

TECHNICAL SPECIFICATION

**Power transformers –
Part 14: Design and application of liquid-immersed power transformers using
high-temperature insulation materials**

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**Power transformers –
Part 14: Design and application of liquid-immersed power transformers using
high-temperature insulation materials**

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POWER TRANSFORMERS –

Part 14: Design and application of liquid-immersed power transformers using high-temperature insulation materials

FOREWORD

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- the subject is still under technical development or where, for any other reason, there is the future but no immediate possibility of an agreement on an International Standard.

Technical specifications are subject to review within three years of publication to decide whether they can be transformed into International Standards.

IEC 60076-14, which is a technical specification, has been prepared by IEC technical committee 14: Power transformers.

This second edition cancels and replaces the first edition published in 2004. It is a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

- additional clarification added to the introduction;
- addition of an introduction to the ageing and lifetime of insulation materials;
- enhancement of insulation system descriptions;
- clarification of temperature rise limits and the addition of overload temperature limits.

The text of this technical specification is based on the following documents:

Enquiry draft	Report on voting
14/591A/DTS	14/600/RVC

Full information on the voting for the approval of this technical specification 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 can be found, under the general title *Power transformers*, on the IEC website.

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

- transformed into an International standard,
- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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

INTRODUCTION

The average temperature rise in liquid-immersed transformer windings has for several tens of years been limited to 65/70 K and the top oil temperature rise to 60 K, as specified in IEC 60076-2.

Winding conductors in these transformers have historically been insulated with cellulosic paper or enamel. Other solid insulation materials have also been cellulose-based products. The insulation liquid has, for the most part been mineral insulating oil. These materials are still dominant.

Consequently, most of the accumulated experience of transformers in service is based on these insulation materials and these temperature limits. In some cases, space or weight limitations require the designer to reduce the transformer dimensions with higher temperature rises as a consequence. The application of insulation materials (both solid and liquid) with better ageing properties at elevated temperatures than the traditional ones is necessary in order to provide an acceptable life expectancy. High-temperature solid insulation materials have also occasionally been used only in certain parts of the windings where high temperature has been expected.

Recent temperature measurements by means of fibre-optics have indicated that the hot-spot temperature may sometimes be higher than predicted, and in certain cases considerably higher. This has created concern regarding higher rate of ageing than expected. The measurements have provided knowledge regarding where the hot-spots are situated and where high-temperature materials might be applied.

High-temperature insulation, from enamel and tape wrap for conductors, to spacer and mechanical support materials are already used in power, distribution, mobile, locomotive and rectifier transformers. Class K liquids, with a fire point greater than 300 °C are suitable for temperatures higher than mineral insulating oil and have been used for decades. Their use and range of application is increasing rapidly. For many years, manufacturers have met the needs of special applications by designing transformers using high-temperature materials to achieve lower weight, higher power density, improved fire safety or increased life.

The purpose of this technical specification is to begin the process of standardizing the development of liquid-immersed transformers that use high-temperature insulation. As a system, the solid insulation may encompass a broad range of materials with varying degrees of thermal capability. The insulating and cooling liquids also vary substantially from mineral oil to any of a number of new class K liquids that also have a broad range of thermal capability.

The liquid and solid insulation materials found in any standard type of modern liquid-immersed transformer compose an insulation system that has evolved and developed over more than 100 years. Accordingly, the rules and guidelines for application are also robust and rather well developed. In contrast, high-temperature insulation materials and applications for transformers that use these materials are relatively new in both development and application.

It should not therefore be surprising that much of the information is neither well developed nor completely understood. However, it is important to establish and maintain a document that provides a starting point for discussion between the manufacturer and the user. It is expected that this technical specification would be updated regularly as development progresses.

This document is not intended to stand alone, but rather builds on the wealth of information and guidelines documented in the other parts of the IEC 60076 series. Accordingly, this document follows two guiding principles. The first principle is that liquid-immersed transformers are well known and are well defined in other parts of this series and therefore, the details of these transformers are not repeated in this technical specification, except where reference has value, or where repetition is considered appropriate for purposes of emphasis or comparison.

The second principle is that the usual liquid-immersed transformer, insulated with kraft paper, pressboard, wood, mineral oil and many other commonly used materials operating at established temperature limits, are well known and considered normal or conventional. All other insulation materials, either solid or liquid that have a thermal capability higher than the materials used in this well known system of insulation materials are considered high-temperature.

Consequently, this “standard” or “normal” insulation system is defined as the “conventional” insulation system for comparison purposes and these normal thermal limits are presented for reference to illustrate the differences between other higher-temperature systems. Commonly used solid and liquid insulations are also tabulated in a general way to allow easy comparison of typical properties and to demonstrate the added range and capabilities of relatively unfamiliar materials.

This technical specification addresses loading, overloading, testing and accessories in the same manner. Only selected information for the “conventional” transformers is included for comparison purposes or for emphasis. All other references are directed to the appropriate IEC document.

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POWER TRANSFORMERS –

Part 14: Design and application of liquid-immersed power transformers using high-temperature insulation materials

1 Scope

This part of IEC 60076 provides specification, design, testing and loading information for use by both the manufacturer and user of liquid-immersed power transformers employing either high-temperature insulation or combinations of high-temperature and conventional insulation.

It is applicable to:

- power transformers designed in accordance with IEC 60076-1,
- convertor transformers designed to IEC 61378 series,
- arc furnace transformers,

and covers the use of various liquid and solid insulation combinations.

Whilst standards for traction transformers fall under the authority of IEC technical committee 9, this part of IEC 60076, however, may be applicable as a guideline for the use of high-temperature insulation materials in traction transformers.

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 60076-1:1993, *Power transformers – Part 1: General*

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

IEC 60076-3, *Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air*

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

IEC 60076-7:2005, *Power transformers – Part 7: Loading guide for oil-immersed power transformers*

IEC 60085, *Electrical insulation – Thermal evaluation and designation*

IEC 60216-1, *Electrical insulating materials – Properties of thermal endurance – Part 1: Ageing procedures and evaluation of test results*

IEC 60296, *Fluids for electrotechnical applications – Unused mineral insulating oils for transformers and switchgear*

IEC 60317 (all parts), *Specifications for particular types of winding wires*

IEC 60554-3 (all parts), *Specification for cellulosic papers for electrical purposes – Part 3: Specifications for individual materials*

IEC 60641-3 (all parts), *Pressboard and presspaper for electrical purposes – Part 3: Specifications for individual materials*

IEC 60674-3 (all parts), *Plastic films for electrical purposes – Part 3: Specifications for individual materials*

IEC 60819-3 (all parts), *Non-cellulosic papers for electrical purposes – Part 3: Specifications for individual materials*

IEC 60836, *Specifications for unused silicone insulating liquids for electrotechnical purposes*

IEC 60851-4, *Winding wires – Test methods – Part 4: Chemical properties*

IEC 60867, *Insulating liquids – Specifications for unused liquids based on synthetic aromatic hydrocarbons*

IEC 60893-3 (all parts), *Insulating materials – Industrial rigid laminated sheets based on thermosetting resins for electrical purposes – Part 3: Specifications for individual materials*

IEC 61099, *Specifications for unused synthetic organic esters for electrical purposes*

IEC 61100, *Classification of insulating liquids according to fire-point and net calorific value*

IEC 61212-3 (all parts), *Insulating materials – Industrial rigid round laminated tubes and rods based on thermosetting resins for electrical purposes – Part 3: Specifications for individual materials*

IEC 61378-1, *Converter transformers – Part 1: Transformers for industrial applications*

IEC 61629-1, *Aramid pressboard for electrical purposes – Part 1: Definitions, designations and general requirements*

ISO 2592, *Determination of flash and fire points – Cleveland open cup method*

ISO 2719, *Determination of flash-point – Pensky-Martens closed cup method*

3 Terms and definitions

For the purposes of this document, the following terms and definitions, as well as those of IEC 60076-1 and IEC 60076-2 apply.

3.1

insulation system

a system composed of solid insulating materials and an insulating liquid

3.2

temperature index TI

numerical value of the temperature in degrees Celsius derived from the thermal endurance relationship at a time of 20 000 hours (or other specified time)

[IEV 212-02-08, modified]

3.3**halving interval HIC**

numerical value of the temperature interval in degrees Celsius which expresses the halving of the time to end-point taken at the temperature equal to TI

[IEV 212-02-10, modified]

3.4**thermal class**

designation of Electrical Insulation Materials (EIM) or Electrical Insulation Systems (EIS) equal to the numerical value of the maximum used temperature in degrees Celsius for which the EIM/EIS is appropriate

[IEC 60085, 3.11, modified]

3.5**conventional**

adjective that refers to temperature rise limits and insulation materials applied in systems consisting of mineral oil and non-thermally upgraded paper

3.6**thermally upgraded paper (TUP)**

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.

