

BS EN 60076-2:2011



BSI Standards Publication

Power transformers

Part 2: Temperature rise for
liquid-immersed transformers

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National foreword

This British Standard is the UK implementation of EN 60076-2:2011. It is identical to IEC 60076-2:2011. It supersedes BS EN 60076-2:1997 which will be withdrawn 30 March 2014.

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

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

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English version

**Power transformers -
Part 2: Temperature rise for liquid-immersed transformers
(IEC 60076-2:2011)**

Transformateurs de puissance -
Partie 2: Echauffement des
transformateurs immergés dans le liquide
(CEI 60076-2:2011)

Leistungstransformatoren -
Teil 2: Übertemperaturen für
flüssigkeitsgefüllte Transformatoren
(IEC 60076-2:2011)

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Foreword

The text of document 14/669/FDIS, future edition 3 of IEC 60076-2, prepared by IEC TC 14, Power transformers, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 60076-2 on 2011-03-30.

This European Standard supersedes EN 60076-2:1997.

EN 60076-2:2011 includes the following significant technical changes with respect to EN 60076-2:1997:

- the standard is applicable only to liquid immersed transformers;
- the winding hot-spot temperature rise limit was introduced among the prescriptions;
- the modalities for the temperature rise test were improved in relation to the new thermal requirements;
- five informative annexes were added in order to facilitate the standard application.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN and CENELEC shall not be held responsible for identifying any or all such patent rights.

The following dates were fixed:

- latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2011-12-30
- latest date by which the national standards conflicting with the EN have to be withdrawn (dow) 2014-03-30

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 60076-2:2011 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

- [2] IEC 60296:2003 NOTE Harmonized as EN 60296:2004 (not modified).
 - [3] IEC 60567:2005 NOTE Harmonized as EN 60567:2005 (not modified).
 - [4] IEC 60599:1999 NOTE Harmonized as EN 60599:1999 (not modified).
 - [5] IEC 60836:2005 NOTE Harmonized as EN 60836:2005 (not modified).
 - [6] IEC 61099:2010 NOTE Harmonized as EN 61099:2010 (not modified).
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Annex ZA (normative)

Normative references to international publications with their corresponding European publications

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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

<u>Publication</u>	<u>Year</u>	<u>Title</u>	<u>EN/HD</u>	<u>Year</u>
IEC 60076-1 (mod)	-	Power transformers - Part 1: General	EN 60076-1	-
IEC 60076-8	1997	Power transformers - Part 8: Application guide	-	-
IEC 60085	2007	Electrical insulation - Thermal evaluation and designation	EN 60085	2008
IEC 61181	2007	Mineral oil-filled electrical equipment - Application of dissolved gas analysis (DGA) to factory tests on electrical equipment	EN 61181	2007
IEC Guide 115	2007	Application of uncertainty of measurement to conformity assessment activities in the electrotechnical sector	-	-

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POWER TRANSFORMERS –

Part 2: Temperature rise for liquid-immersed transformers

1 Scope

This part of IEC 60076 applies to liquid-immersed transformers, identifies power transformers according to their cooling methods, defines temperature rise limits and gives the methods for temperature rise tests.

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 60076-8:1997, *Power transformers – Part 8: Application guide*

IEC 60085:2007, *Electrical insulation – Thermal evaluation and designation*

IEC 61181:2007, *Mineral oil-filled electrical equipment – Application of dissolved gas analysis (DGA) to factory tests on electrical equipment*

IEC Guide 115:2007, *Application of uncertainty of measurement to conformity assessment activities in the electrotechnical sector*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60076-1 and the following apply.

3.1

external cooling medium

the medium external to the transformer cooling system (air or water) into which the heat produced by the transformer losses is transferred

3.2

internal cooling medium

the liquid in contact with the windings and other transformer parts by means of which the heat produced by the losses is transferred to the external cooling medium

NOTE The liquid can be mineral oil or other natural and synthetic liquid.

3.3

temperature rise

the difference between the temperature of the part under consideration (for example, the average winding temperature) and the temperature of the external cooling medium

3.4
top-liquid temperature

θ_o

the temperature of the insulating liquid at the top of the tank, representative of top-liquid in the cooling flow stream

3.5
top-liquid temperature rise

$\Delta\theta_o$

the temperature difference between the top-liquid temperature and the external cooling medium temperature

3.6
bottom-liquid temperature

θ_b

the temperature of the insulating liquid as measured at the height of the bottom of the windings or to the liquid flowing from the liquid cooling equipment

3.7
bottom-liquid temperature rise

$\Delta\theta_b$

the difference between the bottom-liquid temperature and the external cooling medium temperature

3.8
average liquid temperature

θ_{om}

the average temperature of the top-liquid and bottom liquid temperatures

3.9
average liquid temperature rise

$\Delta\theta_{om}$

the difference between the average liquid temperature and the external cooling medium temperature

3.10
average winding temperature

θ_w

the winding temperature determined at the end of temperature rise test from the measurement of winding d.c. resistance

3.11
average winding temperature rise

$\Delta\theta_w$

the difference between the average winding temperature and the external cooling medium temperature

3.12
average winding gradient

g

the difference between the average winding temperature and the average insulating liquid temperature

3.13**hot-spot winding temperature** θ_h

the hottest temperature of winding conductors in contact with solid insulation or insulating liquid

3.14**hot-spot winding temperature rise** $\Delta\theta_h$

the difference between hot-spot winding temperature and the external cooling medium temperature

3.15**hot-spot factor** H

a dimensionless factor to estimate the local increase of the winding gradient due to the increase of additional loss and variation in the liquid flow stream

NOTE H factor is obtained by the product of the Q and S factors (see 3.16 and 3.17).

3.16**Q factor**

a dimensionless factor to estimate the increase of the average winding gradient due to the local increase of the additional loss

3.17**S factor**

a dimensionless factor to estimate the local increase of the average winding gradient due to the variation in the liquid flow stream

3.18**thermally upgraded paper**

cellulose-based paper which has been chemically modified to reduce the rate at which the paper decomposes

A paper is considered as thermally upgraded if it meets the life criteria of the 50 % retention in tensile strength after 65 000 h in a sealed tube at 110 °C or any other time/temperature combination given by the equation:

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

NOTE 1 Ageing effects are reduced either by partial elimination of water forming agents or by inhibiting the formation of water through the use of stabilizing agents.

NOTE 2 See IEC 60076-7, for an alternative test method based on the nitrogen content.

4 Cooling methods**4.1 Identification symbols**

Transformers shall be identified according to the cooling method employed. For liquid-immersed transformers, this identification is expressed by a four-letter code as described below.

First letter: Internal cooling medium:

- O: mineral oil or synthetic insulating liquid with fire point ≤ 300 °C;

- K: insulating liquid with fire point > 300 °C;
- L: insulating liquid with no measurable fire point.

Second letter: Circulation mechanism for internal cooling medium:

- N: natural thermosiphon flow through cooling equipment and in windings;
- F: forced circulation through cooling equipment, thermosiphon flow in windings;
- D: forced circulation through cooling equipment, directed from the cooling equipment into at least the main windings.

Third letter: External cooling medium:

- A: air;
- W: water.

Fourth letter: Circulation mechanism for external cooling medium:

- N: natural convection;
- F: forced circulation (fans, pumps).

NOTE 1 In this standard, the use of insulating liquids K and L is considered only for safety and environmental reasons.

NOTE 2 In a transformer designated as having forced directed insulating liquid circulation (second code letter D), the rate of liquid flow through the main windings is determined by the pumps and is not, in principle, determined by the loading. A minor fraction of the flow of liquid through the cooling equipment may be directed as a controlled bypass to provide cooling for core and other parts outside the main windings. Regulating windings and/or other windings having relatively low power may also have non-directed circulation of bypass liquid.

In a transformer with forced, non-directed cooling (second code letter F), the rates of flow of liquid through all the windings are variable with the loading, and not directly related to the pumped flow through the cooling equipment.

4.2 Transformers with alternative cooling methods

A transformer may be specified with alternative cooling methods. In this case, the specification and the rating plate shall then carry information about the power values at which the transformer fulfils the temperature rise limits when these alternatives apply, see IEC 60076-1.

The power value for the alternative cooling methods with the highest cooling capacity is the rated power of the transformer (or of an individual winding of a multi-winding transformer, see IEC 60076-1). The alternatives cooling methods are conventionally listed in rising order of cooling capacity.

Examples:

- ONAN/ONAF. The transformer has a set of fans which may be put into service as desired at high loading. The insulating liquid circulation is by thermosiphon effect only, in both cases.
- ONAN/OFAF. The transformer has cooling equipment with pumps and fans but is also specified with a reduced rated power under natural cooling (for example, in case of failure or reduction of auxiliary power).

5 Normal cooling conditions

5.1 Air-cooled transformers

Normal ambient temperature limits for power transformers are given in IEC 60076-1.

With regard to normal temperature rise requirements, the temperatures at the intended installation site should not exceed:

- + 40 °C at any time;
- + 30 °C monthly average, of the hottest month;
- + 20 °C yearly average.

NOTE The average temperatures are to be derived from meteorological data as follows (see IEC 60076-1).

Monthly average temperature:

- half the sum of the average of the daily maxima and the average of the daily minima during a particular month, over many years;

Yearly average temperature:

- one-twelfth of the sum of the monthly average temperatures.

5.2 Water-cooled transformers

Normal cooling condition for water cooled transformers is a temperature of cooling water at the inlet not exceeding 25 °C at any time or a 20 °C yearly average.

If the operating water temperature is higher than this, then a lower temperature rise should be specified (see IEC 60076-1).

6 Temperature rise limits

6.1 General

Temperature rise requirements are specified according to different options:

- a set of requirements which refer to continuous rated power (see 6.2).
- an additional set of explicitly specified requirements, that relate to a prescribed loading cycle (see 6.4).

NOTE The additional set of requirements is applicable mainly to large system transformers for which emergency loading conditions deserve particular attention, and should not be regularly used for small and medium-size standardized transformers.

It is assumed throughout this part that the service temperatures of different parts of a transformer can each be described as the sum of the external cooling medium temperature (ambient air or cooling water) and the temperature rise of the transformer part.

Normal temperature rise limits apply unless other service conditions are specified. In such cases, the limits of temperature rise shall be modified as indicated in 6.3.

No plus tolerance is permitted on temperature rise limits.

6.2 Temperature rise limits at rated power

For transformers up to 2 500 kVA (833 kVA single-phase) with a tapping range not exceeding $\pm 5\%$, the temperature rise limits shall apply to the principal tapping corresponding to the rated voltage (see IEC 60076-1).

