BS IEC 60076-7:2018

BSI Standards Publication

Power transformers

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

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

National foreword

This British Standard is the UK implementation of IEC 60076-7:2018. It supersedes BS IEC 60076-7:2005, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee PEL/14, Power transformers.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

© The British Standards Institution 2018
Published by BSI Standards Limited 2018

ISBN 978 0 580 89555 5

ICS 29.180

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 28 February 2018.

Amendments/corrigenda issued since publication

Date	Text affected

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

IEC 60076-7

Edition 2.0 2018-01

INTERNATIONAL STANDARD

colour inside

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

INTERNATIONAL
ELECTROTECHNICAL
COMMISSION

ICS 29.180

ISBN 978-2-8322-5082-2

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

® Registered trademark of the International Electrotechnical Commission

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

CONTENTS

FOREWORD 6
INTRODUCTION 8
1 Scope 9
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

AVA Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

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

AVA Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

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 $\Delta\theta_h(t)/\Delta\theta_{hr}$ 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

AVA Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

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

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

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

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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;

AVA Documents Document Sharing Hub

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

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

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

FDIS	Report on voting
14/933/FDIS	14/942/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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

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

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

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.

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

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.

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

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,

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

dicyandiamide). A paper is considered as thermally upgraded if it meets the life criteria defined in ANSI/IEEE C57.100 [1][1]; 50 % retention in tensile strength after 65 000 h in a sealed tube at 110 °C or any other time/temperature combination given by the equation:

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

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

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

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

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

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

3.16
directed oil flow
OD
flow indicating that the principal part of the pumped oil from heat exchangers or radiators is forced to flow through the windings

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

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

4 Symbols and abbreviations

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

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

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

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

AVA Documents
Document Sharing Hub

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

5 Effect of loading beyond nameplate rating

5.1 General

The normal life expectancy is a conventional reference basis for continuous duty under design ambient temperature and rated operating conditions. The application of a load in excess of nameplate rating and/or an ambient temperature higher than design ambient temperature involves a degree of risk and accelerated ageing. It is the purpose of this part of IEC 60076 to identify such risks and to indicate how, within limitations, transformers may be loaded in excess of the nameplate rating. These risks can be reduced by the purchaser clearly specifying the maximum loading conditions and the supplier taking these into account in the transformer design.

5.2 General consequences

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

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

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

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

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

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

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

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

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

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

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

As a consequence, there will be a risk of premature failure associated with the increased currents and temperatures. This risk may be of an immediate short-term character or come from the cumulative effect of thermal ageing of the insulation in the transformer over many years.