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

[IEC 60076-7, 3.12]

3.7**high-temperature**

refers to temperature rise limits and insulation materials applied in systems consisting of solid materials and/or liquid operating at higher temperatures than conventional

3.8**hybrid insulation system**

high-temperature solid insulation material adjacent to all winding conductors either bare or insulated (including all conductor insulation, spacers, strips and cylinders in direct contact with the winding conductor) and cellulose-based materials in lower temperature areas where thermal class 105 limits are met (see Figure 2)

3.9**semi-hybrid insulation system**

high-temperature materials used only for conductor insulation (see Figure 3)

3.10

mixed insulation system

high-temperature solid insulation material adjacent to the winding conductors located in the hotter regions (including all conductor insulation and, if necessary, spacers, strips and cylinders in contact with these conductors) and cellulose-based materials in the rest of the winding and other lower temperature areas where thermal class 105 limits are met (see Figure 4)

3.11

homogeneous insulation system

high-temperature insulation used in all areas exposed to temperatures higher than would be suitable for conventional insulation systems together with high-temperature insulating liquid

3.12

reference temperature

20 °C + rated mean winding temperature rise

4 Insulation materials

4.1 General

This clause lists many high-temperature Electrical Insulation Materials (EIM) for informational purposes only. The appearance of these materials does not imply that any specific combination is suitable for use in high-temperature liquid-immersed transformer applications, as an Electrical Insulation System (EIS).

Common solid materials currently available are listed in Table 1 along with typical parameters and characteristics, which are necessary for proper evaluation. It is important to note that design parameters specific to the material selected should be obtained from the manufacturer of the product. The insulation materials may be conveniently separated into solids, wire enamels and liquids.

Each material should be evaluated for compatibility with other materials in the system and not only for thermal capability. It should also be noted that whilst the thermal capability of the individual materials may be satisfactory, the interaction of these individual elements in the system might render the system unacceptable.

4.2 Ageing and lifetime of insulation materials¹

Material ageing is the result of a process that splits the molecules of the insulation material and consequently changes some material properties. This is an endothermic process, which means that sufficient energy must be supplied to enable the atoms to split the molecules. In transformers, this energy is provided mainly by the transformer losses. The more energy supplied, the faster the splitting rate. The energy takes the form of heat, which increases the temperature. The temperature is then a relevant indicator of the ageing rate and the lifetime. Other factors than the temperature, such as the presence of acids, oxygen and/or water may influence the lifetime. Assuming that these other factors are constant, the lifetime of insulation material normally follows the equation:

$$L = a \times e^{\frac{b}{T}} \tag{2}$$

¹ This subclause presents the classic theory of ageing for a simple material. More detailed analyses of the complex mechanisms of material ageing in a typical transformer may be found in the technical papers listed in the Bibliography.

where

L is the lifetime in hours;

a is a constant with the dimension hour;

e is the base of the natural logarithm (2,718...);

b is a constant with the dimension Kelvin;

T is the temperature in Kelvin.

Equation (2) is derived from Arrhenius' equation. When taking the natural logarithm on both sides of Equation (2), the result is:

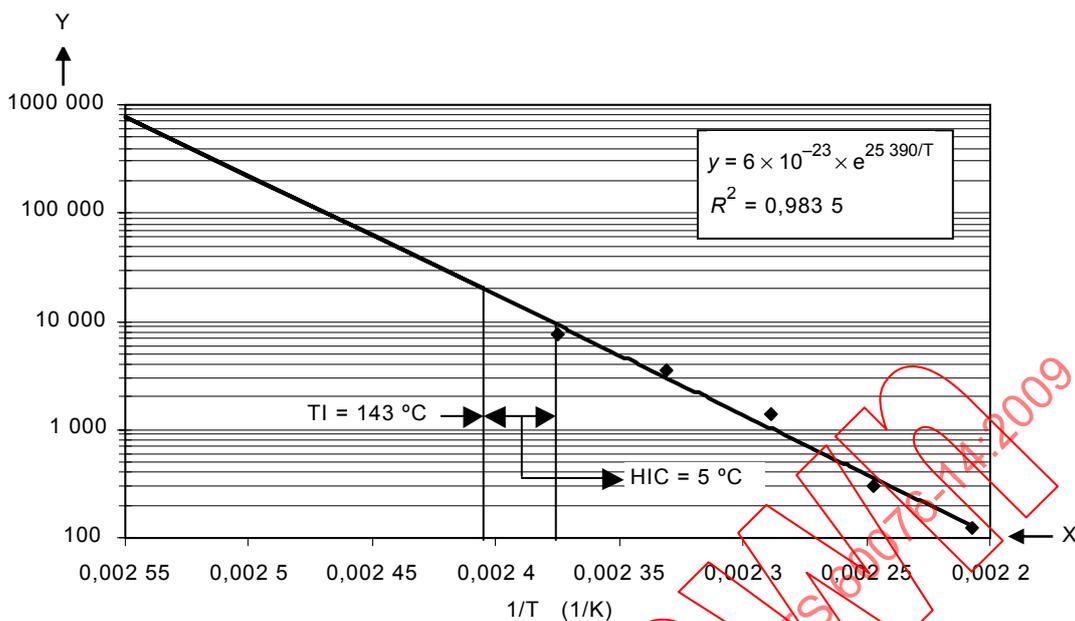
$$\ln(L) = \ln(a) + \frac{b}{T} \quad (3)$$

Equation (3) is represented by a straight line (in semi logarithmic coordinates of L versus $1/T$), which is determined by means of a thermal endurance test described in IEC 60216-1.

End of life criterion must be defined prior to the thermal endurance test. It may be an absolute value or a percentage of the original value of a material property that is crucial for the insulating function of the material, and preferably a property that deteriorates faster than other vital properties of the material. For mineral oil-immersed transformers with cellulose-based insulation, the tensile strength of the paper that covers the winding conductors is often used as one of the parameters that determine the degree of ageing of the whole transformer. The degree of polymerization (DP) is also used as an ageing indicator, with a value of 200 generally considered to be end of life for cellulose-based insulation.

During the thermal endurance test, samples of the material are heated to several different temperatures and the time to end of life is noted. The time durations versus the reciprocal value of the absolute temperatures are plotted in a coordinate system, where the time axis has a logarithmic scale (see Figure 1).

The dots in the diagram are the results from a thermal endurance test. The straight line is the regression line. As will be seen, the dots are situated closely to the regression line, which confirms that the lifetime versus temperature relationship for the tested material follows Arrhenius' equation.



IEC 678/09

Key

X axis: Reciprocal value of the absolute temperature in K⁻¹

Y axis: Lifetime in h (hours)

NOTE The X axis (1/T) is normally represented right-to-left, so that higher temperatures are at the right hand side of the graph.

Figure 1 – Example of a thermal endurance graph

A vertical line is drawn at the point where the extended regression line crosses the 20 000 h ordinate, and this vertical line hits the abscissa axis at a point corresponding to a temperature of 143 °C. This means that the temperature index TI of this material is 143 °C.

Another vertical line is drawn from the point where the regression line crosses the 10 000 h ordinate, and this vertical line hits the abscissa axis at a point corresponding to 148 °C. The halving interval HIC is then the difference between 148 and 143, which equals 5 °C.

A lifetime of 20 000 h (somewhat more than 2 years) at the temperature index TI would normally be too short as an acceptable lifetime. To obtain an acceptable lifetime the thermal class assigned to the material must be chosen lower than TI. How much lower depends on how long a lifetime the user of the material requires. The relation between lifetime and temperature can be read from the extended regression line in the diagram or calculated by means of the regression line equation at the upper right corner of the diagram.

If for example 20 years (175 200 h) lifetime is required, the thermal class should be 128 °C. If 30 years (262 800 h) lifetime is required, the thermal class should be 126 °C.

The thermal class is equal to the maximum service temperature that the user of the material finds appropriate, taking into account the required lifetime of the transformer where the material is going to be used. The loading pattern of the transformer and the real ambient temperatures at the site where the transformer will be situated should also be considered. The transformer may in many cases be loaded below its rated loading for long periods, which would reduce the ageing rate and extend the lifetime.

