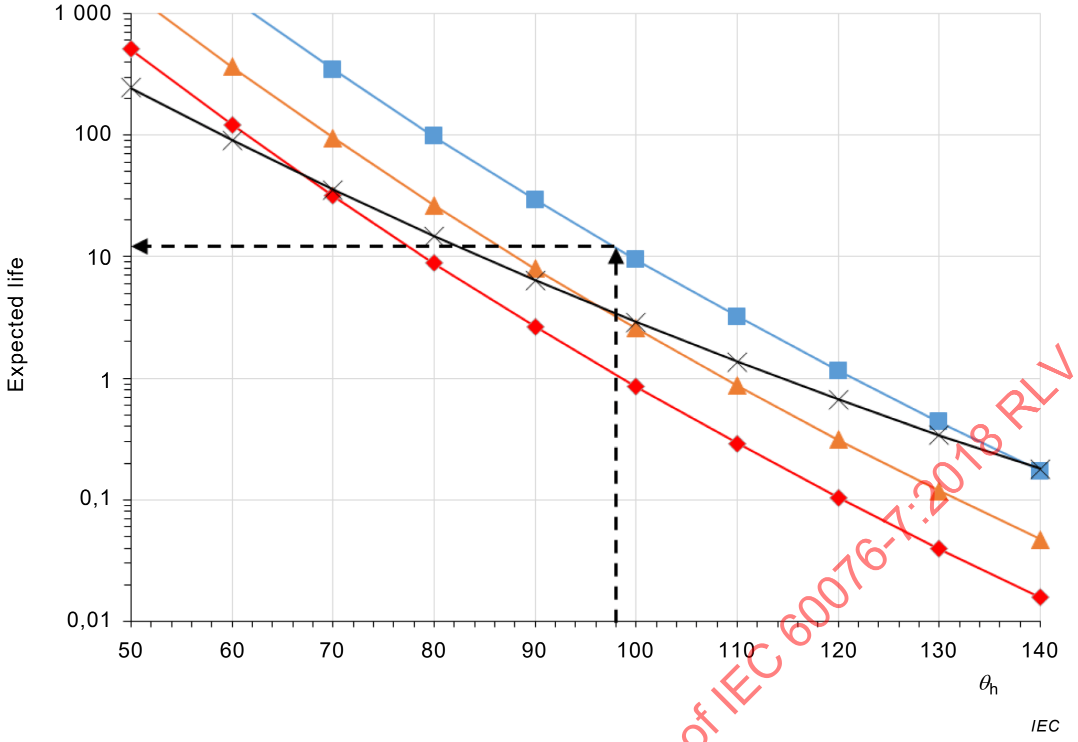
DP degree of polymerization

t time (h)

Δ values for thermally upgraded paper

● values for non-thermally upgraded paper

Figure 3 – Accelerated ageing in mineral oil at 140 °C, oxygen and moisture contents maintained at < 6000 ppm and 0,5 %, respectively



Key

expected life (years)

θ_h hot-spot temperature (°C)

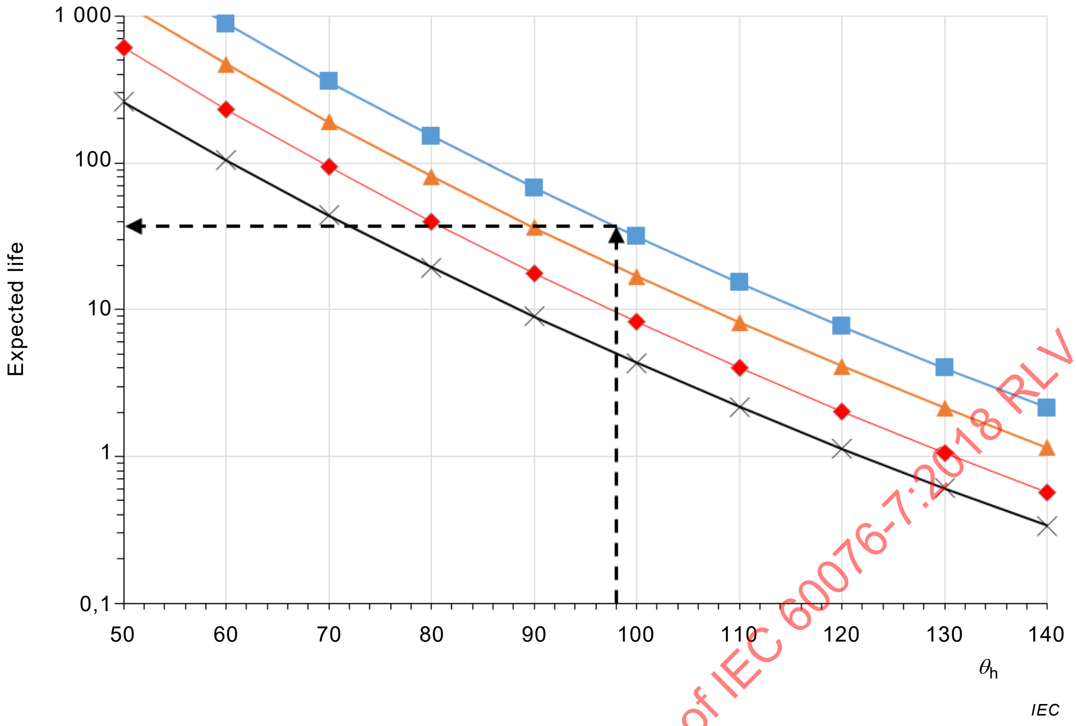
□ 0,5 % moisture, low oxygen

Δ 1,5 % moisture, low oxygen

◊ 3,5 % moisture, low oxygen

× 0,5 % moisture, high oxygen

Figure 4 – Expected life for non-thermally upgraded paper and its dependence upon moisture, oxygen and temperature



Key

expected life (years)

θ_h hot-spot temperature (°C)

□ 0,5 % moisture, low oxygen

Δ 1,5 % moisture, low oxygen

◊ 3,5 % moisture, low oxygen

× 0,5 % moisture, high oxygen

Figure 5 – Expected life for thermally upgraded paper and its dependence upon moisture, oxygen and temperature

NOTE 2 Figure 4 and Figure 5 indicate expected life values that are based on residual DP value of 200, and that are derived under the laboratory controlled condition as given in text above, (e.g. constant moisture content, constant and homogenous temperature, etc.). However, to evaluate the expected life of a transformer the real service conditions are considered (e.g. loading history and prediction, ambient temperature, insulation material and insulation moisture contamination). The moisture contamination estimate is usually based on the corresponding equilibrium curves for moisture partition between oil and paper, (e.g. WCO vs WCP or RH vs WCP).

6.3 Relative ageing rate

Although ageing or deterioration of insulation is a time function of temperature, moisture content, oxygen content and acid content, the model presented in this document is based only on the insulation temperature as the controlling parameter.

An example of how all ageing parameters can be taken into account is given in Annex A.

Since the temperature distribution is not uniform, the part that is operating at the highest temperature will normally undergo the greatest deterioration. Therefore, the rate of ageing is referred to the winding hot-spot temperature. In this case, the relative ageing rate V is defined according to Equation (2) for non-thermally upgraded paper and to Equation (3) for thermally upgraded paper (see [27]).

$$V = 2^{(\theta_h - 98)/6} \quad (2)$$

$$V = e^{\left(\frac{15\ 000}{110+273} - \frac{15\ 000}{\theta_h + 273}\right)} \quad (3)$$

where

θ_h is the hot-spot temperature in °C.

Equations (2) and (3) imply that V is very sensitive to the hot-spot temperature as can be seen in Table 1.

Table 1 – Relative ageing rates due to hot-spot temperature

θ_h °C	**Non-upgraded paper insulation** V	**Upgraded paper insulation** V
80	0,125	0,036
86	0,25	0,073
92	0,5	0,145
98	**1,0**	0,282
104	2,0	0,536
110	4,0	**1,0**
116	8,0	1,83
122	16,0	3,29
128	32,0	5,8
134	64,0	10,1
140	128,0	17,2
The indicated relative ageing rate V = 1,0 corresponds to a temperature of 98 °C for non-thermally upgraded paper and 110 °C for thermally upgraded paper.		

6.4 Loss-of-life calculation

The loss of life L over a certain period of time is equal to

$$L = \int_{t_1}^{t_2} V \, \mathrm{d}t \quad \text{or} \quad L \approx \sum_{n=1}^{N} V_n \times t_n \tag{4}$$

where

V_n is the relative ageing rate during interval n, according to Equation (2) or (3);

t_n is the nth time interval;

n is the number of each time interval;

N is the total number of intervals during the period considered.

The maximum time interval should be less than half the smallest time constant, τ_w, in Equation (4) for an accurate solution.

7 Limitations

7.1 Temperature limitations

With loading values beyond the nameplate rating, none of the individual limits stated in Table 2 should be exceeded and account should be taken of the specific limitations given in 7.3 to 7.5.

The limits given in Table 2 are applicable to transformers specified to have temperature rise requirements according to IEC 60076-2. For transformers specified according to IEC 60076-14, with a higher thermal class insulation materials, the limits given in IEC 60076-14 apply.

Table 2 – Maximum permissible temperature limits applicable to loading beyond nameplate rating

Types of loading	Small transformers	Large and medium power transformers
Normal cyclic loading		
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	120	120
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)	140	140
Inner core hot-spot temperature (°C)	130	130
Top-oil temperature, in tank (°C)	105	105
Long-time emergency loading		
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	140	140
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass-fibre materials) (°C)	160	160
Inner core hot-spot temperature (°C)	140	140
Top-oil temperature, in tank (°C)	115	115
Short-time emergency loading		
Winding hot-spot temperature and metallic parts in contact with cellulosic insulation material (°C)	See 7.3.1	160
Other metallic hot-spot temperature (in contact with oil, aramid paper, glass fibre materials) (°C)	See 7.3.1	180
Inner core hot-spot temperature (°C)	See 7.3.1	160
Top-oil temperature, in tank (°C)	See 7.3.1	115
NOTE For more information on the core temperature, see Annex B.		

7.2 Current limitations

There are limitations on current carrying capability of transformer other than temperature limits given in Table 2, and these are described in 7.3 to 7.5. Therefore, it is recommended that the current limits given in Table 3 are not exceeded even if the circumstances of the overload mean that the temperatures in Table 2 are not exceeded. Specific examples would be in cases of low ambient temperature, low levels of preload or high thermal capacity of the winding. The purchaser can specify higher current limits if required, but it should be recognized that this could lead to a special transformer design. The recommended current limits given in Table 3 should not apply to very short duration overloads, i.e. less than 10 s.