5.3 Effects and hazards of short-time emergency loading

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

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

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

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

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

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

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

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

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

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

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

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

5.4 Effects of long-time emergency loading

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

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

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

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

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

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

5.5 Transformer size

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

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

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

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

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

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

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

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

6 Relative ageing rate and transformer insulation life

6.1 General

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

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

AVA Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

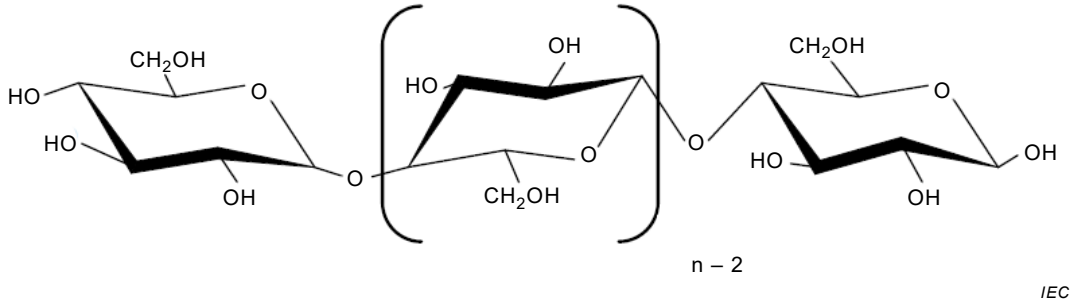


Figure 1 – Structural formula of cellulose

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

6.2 Insulation life

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

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

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

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

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

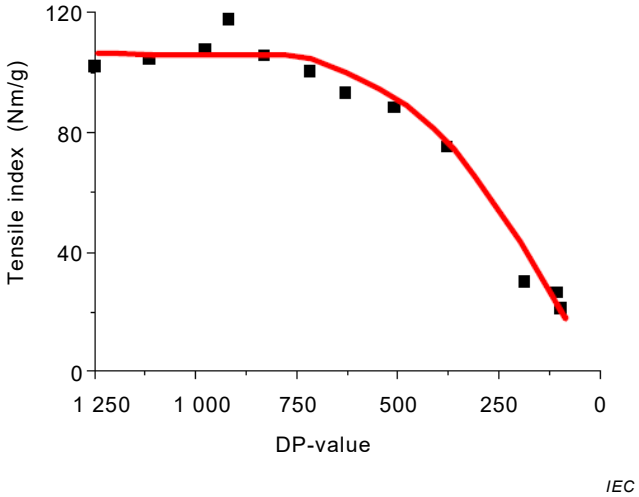


Figure 2 – Correlation between tensile strength and DP value

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

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

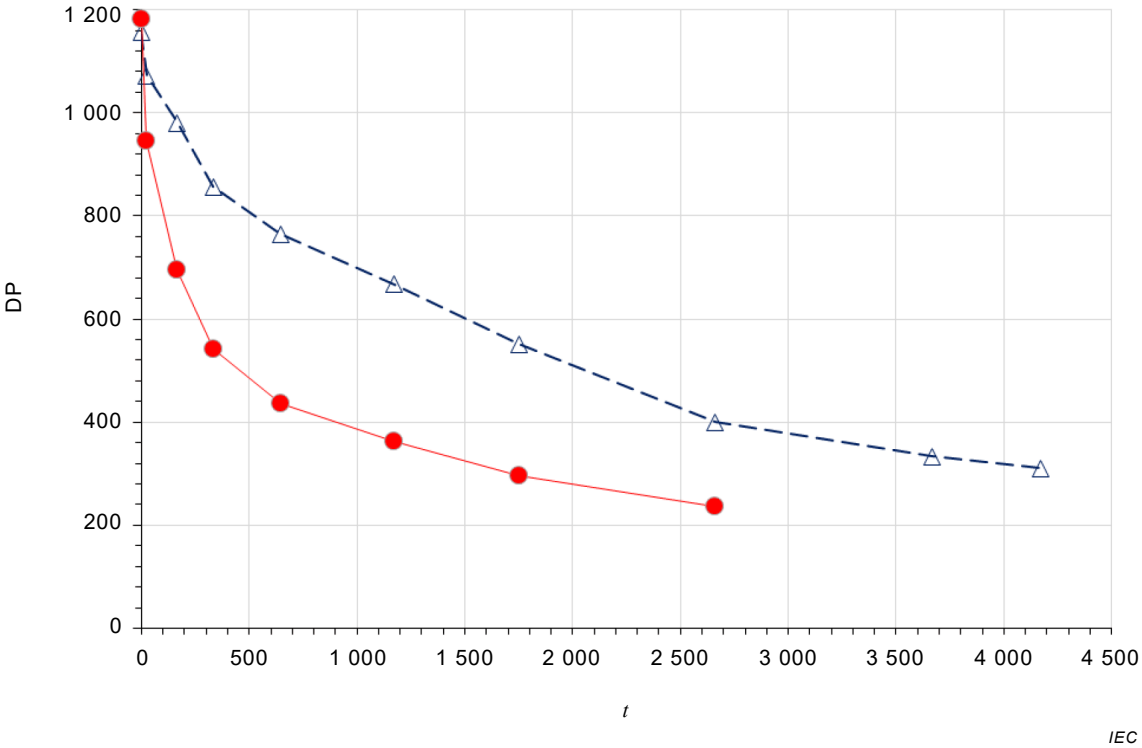
Annex A gives further elaboration of the paper ageing theory providing a mathematical methodology for estimation of the expected insulation life considering different ageing factors such as moisture, oxygen and temperature. The corresponding results for the non-thermally and thermally upgraded paper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