In some performed tests, the end of life has been defined to have occurred when 50 % of the initial tensile strength is consumed. However, this limit, or any other defined limit for end of life, should not be perceived too literally. A transformer may operate satisfactorily for many years after the end of life according to this definition is reached. The decomposition of the material happens gradually. There are no sharp limits. This defined end of life serves more as a warning that the ability of the transformer to withstand stresses under abnormal service conditions, like high short-circuit currents is essentially lower compared to a new transformer. Also transport of the transformer from one site to another involves a higher risk.

4.3 Solid insulation

Solid insulation is available in the form of paper, film, sheet and board as well as various shapes for mechanical applications used within the dielectric structure. Table 1 lists many readily available materials, along with typical parameters. The table also includes cellulose-based products for comparison purposes. Note that this typical performance information is based on components tested individually as isolated samples in air. Dielectric and thermal performance as a system, when immersed in the selected insulating liquid may be substantially different from the component values and the values associated with impregnation in a specific liquid.

It should also not be assumed that the system thermal class would necessarily default to the lowest temperature class of the system's individual components. On the contrary, the thermal capability will often favour the highest temperature component. However, the individual component thermal class should provide guidance in the selection and positioning of the various materials within the insulation design.

Based on the interpretation of test data during the development of alternative fluids, it has been proposed that liquids with significantly higher water saturation levels at operating temperatures may allow higher operating temperature limits for the solid insulation because of their ability to remove the moisture from the paper.

Table 1 – Typical properties of solid insulation materials

Material	Thermal class (IEC 60085) (°C)	IEC standard reference	Relative permittivity at 25 °C	Dissipation factor (%)		Moisture absorption (%)	Density (g/cm ³)	Form
				At 25 °C	At 100 °C			
Cellulose-based	105	60554-3	3,3 – 4,1	0,4	1,0	7,0	0,97 – 1,2	Paper
Cellulose-based Thermally upgraded	120		3,3 – 4,1	0,4	1,0	7,0	0,97 – 1,2	Paper
Cellulose-based	105	60641-3	2,9 – 4,6	0,4	1,0	7,0	0,8 – 1,35	Board
Stratified resin bonded paper (bakelite)	130		5,8	2,5		2,3	1,36	Board
Polyphenylene sulfide (PPS)	155		3,0	0,06	0,12	0,05	1,35	Film
Polyester glass ^a	130 – 200	60893-3	4,8	1,3 – 7,0	N/A	0,2 – 1,1	1,8 – 2,0	Sheet
Polyester glass ^a	130 – 220	61212-3	N/A	N/A	N/A	0,16 – 0,28	1,8 – 2,0	Shapes
Polyimide	220	60674-3	3,4	0,2	0,2	1,0 – 1,8	1,33 – 1,42	Film
Aramid	220	60819-3	1,6 – 3,2	0,5	0,5	5,0	0,72 – 1,10	Paper
Aramid	220	61629-1	2,6 – 3,5	0,5	0,5	5,0	0,70 – 1,15	Board

NOTE 1 All data has been taken from measurements in air.

NOTE 2 Relative permittivity and dissipation factor data are referenced to 50/60 Hz.

NOTE 3 Moisture data is based on air having a relative humidity of 50 %.

^a Typically only used in lower voltage applications due to possible air entrapment during the manufacturing process.

4.4 Wire enamel insulation

The list in Table 2 shows a broad range of available insulating enamels used to coat both round and rectangular copper and aluminium winding wires. Additional information may be found in the specific applicable sections of the IEC 60317 series. Note that the appearance of a coating in this list does not imply compatibility with any of the many available dielectric liquids. Procedures for verifying compatibility with different liquids are defined in IEC 60851-4.

Table 2 – Typical enamels for wire insulation

Chemical name	Thermal class	IEC 60317 applicable part	Common acronym	Common name
Polyvinyl acetal	105 120	1, 14, 17 12, 18	PVF or PVA	Polyvinyl formal
Polyurethane	130 155 180	2, 4 20, 35 51	UEW	Polyurethane
Polyurethane with polyamide overcoat	130 155	19 21	UEWN	Nylon over polyurethane
Polyester	130 155	34, 41, 45 3, 16, 54	PEW	Polyester
Polyester with polyamide overcoat	180	22, 24	PEWN HPEWN	Nylon over polyester
Polyesterimide	180	8, 15, 23, 28, 36, 37	EIW	Polyesterimide
Polyester polyamideimide	200	13, 25, 29, 38	HPEAIW	Polyester polyamideimide
Polyesterimide with polyamideimide overcoat	200	13, 25, 29, 38	EAIW	Amide-imide over polyesterimide
Polyesterimide with polyamide overcoat	180	22, 24		Polyamide over polyesterimide
Aromatic polyamideimide	200	26	AIW	Polyamideimide
Aromatic polyimide	220	7, 30	PIW	Polyimide
The following wire insulations are not yet defined by IEC standards				
Epoxy	155	N/A	Epoxy	Epoxy
Polyarylethersulfone	155	N/A	PPSU PAES	Polyphenylsulfone
Polyarylsulfone	180	N/A	PAS	Polyarylsulfone
Polyaryletheretherketone	220	N/A	PEEK	Polyarylether-etherketone
NOTE Thermal class in air according to IEC 60317.				

4.5 Insulating liquids

Table 3 shows typical performance characteristics of readily available dielectric liquids that are used in liquid-immersed transformers. Mineral insulating oil, complying with IEC 60296 is the most common liquid used in transformers and is generally the performance reference to which all other liquids are compared. This liquid is also the reference for comparing high-temperature performance.

IEC 61100 provides rules for classifying liquids according to fire point and calorific value. A fire point greater than 300 °C, as determined according to ISO 2592, classifies the liquid as class K. However, neither the flash point nor the fire point defines high-temperature capability. Sludge development, affinity to moisture and rate of oxidation all affect the thermal capability

of a liquid. The liquid manufacturer should be contacted to determine if a specific product is suitable for use at higher temperatures than conventional mineral insulating oil, since it may depend on certain additives that may not be present in all products in the same generic category.

The maximum operating temperatures listed in Table 3 are provided only as a starting point for further investigation, since there is no generally accepted procedure for establishing a thermal index for insulating liquids. These temperatures are estimated or generally accepted by the industry, but should not be taken as recommendations of this technical specification.

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Table 3 – Typical performance characteristics of unused insulating liquids

Generic name	IEC standard reference	Thermal class ^a (°C)	Flash point ^c (°C)	Fire point ^c (°C)	Water content (mg/kg)	Density at 25 °C (g/cm ³)	Relative permittivity ^d at 25 °C	Dissipation factor ^d at 25 °C (%)	Kinematic viscosity (mm ² /s)		Thermal conductivity at 25 °C (W/mK)	Specific heat at 25 °C (J/kg °C)
									At 40 °C	At 100 °C		
Mineral insulating oil	60296	105	145	160	25	0,88	2,2	0,05	9,2	2,3	0,12	2 100
Synthetic hydrocarbon	60867	~130	230	250	15	0,83	2,1	0,01		4,1	0,14	2 100
Synthetic ester	61099	~130 ^b	275	310	50	0,97	3,2	0,02	34	5,8	0,16	2 100
Dimethyl silicone	60836	~155 ^b	310	360	50	0,96	2,7	0,01	40	14,3	0,15	1 500
Although the following liquids are used in some transformer applications, they are not yet defined by IEC standards.												
Synthetic PAO hydrocarbon	N/A	~130	264	304	15	0,83	2,1	0,01	-	8,6	0,13	2 300
Natural ester	N/A	~130 ^b	330	360	50	0,91	3,2	0,20	33	9	0,17	2 000
High molecular weight hydrocarbon	N/A	~155	280	312	10	0,87	2,2	0,01	-	11,8	0,14	2 100
NOTE The values in this table are provided only as a general guide for comparison of the different liquids. For specific physical properties and acceptance limits, refer to the IEC standard noted for each liquid. Physical properties and acceptance limits for liquids with no IEC document should be verified with the liquid manufacturer.												
^a Thermal class is equal to the maximum recommendable operating temperature, which is expected to give an acceptable lifetime of the liquid.												
^b Due to the oxidation stability properties of these dielectric liquids, the estimated temperature limits apply to sealed type transformers or transformer with nitrogen preservation systems that essentially eliminate the ingress of air.												
^c Cleveland open cup test per ISO 2592. In IEC technical committee 10 documents, flash point is determined according to the Pensky-Martens closed cup test per ISO 2719, which generally gives lower values than those shown.												
^d Relative permittivity and dissipation factor data are referenced to 50/60 Hz.												