For transformer rated power larger than 2 500 kVA or if the tapping range exceeds $\pm 5\%$, the temperature rise limits shall apply to every tapping at the appropriate tapping power, tapping voltage and tapping current.

NOTE 1 The load losses are different for different tappings and sometimes also the no-load loss when variable flux voltage variation is specified.

NOTE 2 In a separate winding transformer, the tapping with the highest load loss is normally the tapping with the maximum current.

NOTE 3 In an auto-transformer with tapping, the tapping with the highest load loss depends on how the tapings are arranged.

For a multi-winding transformer, when the rated power of one winding is equal to the sum of the rated powers of the other windings, the temperature rise requirements refer to rated power in all windings simultaneously. If this is not the case, one or more particular loading combinations have to be selected and specified for the temperature rise limits.

In the case of a transformer with two or more separate winding sections one above the other, the winding temperature limit shall apply to the average of the measurements of the stacked sections, if they are of equal size and rating.

The temperature rise limits given in Table 1 are valid for transformers with solid insulation designated as class 105 °C according to IEC 60085, and immersed in mineral oil or synthetic liquid with a fire point not above 300 °C (first code letter: O).

The limits refer to steady state conditions under continuous rated power, and 20 °C average yearly temperature of the external cooling medium.

If not otherwise agreed between manufacturer and purchaser, the temperature rise limits given in Table 1 are valid for both Kraft and upgraded paper (see also IEC 60076-7).

Table 1 – Temperature rise limits

Requirements for	Temperature rise limits
	K
Top insulating liquid	60
Average winding (by winding resistance variation):	
– ON.. and OF.. cooling systems	65
– OD.. cooling system	70
Hot-spot winding	78

No numerical limits are specified for the temperature rise of magnetic core, bare electrical connections, electrical or magnetic shields and structural parts in the tank. However, a self-evident requirement is that they shall not reach a temperature which will cause damages to adjacent parts or undue ageing of the insulating liquid. If considered necessary, a temperature rise limit for the magnetic core surface may be agreed between manufacturer and purchaser.

NOTE 4 For some designs, the hot-spot winding temperature rise limit may imply lower top-liquid and/or average winding temperature rises than those indicated in the table.

NOTE 5 The rules for determining the hot-spot winding temperature rise are given in 7.10.

NOTE 6 For large power transformers immersed in mineral oil, in-oil dissolved gas analysis (DGA) performed during the temperature rise test can be a tool for detecting undesirable overheating (see Annex D).

NOTE 7 For large power transformers, the temperature rise of tank and cover surfaces can be checked by means of a thermographic infrared camera.

On windings of very low resistance with numerous bolted connections (e.g., low voltage winding of furnace transformers), the determination of the average winding temperature rise by resistance variation may be difficult and subjected to a large uncertainty. As an alternative and by agreement between manufacturer and purchaser, the winding temperature rise requirements may be limited to the hot-spot winding temperature rise which shall be determined by direct measurement in this case.

Temperature rise limits for transformers having higher temperature resistant insulation systems and immersed in a less flammable liquid (code letter K or L) are subject to agreement.

6.3 Modified requirements for special cooling conditions

6.3.1 General

If the service conditions at the intended installation site do not fall within the limits of normal cooling conditions given in Clause 5, then the limits of temperature rise for the transformer shall be modified in accordance with the rules indicated below.

6.3.2 Air-cooled transformers

If the temperature of the external cooling medium at site exceeds one or more of the normal values given in 5.1, all the temperature rise limits indicated in Table 1 shall be corrected by the same amount as the excess. The obtained values shall be rounded to the nearest whole number of degrees kelvin.

Recommended ambient temperature reference values and relevant temperature rise limit corrections are given in Table 2.

Table 2 – Recommended values of temperature rise corrections in case of special service conditions

Ambient temperatures °C			Correction of temperature rise K ^a
Yearly average	Monthly average	Maximum	
20	30	40	0
25	35	45	–5
30	40	50	–10
35	45	55	–15

^a Referred to the values given in Table 1.

NOTE 1 No rules are given for ambient temperatures lower than the normal ones. The temperature rise limits given in Table 1 are applied unless otherwise specified by the purchaser.

NOTE 2 The values given in the Table 2 may be interpolated.

If the installation site is more than 1 000 m above sea-level but the factory is not, then the allowable temperature rises during the test in the factory shall be reduced as follows:

- for a naturally cooled transformer (...AN), the limit of top-liquid, average and hot-spot winding temperature rises shall be reduced by 1 K for every interval of 400 m by which the installation's altitude exceeds 1 000 m;
- for a forced-cooled transformer (... AF), the reduction shall be 1 K for every 250 m exceeding 1 000 m.

A corresponding reverse correction may be applied in cases where altitude of the factory is above 1 000 m and the altitude of the installation site is below 1 000 m.

Any altitude correction shall be rounded to the nearest whole number of degrees kelvin.

When the specified temperature rise limits of a transformer have been reduced, either because of high cooling medium temperature or because of high-altitude installation, this shall be indicated on the rating plate (see IEC 60076-1).

NOTE 3 When standardized transformers are to be used at high altitudes, a reduced value of power may be calculated, which from the point of view of cooling and temperature rise corresponds to service with rated power under normal ambient conditions.

6.3.3 Water-cooled transformers

If the maximum and/or the yearly cooling water temperature at site exceeds the values indicated in 5.2, all the prescribed temperature rise limits shall be reduced by the same amount as the excess. The values shall be rounded to the nearest whole number of degrees.

NOTE The rule given above does not apply for water temperatures lower than the normal one. In that case, an agreement between manufacturer and purchaser is necessary.

The influence of differing ambient temperature or altitude on the air cooling of the tank shall be disregarded.

6.4 Temperature rise during a specified load cycle

By agreement between manufacturer and purchaser, temperature rise limits can be guaranteed and/or a special test regarding load cycle operation specified (see IEC 60076-7).

7 Temperature rise tests

7.1 General

The following subclauses describe the procedures for the determination of temperature and temperature rise values during factory testing and also the methods for substituting service loading conditions by equivalent test procedures.

During the temperature rise test, the transformer shall be equipped with its protective devices (for example, Buchholz relay). Any indication from these devices during the test shall be noted and the case investigated.

In the case of a transformer with more than one value of rated power (for example, when two or more cooling methods are provided), a temperature rise test shall be in principle performed for each rated power, but by agreement between manufacturer and purchaser the number of tests can be reduced.

7.2 Temperature of the cooling media

7.2.1 Ambient temperature

For the temperature rise test, the cooling air temperature should be in the range between 10 °C and the maximum ambient temperature for which the transformer is designed.

The interpretation of the test results shall be subject to agreement if the external cooling medium temperature during the test is outside the limits indicated.

At least four sensors shall be provided and the average of their readings shall be used to determine the ambient temperature for the evaluation of the test results.

NOTE For tests on large power transformers, the number of sensors should be increased up to six in order to reduce the uncertainty that can affect the average of the readings.

Readings should be taken at regular intervals (e.g., every ten minutes), or automatic continuous recording may be used.

Around an ONAN transformer, the ambient sensors shall be placed at a level about halfway up the cooling surfaces.

The sensors shall be distributed around the tank, about 2 m away from the perimeter of tank and cooling surfaces, and protected from direct heat radiation.

For a forced-air-cooled transformer, the sensors shall be placed in the air at about 0,5 m from the intake of the coolers.

In the case of separate cooling equipment placed at a distance of at least 3 m from the transformer tank, the ambient temperature shall be measured around the cooling equipment applying the same rules given above.

Attention shall be paid to possible recirculation of hot air. The transformer should be placed so as to minimize obstructions to the air flow and to provide stable ambient conditions.

Precautions should be taken to minimize variations of cooling-air temperature, particularly during the last part of the test period when steady state conditions are approached. Rapid variation of readings due to turbulence should be prevented by appropriate means such as heat sinks for the temperature sensors of thermal time constant similar to the transformer thermal time constant.

7.2.2 Water temperature

For the temperature rise test, the cooling water temperature should be in the range between 5 °C and the maximum water temperature for which the transformer is designed.

The interpretation of the test results shall be subject to agreement if the water temperature is outside the limits indicated above.

The temperature shall be measured at the intake of the cooling equipment. Readings of temperature and rate of water flow should be taken at regular intervals (e.g., every ten minutes), or automatic continuous recording may be used.

Precautions shall be taken to minimize the variations of water cooling flow and temperature during the test period.

7.3 Test methods for temperature rise determination

7.3.1 General

The standard method for the determination of the steady-state temperature rises on the test floor is the equivalent test in short-circuit connection according to 7.3.2 below.

In special cases, if agreed, the test can be performed applying rated voltage and current by connection to a suitable load. This is mainly applicable to transformers with low rated power.

A back-to-back method may also be agreed. In this method, two transformers, one of which is the transformer under test, are connected in parallel and excited at the rated voltage of the transformer under test. By means of different voltage ratios or an injected voltage, rated current is made to flow in the windings of the transformer under test.

7.3.2 Test by short-circuit method for two winding transformers

During this test the transformer is not subjected to rated voltage and rated current simultaneously, but to the calculated total losses, previously obtained by two separate determinations of losses, namely load loss at reference temperature and no-load loss (see IEC 60076-1).

The purpose of the test is to establish:

- the top-liquid and average liquid temperature rises in a steady-state condition with dissipation of total losses;
- the average winding temperature rise at rated current for the average liquid temperature rise as determined above;
- the hot-spot winding temperature rise at rated current and for the top-liquid temperature rise as mentioned above.

This is achieved in two testing steps:

a) Total loss injection

The top-liquid and average liquid temperature rises are established when the transformer is subjected to a test current *corresponding* to the total losses of the transformer (see IEC 60076-1). The test current will be above rated current to the extent necessary for producing an additional amount of loss equal to the no-load loss at rated voltage, and the winding temperature rise will be correspondingly elevated.

The top-liquid temperature and cooling medium temperature are monitored, and the test is continued until steady-state liquid temperature rises are established.

The first part of the test may be terminated when the rate of change of top-liquid temperature rise has fallen below 1 K/h and has remained there for a period of 3 h. If discrete readings have been taken at regular intervals, the mean value of the readings during the last hour is taken as the result of the test. If continuous automatic recording is applied, the average value during the last hour is taken.

b) Rated current injection

After the top-liquid temperature rise has been established, the test shall be continued without a break with the test current reduced to rated current for the winding combination connected. This condition is maintained for 1 h, during which time continuous temperature records of top-liquid, winding hot-spot (if measured) and external cooling medium should be taken at least every 5 min.

