IS 2026-7 (2009): Power Transformers, Part 7: Loading Guide for Oil-Immersed Power Transformers [ETD 16: Transformers]

BLANK PAGE

IS 2026 (Part 7) : 2009
IEC 60076-7 : 2005

भारतीय मानक

पॉवर ट्रांसफार्मर

भाग 7 तेल-निमज्जित पॉवर ट्रांसफार्मरों के लदान की मार्गदर्शिका

Indian Standard

POWER TRANSFORMERS

PART 7 LOADING GUIDE FOR OIL-IMMERSED POWER TRANSFORMERS

ICS 29.180

BUREAU OF INDIAN STANDARDS
MANAK BHAVAN, 9 BAHADUR SHAH ZAFAR MARG
NEW DELHI 110002

October 2009 **Price Group 14**

Transformer Sectional Committee, ETD 16

NATIONAL FOREWORD

This Indian Standard (Part 7) which is identical with IEC 60076-7 : 2005 'Power transformers — Part 7: Loading guide for oil-immersed power transformers' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Transformer Sectional Committee and approval of the Electrotechnical Division Council.

The text of IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain terminology and conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.

b) Comma (,) has been used as a decimal marker in the International Standard while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In this adopted standard, reference appears to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

International Standard	*Corresponding Indian Standard*	*Degree of Equivalence*
IEC 60034-1 : 2004 Rotating electrical machines — Part 1: Rating and performance	IS/IEC 60034-1 : 2004 Rotating electrical machines: Part 1 Rating and performance	Identical
IEC 60076-5 : 2000 Power transformers — Part 5: Ability to withstand short circuit	IS/IEC 60076-5 : 2000 Power transformers: Part 5 Ability to withstand short circuit	do

The technical committee responsible for the preparation of this standard has reviewed the provisions of the following International Standard referred in this adopted standard and has decided that it is acceptable for use in conjunction with this standard:

International Standard	*Title*
IEC 60076-4 : 2002	Power transformers — Part 4: Guide to the lightning impulse and switching impulse testing — Power transformers and reactors

Only the English language text has been retained while adopting it in this Indian Standard, and as such the page numbers given here are not the same as in the IEC Standard.

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

Indian Standard
POWER TRANSFORMERS
PART 7 LOADING GUIDE FOR OIL-IMMERSED POWER TRANSFORMERS

1 Scope

This part of IEC 60076 is applicable to 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 consulted in view of the peculiar loading profile.

2 Normative references

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

IEC 60076-2:1993, *Power transformers – Part 2: Temperature rise*

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*

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

3.2
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

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. The cyclic loading may either be a normal loading or a long-time emergency loading

3.5
normal cyclic loading
higher ambient temperature or a higher-than-rated load current is applied during part of the cycle, but, from the point of view of relative thermal ageing rate (according to the mathematical model), this loading is equivalent to the rated load at normal ambient temperature. 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 due to thermal ageing, dielectric stress, short-circuit stress, or mechanical movement, which could occur in normal service and result in a high risk of electrical failure

3.11
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. The equivalent ageing in hours is obtained by multiplying the relative ageing rate with the number of hours

3.12
thermally upgraded paper
cellulose-based paper which has been chemically modified to reduce the rate at which the paper decomposes. 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; 50 % retention in tensile strength after 65 000 hours in a sealed tube at 110 °C or any other time/temperature combination given by the equation:

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

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.

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

3.13
non-directed oil flow
OF

indicates that the pumped oil from heat exchangers or radiators flows freely inside the tank, and is not forced to flow through the windings (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)

3.14
non-directed oil flow
ON

indicates that the oil from the heat exchangers or radiators flows freely inside the tank and is not forced to flow through the windings (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
directed oil flow
OD

indicates that the principal part of the pumped oil from heat exchangers or radiators is forced to flow through the windings (the oil flow inside the windings can be either axial in vertical cooling ducts or zigzag in horizontal cooling ducts)

3.16
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
m_A	Mass of core and coil assembly	kg
m_T	Mass of the tank and fittings	kg
m_O	Mass of oil	kg

Symbol	Meaning	Units
m_W	Mass of winding	kg
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
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	
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	
s	Laplace operator	
t	Time variable	min
tap_r	Number of principal tapping	
tap_{r+1}	Number of tapping r + 1	
tap_{min}	Number of minimum tapping	
tap_{max}	Number of maximum tapping	
V	Relative ageing rate	
V_n	Relative ageing rate during interval n	
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

Symbol	Meaning	Units
θ_h	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

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 [1], [2], [3][1].

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 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, 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.

---

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

a) 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.

b) 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.

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

d) 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.

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

f) 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.

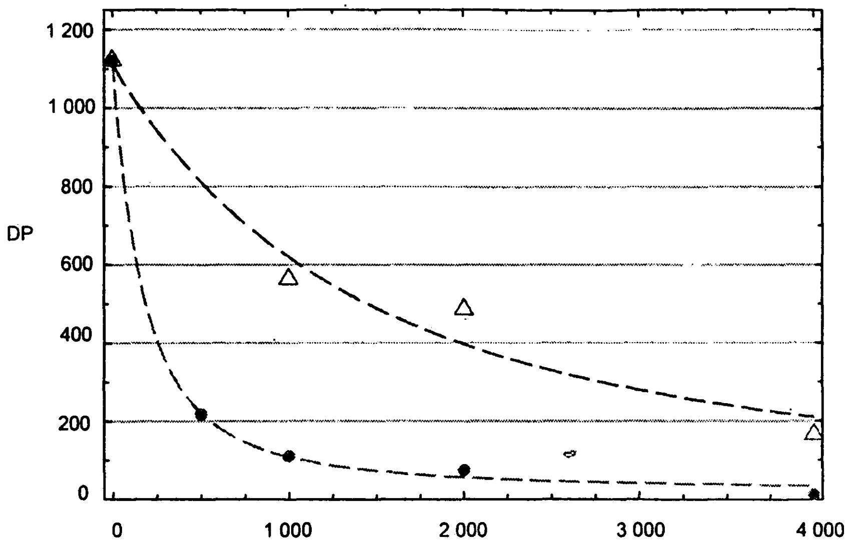
a) Distribution transformers, for which only the hot-spot temperatures in the windings and thermal deterioration shall be considered.

b) Medium power transformers where the variations in the cooling modes shall be considered.

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

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.