5 Insulation systems

5.1 General

An insulation system used in electro-technical devices contains one or more solid materials for insulating the conductive parts and a liquid, for both insulating conductive parts and for heat transfer and cooling. These insulation materials must withstand electrical, mechanical, chemical and thermal stresses for the expected life of the device. A procedure for evaluating a combined solid and liquid insulation system may be found in IEC/TS 62332-1.

For thermal stresses, the capability of the insulation material is based on temperature as the dominating factor. However, the temperature distribution, even in a conventional power transformer is not homogenous. The liquid temperature can vary for example, between 70 °C at the bottom of the transformer and 100 °C at the top, when the transformer is at full load. Correspondingly, the conductors and associated insulating materials will typically reach hot-spot temperatures 10 °C – 20 °C higher than the surrounding liquid. The remaining insulation materials will adopt the approximate temperature of the liquid, depending on the height.

Since ageing and lifetime of the insulation system so strongly depend on the temperature, different combinations of insulating materials may be used in order to optimise the thermal and economical design of the transformer. The application of insulating materials with different thermal classes leads to unconventional insulation systems. To obtain optimum value in the use of these high-temperature insulating materials, it makes sense to match the material capability to the appropriate application temperature.

Many systems could be identified based on the many multiple combinations of various solid insulations together with each liquid. For communication purposes, four distinct categories may be defined in general terms. However, selection and definition of these four categories is not intended to restrict other possible combinations. Additional common combinations may be added as development in high-temperature insulation systems proceeds. These categories also do not include combinations that use high-temperature materials, even though all conventional temperatures are maintained. IEC 60076-2 and IEC 60076-7 adequately cover this type of transformer.

5.2 Insulation system types

5.2.1 Homogeneous high-temperature insulation system

Homogeneous high-temperature insulation systems consist of mainly high-temperature solid insulation materials for all insulation components and high-temperature insulating liquid. However, lower temperature insulation may be used in selected low-temperature areas. For example, mechanical supports outside the hot liquid stream.

Solid: High-temperature in windings and at relevant locations

Liquid: High-temperature

Temperature limits: Higher than conventional for top liquid, average winding and winding hot-spot

5.2.2 Hybrid insulation system

The hybrid insulation system generally uses mineral oil and high-temperature materials throughout the transformer in the windings, but not necessarily every winding. For example a specific winding may be insulated with conventional materials when it is designed to operate at conventional temperatures.

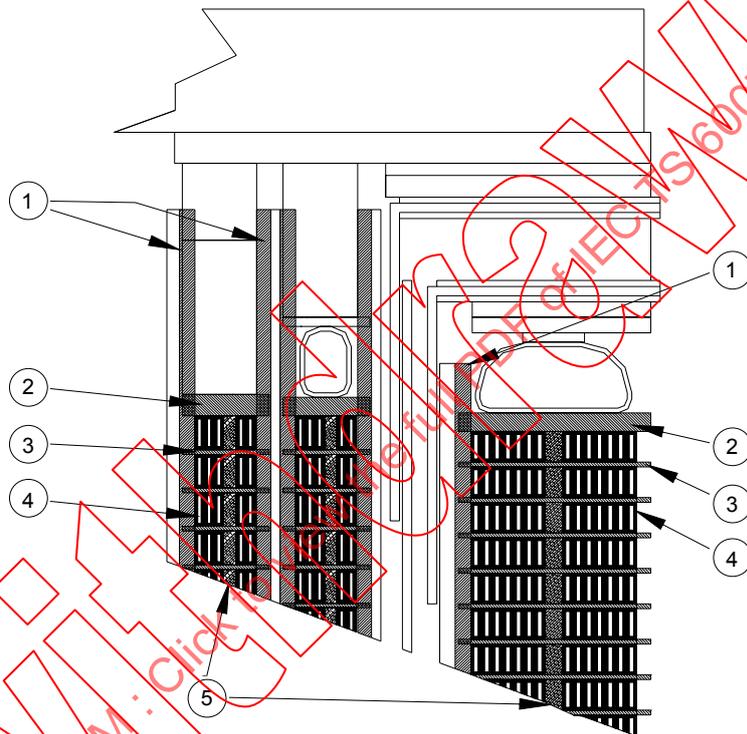
Typically the conductor insulation and the radial and axial spacers separating the coil windings are high-temperature materials. Conventional cellulose-based insulation is used in all other areas, such as cylinders and angle rings that operate at conventional temperatures.

Solid: High-temperature for all insulation in contact with hot conductors

Liquid: Mineral oil or any suitable insulating liquid with equal or higher thermal class

Temperature limits: Conventional for top liquid and higher than conventional for average winding and winding hot-spot for some or all windings

NOTE Exit leads may be insulated with conventional insulation provided they are designed for conventional temperatures.



IEC 679/09

Key

- 1 high-temperature axial spacers against the winding
- 2 high-temperature radial spacers on top and below the winding
- 3 high-temperature radial spacers inside the winding
- 4 high-temperature conductor insulation
- 5 high-temperature axial spacers inside the winding forming axial cooling ducts

Figure 2 – Illustration of solid insulation in a hybrid insulation system

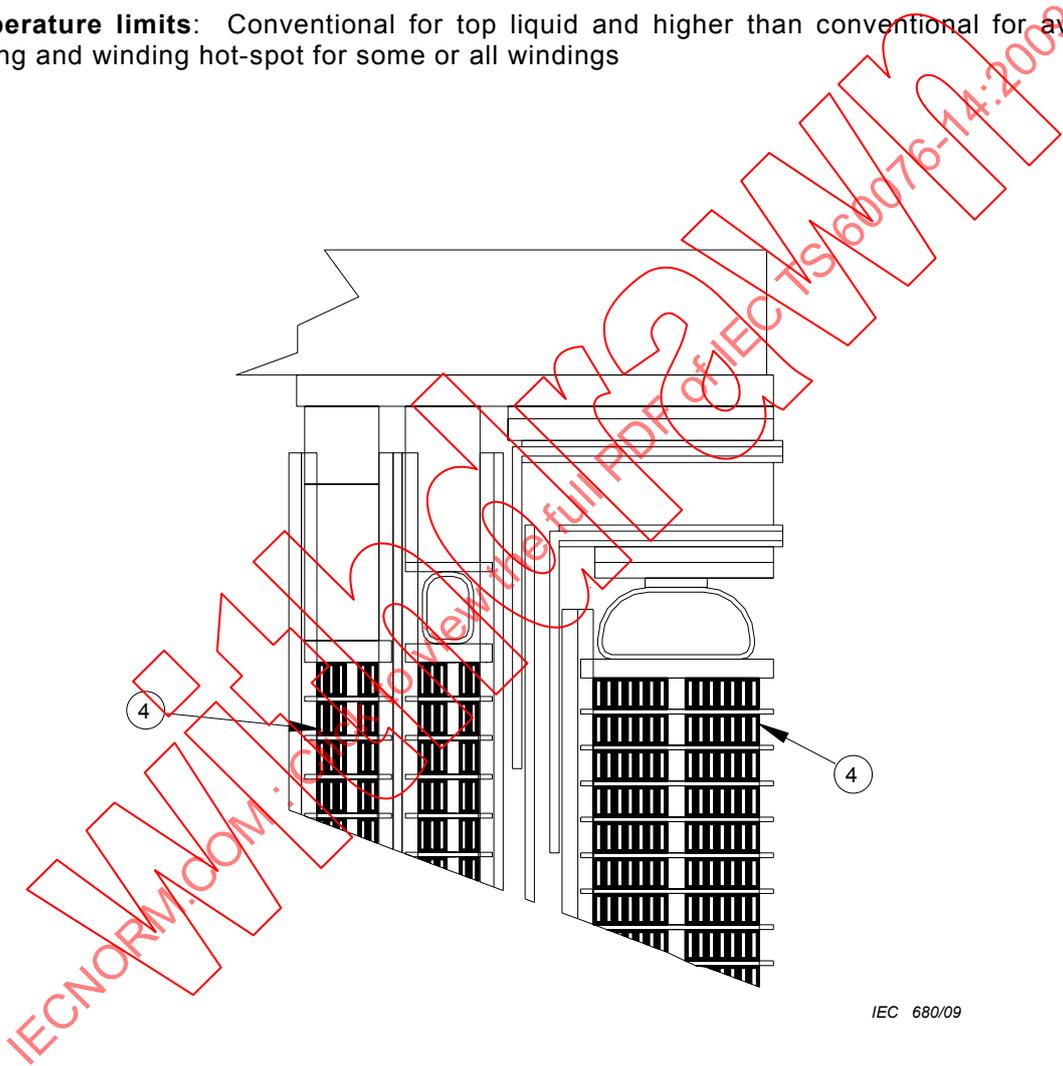
5.2.3 Semi-hybrid insulation system

The semi-hybrid insulation system uses mineral oil and high-temperature materials only for conductor insulation in windings operating above conventional temperatures. All other materials are of conventional insulation. In layer type windings, the conductor insulation also includes the layer to layer insulation.