At the end of the hour, the resistances of the windings are measured, either after a rapid disconnection of the supply and short circuits (see 7.8 and Annex C) or, without switching off the supply, by means of the superposition method which consists of injecting into the windings and measuring direct current of low value superimposed on the load current.

The values of average temperature of the two windings are determined from the resistance variations, and in addition by taking into account the liquid temperature decrease when the current is reduced to the rated value, as well as the variation of the external cooling medium temperature.

If the direct measurement of the hot-spot winding temperature is provided, the corresponding temperature rise is obtained by taking the highest reading before disconnection and applying the correction indicated in 7.10.3 because the liquid temperature decreases when the current is reduced to the rated value.

By agreement, the two steps of the test may be combined in one single application of power at a level between load loss and total loss. For liquid immersed transformers, the temperature rise values for top-liquid, average liquid and for the windings shall then be determined using the correction rules given in 7.13. The power injected during the test shall however be at least 80 % of the total loss value.

7.3.3 Test modification for particular transformers

Two-winding transformer with a tapping range larger than ± 5 %, or having a rated power exceeding 2 500 kVA.

Unless otherwise specified, the temperature rise test is conducted with the transformer connected on the maximum current tapping (see IEC 60076-1) and the tapping current for that tapping is used during the later part of the test (see 7.3.2 b)).

The total losses to be injected during the first part of the test (see 7.3.2 a)), shall be equal to the highest value of total loss appearing at any tapping (corresponding to its tapping quantities). This tapping is also often, but not always, the maximum current tapping. This part of the test determines the maximum top-liquid temperature rise. For the determination of winding temperature rise at the maximum current tapping, the value of liquid temperature rise to be used in the evaluation shall correspond to the total losses of that tapping. The value from the first part of the test will be recalculated if obtained with other data.

Multi-winding transformer

When the rated power of one winding is equal to the sum of the rated powers of the other windings, for the first part of the test, a total loss shall be developed which corresponds to rated power (or tapping power) in all windings.

If this does not apply, there are specified loading cases with different combinations of individual winding loads. That case which will be associated with the highest total loss shall determine the test power for the determination of liquid temperature rise.

The temperature rise value for an individual winding above liquid shall be obtained with rated current in the winding.

In the determination of winding temperature rise above medium cooling medium, the liquid temperature rise for the relevant loading case will be recalculated from the total loss injection test, according to 7.13, and likewise the winding temperature rise above liquid for each winding, as applicable.

Guidance for recalculation of losses in multi-winding transformers is given in IEC 60076-8.

The injection of total loss for the determination of liquid temperature rise may be made:

- either in a manner as near as possible to the actual loading case, by injecting the current corresponding to the total losses in one winding, the other ones being simultaneously short-circuited or connected to an impedance;
- or in an approximate manner by not short-circuiting or closing certain windings; for example if one of the windings has a relatively low rated power and low contribution to the total loss of the transformer, it may be acceptable to leave it open and raise the current in the other windings concerned until the correct total loss is obtained.

If none of the methods above can be applied in full, because of limitations of test facilities, it may be agreed to perform the test with reduced loss, down to 80 % of the correct value. Then the measured temperature value shall be corrected according to 7.13.

The details of the temperature rise test for a multi-winding transformer should, as a rule, be presented and agreed already at the tender stage.

For multi-core transformers with windings that do not have external connections, the temperature rise test method should be agreed at the tender stage. The use of additional test bushings may be appropriate.

7.4 Determination of liquid temperatures

7.4.1 Top-liquid temperature

The top-liquid temperature (θ_o) is conventionally determined by one or more sensors immersed in the insulating liquid at the top of the tank or, in pockets in the cover.

The recommended number of pockets is the following:

- rated power ≥ 100 MVA: 3 pockets;
- rated power from 20 MVA to <100 MVA: 2 pockets;
- rated power < 20 MVA: 1 pocket.

The position of the sensors should be chosen to present the top-liquid temperature possibly in correspondence to the wound columns.

If more than one pocket is used, the readings of the sensors shall be averaged in order to obtain a representative temperature value.

NOTE 1 The temperature of the liquid may be different at different places in the top of the tank, depending on the design. Measurements using a pocket in the cover may be disturbed by eddy current heating

NOTE 2 In transformers with forced circulation the liquid in the cooling equipment is a mixture of liquid from the windings with bypass liquid in the tank, which may not be uniform between different parts of the tank or between different cooling-circuit headers. Concerning the significance of top-liquid temperature in transformers with forced circulation, see Annex A.

By agreement between manufacturer and purchaser, the top-liquid temperature can be determined assuming as the average of the indications of the pockets placed on the cover and the temperature of the liquid of the inlet of the cooling equipment.

NOTE 3 The temperature of the liquid in the inlet of the cooling equipment shall be measured by sensors located in the centre of the pipes.

7.4.2 Bottom and average liquid temperatures

Bottom liquid is the term which actually means the temperature of liquid entering the windings at the bottom. For practical reasons, it is identified with the temperature of the liquid returning from the cooling equipment to the tank.

The bottom liquid temperature (θ_b) shall be determined by sensors placed at the return headers from coolers or radiators. If several batteries of cooling equipment are fitted, more than one sensor should be used and the reading average assumed as bottom liquid temperature.

NOTE 1 The flow of liquid in return headers may be turbulent, if forced by a pump, or mainly laminar, if there is natural circulation through the radiators. This is of importance for a representative determination of the liquid temperature in the header.

The average liquid temperature is in principle intended to be the average temperature of the cooling liquid in the windings.

Average liquid temperature (θ_{om}) is used for the calculation of the average winding gradient and for correction of certain temperature rise test results (see 7.13).

The average liquid temperature is:

$$\theta_{om} = (\theta_o + \theta_b) / 2$$

NOTE 2 The validity of the relation given above for the different cooling systems is also discussed in Annex A.

NOTE 3 For ONAN transformers up to 2 500 kVA, with plain or corrugated tanks, or individual cooling tubes mounted directly on the tank, the average liquid temperature rise above ambient temperature may be taken as 80 % of the top-liquid temperature rise.

7.5 Determination of top, average and bottom liquid temperature rises

The top-liquid temperature rise ($\Delta\theta_o$) shall be determined by difference between the top-liquid temperature measured at the end of the test period with total losses (θ_o) and the external cooling medium temperature at the end of the test period with total losses (θ_a), that is:

$$\Delta\theta_o = \theta_o - \theta_a$$

The average liquid temperature rise ($\Delta\theta_{om}$) shall be determined by difference between the average liquid temperature (θ_{om}) calculated according to 7.4.2 and the external cooling medium temperature (θ_a), that is:

$$\Delta\theta_{om} = \theta_{om} - \theta_a$$

The bottom liquid temperature rise ($\Delta\theta_b$) shall be determined by difference between the bottom liquid temperature (θ_b) defined according to 7.4.2 and the external cooling medium temperature (θ_a), that is:

$$\Delta\theta_b = \theta_b - \theta_a$$

NOTE The different liquid temperatures are the average values of the readings during the last hour with total losses.

7.6 Determination of average winding temperature

The average winding temperature is determined by measurement of winding resistance.

On three-phase transformers, the measurement should be normally performed including the middle phase of the windings.

For star connected, low voltage and high current windings, the measurement should be made between line terminals in order to exclude the neutral connection from the test circuit.

A reference measurement (R_1, θ_1) of all winding resistances is made with the transformer at ambient temperature, in a steady-state condition (see IEC 60076-1).

When the resistance (R_2) is measured after disconnection of the power supply, extrapolated to the instant of shutdown, this yields the temperature value:

$$\theta_2 = \frac{R_2}{R_1} (235 + \theta_1) - 235 \quad \text{for copper}$$

$$\theta_2 = \frac{R_2}{R_1} (225 + \theta_1) - 225 \quad \text{for aluminium}$$

where θ_2 is the average temperature of the winding at the instant of shutdown.

In the formula, the temperatures are expressed in Celsius degrees.

NOTE For the low voltage windings of very large power transformers, attention should be paid to the possible formation of a thermocouple e.m.f. between metallic contacts during the resistance measurement after shutdown.

7.7 Determination of winding resistance at the instant of shutdown

The winding resistance (R_2) before shutdown shall be determined using the rules indicated below.

Immediately after disconnection of the test power supply and removal of the short-circuiting connection, a direct current measuring circuit shall be connected across the winding terminals corresponding to the resistance to be measured.

As the resistance of the winding varies with time as the winding cools down, it shall be measured for a sufficient time to permit extrapolation back to the instant of shutdown.

As the windings have a large electrical time constant (L/R), accurate readings are therefore obtained only after a certain delay.

The delay can be reduced by minimizing as much as possible the time between the shutdown and the switching on the resistance circuit, as well as reducing the electrical time constant by an adequate choice of the parameters of the circuit.

The cooling conditions should preferably not be disturbed during the time the resistance measurements are made. If pumps are operating during the temperature rise test, they should be maintained during the measurements.

Recommendations for the detailed execution of the measurement are given in Annex C.

7.8 Determination of average winding temperature rise at the instant of shutdown

The average winding temperature rise shall be determined using the value of resistance at the instant of shutdown determined as indicated in 7.6.

The measured values of winding average temperature shall be raised by the same amount as the average liquid temperature has fallen from the correct value obtained as given in 7.4.2 to that at the end of the 1 h with rated current.

The corrected winding average temperature rise of the winding ($\Delta\theta_w$) is then:

$$\Delta\theta_w = \theta_2 + \Delta\theta_{\text{ofm}} - \theta_a$$

where θ_2 is the average winding temperature at the instant of shutdown, θ_a is the external cooling medium temperature at the end of the test period with total losses, $\Delta\theta_{\text{ofm}}$ the fall of the temperature of the average liquid during the 1 h test at rated current.

Recommendations for the detailed execution of the measurement are given in Annex C.

NOTE In case of multi-winding transformers, the test methods shall be agreed between manufacturer and purchaser.

7.9 Determination of the average winding to liquid temperature gradient

The average winding to average liquid temperature gradient (g) shall be determined as the difference between the uncorrected average winding temperature (θ_2) and the average liquid temperature θ_{om} at shutdown:

$$g = \theta_2 - \theta_{\text{om}}$$

7.10 Determination of the hot-spot winding temperature rise

7.10.1 General

For transformers having rated power 20/3 MVA/phase and above, the determination of the hot-spot winding temperature rise shall be always determined through calculation based on the result of a temperature rise test, applying a method agreed between manufacturer and purchaser.