NOTE 1 The breaking capacity of tap-changers is limited to twice the rated current according to IEC 60214-1 [3].

Table 3 – Recommended current limits applicable to loading beyond nameplate rating

Types of loading	Small transformers	Medium power transformers	Large power transformers
Normal cyclic loading			
Current (p.u.)	1,5	1,5	1,3
Long-time emergency loading			
Current (p.u.)	1,8	1,5	1,3
Short-time emergency loading			
Current (p.u.)	2,0	1,8	1,5

NOTE 2 For specification beyond rated power, see Annex C.

7.3 Specific limitations for small transformers

7.3.1 Current and temperature limitations

The limits on load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than windings and leads stated in Table 2 and Table 3 should not be exceeded. No limit is set for the top-oil, core and winding hot-spot temperature under short-time emergency loading for distribution transformers because it is usually impracticable to control the duration of emergency loading in this case. It should be noted that when the hot-spot temperature exceeds 140 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 5.3).

7.3.2 Accessory and other considerations

Apart from the windings, other parts of the transformer, such as bushings, cable-end connections, tap-changing devices and leads may restrict the operation when loaded above 1,5 times the rated current. Oil expansion and oil pressure could also impose restrictions.

7.3.3 Indoor transformers

When transformers are used indoors, a correction should be made to the rated top-oil temperature rise to take account of the enclosure. Preferably, this extra temperature rise will be determined by a test (see 8.3.2).

7.3.4 Outdoor ambient conditions

Wind, sunshine and rain may affect the loading capacity of distribution transformers, but their unpredictable nature makes it impracticable to take these factors into account.

7.4 Specific limitations for medium power transformers

7.4.1 Current and temperature limitations

The load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than windings and leads should not exceed the limits stated in Table 2 and Table 3. Moreover, it should be noted that, when the hot-spot temperature exceeds 140 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 5.3).

7.4.2 Accessory, associated equipment and other considerations

Apart from the windings, other parts of the transformer, such as bushings, cable-end connections, tap-changing devices and leads, may restrict the operation when loaded above

1,5 times the rated current. Oil expansion and oil pressure could also impose restrictions. Consideration may also have to be given to associated equipment such as cables, circuit breakers, current transformers, etc.

7.4.3 Short-circuit withstand requirements

During or directly after operation at load beyond nameplate rating, transformers can not conform to the thermal short-circuit requirements, as specified in IEC 60076-5 [67], which are based on a short-circuit duration of 2 s. However, the duration of short-circuit currents in service is shorter than 2 s in most cases.

7.4.4 Voltage limitations

Unless other limitations for variable flux voltage variations are known (see IEC 60076-1), the applied voltage should not exceed 1,05 times either the rated voltage (principal tapping) or the tapping voltage (other tappings) on any winding of the transformer.

7.5 Specific limitations for large power transformers

7.5.1 General

For large power transformers, additional limitations, mainly associated with the leakage flux, should be taken into consideration. It is therefore advisable in this case to specify, at the time of enquiry or order, the amount of loading capability needed in specific applications.

As far as thermal deterioration of insulation is concerned, the same calculation method applies to all transformers.

According to present knowledge, the importance of the high reliability of large units in view of the consequences of failure, together with the following considerations, make it advisable to adopt a more conservative, more individual approach here than for smaller units.

- The combination of leakage flux and main flux in the limbs or yokes of the magnetic circuit (see 5.2) makes large transformers more vulnerable to overexcitation than smaller transformers, especially when loaded above nameplate rating. Increased leakage flux may also cause additional eddy-current heating of other metallic parts.
- The consequences of degradation of the mechanical properties of insulation as a function of temperature and time, including wear due to thermal expansion, may be more severe for large transformers than for smaller ones.
- Hot-spot temperatures outside the windings cannot be obtained from a normal temperature-rise test. Even if such a test at a rated current indicates no abnormalities, it is not possible to draw any conclusions for higher currents since this extrapolation may not have been taken into account at the design stage.
- Calculation of the winding hot-spot temperature rise at higher than rated currents, based on the results of a temperature-rise test at rated current, may be less reliable for large units than for smaller ones.

7.5.2 Current and temperature limitations

The load current, hot-spot temperature, top-oil temperature and temperature of metallic parts other than windings and leads but nevertheless in contact with solid insulating material should not exceed the limits stated in Table 2 and Table 3. Moreover, it should be noted that, when the hot-spot temperature exceeds 140 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 5.3).

7.5.3 Accessory, equipment and other considerations

Refer to 7.4.2.

7.5.4 Short-circuit withstand requirements

Refer to 7.4.3.

7.5.5 Voltage limitations

Refer to 7.4.4.

8 Determination of temperatures

8.1 Hot-spot temperature rise in steady state

8.1.1 General

To be strictly accurate, the hot-spot temperature should be referred to the adjacent oil temperature. This is assumed to be the top-oil temperature inside the winding. Measurements have shown that the top-oil temperature inside a winding might be, dependent on the cooling, up to 15 K higher than the mixed top-oil temperature inside the tank.

For most transformers in service, the top-oil temperature inside a winding is not precisely known. On the other hand, for most of these units, the top-oil temperature at the top of the tank is well known, either by measurement or by calculation.

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

- $\Delta\theta_{\text{or}}$, the top-oil temperature rise in the tank above ambient temperature at rated losses [K];
- $\Delta\theta_{\text{hr}}$, the hot-spot temperature rise above top-oil temperature in the tank at rated current [K].

The parameter $\Delta\theta_{\text{hr}}$ can be defined either by direct measurement during a heat-run test or by a calculation method validated by direct measurements.

NOTE The methods, principles and calculation procedures given in 8.1.2, 8.1.3, 8.1.4 and Annex D are ultimately valid for the converter transformers for HVDC application, however, with the necessary consideration of the effect of harmonics on the transformer thermal performance with a reference to a specific converter operating point and specific system conditions.

8.1.2 Calculation of hot-spot temperature rise from normal heat-run test data

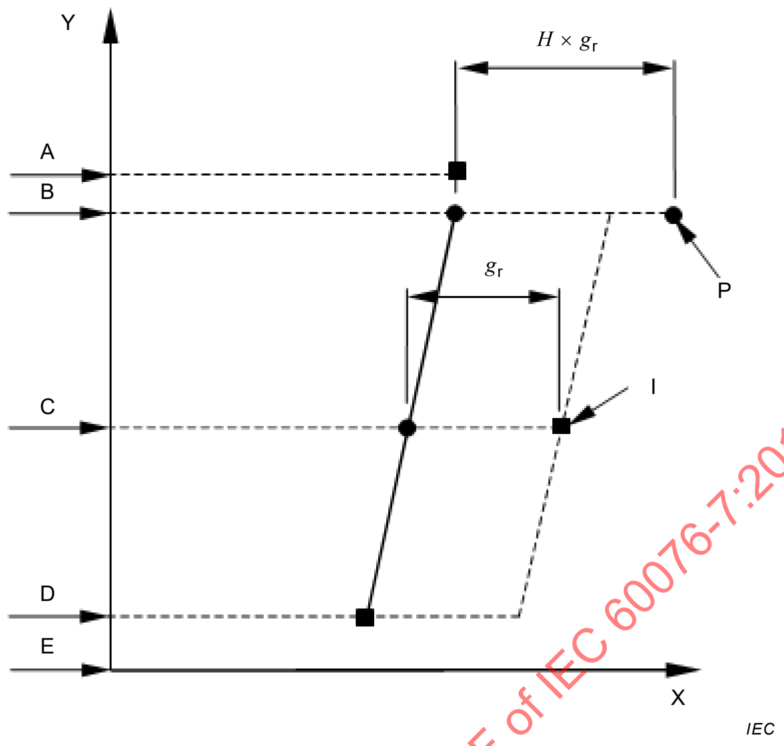
A thermal diagram is assumed, as shown in Figure 6, on the understanding that such a diagram is the simplification of a more complex distribution. The assumptions made in this simplification are as follows.

a) The oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode.

b) As a first approximation, the temperature rise of the conductor at any position up the winding is assumed to increase linearly, parallel to the oil temperature rise, with a constant difference g_{r} between the two straight lines (g_{r} being the difference between the winding average temperature rise by resistance and the average oil temperature rise in the tank).

c) The hot-spot temperature rise is higher than the temperature rise of the conductor at the top of the winding as described in 8.1.2 b), because allowance has to be made for the increase in stray losses, for differences in local oil flows and for possible additional paper on the conductor. To take into account these non-linearities, the difference in temperature between the hot-spot and the top-oil in tank is made equal to $H \times g_{\text{r}}$, that is, $\Delta\theta_{\text{hr}} = H \times g_{\text{r}}$.

   NOTE In many cases, it has been observed that the temperature of the tank outlet oil is higher than that of the oil in the oil pocket. In such cases, the temperature of the tank outlet oil is used for loading.



Key

A Top-oil temperature derived as the average of the tank outlet oil temperature and the tank oil pocket temperature

B Mixed oil temperature in the tank at the top of the winding (often assumed to be the same temperature as A)

C Temperature of the average oil in the tank

D Oil temperature at the inlet of the tank (assumed to be the same as at the bottom of the winding)

E Bottom of the tank

g_r Average winding to average oil (in tank) temperature gradient at rated current

H Hot-spot factor

P Hot-spot temperature

I Average winding temperature determined by resistance measurement

x-axis Temperature

y-axis Relative positions

■ measured point; ● calculated point

Figure 6 – Thermal diagram

8.1.3 Direct measurement of hot-spot temperature rise

Fibre optic probes are installed in windings to measure the hot-spot temperature rise. Although local loss densities and oil circulation speeds are calculated, it is very difficult to know where the hot-spot is exactly located. Thus, a certain minimum number of sensors should be installed in a winding. The sensors are inserted in slots in the radial spacers in such a way that there is only the conductor insulation and an additional thin paper layer between the sensor and the conductor metal. Calibrations have shown that a reasonable accuracy is obtained in this way (see [16]).

This minimum number of sensors is selected in such a way that the maximum measured temperature rise is close enough to the real hot-spot temperature rise for a safe operation of the winding. This maximum measured temperature is at the same time considered as the hot-spot of the winding.

