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Part 7: Loading guide for liquid-immersed power transformers

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Introduction

This draft standard is based on international discussions in which the UK has taken an active part. Your comments on this draft are welcome and will assist in the preparation of the consequent standard. There is a high probability that this text could be adopted by CENELEC as a reference document for harmonization or as a European Standard. Recipients of this draft are requested to comment on the text bearing in mind this possibility.

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1	2	(3)	4	5	(6)	(7)
MB	Clause No./ Subclause No./Annex (e.g. 3.1)	Paragraph/ Figure/ Table/Note	Type of comment	Comment (justification for change) by the MB	Proposed change by the MB	Secretariat observations on each comment submitted
	3.1	Definition 1	ed	Definition is ambiguous and needs clarifying.	Amend to read '...so that the mains connector to which no connection...'	
	6.4	Paragraph 2	te	The use of the UV photometer as an alternative cannot be supported as serious problems have been encountered in its use in the UK.	Delete reference to UV photometer.	

IEC/TC or SC: 14		Project number IEC 60076-7 Ed.2	
Title of TC/SC: Power transformers		Date of circulation 2015-01-16	Closing date for comment 2015-03-27
Also of interest to the following committees		Supersedes document 14/735/DC & 14/743/INF, issued with 14/806/RR	
Proposed horizontal standard ☐ Other TC/SCs are requested to indicate their interest, if any, in this CD to the TC/SC secretary			
Functions concerned: ☐ Safety ☐ EMC ☐ Environment ☐ Quality assurance			
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Title:

IEC 60076-7: Power transformers – Part 7: Loading guide for liquid-immersed power transformers

Introductory note

This CD is circulated for a 2,5 months period to allow MT 60076-7 to examine the comments at its next meeting on 2015-04-16.

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

POWER TRANSFORMERS –

Part 7: Loading guide for liquid-immersed power transformers

FOREWORD

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

This standard cancels and replaces IEC 60076-7 Ed.1 published in 2005. This second edition constitutes a technical revision of the material given in IEC 60076-7 Ed.1. Details of the changes are given in the introduction.

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

FDIS	Report on voting
XX/XX/FDIS	XX/XX/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.

- 53 This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.
- 54 The committee has decided that the contents of this publication will remain unchanged until
55 the stability date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data
56 related to the specific publication. At this date, the publication will be
- 57 • reconfirmed,
 - 58 • withdrawn,
 - 59 • replaced by a revised edition, or
 - 60 • amended.

61

62 The National Committees are requested to note that for this publication the stability date
63 is 2016.

64 THIS TEXT IS INCLUDED FOR THE INFORMATION OF THE NATIONAL COMMITTEES AND WILL BE DELETED
65 AT THE PUBLICATION STAGE.

66

67

INTRODUCTION

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

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

75 This part of IEC 60076 gives mathematical models for judging the consequence of different
76 loadings, with different temperatures of the cooling medium, and with transient or cyclical
77 variation with time. The models provide for the calculation of operating temperatures in the
78 transformer, particularly the temperature of the hottest part of the winding. This hot-spot
79 temperature is, in turn, used for evaluation of a relative value for the rate of thermal ageing
80 and the percentage of life consumed in a particular time period. The modelling refers to small
81 transformers, here called distribution transformers and to power transformers.

82 A major change from IEC 60076-7:2005 is the extensive work on the paper degradation that
83 has been carried out indicating that the aging may be described by combination of the
84 oxidation, hydrolysis and pyrolysis. Also, providing possibility to estimate the expected
85 insulation life considering different ageing factors, i.e. moisture, oxygen and temperature, and
86 more realistic service scenarios. The temperature and current limits are reviewed and the
87 maximum core temperature is recommended. The use of fibre optic temperature sensors has
88 become a standard practice, however, the number of installed sensors per transformer highly
89 varies. This issue and the description of Q, S and H factors are now considered as well. The
90 thermal models are revised and rewritten in generally applicable mathematical form. The
91 geomagnetic induced currents are shortly discussed and corresponding temperature limits are
92 suggested.

93 This part of IEC 60076 further presents recommendations for limitations of permissible
94 loading according to the results of temperature calculations or measurements. These
95 recommendations refer to different types of loading duty – continuous loading, normal cyclic
96 undisturbed loading or temporary emergency loading. The recommendations refer to
97 distribution transformers, to medium power transformers and to large power transformers.
98 Clauses 1 to 7 contain definitions, common background information and specific limitations for
99 the operation of different categories of transformers.