As a special test and by agreement between manufacturer and purchaser, the hot-spot winding temperature rises can be determined by direct measurement.

For transformers having the rated power per phase lower than 20/3 MVA/phase, neither direct measurements nor calculations are required, as the average winding temperature rise requirement is considered sufficient to also meet the hot-spot winding temperature rise requirement.

For a strategic asset or specific operating conditions (e.g., nuclear power plant) for which more severe requirements are to be applied, the hot-spot winding temperature rise can be determined both by calculation and direct measurement and the obtained results compared.

For auto-connected transformers, the indicated limit refers to the rated power of the equivalent double wound transformer.

7.10.2 Determination by calculation

The manufacturer shall submit to the purchaser the results of a study concerning the location of the hot-spots and the estimation of their temperature rise. The study should be based on:

- the results of the temperature rise test during which the measurement of the hot-spot winding temperatures were not directly measured;
- the knowledge of the leakage flux field to determine the additional loss distribution;
- the knowledge of the insulating liquid circulation patterns inside the windings in the regions in which the additional loss is higher.

NOTE In principle, the estimate of the hot-spot winding temperature rises could be made starting from the design data, but attention should be paid to the uncertainties that this procedure implies.

For transformers having rated power between 20/3 MVA and 100/3 MVA per phase and short-circuit impedance not exceeding 14 %, simplified methods for calculating the hot-spot winding temperature rise can be agreed between manufacturer and purchaser (see also Annex B).

7.10.3 Direct measurement during the temperature rise test

A number of thermal sensors (e.g., optical fibre sensors) shall be mounted inside the windings in positions where it is supposed the hot-spots are located.

NOTE 1 Generally, hot-spots are situated at the top of the windings, but their correct location by means of a design review is recommended.

NOTE 2 The use of optical fibre sensors is recommended. Refer to Annex E for suggested installation methods.

When more than one sensor is used on the same winding, the maximum reading shall be taken as the hot-spot winding temperature.

The hot-spot winding temperature rise ($\Delta\theta_h$) is then obtained by:

$$\Delta\theta_h = \theta_h + \Delta\theta_{of} - \theta_a$$

where θ_h is the temperature reading at shutdown, $\Delta\theta_{of}$ the fall of the top-liquid temperature during the 1 h test at rated current, and θ_a the ambient temperature at the end of the total loss test period.

NOTE 3 The methods indicated above can also be applied for the determination of the hot-spot temperature rise in case of very low winding resistance when the average winding temperature rise by resistance variation is affected by large uncertainty (see 6.2).

7.11 Uncertainties affecting the results of the temperature rise test

The results of the temperature rise test are affected by uncertainties related to the test method and instrumentation used. In the test report, estimates should be given of the uncertainties that affect the temperature rises.

NOTE The uncertainty estimations should not be applied for establishing if the prescribed limits are respected or not, but only for information.

General criteria for evaluating the uncertainties are given in the IEC Guide 115 and in the bibliography. As a general recommendation, the extended uncertainties should be related to a confidence level of 95 %.[8]¹

7.12 Dissolved gas-in-oil analysis

For large mineral oil-immersed power transformers, in which additional flux effects are potential risk factors, a chromatographic analysis of dissolved gas-in-oil may allow the detection of possible local overheating.

If agreed between manufacturer and purchaser, the analysis should be performed as a special test before and after the temperature rise test.

Details of the test method and acceptance criteria for evaluating the DGA results are given in Annex D.

7.13 Corrections

If the specified values of injected power or current have not been obtained during the temperature rise test, the results shall be corrected according to the following relations valid within a range of ± 20 % of the target value of power and ± 10 % of the target value of current.

By agreement, corrections may be applied over a wider range, but not lower than of -30 % of the target value of power and -15 % of the target value of current.

The liquid temperature rises over the external cooling medium temperature at the end of the total loss injection shall be multiplied by:

$$\left(\frac{\text{Total losses}}{\text{Test losses}} \right)^x$$

The average winding temperature rise over average liquid temperature at shutdown shall be multiplied by:

$$\left(\frac{\text{Rated current}}{\text{Test current}} \right)^y$$

¹ Figures in square brackets refer to the bibliography.

The hot-spot winding temperature rise over top-liquid temperature at the shutdown shall be multiplied by:

$$\left(\frac{\text{Rated current}}{\text{Test current}} \right)^z$$

The exponents to be applied are given in Table 3 in accordance with the transformer type and cooling system.

The corrections made using the exponent values given in Table 3 are conservative and intended only for reporting the temperature rise during a test in steady state conditions performed within the limits indicated above.

Table 3 – Exponents for the corrections of temperature rise test results

	Distribution transformers	Medium and large power transformers			
	ONAN	ONAN	ONAF	OF....	OD....
Top-liquid exponent x	0,8	0,9	0,9	1,0	1,0
Average winding exponent y	1,6	1,6	1,6	1,6	2,0
Winding gradient exponent z	-	1,6	1,6	1,6	2,0

NOTE For the purposes of this table, distribution transformers are transformers with a rated power up to and equal to 2 500 kVA.

Annex A (informative)

Hot-spot winding temperature rise determination for OFAF and OFWF cooled transformers based on the top-liquid temperature in tank

The hot-spot winding temperature rise above ambient air or cooling water temperature has by tradition been based on the top-liquid temperature rise in the tank as follows:

$$\Delta\theta_h = \Delta\theta_o + Hg$$

where $\Delta\theta_o$ is the top-liquid temperature rise in the tank, H is the hot-spot factor and g is the average winding-to-average liquid gradient. From a strict academic point of view, such a procedure is inaccurate, because duct top-liquid inside the windings obviously offers a more relevant temperature base than the mixed liquid in the tank. In ON-cooled transformers, this inaccuracy has been considered marginal, since the steady-state volume rate of flow of liquid through the windings is in principle equal to the rate of flow through the radiators. In general, the same holds for a genuine OD-cooled transformer where only a moderate leakage or controlled bleed passes from the coolers out into the free tank volume. Conditions are, however, different in OF-cooled transformers, where a minor stream of hot duct liquid from the windings mixes in a turbulent way with the main stream of cooler liquid circulating in the loop “outside windings – coolers – outside windings”.

The question is now: “Can this mixed top-liquid temperature in the tank be used for hot-spot winding temperature determination from the heat run test data, or has such a determination to be based on hot liquid ejecting from the top of the windings?”

An answer to the question above is based on results obtained on some OFAF-cooled transformers, where the hot-spot winding temperatures were directly measured by fibre optic sensors. The transformers selected represent different transformers sizes and different oil circulation modes (axial and zig-zag) through the windings. The results obtained on some specific transformers are shown in Table A.1.

The measured hot-spot winding temperature rise has been obtained as the maximum value yielded by 8 fibre optic sensors per winding.

Attempts have been made to measure the duct oil temperature in some selected test units. This kind of measurement has appeared to be both impractical and difficult, since the duct oil temperature shows a wide range of local variation.

Conclusion

Based on the similarity of the calculated and measured hot-spot winding temperature rise values given in Table A.1, it is recommended that the top-liquid temperature in the tank is used for hot-spot temperature rise calculation.

Table A.1 – Hot-spot winding temperature rises for some specific transformers determined from conventional heat run test data combined with calculated hot-spot winding temperature rise, and from direct fibre-optic measurements

Rated power MVA	Cooling mode/Winding oil circulation	Measured values in heat run test		Hot-spot winding temperature rise K	
		$\Delta\theta_o$ K	<i>g</i> K	Calculated	Measured
230 3-phase	OFAF/Zig-zag	40,6	14,5 (LV) ^a	59,3	57,1
			15,0 (HV)	63,6	60,9
605 3-phase	OFAF/Zig-zag	35,2	11,7 (LV)	58,7	56,5
			23,0 (HV)	67,9	65,3
1 000 3-phase	OFAF/Axial	36,1	21,9 (HV)	71,4	68,9
133 1-phase	OFAF/Axial	37,3	21,1 (LV)	69,4	70,1

^a (LV) means low-voltage winding, and (HV) means high-voltage winding.

Annex B (informative)

Methods to estimate the hot-spot winding temperature rises

B.1 General

The hot-spot is the maximum temperature occurring in any part of a winding insulation system and it is assumed to represent the thermal limitation of the transformers.

If the hot-spot winding temperature rise is not directly measured, an estimate of its value can be made starting from the results of the temperature rise test or using either design data or results of tests performed on similar transformers.

A distinction is made between natural liquid flow cooling systems (codes ON...) and forced liquid flow cooling systems (code OF... or OD...).

In this annex, the rules are given for core and shell type transformers.

B.2 List of used symbols

For the used symbols see Clause 3.

B.3 Mathematical models for natural and direct forced liquid flow cooling systems

B.3.1 Core type transformers

For transformers having concentric windings regularly distributed along the core limbs, the hot-spot winding temperature rise can be calculated starting from the results of the temperature rise test, assuming for the liquid at the winding exit the temperature of the top-liquid (see 7.4.1) and for the average liquid temperature, the average between the top-liquid temperature and the bottom liquid temperature.

The temperature rise of the liquid inside the windings of the transformer is assumed to increase linearly with the height of the windings.

The heat, transferred from the winding to the liquid all along the winding requires a temperature drop between winding and surrounding liquid which is assumed to be constant at all levels of height with the exclusion of the winding extremities.

In the graphic given in Figure B.1, the winding temperature rise and the liquid temperature rise will therefore appear as two parallel lines.