Solid: High-temperature for conductor insulation only in some or all windings

Liquid: Mineral oil or any suitable insulating liquid with equal or higher thermal class

Temperature limits: Conventional for top liquid and higher than conventional for average winding and winding hot-spot for some or all windings



IEC 680/09

Key

4 high-temperature conductor insulation

Figure 3 – Illustration of solid insulation in a semi-hybrid insulation system

5.2.4 Mixed insulation system

The mixed insulation system uses high-temperature insulation for certain components or parts of windings, such as the conductors in regions at temperatures above conventional limits. Examples of zones with extra losses and heat development could be:

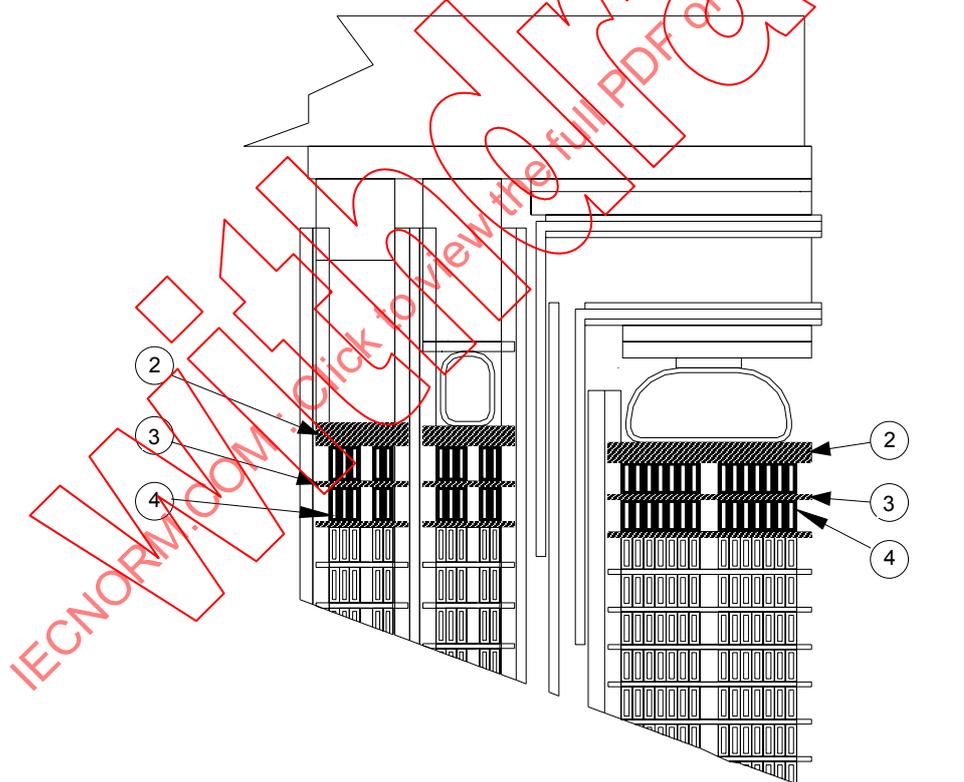
- winding ends due to the radial component of the magnetic leakage field;
- zones of converter transformer windings where harmonic currents might be concentrated.

Due to higher temperature in the upper part of a winding or windings, for example the upper quarter, this part may also contain high-temperature insulation. However, the majority of the solid insulation materials as well as the insulating liquid used in the transformer are conventional.

Solid: High-temperature to protect against too high ageing rate in specific regions of some windings

Liquid: Mineral oil or any suitable insulating liquid with equal or higher thermal class

Temperature limits: Conventional for top liquid and average winding and higher than conventional for winding hot-spot for some or all windings



IEC 681/09

Key

- 2 high-temperature radial spacers on top of the winding
- 3 high-temperature radial spacers inside the winding
- 4 high-temperature conductor insulation in the hottest areas

Figure 4 – Illustration of solid insulation in a mixed insulation system

6 Temperature limits

In most conventional transformers using cellulose-based insulation and mineral oil, the solid insulation material determines the maximum operating temperature. When high-temperature solid insulation materials are used with conventional liquid, the insulating liquid will generally become the limiting factor and will determine the maximum temperature limits. Avoiding overheating of the insulating liquid becomes the design focus, since the ageing that may take place above a certain liquid temperature changes many properties of the insulating liquids. An essential property such as the dielectric strength of the liquid may decline significantly within a relatively short time, if the temperature is not kept below a certain limit.

Maximum temperature limits for various combinations of solid and liquid insulating materials are presented in Tables 4 and 5. Additional information may be found in Annex B. However, these temperatures are intended to be upper limits and are highly dependant on the specific design and application. Accordingly, this technical specification does not select a single temperature rise rating for each insulation system. Rather, it is suggested that rated temperature rise values that are selected lower than the maximum shown should be incremented by 5 °C. An accurate thermal model verified by adequate test data is required to determine the actual maximum values of any specific transformer design. Some of the limiting factors to be considered in determining the permissible maximum temperatures are:

- free breathing units that introduce moisture and free oxygen into the transformer tank, which are major contributors to insulation ageing. This ageing is accelerated as the temperature increases;
- ageing of materials such as cellulose-based insulation, which may introduce moisture and free oxygen inside the transformer tank;
- velocity of the liquid in the cooling ducts, since long exposure of the liquid to high temperature will accelerate degradation;
- accelerated ageing of the liquid and insulating materials due to catalytic action caused by the presence of bare copper and silver surfaces which generate by-products, such as particles and copper derivatives dissolved in insulating liquids;
- gas bubbles caused by overheated trapped moisture between the winding conductors and the conductor covering. See Annex A for more general information on bubbling and an equation for calculating the approximate temperature that bubble generation may occur. While this information is based on cellulose-based insulation and mineral oil, the concepts are essentially the same for high-temperature materials. However, studies indicate that high-temperature insulation materials tend to have lower moisture content than cellulose-based insulation and consequently tend to initiate bubbling at much higher temperatures (for additional information see p.5 of IEEE 1276-1997).

Table 4 – Temperature limits for transformers with mineral oil or alternative liquid operated at 60 K top liquid temperature rise**a) Maximum temperature rise limits**

	Conventional insulation system ^a	Mixed insulation system	Semi-hybrid insulation system	Hybrid insulation system ^b
Minimum high-temperature solid insulation thermal class ^c	N/A	130	120	155
Top liquid temperature rise (K)	60	60	60	60
Average winding temperature rise (K)	65 ^d	65	75	95
Hot-spot temperature rise for conventional solid insulation (K)	78	78	78	78
Hot-spot temperature rise for high-temperature solid insulation (K)	N/A	110	90	130
NOTE The temperature rises shown are based on normal ambient temperatures as defined in IEC 60076-1, but includes the statement on non-standard ambient temperature.				
^a Reference system for comparison purposes.				
^b Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.				
^c This is a material requirement.				
^d The temperature rise for OD units may be 70 K.				

b) Maximum overload temperature limits

	Conventional insulation system ^a	Mixed insulation system	Semi-hybrid insulation system	Hybrid insulation system ^b
Minimum high-temperature solid insulation thermal class ^c	N/A	130	120	155
Maximum top liquid temperature with normal cyclic loading (°C)	105	105	105	105
Maximum top liquid temperature with long-time emergency loading (°C)	115	115	115	115
Maximum conventional hot-spot temperature with normal cyclic loading (°C)	120	120	120	120
Maximum conventional hot-spot temperature with long-time emergency loading (°C)	140	140	140	140
Maximum high-temperature insulation hot-spot temperature with normal cyclic loading (°C)	N/A	150	130	170
Maximum high-temperature ^d insulation hot-spot temperature with long-time emergency loading (°C)	N/A	180	150	200
NOTE Refer to IEC 60076-7 Table 4.				
^a Reference system for comparison purposes.				
^b Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.				
^c This is a material requirement.				
^d The temperatures shown for emergency loading should be used with caution, since they are extrapolated similar to IEC 60076-7, but have not been validated by field experience or by laboratory testing. These values are only intended to be used as a starting point and should be carefully evaluated.				