6.2 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 part of IEC 60076 is based only on the insulation temperature as the controlling parameter.

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 [7].

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

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

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 2.

Table 2 – 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

6.3 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.

6.4 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.

7 Limitations

7.1 Current and temperature limitations

With loading values beyond the nameplate rating, all the individual limits stated in Table 4 should not be exceeded and account should be taken of the specific limitations given in 7.2 to 7.4.

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.			

7.2 Specific limitations for distribution transformers

7.2.1 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 should not be exceeded. No limit is set for the top-oil and 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).

7.2.2 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.

7.2.3 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).

7.2.4 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.

7.3 Specific limitations for medium-power transformers

7.3.1 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. 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).

7.3.2 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.

7.3.3 Short-circuit withstand requirements

During or directly after operation at load beyond nameplate rating, transformers may not conform to the thermal short-circuit requirements, as specified in IEC 60076-5, 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.

7.3.4 Voltage limitations

Unless other limitations for variable flux voltage variations are known (see IEC 60076-4), 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.

7.4 Specific limitations for large power transformers

7.4.1 General

For large power transformers, additional limitations, mainly associated with the leakage flux, shall 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.

7.4.2 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. 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).

7.4.3 Accessory, equipment and other considerations

Refer to 7.3.2.

7.4.4 Short-circuit withstand requirements

Refer to 7.3.3.

7.4.5 Voltage limitations

Refer to 7.3.4.

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 part of IEC 60076 are based on the following:

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

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

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

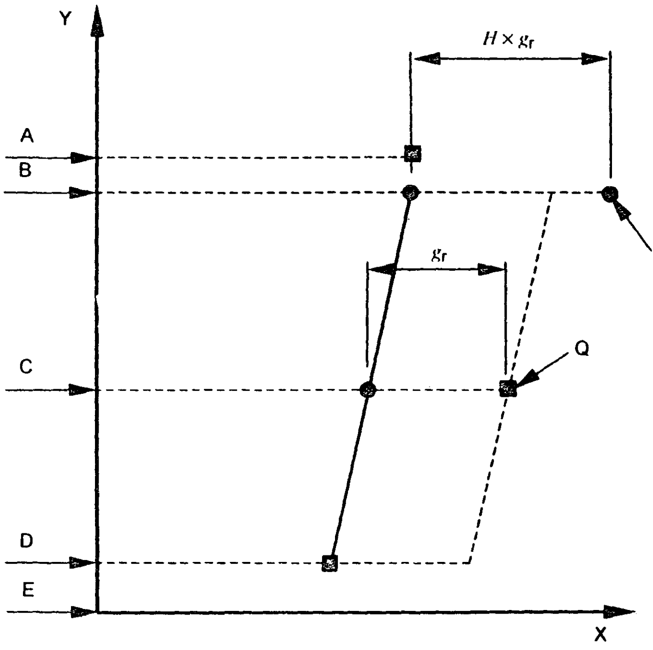
A thermal diagram is assumed, as shown in Figure 2, on the understanding that such a diagram is the simplification of a more complex distribution. The assumptions made in this simplification are as follows.

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 8.1.2b), 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 $H \times g_{\mathrm{r}}$, that is, $\Delta\theta_{\mathrm{hr}} = H \times g_{\mathrm{r}}$.

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 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 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	Average winding temperature determined by resistance measurement
X-axis	Temperature
Y-axis	Relative positions

■ measured point; ● calculated point

Figure 2 – 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. $\Delta\theta_{hr}$ = 28 K for the 120 kV winding and $\Delta\theta_{hr}$ = 36 K for the 410 kV winding.

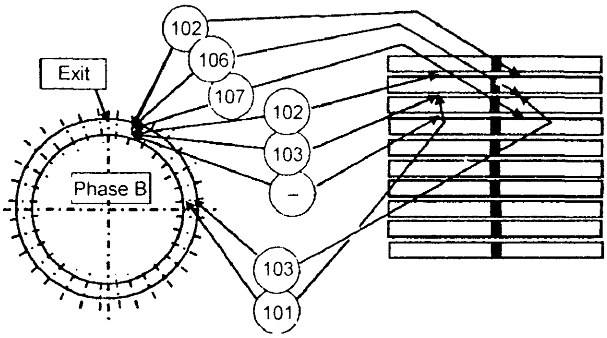


Figure 3 – Local temperature rises above air temperature in a 120 kV winding at a load factor of 1,6

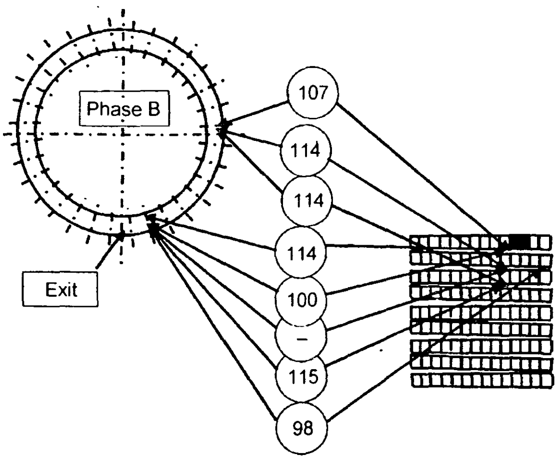


Figure 4 – Local temperature rises above air temperature in a 410 kV winding at a load factor of 1,6

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].

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.

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 [10]. The factor H should be defined either by direct measurement (see 8.1.3) 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 [11].

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 d.c. 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 thickness 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 6).

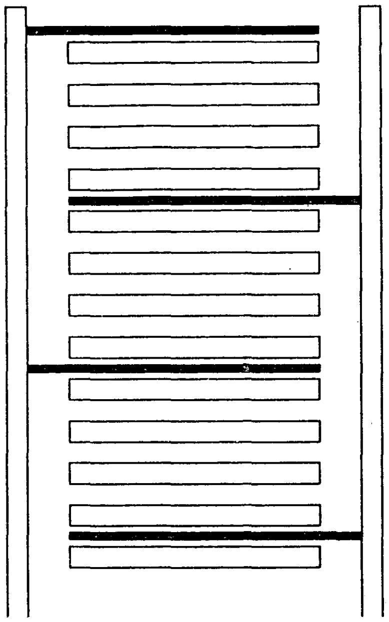


Figure 6 – Zigzag-cooled winding where the distance between all sections is the same and the flow-directing washer is installed in the space between sections

- 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 7). 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.