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

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

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

104

POWER TRANSFORMERS –

Part 7: Loading guide for liquid-immersed power transformers

1 Scope

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

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

2 Normative references

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

IEC 60076-1, *Power transformers – Part 1: General*

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

IEC 60076-5, *Power transformers – Part 5: Ability to withstand short circuit*

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

3 Terms and definitions

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

3.1

distribution transformer

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

3.2

medium power transformer

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

3.3

large power transformer

power transformer exceeding the limits specified in 3.2

3.4

cyclic loading

loading with cyclic variations (the duration of the cycle usually being 24 h) which is regarded in terms of the accumulated amount of ageing that occurs during the cycle. The cyclic loading may either be a normal loading or a long-time emergency loading

3.5**normal cyclic loading**

higher ambient temperature or a higher-than-rated load current is applied during part of the cycle, but, from the point of view of relative thermal ageing rate (according to the mathematical model), this loading is equivalent to the rated load at normal ambient temperature. This is achieved by taking advantage of low ambient temperatures or low load currents during the rest of the load cycle. For planning purposes, this principle can be extended to provide for long periods of time whereby cycles with relative thermal ageing rates greater than unity are compensated for by cycles with thermal ageing rates less than unity

3.6**long-time emergency loading**

loading resulting from the prolonged outage of some system elements that will not be reconnected before the transformer reaches a new and higher steady-state temperature

3.7**short-time emergency loading**

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

3.8**hot-spot**

if not specially defined, hottest spot of the windings

3.9**relative thermal ageing rate**

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

3.10**transformer insulation life**

total time between the initial state for which the insulation is considered new and the final state when due to thermal ageing, dielectric stress, short-circuit stress, or mechanical movement, which could occur in normal service and result in a high risk of electrical failure

3.11**per cent loss of life**

equivalent ageing in hours over a time period (usually 24 h) times 100 divided by the expected transformer insulation life. The equivalent ageing in hours is obtained by multiplying the relative ageing rate with the number of hours

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

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

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, but after the sealed tube test.

3.14

non-directed oil flow

OF

indicates that the pumped oil from heat exchangers or radiators flows freely inside the tank, and is not forced to flow through the windings (the oil flow inside the windings can be either axial in vertical cooling ducts or radial in horizontal cooling ducts with or without zigzag flow)

3.15

non-directed oil flow

ON

indicates that the oil from the heat exchangers or radiators flows freely inside the tank and is not forced to flow through the windings (the oil flow inside the windings can be either axial in vertical cooling ducts or radial in horizontal cooling ducts with or without zigzag flow)

3.16

directed oil flow

OD

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

3.17

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

Symbol	Meaning	Units
m_W	Mass of winding	kg
H	Hot-spot factor	
k_{11}	Thermal model constant	
k_{21}	Thermal model constant	
k_{22}	Thermal model constant	
K	Load factor (load current/rated current)	
L	Total ageing over the time period considered	h
n	Number of each time interval	
N	Total number of intervals during the time period considered	
OD	Either ODAN, ODAF or ODWF cooling	
OF	Either OFAN, OFAF or OFWF cooling	
ON	Either ONAN or ONAF cooling	
P	Supplied losses	W
P_e	Relative winding eddy loss	p.u.
P_W	Winding losses	W
R	Ratio of load losses at rated current to no-load losses	
R_r	Ratio of load losses to no-load loss at principal tapping	
R_{r+1}	Ratio of load losses to no-load loss at tapping $r + 1$	
$R_{\min}$	Ratio of load losses to no-load loss at minimum tapping	
$R_{\max}$	Ratio of load losses to no-load loss at maximum tapping	
s	Laplace operator	
t	Time variable	min
tap_r	Number of principal tapping	
tap_{r+1}	Number of tapping $r + 1$	
$\text{tap}_{\min}$	Number of minimum tapping	
$\text{tap}_{\max}$	Number of maximum tapping	
V	Relative ageing rate	
V_n	Relative ageing rate during interval n	
x	Exponential power of total losses versus top-oil (in tank) temperature rise (oil exponent)	
y	Exponential power of current versus winding temperature rise (winding exponent)	
θ_a	Ambient temperature	°C
θ_E	Yearly weighted ambient temperature	°C