Table 5 – Temperature limits for transformers with homogeneous high-temperature insulation systems

a) Maximum temperature rise limits

	Ester liquid or equivalent			Silicone liquid or equivalent		
Minimum high-temperature solid insulation thermal class ^a	130	155	180	155	180	200
Top liquid temperature rise (K)	80	80	80	100	100	100
Average winding temperature rise (K)	85	100	115	100	115	125
Hot-spot temperature rise (K)	110	135	160	135	160	180
NOTE 1 Essentially oxygen-free application where the liquid preservation system effectively prevents the ingress of air into the tank.						
NOTE 2 The temperature rises shown are based on normal ambient temperatures as defined in IEC 60076-1, but includes the statement on non-standard ambient temperature.						
^a This is a material requirement.						

b) Maximum temperature limits

	Ester liquid or equivalent			Silicone liquid or equivalent		
Minimum high-temperature solid insulation thermal class ^a	130	155	180	155	180	200
Maximum top liquid temperature with normal cyclic loading (°C)	130	130	130	155	155	155
Maximum top liquid temperature with long-time emergency loading (°C)	140	140	140	170	170	170
Maximum hot-spot temperature with normal cyclic loading (°C)	150	175	200	175	200	220
Maximum hot-spot temperature with long-time emergency loading ^b (°C)	170	200	230	200	230	255
NOTE Essentially oxygen-free applications where the liquid preservation system effectively prevents the ingress of air into the tank.						
^a This is a material requirement.						
^b The temperatures shown for emergency loading should be used with caution, since they are extrapolated similar to IEC 60076-7, but have not been validated by field experience or by laboratory testing. These values are only intended to be used as a starting point and should be carefully evaluated.						

7 Transformer accessories and compatibility

7.1 General

When operating at high temperature, it is important that the individual components are checked to ensure that they have electrical, thermal, chemical and mechanical compatibility with their mating parts. Compatible materials will exhibit no abnormal degradation of performance or key parameters in normal use.

This technical specification primarily covers the thermal compatibility. It is essential however, that dielectric and chemical properties of the various components together with their gaskets, as appropriate are also taken into account.

7.2 Bushings

Higher operating temperatures in the winding will not affect the bushings, if the top liquid temperature is not increased above conventional limits. Where the top liquid temperature is higher than that of a conventional design, the bushing performance may be affected. In this case, special high-temperature or over-sized bushings may be required. As an alternate, it may be possible to relocate the bushings to a lower position on the tank to take advantage of lower liquid temperatures.

Special attention should be paid to conventional condenser-type bushings because the condenser body might be damaged due to thermal runaway when exposed to too high ambient temperatures. See IEC 60137, which states the following temperature limits for the transformer insulating liquid that surrounds the bushing:

- for normal load 100 °C;
- for emergency duty 115 °C;
- maximum daily mean 90 °C.

Due to the risk of thermal runaway suppliers of cables and cable end-seals for direct entry into the transformer may also restrict the temperature of the surrounding insulating liquid of the transformer.

7.3 Tap-changer

Off-circuit tap-changers are not always located in the hottest top liquid zone. However, in case the tap-changer is located in liquid temperatures above the commonly used 100 °C in conventional units, special thermal, mechanical and dielectric considerations should be evaluated for the selection of these components.

Higher operating temperatures in the winding could also affect the tap-changer, if the heat is transferred from the winding onto the tap-changer contacts. Accordingly, a higher current rated tap-changer is not necessarily the solution since the source of the heat is the winding and not a higher current. In the application of high temperature operation, the compatibility of contact materials should be considered.

When on-load tap-changers will be exposed to higher temperature than conventional, the supplier of the on-load tap-changer should be consulted at the enquiry and the contract stage in case special accommodations are necessary. For the same reason, the supplier of the on-load tap-changer should also be consulted, if the insulating liquid of the transformer is different from conventional mineral oil.

7.4 Gasket material

Higher operating temperatures in the winding will not affect the gasket performance, if the top liquid temperature is not increased above conventional limits. When operating the insulating liquid at higher temperatures, a higher temperature grade of gasket material may be required that is chemically compatible with the insulating liquid at the application temperature.

7.5 Tank painting

Higher operating temperatures in the winding will not affect the paint performance, if the top liquid temperature is not increased above conventional limits. When operating the insulation liquid at higher temperatures, it is important to use thermally compatible internal and external paint specifications.

7.6 Coolers

Higher operating temperatures in the winding will not affect the cooler performance, if the top liquid temperature is not increased above conventional limits. When operating the insulation liquid at higher temperatures, all the materials in the cooler should be suitable for the higher temperatures. Thermal properties such as viscosity and heat transfer need careful consideration as they could differ significantly from mineral insulating oil. It is also possible that the thermal properties will vary over the increased temperature range. As with the tank, the paint system should also be suitable for the higher temperature.

7.7 Pumps

The pump specification should take into account the viscosity of the insulating liquid over the operational temperature range.

7.8 Tank and conservator

The capacity of the liquid conservator should take into account the temperature range over which the transformer will operate. The expansion/contraction of the high-temperature liquid may differ significantly from that of mineral insulating oil. For sealed transformers, the tank or conservator should be sized accordingly, to prevent abnormally high pressures. For breather systems, which utilise a membrane, a higher temperature grade of membrane material may be required. Furthermore, the material of the membrane shall be compatible with the insulation liquid.

7.9 Adhesives

Adhesives used during the manufacturing process that are expected to maintain a bond throughout the life of the unit should be suitable for the application temperatures and should also be chemically compatible with the insulating liquid used.

7.10 Current transformers

The insulation system used on any current transformer should be thermally and chemically compatible with the insulating liquid used.

7.11 Temperature gauges and indicators

When necessary, the temperature gauges and indicators should be specified to operate to higher temperatures and over greater temperature ranges, as determined by the specific application. In particular, values of the alarm and trip settings should be set accordingly.

7.12 Protective relays

The gases that may be generated in transformers using high-temperature insulation systems may differ from those in a conventional system. The protective relay therefore, should be compatible with the insulating liquid, its operating temperature and the gases that may be developed.

7.13 Auxiliary cables

For transformers where the insulating liquid is expected to operate at temperatures above that of conventional mineral oil, the cables that connect external accessories shall either be thermally insulated from the transformer cover or tank wall or be of a type that can withstand the relevant temperature on a long-term basis.

8 Special design considerations

8.1 Short-circuit considerations

Designing for higher average winding temperature rises than conventional designs may be accomplished by reduced cooling or by higher current densities or both. In the latter case, the high-temperature design may consequently require reinforced mechanical construction to withstand the effects of an external short-circuit.

The mechanical construction of the winding and support structure should also be designed to take into consideration the possible increased expansion or contraction of the transformer windings due to the larger temperature range.

In addition, the processing of the windings should be such that the tightness of the construction will be maintained in service.

The transformer should be designed to withstand short-circuits as defined in IEC 60076-5. The maximum permissible value of the average temperature of each winding should be calculated in accordance with that specification. For category I transformers with high-temperature liquids covered by Table 5 of this standard, the maximum permissible temperature for copper windings during short-circuit is 350 °C.

Where the design incorporates epoxy-bonded winding conductors, the maximum temperatures obtained under short-circuit conditions should be taken into account since the epoxy is mechanically weaker at higher temperatures.