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

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

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

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

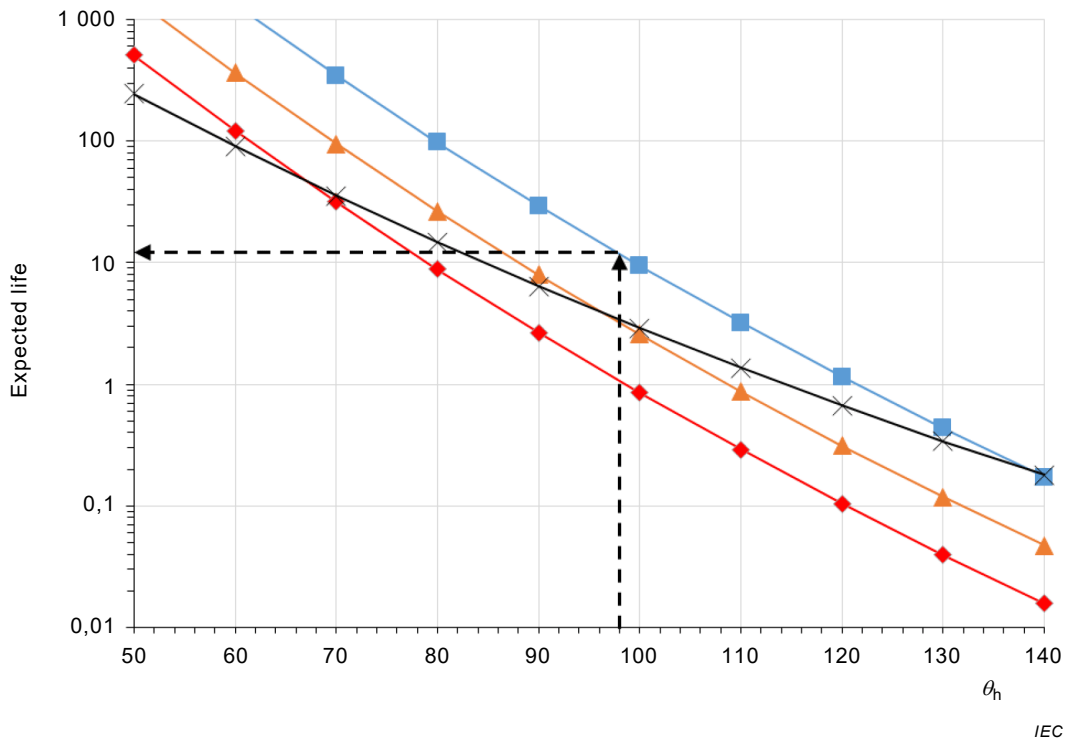


Key

DP	degree of polymerization	*t*	time (h)
Δ	values for thermally upgraded paper	•	values for non-thermally upgraded paper

Figure 3 – Accelerated ageing in mineral oil at 140 °C, oxygen and moisture contents maintained at < 6 000 ppm and 0,5 %, respectively

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018



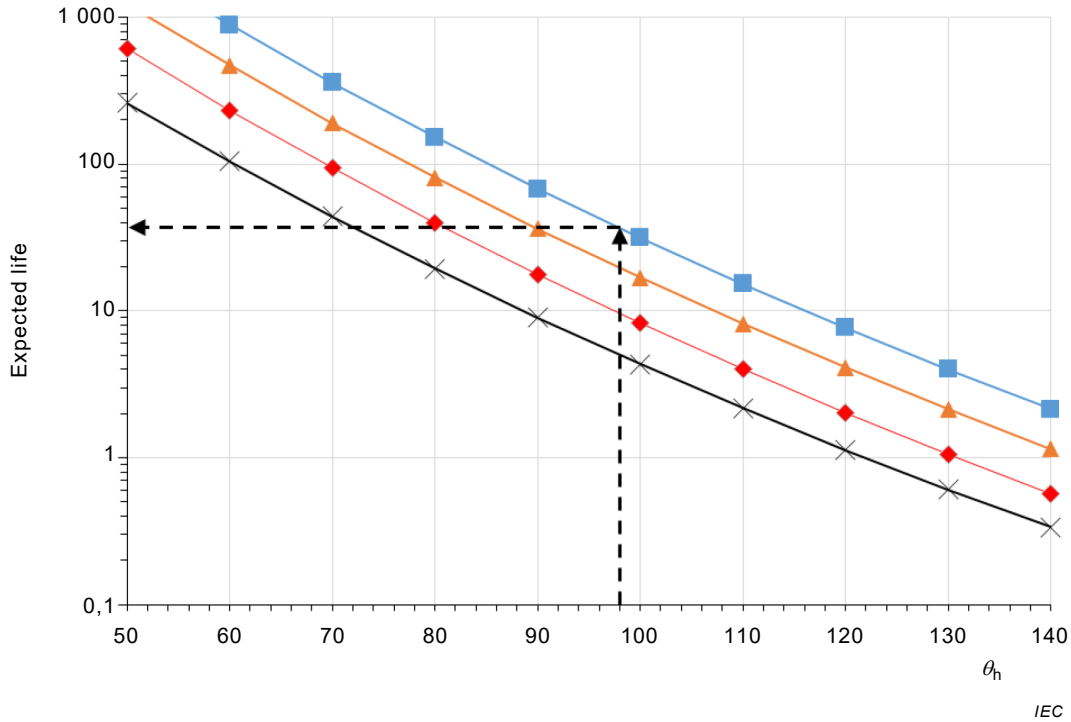
Key

expected life (years) θ_h hot-spot temperature (°C) □ 0,5 % moisture, low oxygen

Δ 1,5 % moisture, low oxygen ◊ 3,5 % moisture, low oxygen × 0,5 % moisture, high oxygen

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

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018



Key

expected life (years)		θ_h	hot-spot temperature (°C)	□	0,5 % moisture, low oxygen
Δ	1,5 % moisture, low oxygen	◊	3,5 % moisture, low oxygen	×	0,5 % moisture, high oxygen

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

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

6.3 Relative ageing rate

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

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

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

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

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

AVA Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018

where

θ_h is the hot-spot temperature in °C.