220
221

Symbol	Meaning	Units
θ_h	Hot-spot temperature	°C
θ_{ma}	Monthly average temperature	°C
θ_{ma-max}	Monthly average temperature of the hottest month, according to IEC 60076-2:1993	°C
θ_o	Top-oil temperature (in the tank) at the load considered	°C
θ_{ya}	Yearly average temperature, according to IEC 60076-2:1993	°C
τ_o	Oil time constant	min
τ_W	Winding time constant	min
$\Delta\theta_{br}$	Bottom oil (in tank) temperature rise at rated load (no-load losses + load losses)	K
$\Delta\theta_h$	Hot-spot-to-top-oil (in tank) gradient at the load considered	K
$\Delta\theta_{hi}$	Hot-spot-to-top-oil (in tank) gradient at start	K
$\Delta\theta_{hr}$	Hot-spot-to-top-oil (in tank) gradient at rated current	K
$\Delta\theta_o$	Top-oil (in tank) temperature rise at the load considered	K
$\Delta\theta_{oi}$	Top-oil (in tank) temperature rise at start	K
$\Delta\theta_{om}$	Average oil (in tank) temperature rise at the load considered	K
$\Delta\theta_{omr}$	Average oil (in tank) temperature rise at rated load (no-load losses + load losses)	K
$\Delta\theta_{or}$	Top-oil (in tank) temperature rise in steady state at rated losses (no-load losses + load losses)	K
$\Delta\theta'_{or}$	Corrected top-oil temperature rise (in tank) due to enclosure	K
$\Delta(\Delta\theta_{or})$	Extra top-oil temperature rise (in tank) due to enclosure	K

5 Effect of loading beyond nameplate rating

5.1 Introduction

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

5.2 General consequences

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

- a) The temperatures of windings, cleats, leads, insulation and oil will increase and can reach unacceptable levels.
- b) The leakage flux density outside the core increases, causing additional eddy-current heating in metallic parts linked by the leakage flux.
- c) As the temperature changes, the moisture and gas content in the insulation and in the oil will change.
- d) Bushings, tap-changers, cable-end connections and current transformers will also be exposed to higher stresses which encroach upon their design and application margins.

The combination of the main flux and increased leakage flux imposes restrictions on possible core overexcitation [1], [2], [3]¹.

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

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

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

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

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

5.3 Effects and hazards of short-time emergency loading

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

¹ Numbers in square brackets refer to the bibliography.

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

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

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

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

- b) Temporary deterioration of the mechanical properties at higher temperatures could reduce the short-circuit strength.
- c) Pressure build-up in the bushings may result in a failure due to oil leakage. Gassing in condenser type bushings may also occur if the temperature of the insulation exceeds about 140 °C.
- d) The expansion of the oil could cause overflow of the oil in the conservator.
- e) Breaking of excessively high currents in the tap-changer could be hazardous.

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

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

5.4 Effects of long-time emergency loading

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

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

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

5.5 Transformer size

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

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

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

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

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

6 Relative ageing rate and transformer insulation life

6.1 General

For the manufacturing 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 78-80% cellulose, 10-20 % hemicellulose and 2-6 % lignin.

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

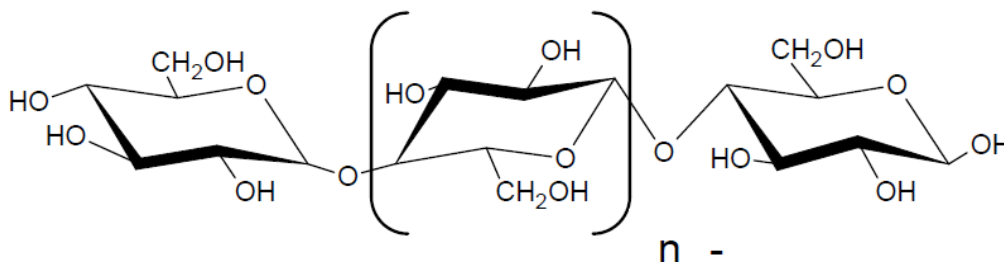


Figure 1-Structural formula of cellulose

From kraft pulp various types of paper and pressboard having varying density are made. By adding various nitrogen containing compounds the ageing characteristics of the cellulose may be improved. Typical values for nitrogen content of thermally upgraded papers are between 1 and 4 percent. 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 [4]-[10], 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 oxidising agent in this environment is oxygen from air ingress, and as the ultimate end product of 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, 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 analyze tensile strength of paper sampled from used transformers. Hence, it is more convenient to characterize the degree of polymerisation (DP) in order to describe the state of an insulation paper. Figure 2 shows a typical correlation between tensile strength and DP value, [6], the same correlation is valid for the thermally upgraded and non-thermally upgraded paper.