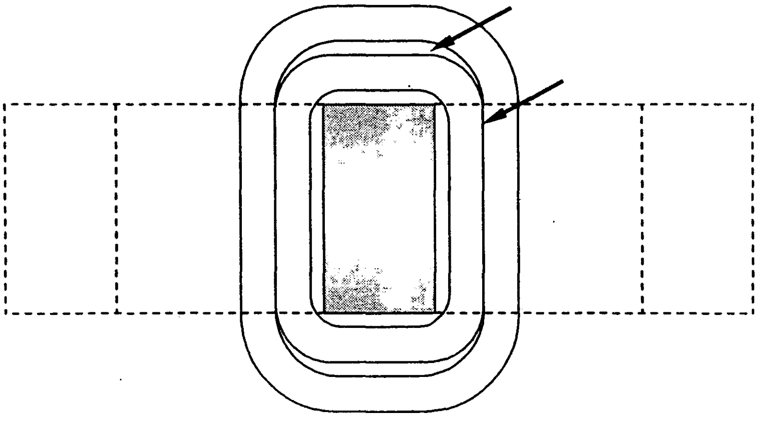


Figure 7 – Top view section of a rectangular winding with "collapsed cooling duct arrangement" under the yokes

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

8.2.1 General

This subclause 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, 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.

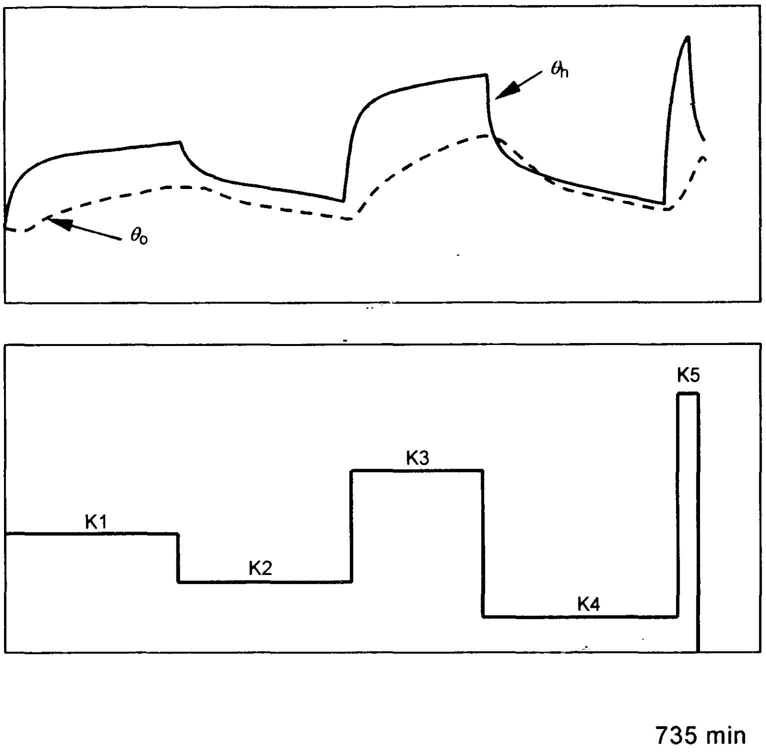
   - Each of the increasing load steps is followed by a decreasing load step or vice versa.
   - In case of N successive increasing load steps ($N \geq 2$), each of the ($N - 1$) first steps has to be long enough for the hot-spot-to-top-oil gradient $\Delta\theta_h$ to obtain steady state. The same condition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

b) Difference equations solution, 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.

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 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

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 8 (the details of the example are given in Annex B).



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 8 – 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:

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

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. 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 A). In the absence of transformer specific values, the values in Table 5 are recommended. The corresponding graphs are shown in Figure 9.

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.

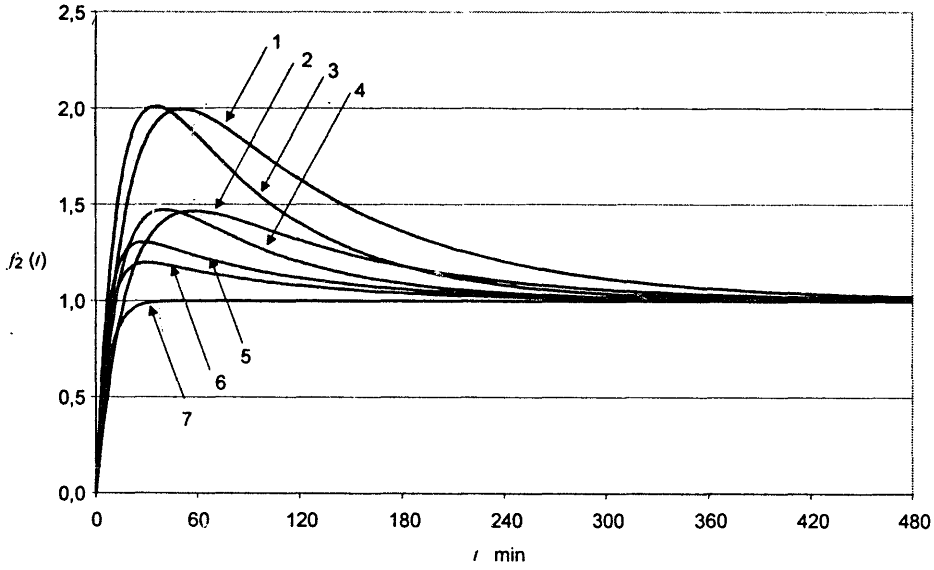
NOTE 2 The $f_2(t)$ graphs observed for distribution transformers are similar to graph 7 in Figure 9, i.e. distribution transformers do not show such a hot-spot "overshoot" at step increase in the load current as ON and OF-cooled power transformers do.

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

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

Table 5 – Recommended thermal characteristics for exponential equations

	Distribution transformers	Medium and large power transformers						
	ONAN	ONAN restricted (see Note)	ONAN	ONAF restricted (see Note)	ONAF	OF restricted (see Note)	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	180	210	210	150	150	90	90	90
Time constant τ_w	4	10	10	7	7	7	7	7
NOTE 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 $f_2(t)$ 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 distribution transformers

Figure 9 – The function $f_2(t)$ generated by the values given in Table 5

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

8.2.3 Differential 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 differential equations are represented in block diagram form in Figure 10.