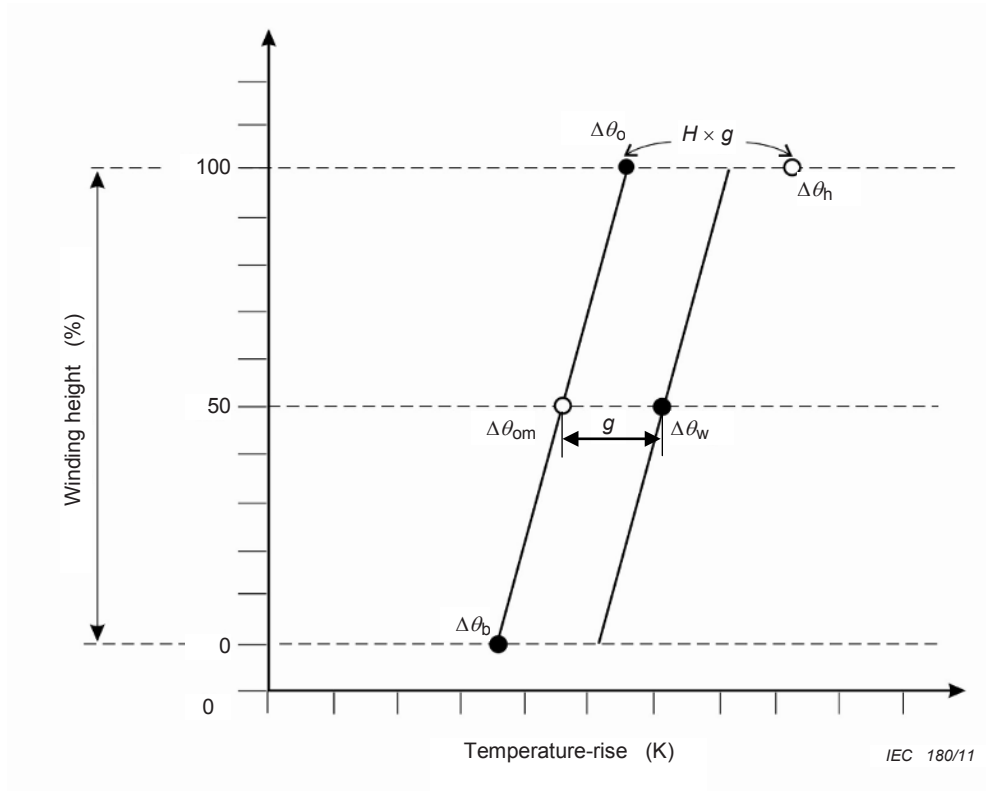


Figure B.1 – Temperature rise distribution model for ON cooling methods

The hot-spot winding temperature rise can be determined using the following equation:

$$\Delta\theta_h = \Delta\theta_o + Hg$$

The average thermal gradient between each winding and liquid along the limb (g) is taken as the difference between the average winding temperature rise ($\Delta\theta_w$) and average liquid temperature rise ($\Delta\theta_{om}$).

The hot-spot is generally expected to be located at the upper extremity of the windings, because of:

- concentration of additional loss because of the deviation of leakage flux lines;
- variations in the liquid ducts at the top of windings.

Therefore, for each winding, the corresponding hot-spot factor ($H = QS$) depends on:

- factor Q relates to the additional loss and depends on the ratio between the specific loss in the region of the leakage flux concentration (top winding) and the average specific loss of the winding;
- factor S related to the efficiency of liquid cooling circuits inside the winding.

Factor Q is an individual factor for each transformer winding which depends on the characteristics of the winding and its estimate can be obtained through the knowledge of the leakage flux field (i.e., by means of a finite element method).

For disk or layer windings of core type three-phase transformers not exceeding 150 MVA (50 MVA for single-phase units), 50 Hz and short-circuit impedance from 10 % to 14 %, the curves of Figure B.2 can be used as a reference. The curves, that give factor Q as a function

of rated power and conductor strand height, were obtained as average of a number of cases for which the calculation was made by means of computer programs and confirmed by experimental results.

NOTE 1 For cable epoxy conductor, the height refers to the elementary strand.

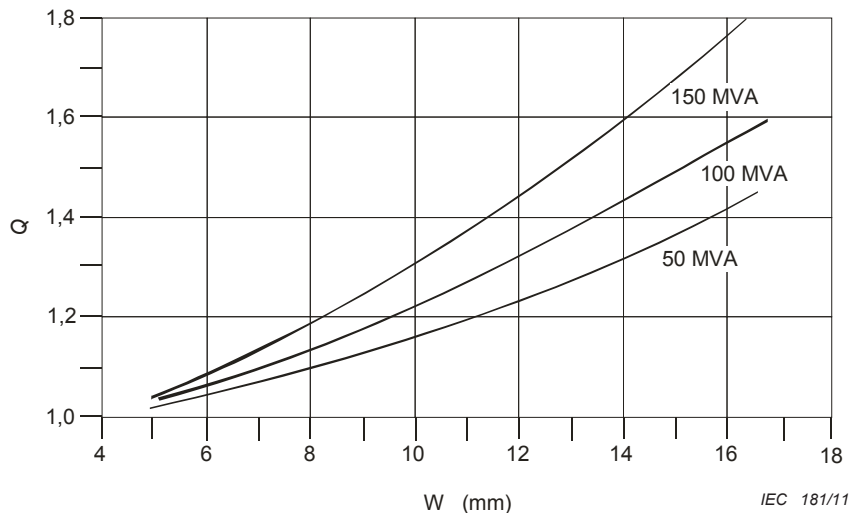


Figure B.2 – Value of factor Q as a function of rated power and strand height (W)

In principle, the evaluation of factor S , related to the effects of the cooling liquid circuit, should be made by solving the hydraulic circuit at the top of any specific winding.

For disk and layer windings without diverting washers with only vertical ducts, factor S can be assumed equal to 1.

The problem is important for windings with diverter washers as the factor varies according to the configuration of liquid ducts.

S factor is generally larger than 1 when the liquid flow distribution inside the winding is not homogeneous along the axial height of the winding. Such a situation may occur due to some dielectric design choice.

Figure B.3 shows some typical examples of liquid circuits for windings with diverting washers and without additional axial ducts inside the winding and with uniform distribution of the diverting washers for which different values of factor S loss should be considered.

Example a) represents the circuit for which factor S can be assumed equal to 1.

Example b) shows an arrangement in which the absence of the last internal diverting washer facilitates the liquid escape through the upper radial duct (indicative value $S=1,1$).

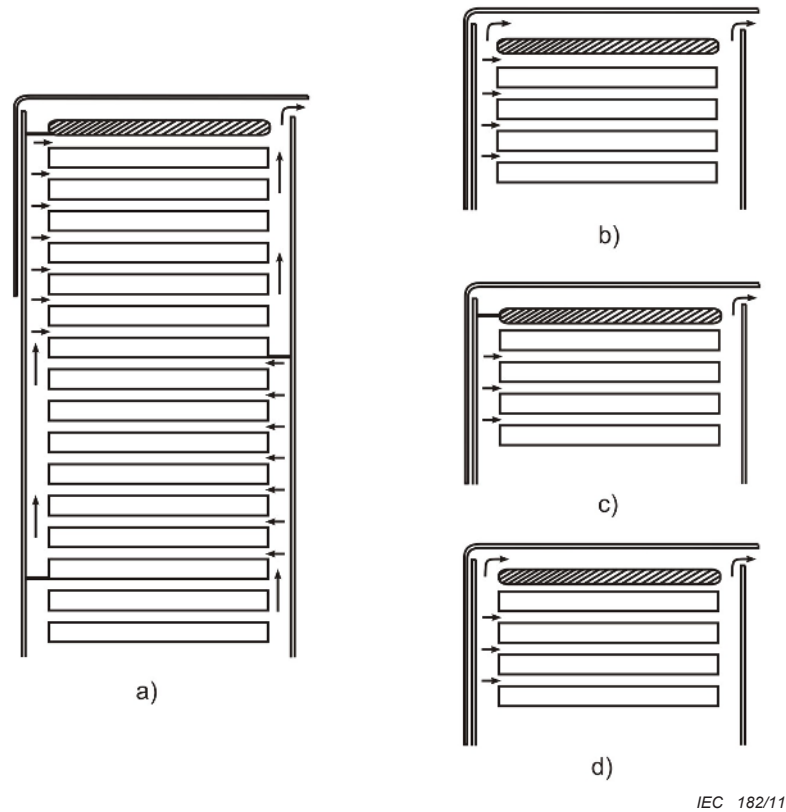
In example c), the duct between the first disk and the equipotential ring is too narrow so that the liquid cannot circulate correctly (indicative value $S=1,1$).

In example d), the arrangement includes the lack of the diverting washer and the restriction of the duct between the first disk and equipotential ring (indicative value $S=1,2$).

In the examined cases and similar others, the consequence is a local overheating of the conductors and of the turn insulation.

Attention should be paid to the relative position of the last two diverting washers that can affect the correct liquid flow in the last radial ducts.

NOTE 2 A more accurate/estimate of the S factor representative of the specific winding arrangements can be indicated by the manufacturer.



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Figure B.3 – Typical liquid flow paths in a disk winding with diverting washers

It can also be noted that the winding regions where factors Q and S assume their maximum values correspond only when factor Q is maximum at the top of the winding.

NOTE 3 Continuous transposed cable can be used at the top and bottom of the disk type windings in order to reduce the local eddy losses.

B.3.2 Shell type transformers

Although the winding arrangement and configuration of shell type transformers are different from those of core type transformers, the thermal model given in Figure B.1 can be still conceptually accepted taking into account the following consideration.

In shell type transformers, multi-conductor wire is usually adopted as the conductor dimension can be adjusted from coil to coil according to the leakage flux distribution, so that significant eddy current loss can be prevented for each coil.

Since factor H is strongly influenced by the conductor, the value to be used for the hot spot calculation should be agreed between manufacturer and purchaser at the design stage.

B.4 Mathematical models for forced liquid flow cooling systems

For transformers with forced liquid flow (codes OF--), the concepts of top-liquid temperature and average liquid temperature are ambiguous and cannot be determined by measurements taken outside the tank (see also Annex A).

In principle, it would be correct to assume for the top-liquid the temperature directly measured at the exit of the internal cooling circuit of each winding as the thermal behaviour depends on the repartition of the liquid flow rates among the various axial ducts.

Only for the purpose of estimating the hot-spot winding temperature rise by calculation, starting from the results of a temperature rise test, the same model indicated for natural liquid flow can be assumed.

The temperature rise of the liquid at the entry of the windings (bottom liquid temperature) can be determined as indicated for natural liquid flow cooling methods.

Annex C (informative)

Techniques used in temperature rise testing of liquid-immersed transformers

C.1 Winding resistance measurement after shutdown

C.1.1 Setting of the cooling equipment during the winding resistance measurement

The cooling device should be preferably maintained to the same state (cooling method) as during the current injection in the winding. With this setting, it is possible to obtain information about the transient thermal behaviour of the winding and liquid from the cooling down curve.

NOTE 1 In general, the condition of the cooling device during the cooling down curve measurement only slightly affects the extrapolated value of the hot resistance at the time of shutdown. Only the final part of the cooling down curve can be affected by the setting of the cooling device.

NOTE 2 In case of OD cooled transformers, the cooling should not be changed after shutdown.

C.1.2 Procedure for winding resistance measurement

The temperature of the winding at the end of the temperature rise test is normally determined by the measurement of the winding resistance, according to 7.7.