In core type transformers the hot-spot is generally located at the top of the windings. If the winding is cooled by axial oil circulation, the most probable location is disc number 1 or 2 seen from the top. At zig-zag cooling one of the first 3 top discs is the most probable location. If the winding has tapping discs at its upper half, the hot-spot is probably located in the first current carrying disc above the currentless tapping discs in the (-) tap position. Therefore, it should be noted that the hot-spot location is transformer specific and highly affected by the transformer design. As such, this predetermined location should be discussed during design review.

Experience has shown that there might be gradients of more than 10 K between different sensors in the top of a normal transformer winding. Hence, it is not self-evident that the insertion of, for example, one or two sensors will detect a relevant temperature rise. An example of this is shown in Figure 7 [17]. The relative local loss densities compared to the average loss of the winding (which corresponded to the average winding gradient g) were 156 %, 133 %, etc. The figures indicated in the discs at the right (114 %, 142 %, 156 %, etc.) are the relative local loss densities in per cent of the average loss density of the whole winding that is the total loss of the winding divided by the number of discs. It should be noted that the highest temperature rise of 23,2 K was measured at the relative loss density 117 %, which was far from the highest value 156 %.

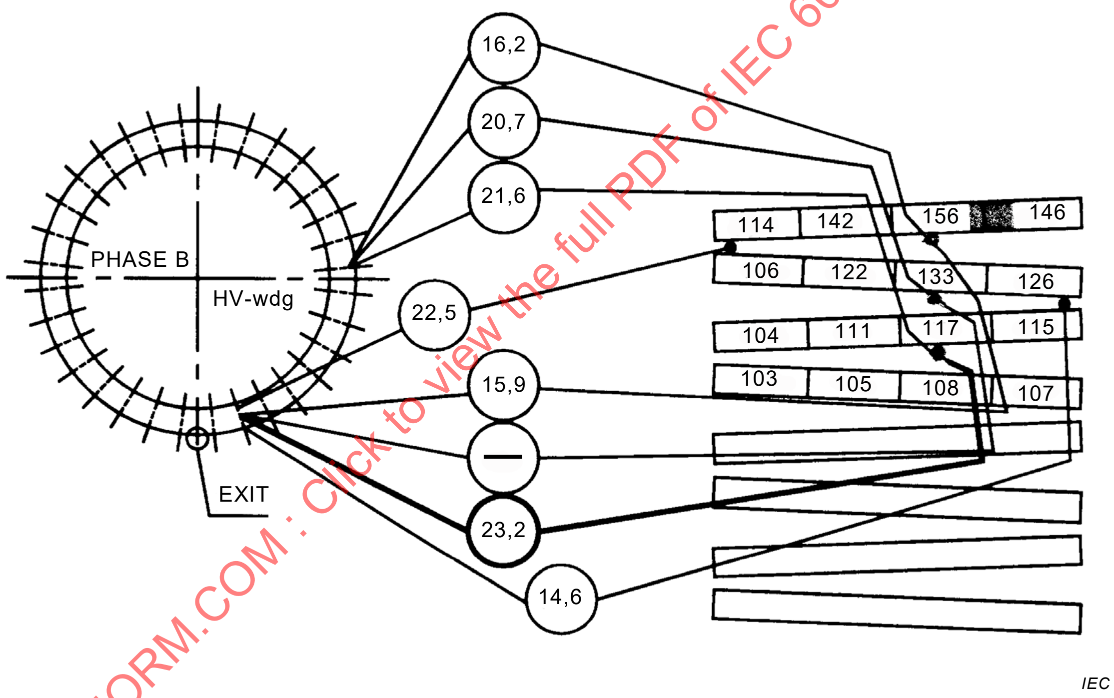


Figure 7 – Temperature rises above top-oil temperature (in tank) 65,8 °C of the zig-zag cooled HV-winding of a 400 MVA ONAF cooled 3-phase transformer, load current 1,0 p.u., tap position (-)

For the temperature rise test, the recommended number of sensors to be installed in one phase of ON-, OF-, OD-cooled core type transformers are as follows:

a) for transformers with a leakage flux ≥ 400 mWb/phase at the rated current, the number of sensors should be 8 per winding with full rating;

b) for transformers with a leakage flux between 150 mWb/phase and 400 mWb/phase at the rated current, the number of sensors should be 6 per winding;

c) for transformers with a leakage flux below 150 mWb/phase at the rated current, the number of sensors should be 4 per winding.

The sensors should be installed in the phase for which the warm resistance curve is recorded. However, each user should decide how accurate the hot-spot measurement needs to be for a particular transformer application (loaded tertiary winding, small transformers, etc.), and based on this should decide on the total sensor number per winding and per phase.

NOTE By leakage flux is here meant the maximum unidirectional flux (crest value), which is the integral of the absolute values of the axial flux densities between two intersections with the x-axis. A transformer might have several such integrals and in this case the maximum of these integrals is considered. An approximate formula for this maximum leakage flux is $1{,}8 \times Z \times S^{0{,}5}$ [18], where Z is the short-circuit impedance in per cent and S is the intrinsic rated power per wound limb in MVA. For auto-connected transformers, Z and S refer to the intrinsic MVA value and not to the MVA transformed. S is therefore equal to the nameplate rated power, multiplied by α, i.e. the auto factor. The auto factor, α, is equal to: (primary voltage – secondary voltage) / primary voltage. Z is equal to the nameplate short-circuit impedance divided by the auto factor.

EXAMPLE For single-phase 550/230 kV auto-connected transformer with the throughput rating S = 334 MVA, the corresponding impedance Z = 15 %, and the auto factor α = (550 − 230)/550 = 0,58, the leakage flux is approximately $[1{,}8 \times (0{,}58 \times 334)^{0{,}5} \times (15/0{,}58)]$ = 650 mWb.

In shell type transformers, the fibre optic sensors should be located in the coil edges (Figure 8) and in the brazed connections between coils.

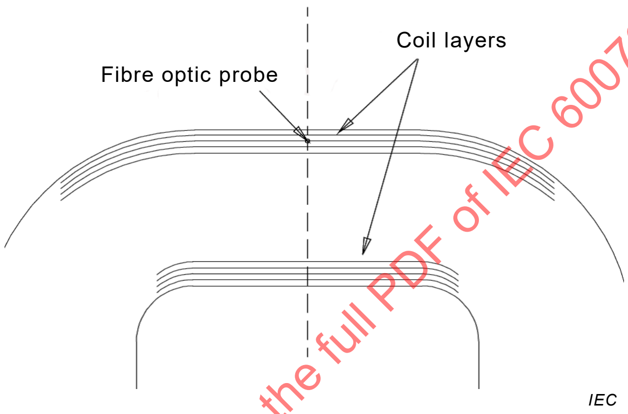


Figure 8 – Coil edges, where the sensors should be located in the edge with the higher calculated temperature rise

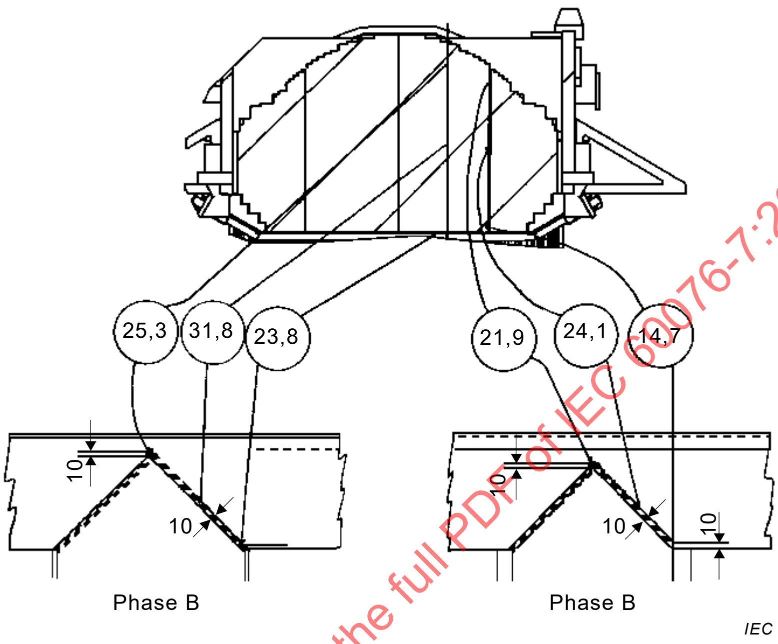
If it is not possible to install the fibre optic sensor in the expected hot-spot location, for example due to high voltage stress, then the installation can be made at a safer location. Consequently, the proposed alternative measuring location and the corresponding correction procedure should be further discussed between purchaser and manufacturer.

Although Table 2 comprises temperature limits for core and structural parts, such temperature rises are not measured in a normal temperature rise test. Those temperature rises are normally estimated by calculation. The manufacturers should install thermal sensors in these parts in selected transformers to calibrate their calculation methods. Manufacturers of fibre optic probes are producing insulation kits for this purpose, but also robust thermocouples or RTDs offer a good alternative. The thermocouples can be installed permanently in the transformer in such a way that they do not reduce the voltage strength and that they remain inside the transformer during its life. Thermocouples inside a transformer should be twisted to eliminate the effect of leakage flux impinging between the two thermocouple strands and causing an extra induced voltage between the two thermocouple metals. If specified such special test (i.e. the temperature rise of the core and structural part during the no-load test) should be discussed during the design review and the following parameters should be defined:

– cooling conditions;
– test duration;
– supply voltage;
– temperature limits.

Thermal sensors should particularly be installed in:

a) yoke clamp made of magnetic steel, e.g. winding supports, supports for exit leads, yoke clamp extensions at the end of cores with wound outer limbs, and in yoke clamps opposite to the centre line of a phase;
b) flitch-plates and outer core packets opposite to the top of the winding block;
c) in the top yoke, particularly at the top of the centre phase in a 3-phase transformer (Figure 9).



NOTE The three right-hand values are measured in the cooling duct.

Figure 9 – Temperature rises above top-oil temperature at the end of an 8 h thermal no-load test at 110 % supply voltage

Installation of sensors in the top yoke makes sense only if an extra thermal no-load test is done.

More details about the installation of thermal sensors are given in [18].