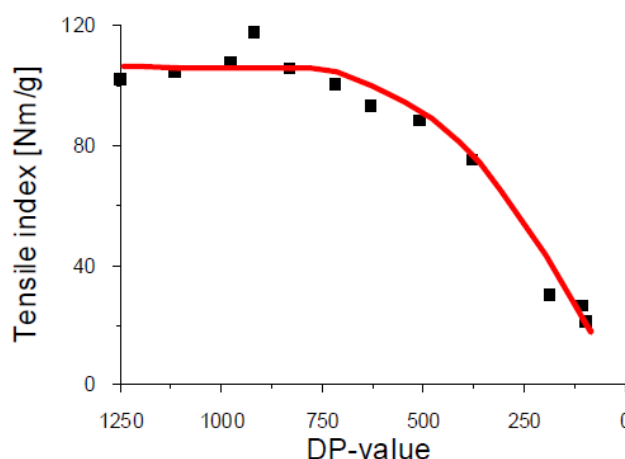


Figure 2 – Correlation between tensile strength and DP value

The degree of polymerization (DP) - being the average number (n) of glycosidic rings in a cellulose macromolecule - is in the order of 1200 for unbleached soft wood kraft. The drying process of the transformer will further reduce it to some 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 < 6000 ppm and water of 0,5% is shown in Figure 3, [10]. The nitrogen content of the thermally upgraded paper used in this experiment was 1.8%.

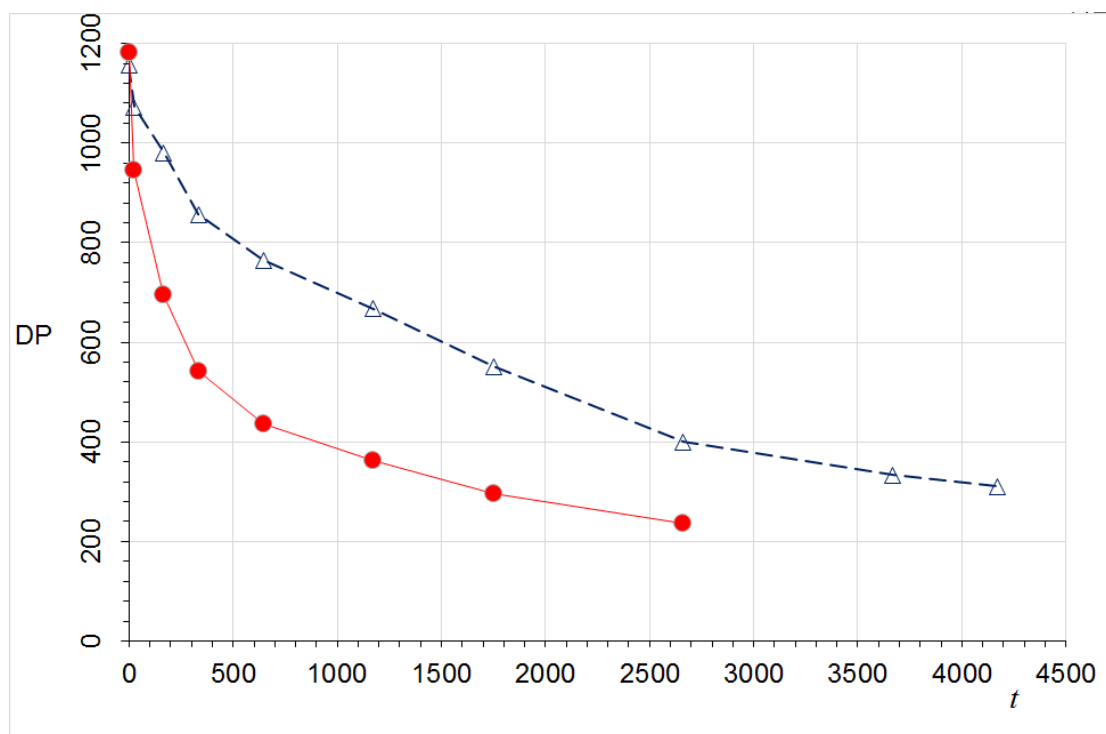
When the DP is reduced to 200 or 35 % retained tensile strength the quality of the paper is normally considered so poor that this defines the “end of life” for such insulating material [6].