Observe in Figure 10 that the inputs are the load factor K, and the ambient temperature θ_a on the left. The output is the desired hot-spot temperature θ_h on the right. The Laplace variable s is essentially the derivative operator d/dt.

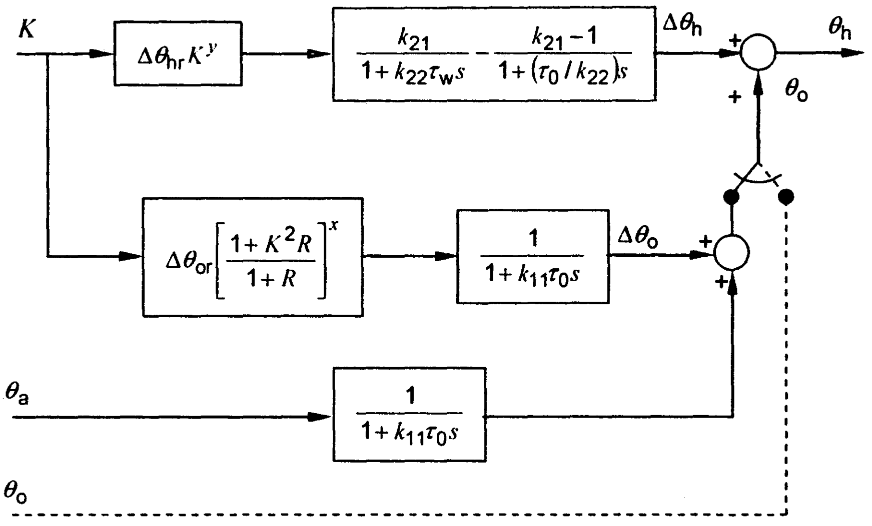


Figure 10 – Block diagram representation of the differential equations

In Figure 10, 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 5.

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 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.

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

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

$$\theta_E = \theta_{ya} + 0{,}01 \times \left[2\left(\theta_{ma\text{-}max} - \theta_{ya}\right)\right]^{1{,}85} \tag{10}$$

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:

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

The ambient temperature used in the calculation examples in Annex E 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 (5) and (6) should be replaced by $\Delta\theta'_{or}$ as follows:

$$\Delta\theta'_{or} = \Delta\theta_{or} + \Delta(\Delta\theta_{or}) \tag{11}$$

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 6 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 (11).

Table 6 – 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 (see Note 2)	1	10	15	20	-

NOTE 1 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.

NOTE 2 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

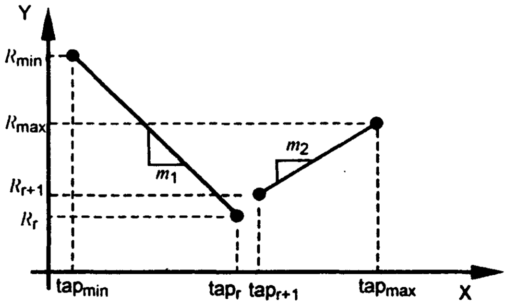
All quantities used in equations (5) and (6) have to be appropriate for the tap at which the transformer is operating.

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

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 11. A linear function is calculated between the rated tap position and the minimum and maximum position.



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

Key

X Tap position

Y Ratio of losses

Figure 11 – 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}):

$$R(tap) = R_{r+1} + (tap - tap_{r+1}) \times m_2 \tag{12}$$

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

$$R(tap) = R_r + (tap - tap_r) \times m_1 \tag{13}$$

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)

Calculation of winding and oil time constant

The winding time constant is as follows:

$$\tau_W = \frac{m_w \times c \times g}{60 \times P_w} \tag{A.1}$$

where

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

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

m_W is the mass of the winding in kg;

c 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 (A.1) is

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

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

where

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

s is the current density in A/mm^2 at the load considered.

The oil time constant is calculated according to the principles in reference [7]. It means that the thermal capacity C for the ONAN and ONAF cooling modes is:

$$C = 0{,}132 \times m_A + 0{,}0882 \times m_T + 0{,}400 \times m_O \tag{A.4}$$

where

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

m_T is the mass of the tank and fittings in kilograms (only those portions that are in contact with heated oil shall be used);

m_O is the mass of oil in kilograms.

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

$$C = 0{,}132 \times (m_A + m_T) + 0{,}580 \times m_O \tag{A.5}$$

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

$$\tau_o = \frac{C \times \Delta\theta_{om} \times 60}{P} \qquad \text{(A.6)}$$

where

τ_o is the average oil time constant in minutes;

$\Delta\theta_{om}$ is the average oil temperature rise above ambient temperature in K at the load considered;

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

Annex B
(informative)

Practical example of the exponential equations method

B.1 Introduction

The curves in Figure 8 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 D.

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

Time period min	Load factor
0 – 190	1,0
190 – 365	0,6
365 – 500	1,5
500 – 710	0,3
710 – 735	2,1
735 – 750	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 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 to 8,7 min (depending on the loading case. The value in Table 5, that is, 7 min will be used in the calculation)

τ_o = 162 to 170 min (depending on the loading case. The value in Table 5, that is, 150 min will be used in the calculation)

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

B.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):

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

From equation (7):

$$f_1(t) = \left(1 - e^{(-t)/(0{,}5 \times 150)}\right)$$

From equation (8):

$$f_2(t) = 2{,}0 \times \left(1 - e^{(-t)/(2{,}0 \times 7)}\right) - (2{,}0 - 1{,}0) \times \left(1 - e^{(-t)/(150/2{,}0)}\right)$$

B.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):

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

From equation (9):

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

B.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

B.6 Time period 500 min to 710 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

B.7 Time period 710 min to 735 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