8.1.4 Hot-spot factor

The hot-spot factor H is winding-specific and should be determined on a case-by-case basis when required. Studies show that the factor H varies within the ranges 1,0 to 2,1 depending on the transformer size, its short-circuit impedance and winding design [19]. The factor H should be defined either by direct measurement (see 8.1.3 and Annex D) or by a calculation procedure based on fundamental loss and heat transfer principles, and substantiated by direct measurements on production or prototype transformers or windings.

A calculation procedure based on fundamental loss and heat transfer principles should consider the following as given in Annex D, [18], and [20].

a) The fluid flow within the winding ducts, the heat transfer, flow rates and resulting fluid temperature should be modelled for each cooling duct.
b) The distribution of losses within the winding. One of the principal causes of extra local loss in the winding conductors is radial flux eddy loss at the winding ends, where the leakage flux intercepts the wide dimension of the conductors. The total losses in the subject conductors should be determined using the eddy and circulating current losses in

addition to the DC resistance loss. Connections that are subject to leakage flux heating, such as coil-to-coil connections and some tap-to-winding brazes, should also be considered.

c) Conduction heat transfer effects within the winding caused by the various insulation thicknesses used throughout the winding.

d) Local design features or local fluid flow restrictions.

- Layer insulation may have a different thickness throughout a layer winding, and insulation next to the cooling duct affects the heat transfer.
- Flow-directing washers reduce the heat transfer into the fluid in the case of a zigzag-cooled winding (Figure 10).

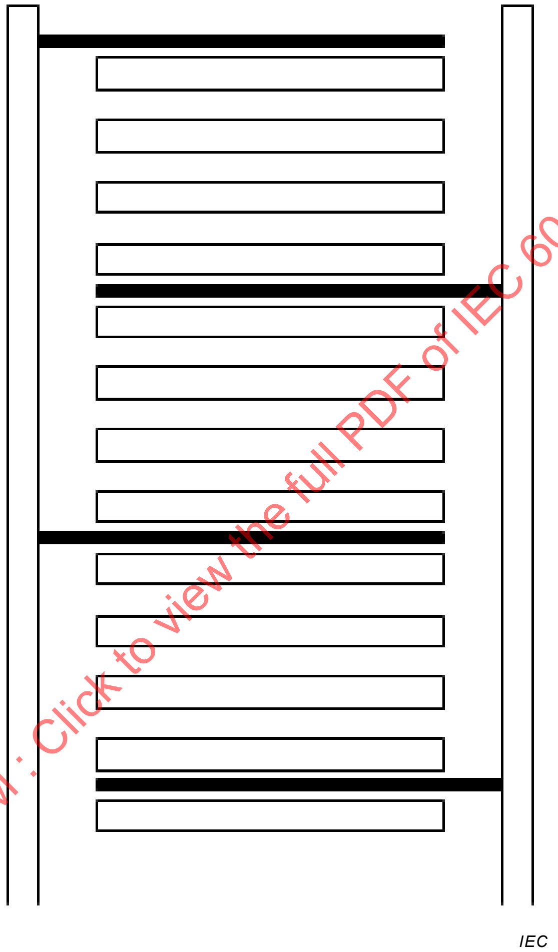


Figure 10 – Zigzag-cooled winding where the distance between all sections is the same and the flow-directing washer is installed in the space between sections

- Possible extra insulation on end turns and on winding conductors exiting through the end insulation.
- Not all cooling ducts extend completely around the winding in distribution transformers and small power transformers. Some cooling ducts are located only in the portion of the winding outside the core (see Figure 11). Such a “collapsed duct arrangement” causes a circumferential temperature gradient from the centre of the winding with no ducts under the yoke to the centre of the winding outside core where cooling ducts are located.

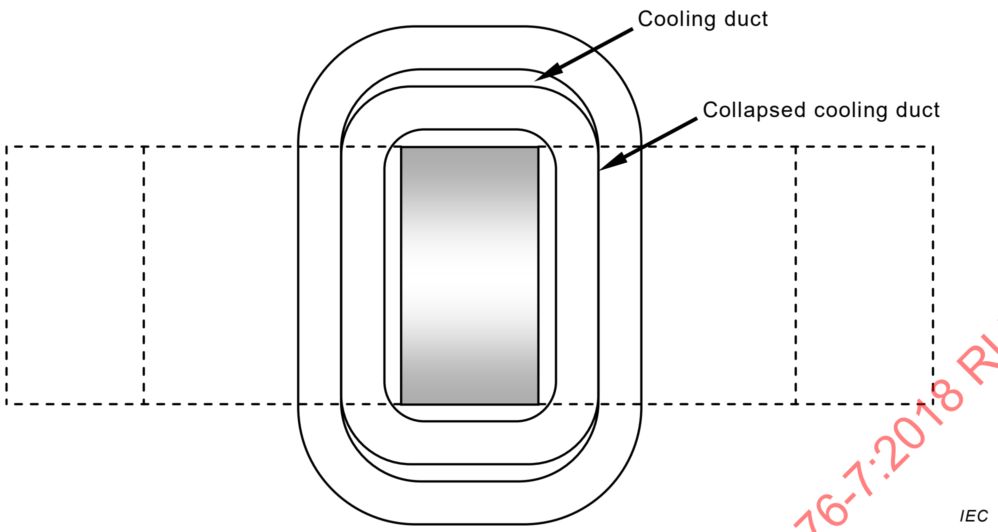


Figure 11 – Top view section of a rectangular winding with "collapsed cooling duct arrangement" under the yokes

8.2 Top-oil and hot-spot temperatures at varying ambient temperature and load conditions

8.2.1 General

Subclause 8.2 provides two alternative ways of describing the hot-spot temperature as a function of time, for varying load current and ambient temperature:

a) exponential equations solution [18], [21];

b) difference equations solution [22].

Both of these methods are suitable for arbitrarily time-varying load factor K and time-varying ambient temperature θ_a. The former method is particularly more suited to determination of the heat transfer parameters by test, especially by manufacturers, while the latter method is more suitable for on-line monitoring due to applied mathematical transformation. In principle, both methods yield the same results as they represent solution variation to the identical heat transfer differential equations.

The heat transfer differential equations are represented in block diagram form in Figure 12.

Observe in Figure 12 that the inputs are the load factor K, and the ambient temperature θ_a on the left. The output is the calculated hot-spot temperature θ_h on the right. The Laplace variable s is essentially the derivative operator d/dt.

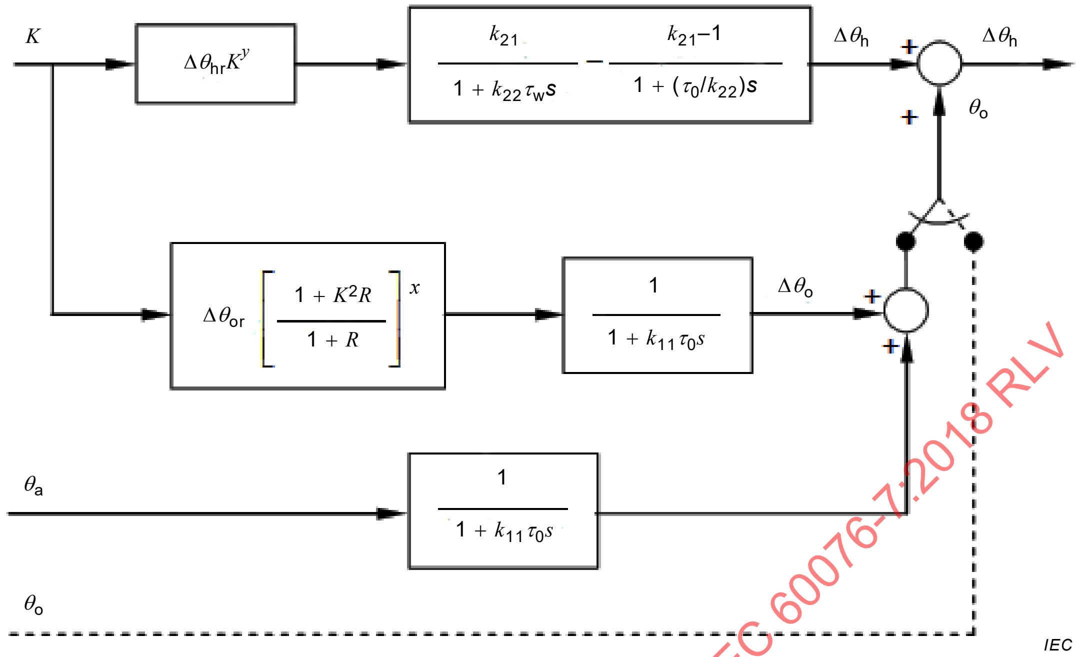


Figure 12 – Block diagram representation of the differential equations

In Figure 12, the second block in the uppermost path represents the hot-spot rise dynamics. The first term (with numerator k_{21}) represents the fundamental hot-spot temperature rise, before the effect of changing oil flow past the hot-spot is taken into account. The second term (with numerator $k_{21}-1$) represents the varying rate of oil flow past the hot-spot, a phenomenon which changes much more slowly. The combined effect of these two terms is to account for the fact that a sudden rise in load current may cause an otherwise unexpectedly high peak in the hot-spot temperature rise, very soon after the sudden load change. Values for k_{11}, k_{21}, k_{22} and the other parameters shown are discussed in 8.2.2 and suggested values given in Table 4.

If the top-oil temperature can be measured as an electrical signal into a computing device, then an alternative formulation is the dashed line path, with the switch in its right position; the top-oil calculation path (switch to the left) is not required. All of the parameters have been defined in 8.2.2.

The mathematical interpretation of the blocks in Figure 12 is given as follows:

The differential equation for top-oil temperature (inputs K, θ_a, output θ_o) is

$$\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) = k_{11}\tau_o \times \frac{d\theta_o}{dt} + [\theta_o - \theta_a] \quad (5)$$

The differential equation for hot-spot temperature rise (input K, output $\Delta\theta_h$) is most easily solved as the sum of two differential equation solutions, where

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \quad (6)$$

The two equations are

$$k_{21} \times K^{y} \times (\Delta\theta_{hr}) = k_{22} \times \tau_{w} \times \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \tag{7}$$

and

$$(k_{21} - 1) \times K^{y} \times (\Delta\theta_{hr}) = (\tau_{o} / k_{22}) \times \frac{d\Delta\theta_{h2}}{dt} + \Delta\theta_{h2} \tag{8}$$

the solutions of which are combined in accordance with Equation (6).