8.2 Dielectric requirements

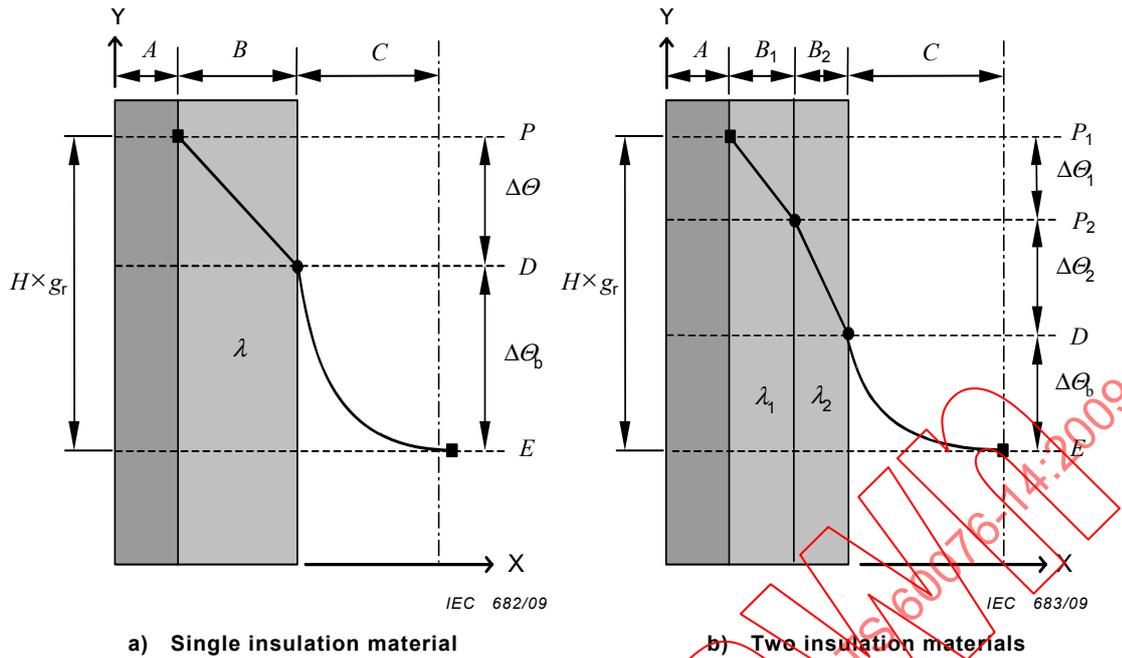
Although the basic requirements of IEC 60076-3 apply, the dielectric properties of a high-temperature insulation system composed of solid materials and a dielectric liquid may differ from the conventional system. Hence the effects of these changes need to be fully analysed at the design stage. The design should ensure that there is no unacceptable degradation of the dielectric properties over the wider operating temperature range of the transformer.

8.3 Temperature requirements

The numerical value of the hot-spot temperature of the winding and its location is critical for the satisfactory operation of the transformer. As with any transformer these are design specific and hence an adequate thermal model of the winding is required, which should be verified by a model test. In mixed insulation systems there will be several hot-spots (one for each type of insulation) and all need careful consideration. See Figure 5b and Figure 6.

It is important to note that in many cases the liquid in the winding cooling duct can have a higher temperature than that of the liquid in the top of the tank and this should be taken into consideration, since the hot-spot is determined by the liquid adjacent to the winding. The conductor to liquid temperature gradient of an insulated winding is generally the sum of the temperature gradient across the solid insulation and the temperature gradient across the boundary layer. In high-temperature insulation systems the temperature gradient across the boundary layer is usually greater than in conventional insulation systems. This means that in most cases, the surface temperature of the winding is limited by the thermal capability of the insulation liquid.

The maximum winding surface temperature in point *D* is given by the sum of the liquid temperature in the cooling duct and the temperature rise across the boundary layer. It depends on the heat transfer coefficient at the winding surface and the heat flux density through the winding surface. The insulation liquid needs to withstand the maximum surface temperature without accelerated ageing, unacceptable gas generation or bubble generation.



Key

- X axis distance from conductor
- Y axis temperature
- A thickness of the conductor
- B thickness of the solid insulation material
- B₁ thickness of the high-temperature insulation material
- B₂ thickness of the conventional insulation material
- C thickness of the boundary layer of the liquid
- D winding surface temperature
- E liquid temperature in the cooling duct
- g_r average winding to liquid temperature gradient at rated current
- H hot-spot factor
- P hot-spot temperature in contact with the solid insulation material
- P₁ hot-spot temperature in contact with the high-temperature insulation material
- P₂ hot-spot temperature in contact with the conventional insulation material
- Δθ temperature gradient inside the solid insulation
- Δθ₁ temperature gradient inside the high-temperature insulation
- Δθ₂ temperature gradient inside the conventional insulation
- Δθ_b temperature gradient inside the boundary layer of the liquid
- λ thermal conductivity of the solid insulation material
- λ₁ thermal conductivity of the high-temperature insulation material
- λ₂ thermal conductivity of the conventional insulation material

Figure 5 – Temperature gradient conductor to liquid

8.4 Overload

Depending on the transformer design and the thermal capability of the insulation system, the transformer may have different overload capability from that of a conventional design.

The general principles and equations of the loading guide for oil-immersed transformers as described in IEC 60076-7 apply, except for the overload levels, since temperatures and time constants may not be applicable for different insulating systems. Maximum overload temperatures are listed in Tables 4b and 5b. Any other overload requirements should preferably be specified in the enquiry, or be agreed upon at the contract stage.

8.5 Effects of harmonic currents

Harmonic currents will increase the transformer eddy and stray losses when compared with a sinusoidal current with the same RMS value. These higher losses will increase the average temperature rise of the windings and hot-spot temperatures.

The higher losses due to harmonic currents may increase the difference between the winding's average temperature rise and its hot-spot temperature. This difference can be quite significant for convertor transformers having two or more valve windings loosely coupled. See IEC 61378-1 for additional information.

8.6 Liquid preservation system

The type of liquid preservation system should be specified in the enquiry and order as described in IEC 60076-1. All liquid-immersed transformers will benefit from the exclusion of oxygen. However, this is especially important for transformers operating at high temperatures. The use of preservation systems that do not inherently prevent the liquid from coming in contact with the atmosphere should be restricted to applications where more frequent liquid processing is possible and acceptable, such as mobile transformers. Even then, some active means should be employed to dry the air, such as a moisture-removing breather.

9 Required information

9.1 Information to be provided by the purchaser

9.1.1 Ambient temperatures and loading cycle

The ambient temperature should be in accordance with IEC 60076-1 and IEC 60076-2. The temperature limits noted in Tables 4 and 5 should be modified accordingly if the ambient temperatures differ from normal service conditions. Any particular loading cycle information must be supplied by the purchaser.

9.1.2 Harmonic currents

Harmonic currents affect transformer losses and therefore temperatures as mentioned in 8.5. The most common sources of harmonic currents are convertors, to which transformers are connected. The characteristics of these harmonics depend on the following:

- convertor power circuit configuration;
- convertor control technique;
- interaction between the convertor and the system to which it is applied;
- characteristics of the power electronic components.

The transformer manufacturer does not have the necessary information or knowledge to predict the current harmonics generated by the convertor. Accordingly, IEC 61378 series require that a harmonic spectrum be included in the specification. The purchaser has the responsibility of specifying the harmonics to which the transformer will be subjected, whilst the transformer manufacturer has the responsibility of designing the transformer, taking into account these specified harmonics.

9.1.3 Other unusual service conditions

For all other unusual service conditions, see IEC 60076-1.

9.2 Information to be provided by the manufacturer

9.2.1 Thermal characteristics

The rated top liquid temperature rise and average winding temperature rise should be given at quotation and contract stage.

In addition to the temperature rise specified in IEC 60076-2, the hot-spot temperature rise of the winding conductor should also be provided.

The type of insulation system to be used should be given at quotation and contract stage.

The IEC specification for the insulating liquid should be given where applicable and also its classification according to IEC 61100.

9.2.2 Reference temperature

When a transformer has windings of different insulation system temperatures, the reference temperature relating to the winding having the higher insulation system temperature shall be used.

9.2.3 Guarantees

The load losses and the short-circuit impedance shall be guaranteed at the reference temperature. The load losses at the reference temperature shall also be used in a temperature-rise test. The same tolerances for guarantees apply, as recommended in IEC 60076-1.

The guaranteed top liquid and average winding temperature rises shall not exceed the values given in Tables 4 and 5.

10 Rating plate and additional information

10.1 Rating and warning plates

10.1.1 Rating plate

In addition to the requirements in IEC 60076-1, the rating plate shall include the following information:

- the number of this IEC publication;
- type of insulation system, (homogenous, hybrid, semi-hybrid or mixed);
- thermal classes of insulation system (EIS) according to Table 4 or 5;
- rated top liquid and average winding temperature rises;
- type of liquid by trade name, standard and year of standard.

10.1.2 Warning plate

If the tank surface may exceed 60 °C a warning plate should be provided to advise caution to avoid touching such surface. IEC standards should be consulted and based on specific design temperatures, appropriate warning signs should be placed on the transformer when the surface is accessible.

10.2 Transformer manual

The manual shall highlight that, due to the presence of insulating materials different from cellulose-based insulation and mineral insulating oil, different behaviour can be expected in

respect to gas and moisture development. Consequently, this should be considered for onsite degassing and drying treatment.

11 Testing

11.1 General

The test requirements for power transformers and reactors are described in the IEC 60076 series and the IEC 61378 series for convertor transformers.

11.2 Requirements for routine, type and special tests

11.2.1 General

It is required to correct the measured results to the reference temperature. On category II and III transformers as defined in IEC 60076-5, it may be desirable to collect DGA (dissolved gas analysis) data for future reference as a diagnostic tool, since the characteristics are likely to differ from conventional transformers.