B.8 Time period 735 min to 750 min

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

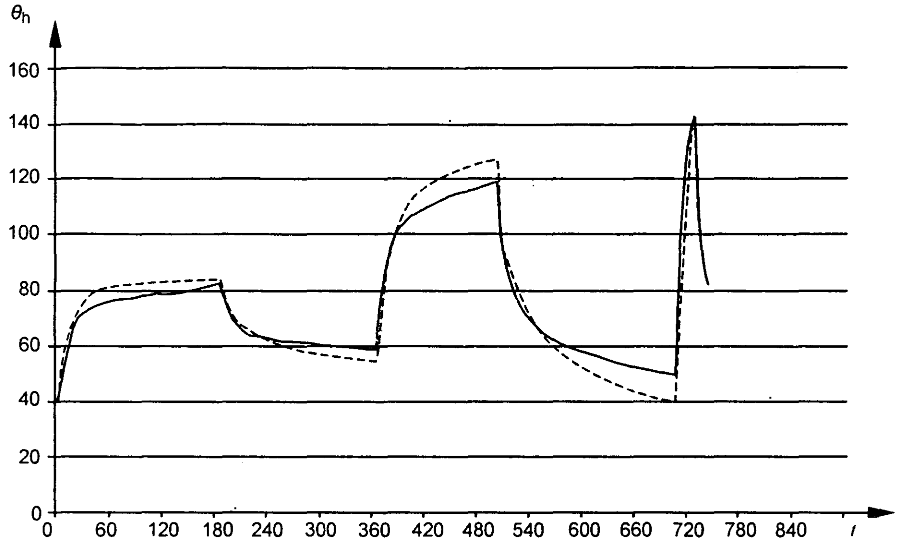
K = 0,0

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

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

B.9 Comparison with measured values

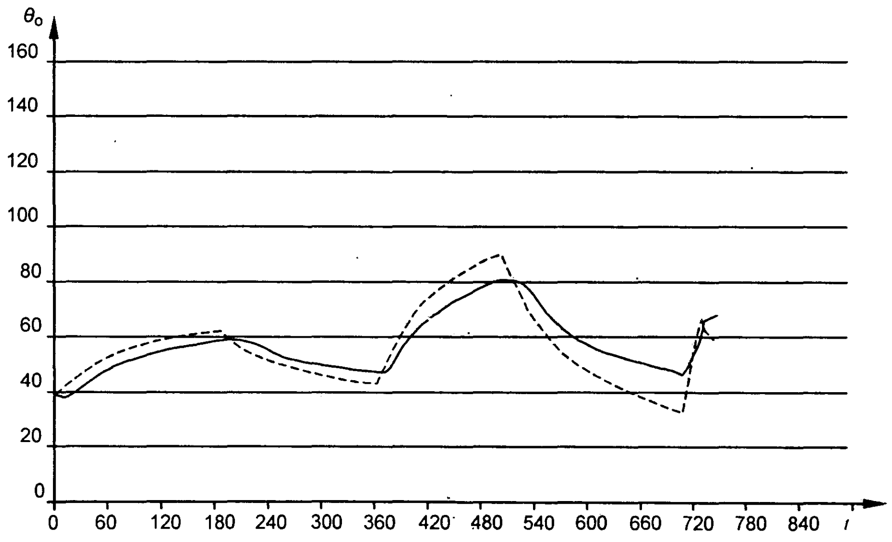
The calculated and measured hot-spot temperature curves are shown in Figure B.1. The corresponding curves for the top-oil temperature are shown in Figure B.2. The numerical values at the end of each load step are shown in Table B.2.



Key

x-axis time t in minutes   y-axis temperature θ_h in °C   —— Measured values   ---- Calculated values

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



Key

x-axis time t in min   y-axis temperature θ_o in °C   —— Measured values   ---- Calculated values

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

Table B.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**	**58,8**	**83,8**	**82,2**
365 / 0,6	44,4	47,8	54,9	58,6
500 / **1,5**	**89,7**	**80,8**	**127,5**	**119,2**
710 / 0,3	35,3	46,8	39,5	49,8
735 / **2,1**	**67,0**	**65,8**	**138,2**	**140,7**
750 / 0,0	59,5	68,2	59,5	82,4

The calculation method in this part of IEC 60076 is intended to yield relevant values, especially at load increase (noted by bold entries in Table B.2).

Annex C
(informative)

Illustration of the differential equations 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

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

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

$$\Delta\theta_h = \Delta\theta_{h1} - \Delta\theta_{h2} \tag{C.2}$$

The two equations are

$$k_{21} \times K^y \times (\Delta\theta_{hr}) = k_{22} \times \tau_w \times \frac{d\Delta\theta_{h1}}{dt} + \Delta\theta_{h1} \tag{C.3}$$

and

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

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

The final equation for the hot-spot temperature is

$$\theta_h = \theta_o + \Delta\theta_h \tag{C.5}$$

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:

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

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

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

and

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

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:

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

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

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

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

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

implying

$$DL_{(n)} = V_{(n)} \times Dt \tag{C.13}$$

and

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

C.5 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 $\tau_o = 150$ min $R = 8$ $y = 1{,}3$ $k_{21} = 2$

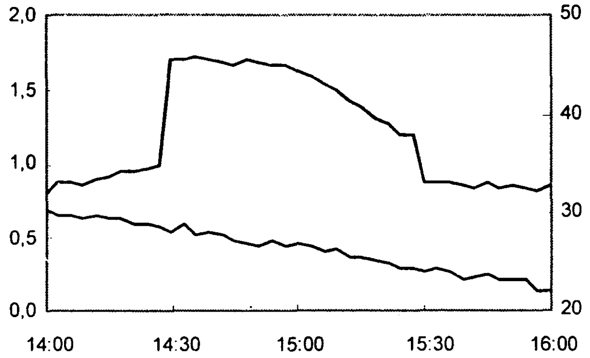
$\Delta\theta_{hr} = 35$ K $\tau_w = 7$ min $x = 0{,}8$ $k_{11} = 0{,}5$ $k_{22} = 2$

2 – Establish the input data

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

Table C.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)

Figure C.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 (C.1), (C.3) and (C.4), resulting in the following values.

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

From equation (C.3), 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 (C.4), 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 (C.6) and (C.7), the top-oil temperature changes as follows:

$$D\theta_{o(1)} = \frac{3}{0{,}5\times150}\left[\left[\frac{1+0{,}87^2\times8}{1+8}\right]^{0{,}8}\times45-[63{,}9-29{,}9]\right] = 0{,}121 \text{ and}$$

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

Similarly, from equation (C.8), the hot-spot temperature rise first term changes as follows:

$$D\Delta\theta_{h1(1)} = \frac{3}{2{,}0\times7}\left(2{,}0\times35\times0{,}87^{1{,}3}-53{,}2\right) = 1{,}12 \text{ and}$$

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

Similarly, from equation (C.9), the hot-spot temperature rise second term changes as follows:

$$D\Delta\theta_{h2(1)} = \frac{3}{(1/2{,}0)\times150}\left((2{,}0-1)\times35\times0{,}87^{1{,}3}-26{,}6\right) = 0{,}104 \text{ and}$$

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

Then the total hot-spot temperature rise, from equation (C.10) 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 (C.11)

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

The loss of life L over this time step is given by equation (C.13):

$$DL_{(1)} = V_{(1)}\times Dt = \left[e^{\frac{15\,000}{110+273}-\frac{15\,000}{\theta_{h(1)}+273}}\right]\times3 = 0{,}42 \text{ min}$$

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

The total loss of life to this point is:

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

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.