The measurement of winding resistance is started after shutdown of the test power and connection to the windings of d.c. measuring current sources.

As winding temperature and resistance vary with time, the problem is to extrapolate backwards in time to the instant of shutdown. This extrapolation procedure is discussed in C.2.

Resistance measurement should be commenced as soon as possible after the connection of the windings to the measuring equipment. At the beginning, before the d.c. measuring current is stabilized, the readings are false because of the inductive voltage drop in the winding. The necessary time for this stabilization may be reduced by:

- driving the core into saturation so that the effective inductance drops down to a value of the same order of magnitude as the short-circuit inductance;
- using a constant-current supply, an electronically stabilized supply source or a powerful battery with a large additional series resistor.

Driving the core into saturation means building up a certain amount of flux that reduces the delay, in practice to the order of a few seconds.

The two windings of the tested pair may either be connected to two separate d.c. circuits or connected in series to one in common. In both cases, the current directions should co-operate for the saturation of the core.

The electrical time-constant of the d.c. circuit, after saturation is reached, may also be brought down to the order of a few seconds, even in difficult cases. A temperature difference of 1 K corresponds to a relative difference of resistance in the order of 1/300, which, for an exponential decay of the error, would correspond to a delay of five to six times the electrical time constant. This all means that, in general, useful measurements should be obtainable within not more than 1 min after effective saturation has been established.

The resistance measurement of LV windings of large step up transformers is very sensitive to residual inductive e.m.f., which disturb the measurement even at the time, when the d.c. current has stabilized. The inductive e.m.f. is superimposed to the resistive voltage (in the range of millivolts) and the resistance values evaluated in presence of these disturbed voltages are artificially enhanced or decreased, depending on the polarity of the induced voltages. This can be clearly recognized, when the resistance curve comes from the high end or, in some cases, from the lower end during the initial part of the cooling down curve. On large transformers, the best results may be obtained, when the d.c. current is circulated through the entire turns of the HV winding, as indicated in Figures C.1 and C.2 below. In extreme cases, with winding resistances close to or below 1 mΩ, reasonable resistance values will be obtained one or two minutes from stabilizing the d.c. current.

Additionally, the operating time for the connections and the time for stabilizing the d.c. current have to be regarded.

The first useful resistance value can be obtained, depending on the size of the core.

It is recommended that the time starting from the shutdown until the first valid point of hot resistance measurement should not exceed:

- 2 min for transformers < 100 MVA;
- 3 min for transformers from 100 MVA to < 500 MVA;
- 4 min for transformers ≥ 500 MVA.

The duration of the cooling down curve should be at least two times the thermal time constant of the winding in order to provide information about the transient thermal behaviour of windings and liquid. The duration may vary according to the transformer characteristics and the test modalities.

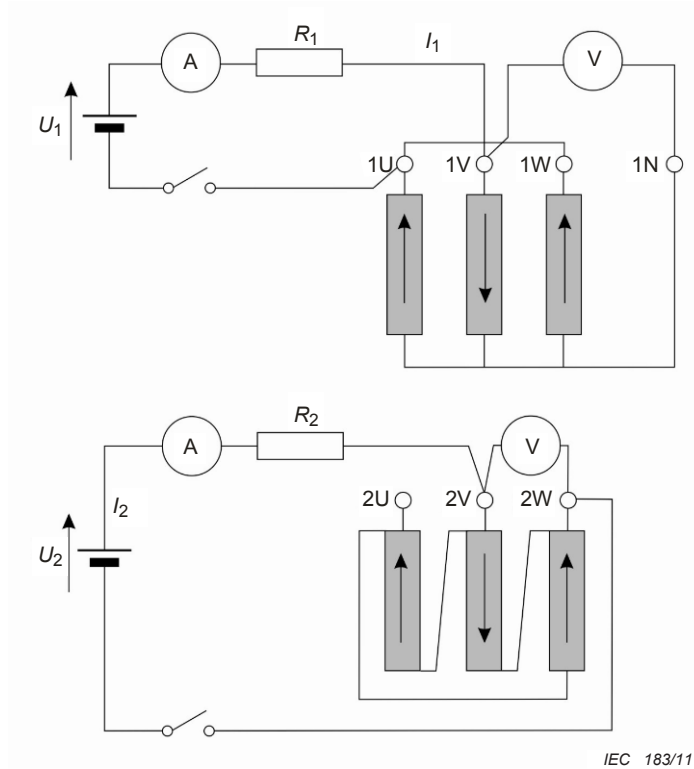
A total duration of 20 min for medium size transformers and up to 30 min for large transformers is appropriate for the determination of the cooling down curve.

Two possible circuits used during the measurement of the cooling down curve on transformers with low resistance windings are shown in Figures C.1 and C.2.

The resistance of low voltage, star or zigzag connected windings (e.g. 400 V winding) of a distribution type transformer should be measured between two phase terminals and not between a phase terminal and neutral terminal.

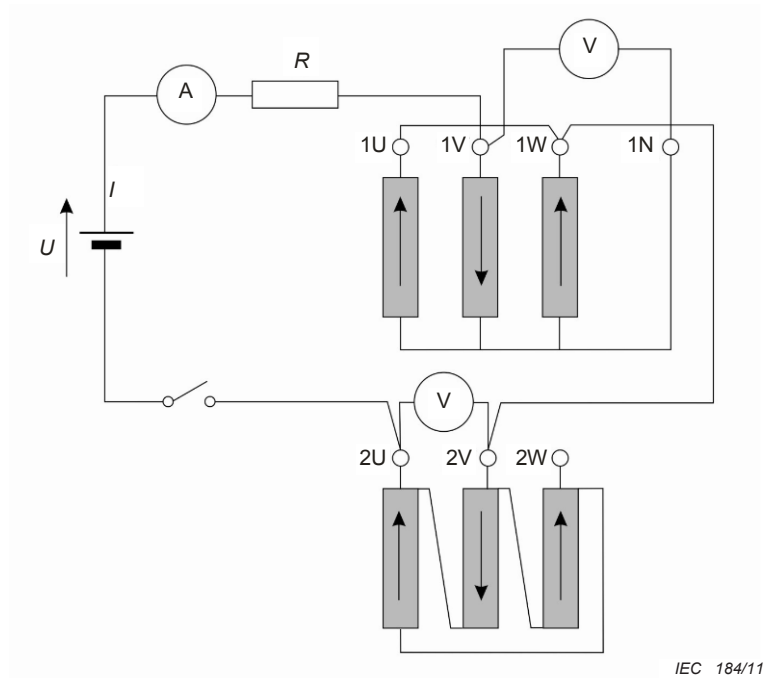
There are also other methods, the use of which shall be subjected to agreement between manufacturer and purchaser:

- to pick up the inductive component of voltage across an open winding, which is not part of the direct current circuit, and use this voltage for correction of the voltage across the winding subjected to resistance measurement (this method is not recommended for large step-up transformers);
- in case of two well-balanced, parallel halves of a winding, it is possible to circulate a direct current into one and back through the other. This permits monitoring of the resistance, in principle without inductive effects, and possibly even while a.c. power is supplied to the transformer.



NOTE The resistors R_1 and R_2 are used to accelerate the extinction of the transient

Figure C.1 – Recommended circuit for transformers with a low resistance winding using two separate direct current sources, one for each winding



NOTE R is an additional resistor to accelerate the extinction of the transient.

Figure C.2 – Alternative recommended circuit using only one direct current source for both windings

C.2 Extrapolation of winding temperature to the instant of shutdown

Clause C.1 discusses the d.c. supply circuit for resistance measurement and the delay before the inductive effects have died away.

The instrumentation used for the measurement may be for manual reading or for automatic recording, analogue or digital. A considerable number of discrete readings are to be made over a period of time, and these have to be evaluated for the extrapolation backwards in time to the instant of shutdown.

The first step of the extrapolation procedure is to pass from the resistance variation to the temperature in accordance with 7.6.

A plot of the winding temperature would look as shown on Figure C.3, where the temperature of the winding is falling relatively rapidly for a period of some minutes and then flattens out.

In a transformer with very large thermal time-constant for liquid-temperature variation (this applies mainly to ON.. transformers of relatively low rated power), it may be assumed that the asymptote is a constant value.

In the majority of the cases, particularly when large transformers with forced cooling are tested, and the cooling equipment is left operating after test power shutdown, it may be necessary to recognize a falling asymptote, on which the more rapid initial variation is superimposed.

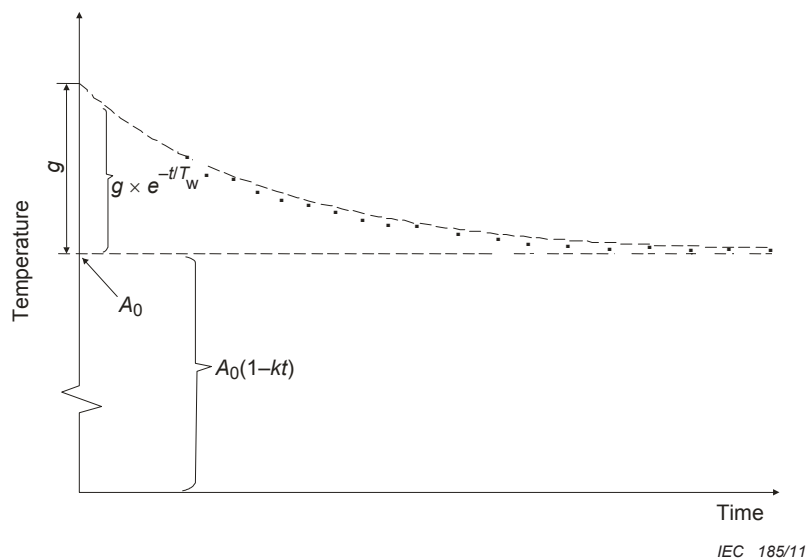


Figure C.3 – Average winding temperature variation after shutdown

The decay of the average winding temperature ($\theta_w(t)$) with time t can be expressed with the relation:

$$\theta_w(t) = \theta_{om}(t) + Be^{-t/T_w} \quad (C.1)$$

where

$\theta_{om}(t)$ is an estimate for the average liquid temperature using slowly dropping function;

B is an estimate for the winding-to-liquid gradient at the instant of the shutdown;

T_w is an estimate for the time constant of the winding cooling down to the oil with an exponential decay.

