IEC 60076-7
Edition 2.0  2018-01

INTERNATIONAL
STANDARD

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

IEC 60076-7:2018
https://standards.itech.ai/catalog/standards/sist/0e204cc0-4cfd-4090-84c6-6dbb71e398a1/iec-60076-7-2018

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.180

© Registered trademark of the International Electrotechnical Commission

Warning! Make sure that you obtained this publication from an authorized distributor.
CONTENTS

FOREWORD ............................................................................................................................................. 6
INTRODUCTION ........................................................................................................................................... 8
1 Scope ....................................................................................................................................................... 8
2 Normative references ............................................................................................................................. 9
3 Terms and definitions ............................................................................................................................. 9
4 Symbols and abbreviations .................................................................................................................... 11
5 Effect of loading beyond nameplate rating ........................................................................................... 13
  5.1 General ............................................................................................................................................... 13
  5.2 General consequences ....................................................................................................................... 13
  5.3 Effects and hazards of short-time emergency loading ..................................................................... 14
  5.4 Effects of long-time emergency loading ......................................................................................... 15
  5.5 Transformer size ................................................................................................................................ 15
6 Relative ageing rate and transformer insulation life ............................................................................... 15
  6.1 General ............................................................................................................................................... 15
  6.2 Insulation life ....................................................................................................................................... 16
  6.3 Relative ageing rate ........................................................................................................................... 20
  6.4 Loss-of-life calculation ....................................................................................................................... 21
7 Limitations .............................................................................................................................................. 21
  7.1 Temperature limitations ..................................................................................................................... 21
  7.2 Current limitations ............................................................................................................................ 22
  7.3 Specific limitations for small transformers ..................................................................................... 23
    7.3.1 Current and temperature limitations ......................................................................................... 23
    7.3.2 Accessory and other considerations ......................................................................................... 23
    7.3.3 Indoor transformers .................................................................................................................... 23
    7.3.4 Outdoor ambient conditions ...................................................................................................... 23
  7.4 Specific limitations for medium power transformers ........................................................................ 23
    7.4.1 Current and temperature limitations ......................................................................................... 23
    7.4.2 Accessory, associated equipment and other considerations .................................................... 23
    7.4.3 Short-circuit withstand requirements ........................................................................................ 24
    7.4.4 Voltage limitations ....................................................................................................................... 24
  7.5 Specific limitations for large power transformers ............................................................................ 24
    7.5.1 General ......................................................................................................................................... 24
    7.5.2 Current and temperature limitations ......................................................................................... 24
    7.5.3 Accessory, equipment and other considerations ....................................................................... 24
    7.5.4 Short-circuit withstand requirements ........................................................................................ 25
    7.5.5 Voltage limitations ....................................................................................................................... 25
8 Determination of temperatures .............................................................................................................. 25
  8.1 Hot-spot temperature rise in steady state .......................................................................................... 25
    8.1.1 General ......................................................................................................................................... 25
    8.1.2 Calculation of hot-spot temperature rise from normal heat-run test data ............................... 25
    8.1.3 Direct measurement of hot-spot temperature rise ..................................................................... 26
    8.1.4 Hot-spot factor ............................................................................................................................ 29
  8.2 Top-oil and hot-spot temperatures at varying ambient temperature and load conditions .............. 31
    8.2.1 General ......................................................................................................................................... 31
8.2.2 Exponential equations solution .............................................................. 33
8.2.3 Difference equations solution ............................................................... 37
8.3 Ambient temperature................................................................................. 39
8.3.1 Outdoor air-cooled transformers ............................................................ 39
8.3.2 Correction of ambient temperature for transformer enclosure ................. 39
8.3.3 Water-cooled transformers .................................................................... 40
9 Influence of tap-changers ........................................................................... 40
9.1 General....................................................................................................... 40
9.2 Load loss .................................................................................................... 41
9.3 Ratio of losses ............................................................................................. 41
9.4 Load factor ................................................................................................ 41
Annex A (informative) Insulation life expectancy and relative ageing rate considering oxygen and water effect ................................................................. 42
A.1 Insulation life expectancy .......................................................................... 42
A.2 Relative ageing rate considering oxygen and water effect ......................... 44
Annex B (informative) Core temperature ......................................................... 47
B.1 General ...................................................................................................... 47
B.2 Core hot-spot locations ............................................................................. 47
Annex C (informative) Specification of loading beyond rated power ................. 48
Annex D (informative) Description of $Q$, $S$, and $H$ factors ......................... 50
Annex E (informative) Calculation of winding and oil time constant .................. 53
Annex F (informative) Thermal model parameters .......................................... 55
F.1 General ...................................................................................................... 55
F.2 Thermal constant estimation: experimental approach .................................. 55
F.3 Dynamic thermal modelling: further development ...................................... 57
Annex G (informative) Oil and winding exponents .......................................... 58
G.1 General ...................................................................................................... 58
G.2 Historical background ............................................................................. 58
G.3 Theoretical approach .............................................................................. 60
G.4 Extended temperature rise test approach ................................................. 62
Annex H (informative) Practical example of the exponential equations method .... 64
H.1 General ...................................................................................................... 64
H.2 Time period 0 min to 190 min .................................................................. 65
H.3 Time period 190 min to 365 min ............................................................... 65
H.4 Time period 365 min to 500 min ............................................................... 66
H.5 Time period 500 min to 705 min ............................................................... 66
H.6 Time period 705 min to 730 min ............................................................... 67
H.7 Time period 730 min to 745 min ............................................................... 67
H.8 Comparison with measured values ......................................................... 68
Annex I (informative) Application of the difference equation solution method ...... 70
I.1 General ...................................................................................................... 70
I.2 Example ..................................................................................................... 70
I.3 Use of measured top-oil temperature ......................................................... 75
Annex J (informative) Flowchart, based on the example in Annex H .................. 76
Annex K (informative) Example of calculating and presenting overload data ....... 78
Annex L (informative) Geomagnetic induced currents ...................................... 82
L.1 Background ............................................................................................... 82
L.2 GIC capability of power transformers [54],[55] ................................................. 82
Annex M (informative) Alternative oils ................................................................. 84
Bibliography ............................................................................................................. 85