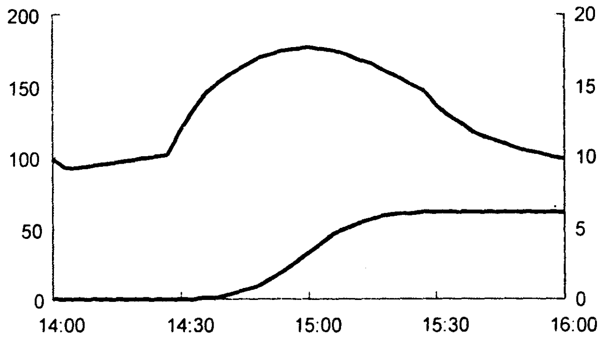
5 – Tabulate the output data

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

Table C.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	1402	0,97
17	51	14:51	171,5	2076	1,44
18	54	14:54	173,6	2871	1,99
19	57	14:57	175,7	3796	2,64
20	60	15:00	176,1	4754	3,30
21	63	15:03	175,6	5675	3,94
22	66	15:06	173,8	6480	4,50
23	69	15:09	171,5	7156	4,97
24	72	15:12	167,8	7667	5,32
25	75	15:15	164,3	8055	5,59
26	78	15:18	160,1	8335	5,79
27	81	15:21	156,0	8534	5,93
28	84	15:24	151,1	8668	6,02
29	87	15:27	146,8	8761	6,08
30	90	15:30	136,9	8800	6,11
31	93	15:33	129,1	8819	6,12
32	96	15:36	122,8	8830	6,13
33	99	15:39	117,5	8836	6,14
34	102	15:42	113,1	8840	6,14
35	105	15:45	110,0	8843	6,14
36	108	15:48	106,6	8846	6,14
37	111	15:51	104,5	8847	6,14
38	114	15:54	102,6	8849	6,14
39	117	15:57	100,4	8850	6,15
40	120	16:00	99,3	8851	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)

Figure C.2 – Plotted output data for the example

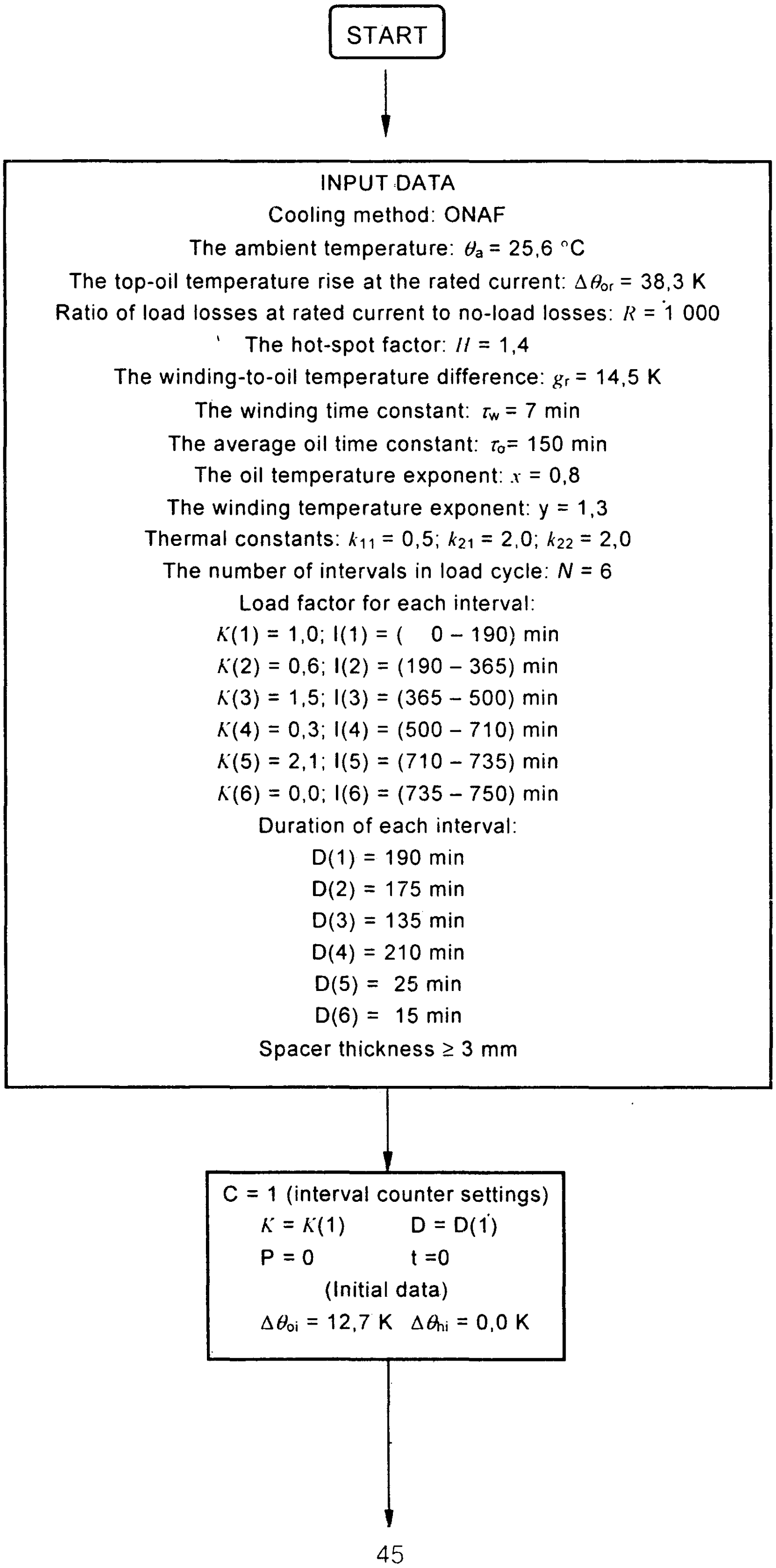
Since the elapsed time of the plot is 2 h or 0,083 3 days, and the loss of life is 6,15 days, the relative loss of life during this overload is 6,15/0,083 3 = 74 times normal. This is not serious if there are otherwise long periods of time (usually the case) at relatively low hot-spot temperatures.