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 to 110 °C for thermally upgraded paper.

NOTE 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, Figures 4 and 5 should be considered as unconfirmed and may be disputable. However, the numbers give a reader possibility to simulate different ageing scenarios.

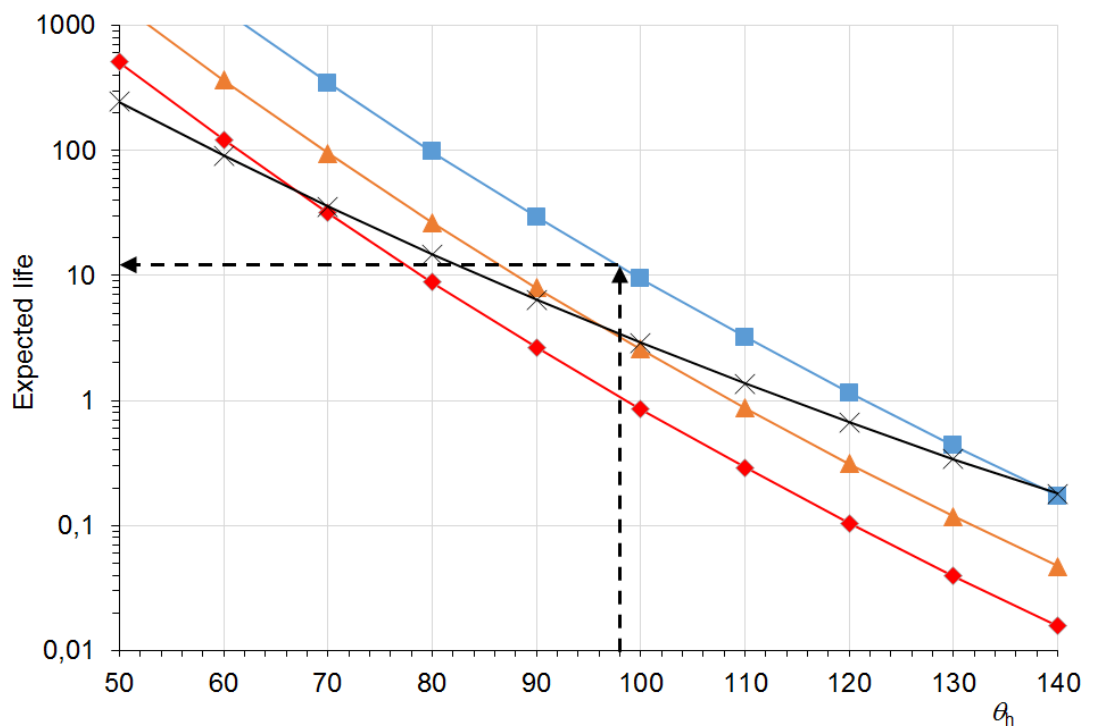
**Key**

DP Degree of polymerization

 t Time (h) Δ Values for thermally upgraded paper

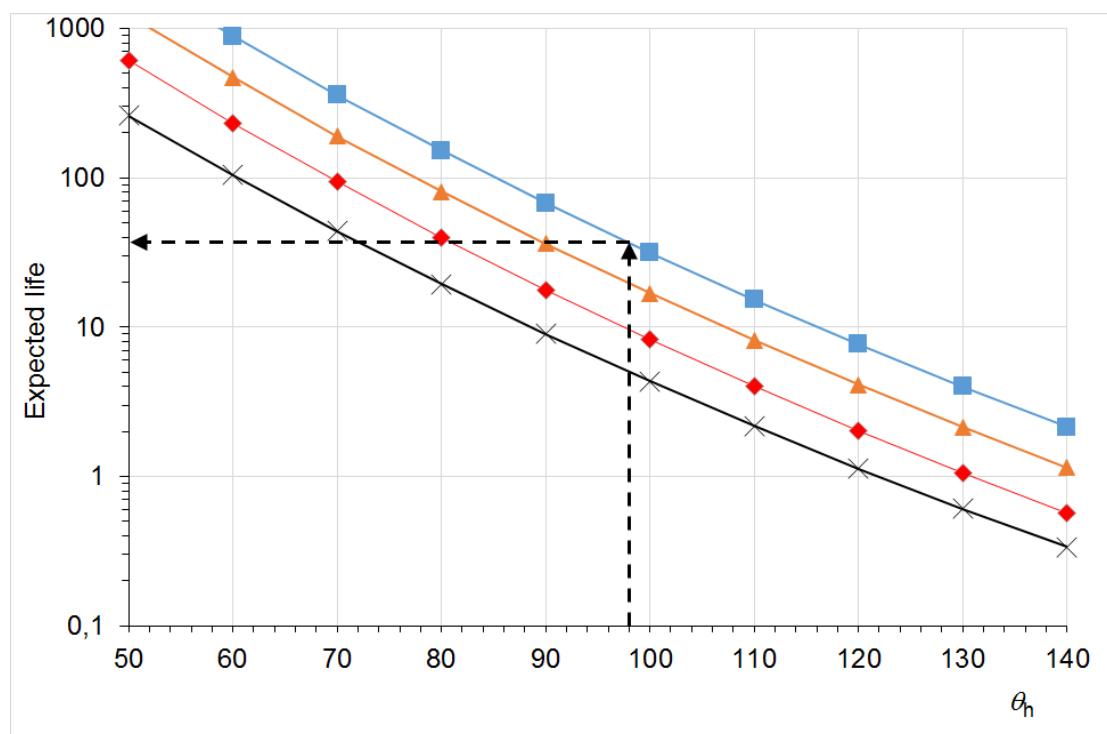
• Values for non-thermally upgraded paper

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

**Key**

Expected life	Time (years)	θ_h	Hot-spot temperature (°C)	□	0.5% moisture, low oxygen
Δ	1.5% moisture, low oxygen	◇	3.5% moisture, low oxygen	X	0.5% moisture, high oxygen

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

**Key**

Expected life	Time (years)	θ_h	Hot-spot temperature (°C)	□	0.5% moisture, low oxygen
Δ	1.5% moisture, low oxygen	◇	3.5% moisture, low oxygen	X	0.5% moisture, high oxygen

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

NOTE: Figures 4 and 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 must be considered, (e.g. loading history and prediction, ambient temperature, insulation material and insulation moisture contamination).

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

An example 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 [22].

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

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

where θ_h is the hot-spot temperature in °C.

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

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

θ_h °C	Non-upgraded paper insulation V	Upgraded paper insulation V
80	0,125	0,036
86	0,25	0,073
92	0,5	0,145
98	1,0	0,282
104	2,0	0,536
110	4,0	1,0
116	8,0	1,83
122	16,0	3,29
128	32,0	5,8
134	64,0	10,1
140	128,0	17,2

441 6.4 **Loss-of-life calculation**442 The loss of life L over a certain period of time is equal to

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

443 where