Figure 1 – Structural formula of cellulose ................................................................. 16
Figure 2 – Correlation between tensile strength and DP value ................................. 17
Figure 3 – Accelerated ageing in mineral oil at 140 °C, oxygen and moisture contents maintained at < 6 000 ppm and 0.5 %, respectively .................................................. 18
Figure 4 – Expected life for non-thermally upgraded paper and its dependence upon moisture, oxygen and temperature ......................................................... 19
Figure 5 – Expected life for thermally upgraded paper and its dependence upon moisture, oxygen and temperature ................................................................. 20
Figure 6 – Thermal diagram .................................................................................... 26
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 ( ) ............................................................... 27
Figure 8 – Coil edges, where the sensors should be located in the edge with the higher calculated temperature rise ................................................................. 28
Figure 9 – Temperature rises above top-oil temperature at the end of an 8 h thermal no-load test at 110 % supply voltage ................................................................. 29
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 ................................................................. 30
Figure 11 – Top view section of a rectangular winding with “collapsed cooling duct arrangement” under the yokes ................................................................. 31
Figure 12 – Block diagram representation of the differential equations ..................... 32
Figure 13 – Temperature responses to step changes in the load current .................... 34
Figure 14 – The function $\Delta \theta_h(t)/\Delta \theta_H$ generated by the values given in Table 4 ................................................................. 37
Figure 15 – Principle of losses as a function of the tap position .................................. 41
Figure A.1 – Arrhenius plot for an ageing process .................................................... 43
Figure F.1 – Hot-spot and top-oil overall model ........................................................ 57
Figure G.1 – Extended temperature rise test ............................................................. 62
Figure G.2 – Transformer exponent estimation plots .................................................... 63
Figure H.1 – Hot-spot temperature response to step changes in the load current ......... 68
Figure H.2 – Top-oil temperature response to step changes in the load current ......... 68
Figure I.1 – Plotted input data for the example ............................................................ 72
Figure I.2 – Plotted output data for the example .......................................................... 75
Figure K.1 – OF large power transformers: permissible duties for normal loss of life ........ 81
Figure L.1 – GIC flow into a power transformer .......................................................... 82

Table 1 – Relative ageing rates due to hot-spot temperature .................................... 21
Table 2 – Maximum permissible temperature limits applicable to loading beyond nameplate rating ................................................................. 22
Table 3 – Recommended current limits applicable to loading beyond nameplate rating .... 23
Table 4 – Recommended thermal characteristics for exponential equations ............... 36
Table 5 – Correction for increase in ambient temperature due to enclosure .............. 40
Table A.1 – Activation energy ($E_A$) and environment factor ($A$) for oxidation, hydrolysis .... 43
Table A.2 – Expected life of paper under various conditions .........................................................44
Table A.3 – Relative ageing rates due to hot-spot temperature, oxygen and moisture for non-upgraded paper insulation ..................................................................................................45
Table A.4 – Relative ageing rates due to hot-spot temperature, oxygen and moisture for upgraded paper insulation ......................................................................................................46
Table H.1 – Load steps of the 250 MVA transformer ....................................................................64
Table H.2 – Temperatures at the end of each load step ................................................................69
Table I.1 – Input data for example ...............................................................................................71
Table I.2 – Output data for the example ......................................................................................74
Table K.1 – Example characteristics related to the loadability of transformers .........................78
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 ............................................................80
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.

2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.

3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.

4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.

5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.

6) All users should ensure that they have the latest edition of this publication.

7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.

8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

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:

<table>
<thead>
<tr>
<th>FDIS</th>
<th>Report on voting</th>
</tr>
</thead>
<tbody>
<tr>
<td>14/933/FDIS</td>
<td>14/942/RVD</td>
</tr>
</tbody>
</table>

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,
A paper is considered as thermally upgraded if it meets the life criteria defined in ANSI/IEEE C57.100 [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:

\[
\text{Time (h)} = c \left( \frac{15 000}{\theta + 273} - 28,082 \right) = 65 000 \times c \left( \frac{15 000}{\theta + 273} - \frac{15 000}{110 + 273} \right)
\]

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

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

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

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

### 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.