C.6 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 (C.8), (C.9) and (C.10) and added directly to the measured top-oil temperature data, at each time step. See the dashed line path in Figure 10.

Annex D
(informative)

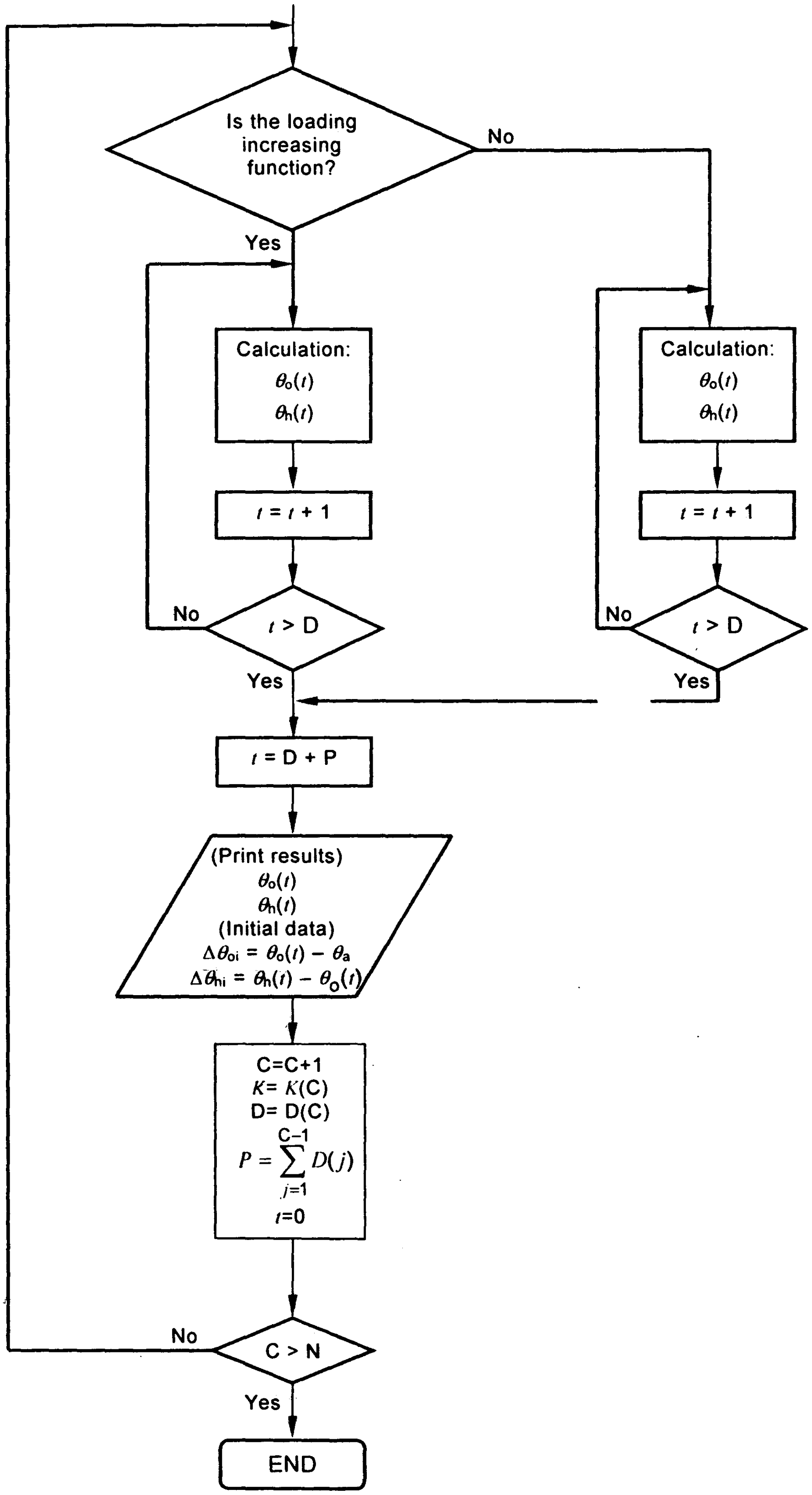
Flowchart, based on the example in Annex B



INPUT DATA

Cooling method: ONAF
The ambient temperature: $\theta_a = 25{,}6$ °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: $\tau_w = 7$ min
The average oil time constant: $\tau_o = 150$ 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 – 710) min
$K(5) = 2{,}1$; I(5) = (710 – 735) min
$K(6) = 0{,}0$; I(6) = (735 – 750) min
Duration of each interval:
D(1) = 190 min
D(2) = 175 min
D(3) = 135 min
D(4) = 210 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 $\Delta\theta_{hi} = 0{,}0$ K


Is the loading increasing function?
No
Yes
Calculation:
$\theta_o(t)$
$\theta_h(t)$
$t = t + 1$
No
$t > D$
Yes
Calculation:
$\theta_o(t)$
$\theta_h(t)$
$t = t + 1$
No
$t > D$
Yes
$t = D + P$
(Print results)
$\theta_o(t)$
$\theta_h(t)$
(Initial data)
$\Delta\theta_{oi} = \theta_o(t) - \theta_a$
$\Delta\theta_{hi} = \theta_h(t) - \theta_o(t)$
C=C+1
$K = K(C)$
D= D(C)
$P = \sum_{j=1}^{C-1} D(j)$
$t=0$
No
C > N
Yes
END

Annex E
(informative)

Example of calculating and presenting overload data

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

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

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

		Distribution transformers	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. The equations (5), (6), (7), (8) and (9) from 8.2.2 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 $\Delta\theta_{hi}$ can be determined with $f_1(t) = 0$, $f_2(t) = 0$ and $f_3(t) = 1$, with $t \rightarrow \infty$.

When the hot-spot temperature is known, the relative ageing can be calculated with equation (2) of 6.2. With equation (4) of 6.3 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 E.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

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

The values after $t = 1\,440$ min from start:

$K_1 = 0{,}8$
$f_3(t{=}1410) = 1{,}6\text{E} - 07$
$\theta_o(t{=}1410) = 58{,}7$ °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 E.2.