The final equation for the hot-spot temperature is

$$\theta_{h} = \theta_{o} + \Delta\theta_{h} \tag{9}$$

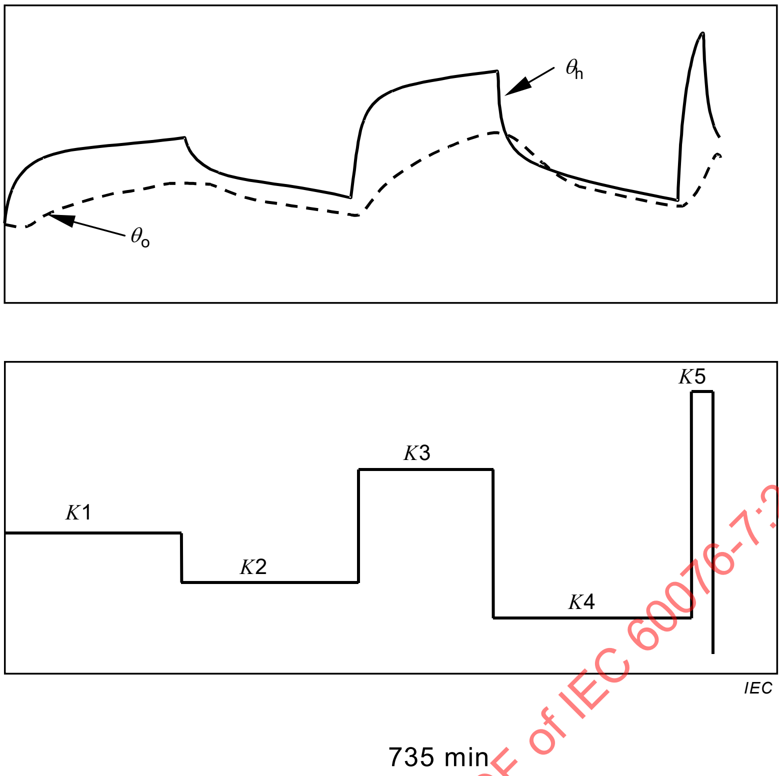
Regarding Equations (5) to (8), the complexity is in order to account for the fact that the oil-cooling medium has mechanical inertia in addition to thermal inertia. The effect is greatest for natural cooling (ON), somewhat less for non-directed-flow pumped-oil cooling (OF), and negligible for directed-flow pumped-oil cooling (OD), as regards power transformers. It is also negligible for small transformers (see 8.2.2).

NOTE For ON and OF cooling, the oil viscosity change counteracts the effect of the ohmic resistance variation of the conductors. In fact, the cooling effect of the oil viscosity change is stronger than the heating effect of the resistance change. This has been taken into account implicitly by the winding exponent of 1,3 in Table 5. For OD cooling, the influence of the oil viscosity on temperature rises is slight, and the effect of the ohmic resistance variation is considered. An approximate correction term (with its sign) for the hot-spot temperature rise at OD is $0{,}15 \times (\Delta\theta_{h} - \Delta\theta_{hr})$.

8.2.2 Exponential equations solution

Subclause 8.2.2 describes the exponential equation solution to the heat transfer differential Equations (5) to (8).

An example of a load variation according to a step function is shown in Figure 13 (the details of the example are given in Annex H).



Key

θ_h Winding hot-spot temperature

θ_o Top-oil temperature in tank

$K1$ is 1,0 $K2$ is 0,6 $K3$ is 1,5 $K4$ is 0,3 $K5$ is 2,1

Figure 13 – Temperature responses to step changes in the load current

The hot-spot temperature is equal to the sum of the ambient temperature, the top-oil temperature rise in the tank, and the temperature difference between the hot-spot and top-oil in the tank.

The top-oil temperature increase to a level corresponding to a load factor of K is given by:

$$\theta_o(t) = \theta_a + \Delta\theta_{oi} + \left\{ \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x - \Delta\theta_{oi} \right\} \times \left(1 - e^{(-t)/(k_{11} \times \tau_0)} \right) \tag{10}$$

Correspondingly, the top-oil temperature decrease to a level corresponding to a load factor of K is given by:

$$\theta_o(t) = \theta_a + \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x + \left\{ \Delta\theta_{oi} - \Delta\theta_{or} \times \left[\frac{1 + R \times K^2}{1 + R} \right]^x \right\} \times e^{(-t)/(k_{11} \times \tau_0)} \tag{11}$$

The hot-spot to top-oil temperature gradient increase to a level corresponding to a load factor of K is given by:

$$\Delta\theta_h(t) = \Delta\theta_{h1}(t) - \Delta\theta_{h2}(t) \tag{12}$$

where two gradients are

$$\Delta\theta_{h1}(t) = \Delta\theta_{h1_i} + \left\{k_{21} H g_r K^y - \Delta\theta_{h1_i}\right\} \times \left(1 - e^{(-t)/(k_{22} \times \tau_w)}\right) \tag{13}$$

and

$$\Delta\theta_{h2}(t) = \Delta\theta_{h2_i} + \left\{(k_{21} - 1) H g_r K^y - \Delta\theta_{h2_i}\right\} \times \left(1 - e^{(-t)/(\tau_0 / k_{22})}\right) \tag{14}$$

Correspondingly, the hot-spot to top-oil temperature gradient decrease to a level corresponding to a load factor of K is given by:

$$\Delta\theta_{h1}(t) = k_{21} H g_r K^y + \left\{\Delta\theta_{h1_i} - k_{21} H g_r K^y\right\} \times e^{(-t)/(k_{22} \times \tau_w)} \tag{15}$$

and

$$\Delta\theta_{h2}(t) = (k_{21} - 1) H g_r K^y + \left\{\Delta\theta_{h2_i} - (k_{21} - 1) H g_r K^y\right\} \times e^{(-t)/(\tau_0 / k_{22})} \tag{16}$$

The final equation for the hot-spot temperature is:

$$\theta_h(t) = \theta_o(t) + \Delta\theta_h(t) \tag{17}$$

where

τ_w is the winding time constant (min);

τ_0 is the oil-time constant (min).

The top-oil exponent x and the winding exponent y are given in Table 4 [23], [24].

The constants k_{11}, k_{21}, k_{22} and the time constants τ_w and τ_0 are transformer specific. They can be determined in a prolonged heat-run test during the “no-load loss + load loss” period, if the supplied losses and corresponding cooling conditions, for example AN or AF, are kept unchanged from the start until the steady state has been obtained (see Annex F). In this case, it is necessary to ensure that the heat-run test is started when the transformer is approximately at the ambient temperature. It is obvious that k_{21}, k_{22} and τ_w can be defined only if the transformer is equipped with fibre optic sensors. If τ_0 and τ_w are not defined in a prolonged heat-run test they can be defined by calculation (see Annex E). In the absence of transformer-specific values, the values in Table 4 are recommended. The corresponding graphs are shown in Figure 14.

NOTE 1 Unless the current and cooling conditions remain unchanged during the heating process long enough to project the tangent to the initial heating curve, the time constants cannot be determined from the heat-run test performed according to IEC practice.

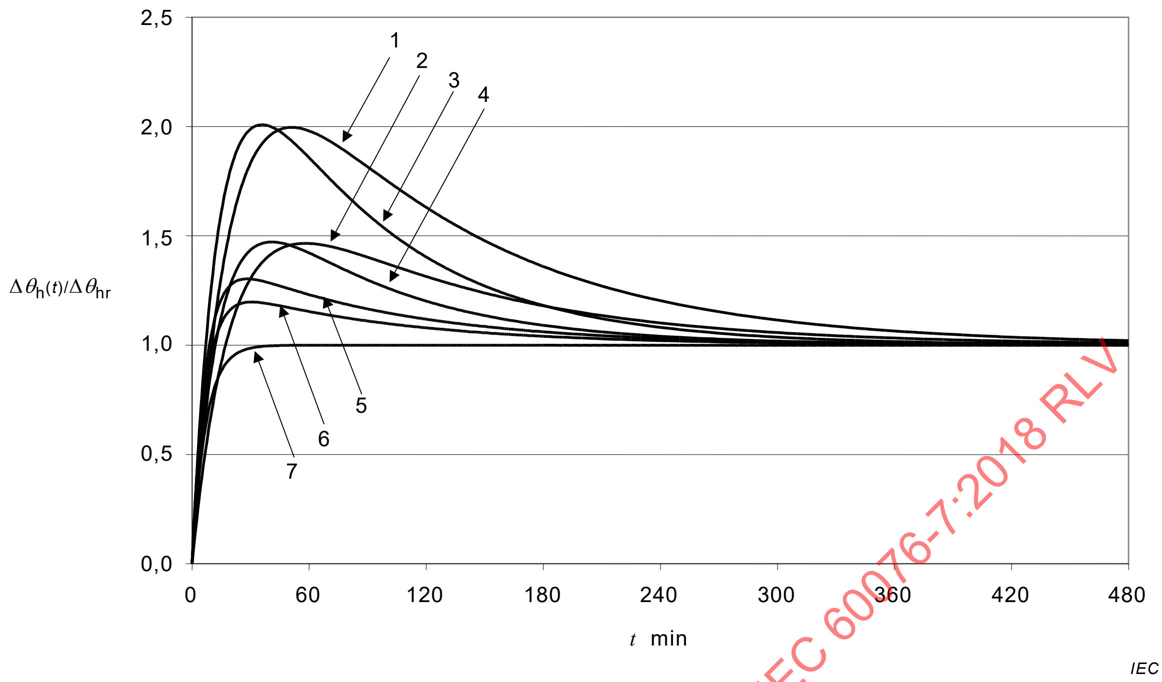
NOTE 2 The $\Delta\theta_h(t)/\Delta\theta_{hr}$ graphs observed for small transformers are similar to graph 7 in Figure 14, i.e. small transformers do not show such a hot-spot “overshoot” at step increase in the load current as ON- and OF-cooled power transformers do.

NOTE 3 The background of the oil, x, and winding, y, exponents and corresponding determining procedure are given in Annex G.