444 V_n is the relative ageing rate during interval n , according to equation (2) or (3);445 t_n is the n th time interval;446 n is the number of each time interval;447 N is the total number of intervals during the period considered.448 NOTE The maximum time interval should be less than half the smallest time constant, τ_w , in the equation (7) for
449 an accurate solution.
450

7 Limitations

7.1 Temperature limitations

With loading values beyond the nameplate rating, all the individual limits stated in Table 2 should not be exceeded and account should be taken of the specific limitations given in 7.3 to 7.5.

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

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

Types of loading	Distribution 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
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
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
Top-oil temperature, in tank, (°C)	See 7.3.1	115
NOTE To avoid the generation of gasses in the core, the inner core hot spot temperature should be limited to: a) 130°C for the condition of highest core over-excitation, rated load, the highest ambient temperature for transformers filled with mineral oil, (see Annex B). b) 140°C for the condition of highest core over-excitation, long time emergency loading, and the highest ambient temperature for transformers filled with mineral oil, (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. These recommended current limits should not apply to very short duration overloads, i.e. less than 10 sec.

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

Types of loading	Distribution 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 For specification beyond rated power see Annex C.

7.3 Specific limitations for distribution 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 should not be exceeded. No limit is set for the top-oil and hot-spot temperature under short-time emergency loading for distribution transformers because it is usually impracticable to control the duration of emergency loading in this case. It should be noted that when the hot-spot temperature exceeds 140 °C, gas bubbles may develop which could jeopardize the dielectric strength of the transformer (see 5.3).

7.3.2 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.