Table E.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

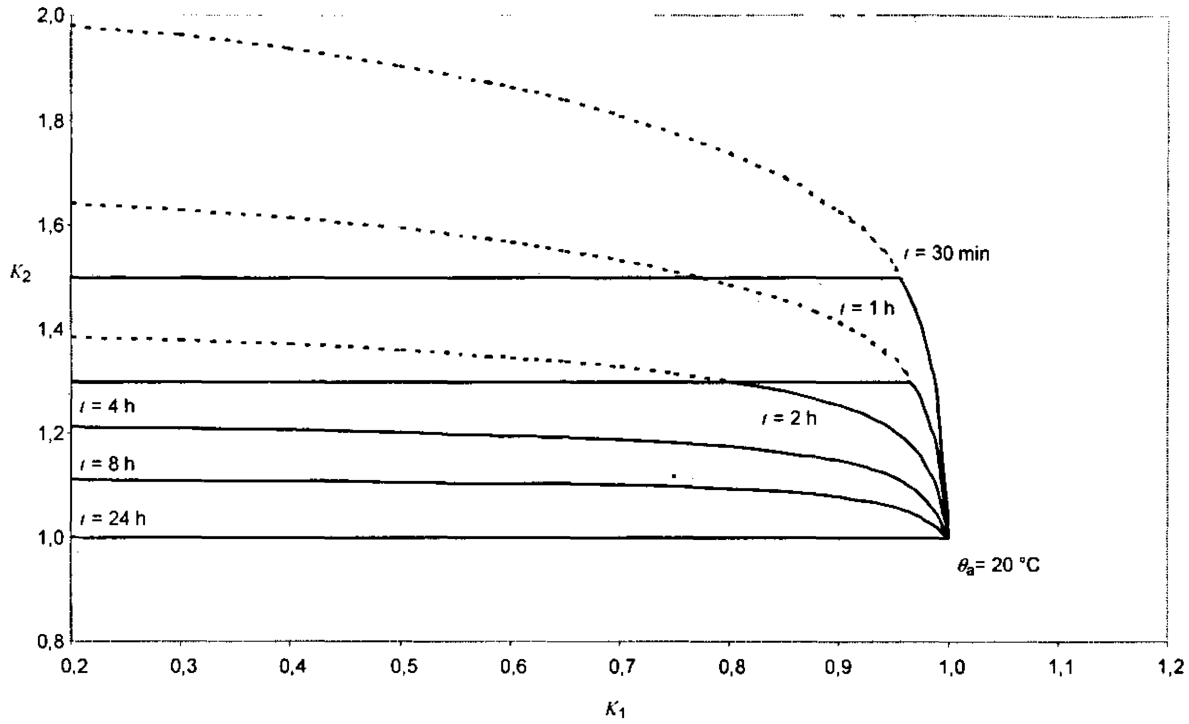
K_1	0,25	0,5	0,7	0,8	0,9	1,0	1,1	1,2	1,3	1,4	1,5
K_2											
0,7	0.001	0.004	0,02								
	33	38	45								
0,8	0.001	0.004	0,02	0,07							
	38	43	51	55							
0,9	0.001	0,004	0,03	0,07	0,25						
	43	49	56	61	66						
1,0	0.001	0,004	0,03	0,08	0,26	1,00					
	49	55	62	67	72	78					
1,1	0.001	0.01	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 1 410 min

NOTE The italic style values in Table E.2 show the results of the calculation, disregarding the limits from Table 4.

The data can also be presented in a graph. In Figure E.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 in Figure E.1 show the results of the calculation, disregarding the limits from Table 4.

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

MGIPF—351 Deptt. of BIS/2009—3.11.2009—300 Books.

Bureau of Indian Standards

BIS is a statutory institution established under the *Bureau of Indian Standards Act*, 1986 to promote harmonious development of the activities of standardization, marking and quality certification of goods and attending to connected matters in the country.

Copyright

BIS has the copyright of all its publications. No part of the these publications may be reproduced in any form without the prior permission in writing of BIS. This does not preclude the free use, in the course of implementing the standard, of necessary details, such as symbols and sizes, type or grade designations. Enquiries relating to copyright be addressed to the Director (Publications), BIS.

Review of Indian Standards

Amendments are issued to standards as the need arises on the basis of comments. Standards are also reviewed periodically; a standard alongwith amendments is reaffirmed when such review indicates that no changes are needed; if the review indicates that changes are needed, it is taken up for revision. Users of Indian Standards should ascertain that they are in possession of the latest amendments or edition by referring to the latest issue of 'BIS Catalogue' and 'Standards: Monthly Additions'.

This Indian Standard has been developed from Doc No.: ETD 16 (5991).

Amendments Issued Since Publication

Amend No.	Date of Issue	Text Affected

BUREAU OF INDIAN STANDARDS

Headquarters:

Manak Bhavan, 9 Bahadur Shah Zafar Marg, New Delhi 110002
Telephones: 2323 0131, 2323 3375, 2323 9402 *Website*: www.bis.org.in

Regional Offices:

			Telephones
Central	:	Manak Bhavan, 9 Bahadur Shah Zafar Marg NEW DELHI 110002	2323 7617 2323 3841
Eastern	:	1/14 C.I.T. Scheme VII M, V.I.P. Road, Kankurgachi KOLKATA 700054	2337 8499, 2337 8561 2337 8626, 2337 9120
Northern	:	SCO 335-336, Sector 34-A, CHANDIGARH 160022	260 3843 260 9285
Southern	:	C.I.T. Campus, IV Cross Road, CHENNAI 600113	2254 1216, 2254 1442 2254 2519, 2254 2315
Western	:	Manakalaya, E9 MIDC, Marol, Andheri (East) MUMBAI 400093	2832 9295, 2832 7858 2832 7891, 2832 7892

Branches : AHMEDABAD. BANGALORE. BHOPAL. BHUBANESHWAR. COIMBATORE. DEHRADUN. FARIDABAD. GHAZIABAD. GUWAHATI. HYDERABAD. JAIPUR. KANPUR. LUCKNOW. NAGPUR. PARWANOO. PATNA. PUNE. RAJKOT. THIRUVANANTHAPURAM. VISAKHAPATNAM.

Printed by the Manager, Govt. of India Press, Faridabad