Table 4 – Recommended thermal characteristics for exponential equations

Characteristic	Small transformers	Medium and large power transformers						
	ONAN	ONAN restricted[a]	ONAN	ONAF restricted[a]	ONAF	OF restricted[a]	OF	OD
Oil exponent x	0,8	0,8	0,8	0,8	0,8	1,0	1,0	1,0
Winding exponent y	1,6	1,3	1,3	1,3	1,3	1,3	1,3	2,0
Constant k_{11}	1,0	0,5	0,5	0,5	0,5	1,0	1,0	1,0
Constant k_{21}	1,0	3,0	2,0	3,0	2,0	1,45	1,3	1,0
Constant k_{22}	2,0	2,0	2,0	2,0	2,0	1,0	1,0	1,0
Time constant τ_0, min	180	210	210	150	150	90	90	90
Time constant τ_w, min	4	10	10	7	7	7	7	7

[a] If a winding of an ON- or OF-cooled transformer is zigzag-cooled, a radial spacer thickness of less than 3 mm might cause a restricted oil circulation, i.e. a higher maximum value of the function $\Delta\theta_h(t)/\Delta\theta_{hr}$ than obtained by spacers ≥ 3 mm.



Key

1 ONAN – restricted oil flow

2 ONAN

3 ONAF – restricted oil flow

4 ONAF

5 OF – restricted oil flow

6 OF

7 OD and small power transformers

Figure 14 – The function $\Delta\theta_h(t)/\Delta\theta_{hr}$ generated by the values given in Table 4

An application example of the exponential equations solution is given in Annex H.

8.2.3 Difference equations solution

Subclause 8.2.3 describes the difference equation solution to the heat transfer differential equations, applicable for arbitrarily time-varying load factor K and time-varying ambient temperature θ_a.

If the differential equations are converted to difference equations, then the solution is quite straightforward, even on a simple spreadsheet.

The differential Equations (5) to (8) can be written as the following difference equations, where D stands for a difference over a small time step.

Equation (5) becomes:

$$D\theta_o = \frac{Dt}{k_{11}\tau_o}\left[\left[\frac{1+K^2R}{1+R}\right]^x \times (\Delta\theta_{or}) - [\theta_o - \theta_a]\right] \tag{18}$$

The "D" operator implies a difference in the associated variable that corresponds to each time step Dt. At each time step, the nth value of $D\theta_o$ is calculated from the $(n – 1)$th value using

$$\theta_{o(n)} = \theta_{o(n-1)} + D\theta_{o(n)} \tag{19}$$

Equations (7) and (8) become

$$D\Delta\theta_{\mathrm{h1}} = \frac{Dt}{k_{22}\tau_{\mathrm{w}}} \times \left[k_{21} \times \Delta\theta_{\mathrm{hr}} K^{y} - \Delta\theta_{\mathrm{h1}}\right] \tag{20}$$

and

$$D\Delta\theta_{\mathrm{h2}} = \frac{Dt}{(1/k_{22})\tau_{\mathrm{o}}} \times \left[(k_{21} - 1) \times \Delta\theta_{\mathrm{hr}} K^{y} - \Delta\theta_{\mathrm{h2}}\right] \tag{21}$$

The nth values of each of $\Delta\theta_{\mathrm{h1}}$ and $\Delta\theta_{\mathrm{h2}}$ are calculated in a way similar to Equation (19).

The total hot-spot temperature rise at the nth time step is given by:

$$\Delta\theta_{\mathrm{h}(n)} = \Delta\theta_{\mathrm{h1}(n)} - \Delta\theta_{\mathrm{h2}(n)} \tag{22}$$

Finally, the hot-spot temperature at the nth time step is given by:

$$\theta_{\mathrm{h}(n)} = \theta_{\mathrm{o}(n)} + \Delta\theta_{\mathrm{h}(n)} \tag{23}$$

For an accurate solution, the time step Dt should be as small as is practicable, certainly no greater than one-half of the smallest time constant in the thermal model. For example, if the time constant for the winding considered is 4 min, the time step should be no larger than 2 min. τ_{w} and τ_{o} should not be set to zero.

Also, there are theoretically more accurate numerical analysis solution methods than the simple one used in Equations (18) to (21), for example trapezoidal or Runge-Kutta methods. However, the increased complexity is not warranted here considering the imprecision of the input data.

The loss of life of cellulose insulation differential equations of 6.4 can also be converted to difference equations. The fundamental differential equation is

$$\frac{\mathrm{d}L}{\mathrm{d}t} = V \tag{24}$$

implying

$$DL_{(n)} = V_{(n)} \times Dt \tag{25}$$

and

$$L_{(n)} = L_{(n-1)} + DL_{(n)} \tag{26}$$

An application example of the difference equations solution is given in Annex I.

8.3 Ambient temperature

8.3.1 Outdoor air-cooled transformers

For dynamic considerations, such as monitoring or short-time emergency loading, the actual temperature profile should be used directly.

For design and test considerations, the following equivalent temperatures are taken as ambient temperature:

a) the yearly weighted ambient temperature is used for thermal ageing calculation;

b) the monthly average temperature of the hottest month is used for the maximum hot-spot temperature calculation.

NOTE Concerning the ambient temperature, see also IEC 60076-2.

If the ambient temperature varies appreciably during the load cycle, then the weighted ambient temperature is a constant, fictitious ambient temperature which causes the same ageing as the variable temperature acting during that time. For a case where a temperature increase of 6 K doubles the ageing rate and the ambient temperature can be assumed to vary sinusoidally, the yearly weighted ambient temperature, θ_E, is equal to

$$\theta_E = \theta_{ya} + 0{,}01 \times \left[2\left(\theta_{ma\text{-}max} - \theta_{ya}\right)\right]^{1{,}85} \tag{27}$$

where

$\theta_{ma\text{-}max}$ is the monthly average temperature of the hottest month (which is equal to the sum of the average daily maxima and the average daily minima, measured in °C, during that month, over 10 or more years, divided by 2);

θ_{ya} is the yearly average temperature (which is equal to the sum of the monthly average temperatures, measured in °C, divided by 12).

EXAMPLE Using monthly average values (more accurately using monthly weighted values) for θ_a:

$$\left.\begin{array}{l} \theta_{ma\text{-}max} = 30\ °C \text{ for 2 months} \\ \theta_{ma} = 20\ °C \text{ for 4 months} \\ \theta_{ma} = 10\ °C \text{ for 4 months} \\ \theta_{ma} = 0\ °C \text{ for 2 months} \end{array}\right\} \quad \begin{array}{l} \text{Average } \theta_{ya} = 15{,}0\ °C \\ \text{Weighted average } \theta_E = 20{,}4\ °C \end{array}$$

The ambient temperature used in the calculation examples in Annex J is 20 °C.

8.3.2 Correction of ambient temperature for transformer enclosure

A transformer operating in an enclosure experiences an extra temperature rise which is about half the temperature rise of the air in that enclosure.

For transformers installed in a metal or concrete enclosure, $\Delta\theta_{or}$ in Equations (10) and (11) should be replaced by $\Delta\theta'_{or}$ as follows:

$$\Delta\theta'_{or} = \Delta\theta_{or} + \Delta(\Delta\theta_{or}) \tag{28}$$

where

$\Delta(\Delta\theta_{or})$ is the extra top-oil temperature rise under rated load.

It is strongly recommended that this extra temperature rise be determined by tests, but when such test results are not available, the values given in Table 5 for different types of enclosure may be used. These values should be divided by two to obtain the approximate extra top-oil temperature rise.

NOTE When the enclosure does not affect the coolers, no correction is necessary according to Equation (28).

Table 5 – Correction for increase in ambient temperature due to enclosure

Type of enclosure	Number of transformers installed	Correction to be added to weighted ambient temperature K Transformer size kVA 250	500	750	1 000
Underground vaults with natural ventilation	1	11	12	13	14
	2	12	13	14	16
	3	14	17	19	22
Basements and buildings with poor natural ventilation	1	7	8	9	10
	2	8	9	10	12
	3	10	13	15	17
Buildings with good natural ventilation and underground vaults and basements with forced ventilation	1	3	4	5	6
	2	4	5	6	7
	3	6	9	10	13
Kiosks[a]	1	10	15	20	–

NOTE The above temperature correction figures have been estimated for typical substation loading conditions using representative values of transformer losses. They are based on the results of a series of natural and forced cooling tests in underground vaults and substations and on random measurements in substations and kiosks.

[a] This correction for kiosk enclosures is not necessary when the temperature rise test has been carried out on the transformer in the enclosure as one complete unit.

8.3.3 Water-cooled transformers

For water-cooled transformers, the ambient temperature is the temperature of the incoming water, which shows less variation in time than air.

9 Influence of tap-changers

9.1 General

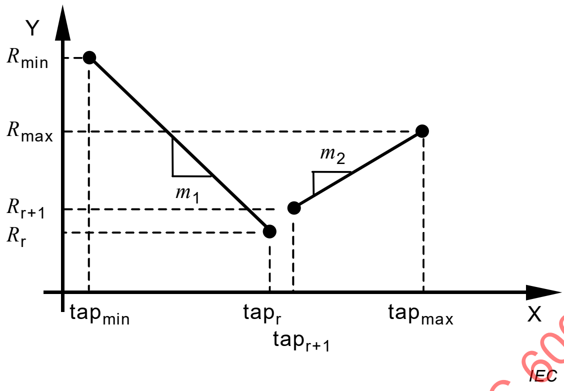
All quantities used in Equations (10), (11), (13), (14), (15), (16) and (17) have to be appropriate for the tap at which the transformer is operating.

For example, consider the case where the HV voltage is constant, and it is required to maintain a constant LV voltage for a given load. If this requires the transformer to be on a +15 % tap on the LV side, the rated oil temperature rise, losses and winding gradients have to be measured or calculated for that tap.

Consider also the case of an auto transformer with a line-end tap-changer – the series winding will have maximum current at one end of the tapping range whilst the common winding will have maximum current at the other end of the tapping range.

9.2 Load loss

The transformer's short-circuit loss is a function of the tap position. Several different connections of the tapped windings and the main winding can be realized. A universal approach to calculate the transformer's ratio of losses as a function of the tap position is shown in Figure 15. A linear function is calculated between the rated tap position and the minimum and maximum position. Figure 15 can be changed according to regulating winding arrangement regarding tapping method selected.



$$m_1 = \frac{R_r - R_{min}}{tap_r - tap_{min}} \qquad m_2 = \frac{R_{max} - R_{r+1}}{tap_{max} - tap_{r+1}}$$

Key

X Tap position

Y Ratio of losses

Figure 15 – Principle of losses as a function of the tap position

9.3 Ratio of losses

The transformer's top-oil temperature rise is a function of the loss ratio R. The no-load losses are assumed to be constant. Using a linear approximation, R can be determined as a function of the tap position.