For the first term ($\theta_{om}(t)$), a constant, a linear variation, or an exponential decay may be considered:

$$\theta_{om}(t) = A_0 \quad \theta_{om}(t) = A_0 (1 - kt) \quad \theta_{om}(t) = A_0 e^{-t/T_0} \quad (\text{C.2})$$

where

T_0 is an estimate of the thermal time constant of the liquid.

The result of the extrapolation estimate is therefore:

$$\theta_w(t=0) = A_0 + B \quad (\text{C.3})$$

which corresponds to the average winding temperature at the instant of shut-down.

C.3 A numerical extrapolation procedure of cooling down curve

The extrapolation of the cooling down curve should be performed using a numerical computer procedure, which fits an analytical function to a set of temperature readings.

The numerical procedure described below can be used to fit an analytical function to a set of timewise equidistant temperature readings.

The advantage of this method is that the best estimate of the average winding temperature is determined in an objective way.

The method is based on the assumption that the dropping of the top-liquid temperature rise is linear $\theta_{om}(t) = A_0 - kt$.

Measured quantities

t_{\max}	duration of the cooling down curve measurement (20 min in the example)
Δt	time increment (1 min in the example)
i	
n	total number of the valid measurements, reduced by 1 ($n = n_{\text{val. meas}} - 1$)
θ_{om_start}	average liquid temperature as measured at the instant of shutdown
θ_{om_end}	average liquid temperature as measured at the end of the cooling down curve
$\theta_{wm}(i)$	average winding temperature as measured at the time instant i (evaluated from the hot resistance measurement as per 7.6)
k	the difference in top-liquid temperature at the beginning and at the end of cooling-down curve test, divided by duration of the test
	validation factor (0 or 1)

Calculated quantities as per Table C.1

The procedure to be applied is the following:

The grey cells shall be filled with the measured quantities or parameters.

The measured winding temperature values, as converted from the hot resistance values (see 7.6) are inserted in Table C.1 as values in column $\theta_{wm}(i)$.

In some cases, at the initial time after shutdown, some measured values, being not in line with the following measured values, have to be disregarded in order to obtain a reasonable extrapolation curve. Validated values taken into account and designated as values are designated as $\theta_{w\text{ val}}(i) = \nu \times \theta_{wm}(i)$.

The corrected winding temperature is then:

$$\theta_{w\text{ cor}}(i) = \theta_{w\text{ val}}(i) + k t \quad (\text{C.4})$$

Difference between sequential corrected winding temperature values:

$$\Delta\theta_w(i) = \theta_w(i) - \theta_w(i-1) \quad (\text{C.5})$$

Absolute value of sum of the differences between sequential corrected winding temperature values:

$$S_a = |\Sigma(\Delta\theta_w(i))| \quad (\text{C.6})$$

Absolute value of sum of the corrected winding temperature values:

$$S_b = |\Sigma\theta_w(i)| \quad (\text{C.7})$$

Absolute value of sum of the corrected winding temperature values multiplied by sequential temperature differences:

$$S_c = |\Sigma(\theta_w(i)\Delta\theta_w(i))| \quad (\text{C.8})$$

Sum of the squared, corrected winding temperature values:

$$S_d = \Sigma(\theta_w(i))^2 \quad (\text{C.9})$$

Auxiliary variables:

$$\begin{aligned} t_e &= (nS_c - S_b \times S_a) / (nS_d - S_b^2) \\ t_c &= (S_d S_a - S_b \times S_c) / (nS_d - S_b^2) \end{aligned} \quad (\text{C.10})$$

Winding time constant:

$$T_w = \Delta t / \ln(1 + t_e) \quad (\text{C.11})$$

Constants A_0 and B :

$$\begin{aligned} S_e &= \sum e^{(-i/T_w)} \\ A_0 &= -t_c/t_e \\ B &= (S_b - n \times A_0)/S_e \end{aligned} \quad (C.12)$$

The average winding temperature at the instant of shutdown is then:

$$\theta_w(t=0) = A_0 + B \quad (C.13)$$

This result is to be used for determining the average winding temperature according to 7.9.

Validation of the extrapolation

If agreed between manufacturer and purchaser, the validation of the extrapolated results described above can be made repeating the procedure, disregarding the first measurement. The result obtained should not deviate more than $\pm 0,5$ K from the previous one. In case this deviation is exceeded, the validation can be repeated excluding another measurement. This last operation can be made putting in the Table C.1 in the column of the parameter ν value 0 instead of 1.

In the example given above, the first point was excluded because the deviation between the first and second calculations exceeds + 0,5 K.

Table C.1 – Example of cooling down curve calculation spreadsheet

Legend: Data to be inserted											
Time interval	$\Delta t =$	1 min		Estimated winding time constant	$\tau_w =$	5,1 min					
Initial average- liquid temp.	$\theta_{om_start} =$	56 °C		Estimated average liquid temp.	$\tau_0 =$	56,1 °C					
Final average liquid temp.	$\theta_{om_end} =$	53 °C		Estimated winding-to-liquid gradient	$B =$	11,0 K					
Liquid temperature slope	$k =$	0,15 K/min		Average winding temp. at the instant of shut-down	$\tau_{w0} =$	67,1 °C					

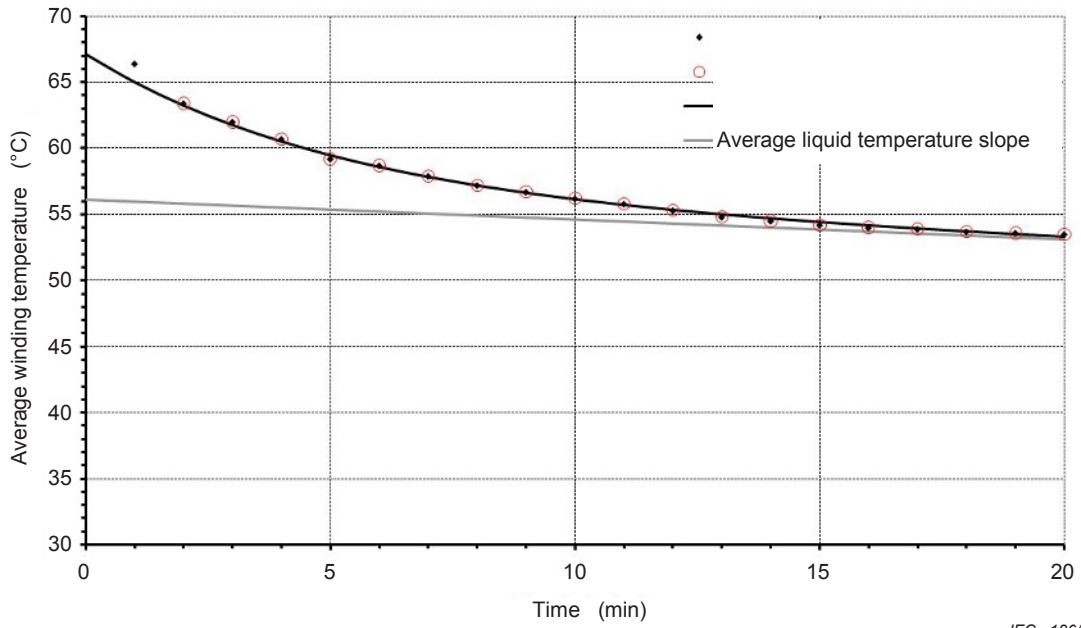
$\tau_c =$	-12,183 6	n	18	s_b	1 042,95	s_a	7,2	s_c	429,6	s_d	6 0488	s_e	3,02
$\tau_e =$	0,217 176	Abs Sums											

(min)	θ_{om} $A_0 - kt$	θ_{wm} measured	$\theta_{w\ val} (i)$	$\theta_{w\ cor} (i)$	(0/1)	θ_w validated	τ_w (C.5)	$\theta_w(i) \times \Delta \theta_w(i)$	$\theta_w(i)^2$	e^{-i / τ_w}	θ_w calculated
0	56,1	0,0		0,0	0						67,1
1	55,9	66,4		66,6	0	0,0	0	0,0	0	0	65,0
2	55,8	63,4	63,4	63,7	1	0,0	0	0,0	0	0	63,2
3	55,6	62,0	62,0	62,5	1	62,5	-1,25	-78,1	3900	0,5545	61,7
4	55,5	60,7	60,7	61,3	1	61,3	-1,15	-70,5	3758	0,4556	60,5
5	55,3	59,2	59,2	60,0	1	60,0	-1,35	-80,9	3594	0,3743	59,5
6	55,2	58,7	58,7	59,6	1	59,6	-0,35	-20,9	3552	0,3075	58,6
7	55,0	57,9	57,9	59,0	1	59,0	-0,65	-38,3	3475	0,2527	57,8
8	54,9	57,2	57,2	58,4	1	58,4	-0,55	-32,1	3411	0,2076	57,2
9	54,7	56,7	56,7	58,1	1	58,1	-0,35	-20,3	3370	0,1705	56,6
10	54,6	56,2	56,2	57,7	1	57,7	-0,35	-20,2	3329	0,1401	56,1
11	54,4	55,8	55,8	57,5	1	57,5	-0,25	-14,4	3301	0,1151	55,7
12	54,3	55,3	55,3	57,1	1	57,1	-0,35	-20,0	3260	0,0946	55,3
13	54,1	54,8	54,8	56,8	1	56,8	-0,35	-19,9	3221	0,0777	55,0
14	54,0	54,5	54,5	56,6	1	56,6	-0,15	-8,5	3204	0,0638	54,7
15	53,8	54,2	54,2	56,5	1	56,5	-0,15	-8,5	3187	0,0524	54,4
16	53,7	54,0	54,0	56,4	1	56,4	-0,05	-2,8	3181	0,0431	54,2
17	53,5	53,9	53,9	56,5	1	56,5	0,05	2,8	3187	0,0354	53,9
18	53,4	53,7	53,7	56,4	1	56,4	-0,05	-2,8	3181	0,0291	53,7
19	53,2	53,6	53,6	56,5	1	56,5	0,05	2,8	3187	0,0239	53,5
20	53,1	53,5	53,5	56,5	1	56,5	0,05	2,8	3192	0,0196	53,3

NOTE 1 The winding temperature values indicated “as measured” are directly obtained from the winding resistance variations at the instant of shutdown.

NOTE 2 The value of A_0 (respectively $\theta_{om} (0)$) is an estimate of the average liquid temperature at the instant of shutdown. In general, this value differs from that of the average liquid temperature θ_{om} as per 7.4.2 measured during the temperature rise test.

NOTE 3 The fall of the average liquid temperature during the cooling down curve can be also evaluated from the fall of the top-liquid temperature.