11.2.2 Routine tests

The tests shall be as prescribed in IEC 60076-1.

11.2.3 Type tests

The tests shall be as prescribed in IEC 60076-1.

11.2.4 Special tests

The tests shall be as prescribed in IEC 60076-1.

11.3 Temperature-rise test

11.3.1 General

The time constant of OD-cooled compact transformers with a high winding to liquid temperature rise is smaller than in conventionally insulated transformers. Particular care is required to shorten the time between switch off and measurement of the winding resistance.

The time from switch off to first recording should ideally be less than 1 min. If this short switch off time cannot be achieved, it is permitted to switch off the cooling fans and pumps at the same time as the shut down in order to reduce the measuring uncertainty of the cooling curve.

11.3.2 Evaluation of temperature-rise tests for mixed insulation systems

Two different hot-spot temperatures need to be verified either by calculation or test: P_1 for the insulation system between B and C and P_2 for the insulation system between E and C . The temperatures in each part of the winding should be evaluated as described in IEC 60076-7. The hot-spot factors, H_1 and H_2 need to be calculated by the manufacturer.

The temperature difference of the liquid in the tank between the top and the bottom is:

$$\Delta\theta_{LW} = \theta_o - \theta_b \quad (4)$$

where:

θ_o is the top liquid temperature in the tank;

θ_b is the bottom liquid temperature in the tank.

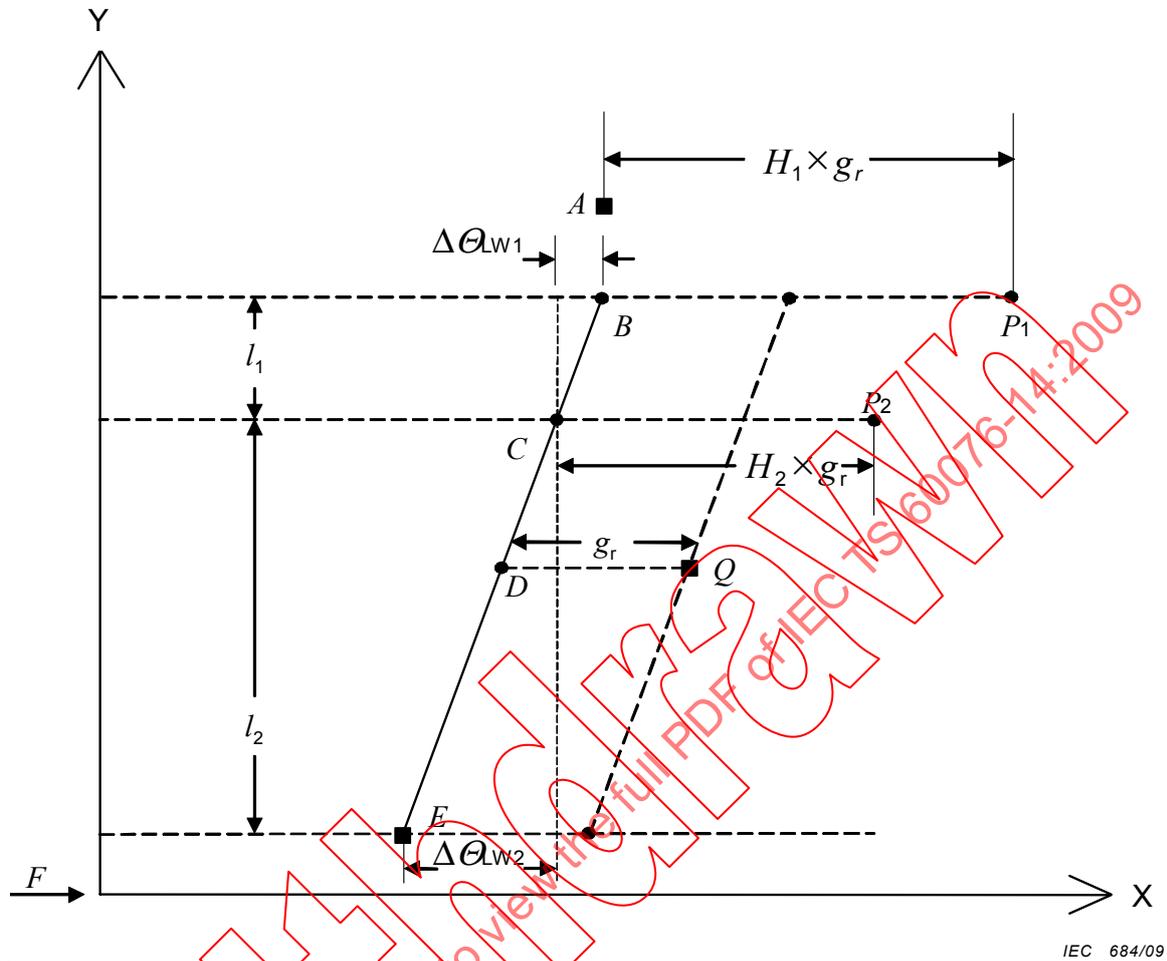
To obtain the liquid temperature in the cooling ducts at the boundary of two different winding parts, (Point C, in Figure 6), this temperature gradient is split into two parts:

$$\Delta\theta_{LW1} = \frac{l_1}{l_1 + l_2} \times \Delta\theta_{LW} \text{ for section 1} \quad (5)$$

$$\Delta\theta_{LW2} = \Delta\theta_{LW} - \Delta\theta_{LW1} \text{ for section 2} \quad (6)$$

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Key

- X axis indicates temperature
- Y axis indicates the axial position along the transformer height
- A average temperature of the tank outlet and the tank liquid pocket
- B liquid temperature in the tank at the top of the winding (assumed to be the same as A)
- C liquid temperature in the winding at the boundary of two different insulation materials
- D average liquid temperature in tank
- g_r average winding to liquid temperature gradient at rated current
- E bottom liquid temperature entering the winding
- F represents the bottom of the tank
- H_1 hot-spot factor associated with part of the winding using high-temperature insulation
- H_2 hot-spot factor associated with part of the winding using conventional insulation
- l_1 length of the upper part of the winding using high-temperature insulation
- l_2 length of the lower part of the winding using conventional insulation
- P_1 hot-spot temperature in contact with the high-temperature insulation material
- P_2 hot-spot temperature in contact with the conventional insulation material
- Q average winding temperature determined by resistance measurement
- $\Delta\theta_{LW1}$ axial temperature rise of the liquid in the upper part of the winding
- $\Delta\theta_{LW2}$ axial temperature rise of the liquid in the lower part of the winding
- measured point; ● calculated point

Figure 6 – Modified temperature diagram for windings with mixed insulation system

11.4 Dielectric type tests

The insulating system should be dielectrically suitable for operation at elevated temperatures, when required.

12 Supervision, diagnostics, and maintenance

12.1 General

Supervision and diagnostics of transformers are part of the strategic approach for risk analysis and asset management which should result in an appropriate maintenance programme and reliable service life. In high-temperature transformers, it may be more important to monitor the performance of the insulation system since significant historical data is not yet available.

A good general diagnostic approach can be found in IEEE 62.

12.2 Transformers filled with mineral insulating oil

Because of the temperature limitation of the mineral insulating oil in insulation systems containing cellulose-based insulation, the amount of solid high-temperature insulating material will generally be small relative to the total amount of insulation material. Hence it is likely that the composition of gases, due to heating, inception of partial discharges and electrical arcing will be close to that of conventional transformers, operating under the same conditions.

In transformers with hybrid insulation systems, the most probable source of gas generation is the mineral insulating oil. However, when overheating, thermal faults, partial discharges or electrical arcing arise, decomposition of high-temperature solid insulation is possible with the potential for generating gases and other by-products (moisture, particles, furans, metals).

It may be desirable to periodically take oil samples for analysis. IEC 60422 provides guidance for the supervision and maintenance of mineral insulating oils.

12.3 Transformers filled with high-temperature insulating liquids

When overheating, thermal faults, partial discharges or electrical arcing arise in transformers with high-temperature homogeneous insulation systems, decomposition of the liquid and/or solid insulation is possible with the potential for generating gases and other by-products (moisture, particles, furans, metals).

On category II and III transformers as defined in IEC 60076-5, it may be desirable to collect DGA data for future reference as a diagnostic tool, since the characteristics are likely to differ from conventional transformers. IEC 60944 and IEC 61203 provide guidance for the supervision and maintenance of silicone transformer liquids and transformer esters in equipment respectively.