For tap positions beyond the rated tap-changer position (from tap_{r+1} to tap_{max}):

$$R(tap) = R_{r+1} + (tap - tap_{r+1}) \times m_2 \tag{29}$$

For tap positions below the rated tap position (from tap_{min} to tap_r):

$$R(tap) = R_r + (tap - tap_r) \times m_1 \tag{30}$$

9.4 Load factor

The winding-to-oil temperature rise mainly depends on the load factor. K is not dependent on the tap position.

Annex A
(informative)

Insulation life expectancy and relative ageing rate considering oxygen and water effect

A.1 Insulation life expectancy

Ageing or change of polymerization of paper insulation is often described as a first order process that can be described by the following Arrhenius equation:

$$\frac{1}{DP_{\text{end}}} - \frac{1}{DP_{\text{start}}} = A \times t \times e^{-\frac{E_{\text{A}}}{R \times (\theta_{\text{h}} + 273)}} \qquad \text{(A.1)}$$

where

DP_{end} is the insulation DP value at the moment of the sampling or the end of life criterion;

DP_{start} is the initial insulation DP value;

A is the pre-exponential factor in 1/h;

E_{A} is the activation energy in kJ/mol;

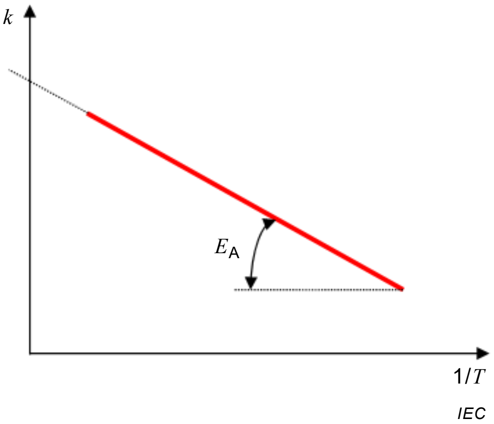
t is the life time of a transformer in h;

R is the gas constant in J/(K·mol);

θ_{h} is the hot-spot temperature, °C.

Arrhenius extrapolations assume that a chemical degradation process is controlled by a reaction rate k proportional to exp($-E_{\text{A}}/RT$), where E_{A} is the Arrhenius activation energy, R the gas constant (8,314 J/(K·mol), T the absolute temperature and A the pre-exponential factor. The pre-exponent value A is a constant depending on the chemical environment. In an Arrhenius plot, the natural logarithm of the ageing rate (ln k) is plotted against the inverse absolute temperature (1/T) and a straight line is obtained as shown in Figure A.1 – illustrating how the ageing rate depends on temperature. The condition for achieving a straight line is that it is the same ageing process over the whole temperature range. The activation energy describes how much the reaction rates depend on temperature; if the ageing process is independent of temperature the activation energy is zero and the line becomes parallel with the x-axis, while if it increases fast with increasing temperature the line falls quickly. One should bear in mind that A and E_{A} values come in pairs. In principle, E_{A} is the slope of the line in Figure A.1, and the A-value is the value of interception with a virtual y-axis from 0, the higher the value the higher the location of the curve above the abscissa and the ageing is faster. The point is that a small change in slope will influence the A-value significantly.

NOTE The temperature and moisture values used in the transformer life estimation always refer to the same location.



Key

$1/T$	inverse absolute hot-spot temperature
ln k	logarithm of the ageing rate

Figure A.1 – Arrhenius plot for an ageing process

Knowing the end-of-life (EOL) criterion we can rearrange the Equation (A.1) to express life expectancy, t_{exp}, as a function of hot-spot temperature θ_h, and the parameters E_A and A:

$$t_{exp} = \frac{\frac{1}{DP_{end}} - \frac{1}{DP_{start}}}{A \times 24 \times 365} \times e^{\frac{E_A}{R \times (\theta_h + 273)}} \quad \text{(years)} \qquad \text{(A.2)}$$

The feasibility of this procedure depends on a valid selection of E_A and A values. As main result of extensive research work (see references [9] to [15]), the activation energy over the range from 70 °C to 160 °C was calculated and an A value was estimated for each single case based on the first order ageing models. The corresponding coefficients applicable to the power transformers, where oil is separated from and in contact with air, are provided in Table A.1.

Table A.1 – Activation energy (E_A) and environment factor (A) for oxidation, hydrolysis

Paper type/ageing parameters		Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
Non-thermally upgraded paper	A (h^{-1})	$4{,}1 \times 10^{10}$	$1{,}5 \times 10^{11}$	$4{,}5 \times 10^{11}$	$4{,}6 \times 10^{5}$
	E_A (kJ/mol)	128	128	128	89
Thermally upgraded paper	A (h^{-1})	$1{,}6 \times 10^{4}$	$3{,}0 \times 10^{4}$	$6{,}1 \times 10^{4}$	$3{,}2 \times 10^{4}$
	E_A (kJ/mol)	86	86	86	82

The results of the expected life based on coefficients given in Table A.1, and starting with a DP of 1 000 and ending with a DP of 200, i.e. as “end of life criteria”, for a range of hot-spot temperatures are shown in Table A.2. The corresponding graphical illustration considering the influence of temperature, oxygen and moisture content is shown in Figure 4 and Figure 5.

Table A.2 – Expected life of paper under various conditions

Paper type/ageing temperature		Expected life years			
		Free from air and 0,5 % moisture	**Free from air and 1,5 % moisture**	**Free from air and 3,5 % moisture**	**With air and 0,5 % moisture**
Non-thermally upgraded paper at	80 °C	97,3	26,6	8,9	14,7
	90 °C	29,3	8	2,7	6,4
	98 °C	11,7	3,2	1,1	3,4
	110 °C	3,2	0,9	0,3	1,4
Thermally upgraded paper at	80 °C	151,9	81	39,9	19,4
	90 °C	67,8	36,1	17,8	9
	98 °C	36,7	19,6	9,6	5
	110 °C	15,3	9,6	4	2,2

A.2 Relative ageing rate considering oxygen and water effect

In 6.3, the rate of ageing of the interturn insulation of transformers under the effect of time and temperature is referred to a hot-spot temperature of 98 °C and 110 °C for the non-thermally and thermally upgraded paper, respectively. Further, the relative ageing rate V is defined according to Equations (2) and (3). These equations are based on the life expectancy formula of Montsinger [25], and Dakin's ageing rate formula [26], which are a simplification of the more general Arrhenius relation given in Equation (A.1), and valid only in a limited temperature range. On the other hand, the IEEE Loading Guide [27], recommends Equation (3), which is an equivalent to the acceleration ageing factor, F_{AA}, for a wide range of temperatures. Further, Equations (2) and (3) imply that the ageing rate is only dependent on the hot-spot temperature and do not consider different insulation conditions, which are defined in references [9] to [15].

Therefore, if the ageing rate of the paper insulation is given as follows:

$$k = A \times e^{-\frac{E}{R \times (\theta_{\mathrm{h}} + 273)}} \tag{A.3}$$

and if an ageing rate at a certain temperature and at an insulation condition is chosen to be the rated one, k_{r}, then the ageing rate, k, determined for any temperature and insulation condition can be related to this rated rate, k_{r}, by a new relative ageing rate, V, given as their ratio [28]:

$$V = \frac{k}{k_{\mathrm{r}}} = \frac{A}{A_{\mathrm{r}}} e^{\frac{1}{R} \times \left(\frac{E_r}{\theta_{\mathrm{h,r}} + 273} - \frac{E}{\theta_{\mathrm{h}} + 273} \right)} \tag{A.4}$$

where

the subscript r stands for the rated condition.

The chosen rated insulation condition for both the non-thermally and thermally upgraded paper is “free from air and 0,5 % moisture” taken from Table A.1. Also, similar to the approach given in Clause 6, the rated relative ageing rate V = 1,0 at this condition corresponds to a temperature of 98 °C for non-thermally upgraded paper and to 110 °C for thermally upgraded paper.

The calculated relative ageing rates for different temperatures and insulation contamination conditions are compared with values given in Table 1. The results are summarized in Table A.3 and Table A.4.

The same could be applied to improve the IEEE equations for the ageing acceleration factor, F_{AA}, and the equivalent ageing factor, F_{EQA}.

It is obvious from the tables that the dominant ageing factor at higher temperatures for the kraft paper is the moisture. However, at lower temperatures the oxygen influence will prevail, Table A.3. On the other hand, the main factor responsible for the thermally upgraded paper ageing over the range of the temperatures is oxygen, Table A.4. This is in line with the conclusions in [13].

Table A.3 – Relative ageing rates due to hot-spot temperature, oxygen and moisture for non-upgraded paper insulation

Temperature °C	**Relative ageing rate, V**				
	Table 1	**Free from air and 0,5 % moisture**	**Free from air and 1,5 % moisture**	**Free from air and 3,5 % moisture**	**With air and 0,5 % moisture**
80	0,125	0,12	0,44	1,323	0,80
86	0,25	0,25	0,91	2,742	1,32
92	0,5	0,50	1,84	5,548	2,16
98	**1,0**	**1,00**	**3,66**	**10,976**	**3,47**
104	2	1,94	7,08	21,245	5,50
110	4	3,67	13,43	40,281	8,58
116	8	6,82	24,96	74,880	13,21
122	16	12,44	45,53	136,601	20,07
128	32	22,30	81,58	244,755	30,10
134	64	39,27	143,69	431,061	44,62
140	128	68,04	248,93	746,802	65,39
The relative ageing rates, V, for different ageing factors at temperature of 98 °C are indicated to be compared to the rated insulation condition, i.e. where the relative ageing rate is 1.					

Table A.4 – Relative ageing rates due to hot-spot temperature, oxygen and moisture for upgraded paper insulation

Temperature °C	Relative ageing rate, V				
	Table 1	Free from air and 0,5 % moisture	Free from air and 1,5 % moisture	Free from air and 3,5 % moisture	With air and 0,5 % moisture
80	0,036	0,10	0,19	0,38	0,79
86	0,073	0,16	0,31	0,63	1,25
92	0,145	0,26	0,5	1,00	1,97
98	0,282	0,42	0,78	1,59	3,05
104	0,536	0,65	1,22	2,48	4,66
110	**1,00**	**1,00**	**1,88**	**3,81**	**7,02**
116	1,83	1,52	2,84	5,78	10,45
122	3,29	2,27	4,26	8,66	15,36
128	5,8	3,36	6,30	12,82	22,32
134	10,07	4,91	9,22	18,74	32,07
140	17,2	7,11	13,33	27,12	45,60

The relative ageing rates, V, for different ageing factors at temperature of 110 °C are indicated to be compared to the rated insulation condition, i.e. where the relative ageing rate is 1.