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

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

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

6.4 Loss-of-life calculation

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

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

where

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

t_n is the nth time interval;

n is the number of each time interval;

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

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

7 Limitations

7.1 Temperature limitations

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

AVA Documents Document Sharing Hub

Full document details: BS IEC 60076-7:2018

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

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

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

7.2 Current limitations

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

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

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

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

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

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

7.3 Specific limitations for small transformers

7.3.1 Current and temperature limitations

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

7.3.2 Accessory and other considerations

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

7.3.3 Indoor transformers

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

7.3.4 Outdoor ambient conditions

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

7.4 Specific limitations for medium power transformers

7.4.1 Current and temperature limitations

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

7.4.2 Accessory, associated equipment and other considerations

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

AVA Documents
Document Sharing Hub

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

7.4.3 Short-circuit withstand requirements

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

7.4.4 Voltage limitations

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

7.5 Specific limitations for large power transformers

7.5.1 General

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

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

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

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

7.5.2 Current and temperature limitations

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

7.5.3 Accessory, equipment and other considerations

Refer to 7.4.2.

Documents
Document Sharing Hub

Full document details: BS IEC 60076-7:2018

7.5.4 Short-circuit withstand requirements

Refer to 7.4.3.

7.5.5 Voltage limitations

Refer to 7.4.4.

8 Determination of temperatures

8.1 Hot-spot temperature rise in steady state

8.1.1 General

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

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

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

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

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

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

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

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

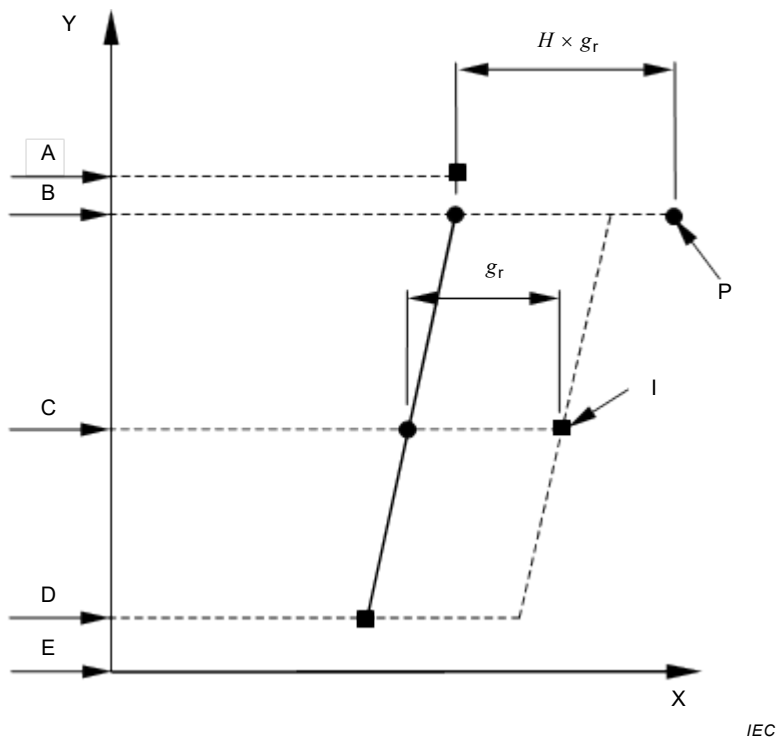
a) The oil temperature inside the tank increases linearly from bottom to top, whatever the cooling mode.

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

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

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

Documents
Document Sharing Hub
Full document details: BS IEC 60076-7:2018



Key

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

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

C Temperature of the average oil in the tank

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

E Bottom of the tank

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

H Hot-spot factor

P Hot-spot temperature

I Average winding temperature determined by resistance measurement

x-axis Temperature

y-axis Relative positions

■ measured point; ● calculated point

Figure 6 – Thermal diagram

8.1.3 Direct measurement of hot-spot temperature rise

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

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

AVA Documents
Document Sharing Hub