The loss of life, L, over certain period of time is calculated as given in 6.4.

Annex B
(informative)

Core temperature

B.1 General

In transformer cores, there are two different core hot-spots which, if not controlled, can cause insulation material degradation and subsequent gassing.

a) Core hot-spot inside the core, should be limited to 130 °C under conditions of highest core excitation, rated load and maximum ambient temperature. This is in order to prevent the core heating which results in the break-up of the thin oil film between core laminations, the consequence of which is the generation of mainly H_2 and CH_4, in addition to small quantities of other hydrocarbons [29], [30]. It is important to understand that any possible oil gas saturation should be prevented.
b) Core surface hot-spot, which is in contact with oil and solid insulation materials, should be limited according to Table 2.

B.2 Core hot-spot locations

The location of the internal core hot-spot depends largely on the core type and whether it is a shell form or a core form transformer. In the most common core type (three-phase, three-limb cores), this hot-spot is located in the middle of the top yoke between cooling ducts. In other core types, the location of the core hot-spot is typically at the top of the middle core limb [30].

The total core surface temperature rise is the sum of the following three components:

a) temperature rise due to the leakage flux impinging on the surface of the laminations of the outermost core step(s) – this value can vary from a few kelvins to several tens of kelvins over the adjacent oil depending on the transformer winding, core, and tank shielding design;
b) temperature rise due to the main flux in the core – this value can again vary from a few kelvins to several tens of kelvins over the adjacent oil depending on the transformer core design (diameter and number of cooling ducts), core induction, and core material;
c) temperature rise of the oil around the area of the surface hot-spot.

Therefore, in almost all cores, this core surface hot-spot is not located in the yoke but is located at the top of the middle core-limb, where the leakage flux enters the surface of the core laminations. Also, the relative magnitudes of the temperature rise due to the leakage flux versus the rise due to the core main flux depends wholly on the design of the transformer.

Consequently, the correct way to determine the core surface hot-spot is to determine the temperature increase at rated load (including temperature rise of adjacent oil) and add to it the temperature rise due to the highest core over-excitation. These temperatures are to be determined for the appropriate location of the core surface hot-spot in the core type evaluated.

Annex C
(informative)

Specification of loading beyond rated power

This document gives advice on the calculation of the capability of an existing transformer to be loaded beyond rated power. All transformers will have some overload capability. However since no specific loading requirements beyond rated power are specified in IEC 60076-1 [5] or IEC 60076-2 [52], it is up to the purchaser to specify any particular loading requirements (load, duration and ambient temperature).

Specification of loading beyond rated power can be done in the following ways.

a) Long time emergency loading

Since the hot-spot temperature limit in IEC 60076-2 is less than that given in Table 2, it is possible to have an increased loading available for emergency situations provided that the loss of life is accepted. The extent of this loading capability will depend on ambient temperature, while preload and the duration of loading are only relevant to loss of life.

The following need to be specified at the enquiry stage:

1) the ambient temperature at which the loading is required;
2) the load as per unit (p.u.) of rated current;
3) the winding(s) to which the loading is to be applied;
4) the tap position;
5) the cooling stage(s) in service.

If loading according to this document is specified, then the transformer should not exceed the temperatures and currents given in Table 2 and Table 3, respectively, under the following conditions:

- a yearly average ambient temperature (20 °C unless otherwise specified);
- current flowing in the highest rated winding is considered;
- the tap position that gives the rated voltage on the lower voltage side with rated voltage on the higher voltage side taking account of the voltage drop caused by the load for a unity power factor load;
- all normal cooling in service but with no standby cooling capacity.

b) Short time emergency loading

If the transformer is used at a load less than rated current, then there will be an additional short time loading capability caused by the thermal time constants of the oil and windings. If a specific short time loading capability is required then the following need to be specified:

1) the ambient temperature at which the loading is required;
2) the short time current that is required in p.u. of rated current;
3) the winding(s) to which the load will be applied;
4) the tap position;
5) the preload current applied before the short time emergency loading in p.u. of rated current;
6) the duration of the loading;
7) the cooling stage(s) in service.

If loading according to this document is specified, then the transformer should not exceed the temperatures and currents given in Table 2 and Table 3, respectively, and under the following conditions:

- a yearly average ambient temperature (20 °C unless otherwise specified);

- current flowing in the highest rated winding is considered;
- the tap position that gives the rated voltage on the lower voltage side with rated voltage on the higher voltage side taking account of the voltage drop caused by the preload for a unity power factor load;
- a preload of 0,75 p.u.;
- a duration of 15 min;
- all normal cooling in service appropriate to the preload condition but with no standby cooling capacity

c) Loading according to a specific cycle

Specify in detail the load and ambient temperature cycles.

Annex D
(informative)

Description of Q, S and H factors

IEC 60076-2 notes also that the hot-spot factor H is obtained by the product of the Q and S factors:

$$H = QS \tag{D.1}$$

The Q and S factors are dimensionless factors described in IEC 60076-2 as:

- Q is "a dimensionless factor to estimate the increase of the average winding gradient due to the local increase of additional loss."
- S is "a dimensionless factor to estimate the local increase of the average winding gradient due to the variation in the oil flow stream."

According these definitions, Q should be calculated by modelling the winding with the correct heat loss distribution, but with uniform oil velocity. The Q factor is then the ratio of the maximal winding to local oil gradient over the average winding to average oil gradient.

On the other hand, S should be calculated by modelling the winding with uniform heat losses and with the correct oil velocity inside the winding. The S factor is the ratio of the maximal winding to local oil gradient over the average winding to average oil gradient.

However after calculating Q and S in line with the IEC 60076-2 definition, the hot-spot factor H cannot be calculated directly as the product of Q and S factors, as mentioned in IEC 60076-2, because:

– discs with maximal Q factor and discs with maximal S factor can (and probably will) be different discs;

– when modelling the winding with correct heat loss distribution and oil flows, Q and S factors will not be independent from each other as explained later.

For the above reasons, CIGRE WG A2.38 [18] proposes more practical definitions of Q and S and H factors, as given below.

The H factor can be derived out of Figure 6 and is:

$$H = \frac{P - B}{I - \dfrac{B + D}{2}} \tag{D.2}$$

Equation (D.2) is different from the current IEC 60076-2 definition, because the hot-spot temperature is referenced to the mixed top-oil, while increase in local winding to oil gradient refers to local winding oil.

This formula for H has the following advantages:

– the H factor can be calculated directly from the calculation results (calculated with correct loss and oil flow distribution);

– this is the correct hot-spot factor to predict the hot-spot temperature out of the temperature rise results, obtained in the standard temperature rise test;

– this hot-spot factor can also be checked in case fibre optic measurements are made (the hot-spot temperature is known);

– the hot-spot is not always located at the top of the winding. However, this formulation is a practical solution to overcome this issue.

The Q factor is a dimensionless factor as a ratio of two losses, and in cylindrical coordinates can be defined as:

$$Q = Q(r, z, \varphi, T)/Q_{\text{ave}} \tag{D.3}$$

where

$Q(r, z, \varphi, T)$ is the local loss density at a location (W/m³);

r is the radial position;

φ is the angle in circumferential position;

z is the axial position;

T is the local temperature at (r, z, φ), and

Q_{ave} is the average loss of the winding at average temperature.

For calculation purposes, one can redefine the Q factor for a disc winding in which each disc has several conductors in radial direction and consists of numerous discs in axial direction, as:

$$Q = Q(conductor\_number\_in\_disc, disk\_number, \varphi, T)/Q_{\text{ave}} \tag{D.4}$$

The Q factor is a scalar function and is based on the steady state condition of a defined loading at a defined tap position (if applicable).

It is important to note that the Q factor in this definition is not a ratio of temperatures but a ratio of losses.

Finally the S factor used in this document is defined as:

$$S = \frac{H}{Q} \tag{D.5}$$

which can be easily calculated as soon as H and Q are known.

This S factor is an indication of the local cooling inefficiency. Higher S factor means higher local temperature gradient thus worse cooling efficiency.

According to the current IEC 60076-2 calculation this S factor should be calculated as the ratio of local hot-spot gradient over winding gradient with constant heat losses. With this definition the S factor is proportional to the ratio of two thermal resistances, resulting in:

$$S \propto S(r, z, \varphi, T)/S_{\text{ave}} \tag{D.6}$$

where

$S(r, z, \varphi, T)$ is the local cooling resistance (K/W), and

S_{ave} is the average cooling resistance (K/W).

We should note that heat transfer can be in different directions. The (overall) local heat transfer consists of series and parallel parts, such as:

– the insulation between the neighbouring conductors, that are in direct contact with each other, in the radial direction.

– the insulation paper and oil boundary layer between conductor and the oil flow in axial direction. Note that heat transfer functions for the oil boundary layer are often function of q''.

– the copper (which almost can be neglected) in the tangential direction.

This implies that the Q and S factors are not fully independent, because they are linked by temperature, heat flux, etc. For example, if the local losses are higher, the local temperature will also increase and will influence the local flow stream and the local convection heat transfer coefficient from conductor to oil.

Remark 1 We should note that the size of one (paper insulated) conductor is the smallest element in which one calculates the losses. Inside each element there exists the same temperature, so thermal resistances inside the element are neglected. In the case one calculates the Q factor based on a number of conductors in one (or sometimes even 4) top discs, one increases in essence the element size to a large extent and one neglects the temperature distribution between conductors in the disc (and even between discs), which results in a too low estimate of the hot-spot. The approach of using one or more discs as smallest element results in a too low estimate of the hot-spot temperature and should be rejected.

Remark 2 In the case of a high Q factor in a transformer, one is able to limit the hot-spot factor by creating locally more cooling surface and so design for a low S factor at that location. This principle is easy to do by adding an axial cooling channel inside a radial spacer disc or by adding a radial spacer inside a winding with axial cooling channels. The location of the hot-spot does not necessarily have to correspond with the location of the maximum losses.