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Figure C.4 – Extrapolation of the cooling down curve, using the fitting curve

$$\theta_w(t) = A_0 - kt + Be^{-t/T_w}$$

Annex D (informative)

Dissolved gases analysis for the detection of local overheating

D.1 General

For mineral oil-immersed power transformers, the use of dissolved gas analysis (DGA) performed on oil samples extracted before and after the temperature rise test may allow the detection of local overheating due to stray flux effects, incorrect circulation of the cooling oil, or loose connections of current-carrying leads.

The evaluation of dissolved gas analysis results associated with the temperature rise testing is based on the principle that some gases are released by organic insulating materials (paper and oil) when subjected to high temperature. The different gas compounds may indicate the materials involved, while their concentration and rate of increase is related to the severity of the phenomena in progress.

If agreed between manufacturer and purchaser, DGA can be used as a special tool for evaluating the results of temperature rise tests. The analysis should be performed according to IEC 61181 by means of a high precision gas-chromatographic method.

In principle, the application of DGA is recommended for:

- a) three-phase transformers with separated windings having rated power ≥ 100 MVA;
- b) single-phase transformers with separate windings having rated power ≥ 33 MVA;
- c) auto connected transformers with equivalent double-wound transformer having rating as a) and b);
- d) transformers of smaller rated powers than those stated above, but having leakage flux and/or leakage field strength of the same order as those of the above-mentioned cases.

D.2 Temperature rise test duration

For a correct interpretation of the analysis results, the temperature rise test should be performed with total rated losses. The top-oil temperature rise should be maintained at least 80 % of the estimated final top-oil temperature rise for not less than 8 h.

DGA performed during a temperature rise test at reduced total losses (see 7.12) is meaningless and therefore not recommended.

In case of transformers with alternative cooling methods, the DGA should be performed only for maximum cooling capacity.

D.3 Sampling of oil

The extraction of the samples should be made according to the procedure proposed in IEC 60567, and precautions should be taken to avoid oxidation.

The first sample should be taken immediately before starting temperature rise test and for oil forced cooling systems after at least 2 h of oil circulation. Preferably, the second sample should be taken approximately 24 h after the conclusion of the temperature rise test.

D.4 Gas analysis and result interpretation

The oil samples extracted as indicated above should be analyzed as soon as possible, but in any case not later than 3 days thereafter. It is recommended that the analysis be performed by the same laboratory in order to reduce the uncertainty affecting the results.

For the interpretation of the results, it is suggested to take as a basis the so called *maximum analytical spread* which is the spread that can be expected between samples taken at the same time and at the same place, including the variability of the sample, extraction process and analysis.

The maximum analytical spread $S_A(X)$ may be evaluated as a function of the minimum detectable gas quantity, $S_D(X)$, and the quantity of the relevant gas dissolved in the oil before the temperature rise test $(X)_1$, X being the chemical notation of the gas expressed in micro-litre/litre:

$$S_A(X) = 0,1(X)_1 + 2S_D(X)$$

Table D.1 gives the minimum detectable values of gas in oil that normally a laboratory can assure according to IEC 61181.

Table D.1 – Minimum detectable value S_D of gases in oil

Gas	S_D μl/l
CO ₂	10
CO	5
H ₂	2
CH ₄	0,1
C ₂ H ₆	0,1
C ₂ H ₄	0,1
C ₂ H ₂	0,1

The criteria for the evaluation of the gas analysis during a temperature rise test are based on the rate of increase of some gases and relevant fixed permissible limits.

In principle, the admissible limits should be agreed between manufacturer and purchaser.

Otherwise it is suggested to make reference to the two series of values listed in Table D.2, after having checked that the results obtained are exceeding the maximum analytical spread indicated above [9, 10].

Table D.2 – Admissible limits for gas rate increases

Compounds	Rate of increase μl/(l h)	
	First series	Second series
$\frac{1}{t} \times [(C_2H_2)_2 - (C_2H_2)_1]$	< S_A	< S_A
$\frac{1}{t} \times [(CO)_2 - (CO)_1]$	< 5	< 25
$\frac{1}{t} \times [(CO_2)_2 - (CO_2)_1]$	< 20	< 100
$\frac{1}{t} \times \left\{ [(H_2)_2 - (H_2)_1] + [(CH_4)_2 - (CH_4)_1] + [(C_2H_4)_2 - (C_2H_4)_1] + [(C_2H_6)_2 - (C_2H_6)_1] \right\}$	< 2	< 5

NOTE 1 The subscripts 1 and 2 indicate the concentrations before and after the test.

NOTE 2 t is the time interval during which the top-oil temperature rise is at least 80 % of the final value in steady state condition.

If the values of rate of increases determined by gas analysis performed before and after the temperature rise test fulfil all the limits of the first series, it may be concluded that the transformer has no local overheating.

If however, all values determined lie below the second series limits, but one or more values exceed the limits of the first series, the possibility exists of local overheating. In this case, it is recommended that in service, oil samples should be taken at regular intervals from the transformer, and the gas analysis performed.

If one or more of the second series of values are exceeded, the probability of a thermal fault is greater and therefore further investigations should be started to identify and remove the causes of the overheating.

The repetition of the final analysis is however recommended before taking any further decision about the corrective actions to be undertaken.

As an alternative, the temperature rise test can be started again for a longer duration.

The rate of increase of dissolved hydrocarbon gas in oil can be used to provide additional evidence of local overheating in the oil, using the relation given in IEC 60599:

$$R = \frac{\Delta C m_o}{\rho \Delta t}$$

where

- R is the rate of gas formation (ml/h);
- ΔC is the gas concentration variation (μl/l);
- Δt is the duration of the test (h);
- m_o is the mass of the oil (kg);
- ρ is the oil density (kg/m³).

The value obtained is directly related to the consistency of the local phenomena, and is therefore independent of the mass of the oil present in the tank.

Criteria for the interpretation of the gas rate increase and admissible limits for hydrocarbon gases shall be matter of agreement between manufacturer and purchaser at the moment of the contract award.

Annex E (informative)

Application of optical fibre sensors for winding hot-spot measurements

E.1 General

Optical fibre sensors for the direct measurement of the winding hot-spot temperatures should be installed according the following rules.

Because of the intrinsic fragility of sensors and optical fibre cables, attention shall be paid for avoiding dangerous mechanical stresses and vibrations during the manufacturing process and in operation.

E.2 Number of sensors

The minimum recommended number of sensors to be applied varies with the characteristics of the transformers.

For two winding three phase transformers, it depends on the transformer rated power (the highest value when two or more different cooling methods are provided). The number of sensors should be those indicated in Table E.1.

Different arrangements can be agreed between manufacturer and purchaser, but as the sensors and optical fibre cables are very fragile, their number should take into consideration the risk of damage during the various operations and stresses which the windings are subjected to in the factory and in service.

Table E.1 – Minimum recommended number of sensors for three-phase transformers

Rated power MVA	Cooling system	Number and phases of installation				
		Total	On central phase		On each lateral phase	
			HV winding	LV winding	HV winding	LV winding
≥ 100	All system	8	2	2	1	1
From ≥ 20 to < 100	ON.. – OF..	6	1	1	1	1
	OD..	8	2	2	1	1

For single-phase transformers, the minimum recommended number of sensors for each wound column should be those indicated in Table E.2.

Table E.2 – Minimum recommended number of sensors for single-phase transformers

Rated power MVA	Cooling system	Number of sensor		
		Total	HV winding	LV winding
≥ 50	All system	4	2	2

For transformers with more than two windings, the number of sensors to be mounted is left to agreement between manufacturer and purchaser, but the general principle should be the same.

E.3 Installation of the sensors

The methods of installation of the optical fibre sensors vary according to the winding characteristics.

As far as possible, the sensors should be placed in direct contact with the insulation of the winding conductors, in the regions where the hot-spots are expected (i.e., at the upper winding extremities).

For transformers with concentric windings and horizontal spacers between disks or turns, the sensors should be mounted inside the spacers. Figures E.1 and E.2 show a possible arrangement for a disk winding.

The sensor should be placed at the centre of the spacer, as indicated in Figure E.3. For avoiding reading errors, the movement of oil around the sensor head should be impeded reducing to the minimum the dimensions of the channel made on the spacer or/and blocking the entering.

For windings without vertical spacers between disks or turns (e.g., barrel windings or similar), the sensors should be placed between turns inside a suitable pressboard strip.

For cable transposed conductor (CTC) and when there is a high risk of mechanical damages during the installation of the sensors, different criteria can be applied.

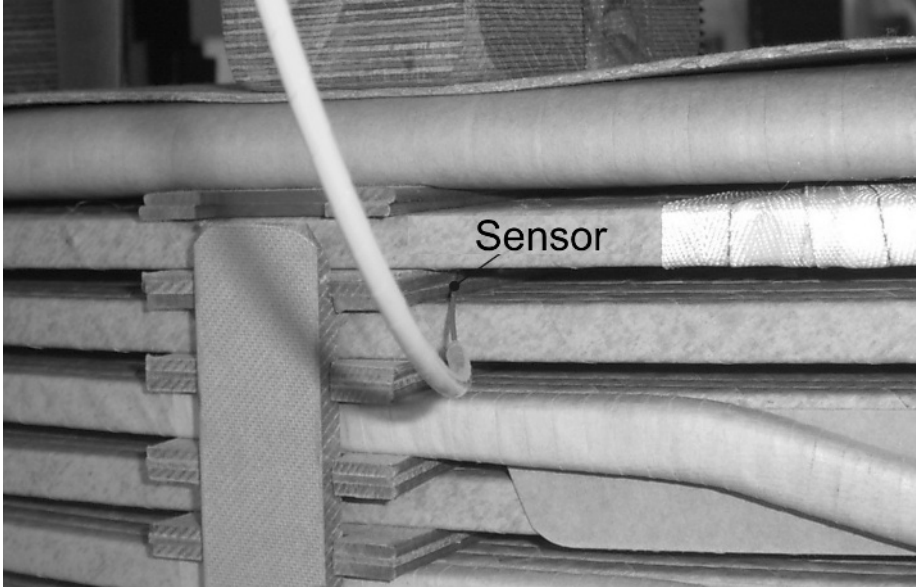
Figure E.4 shows how the a sensor could be mounted in a winding of a shell type transformer. Other mounting configurations can be agreed considering the characteristics of the windings.

In all cases, special attention should be paid to avoid the sensors being partially in contact with the cooling liquid because their indications can be largely affected.

E.4 Installation of the optical fibre cables

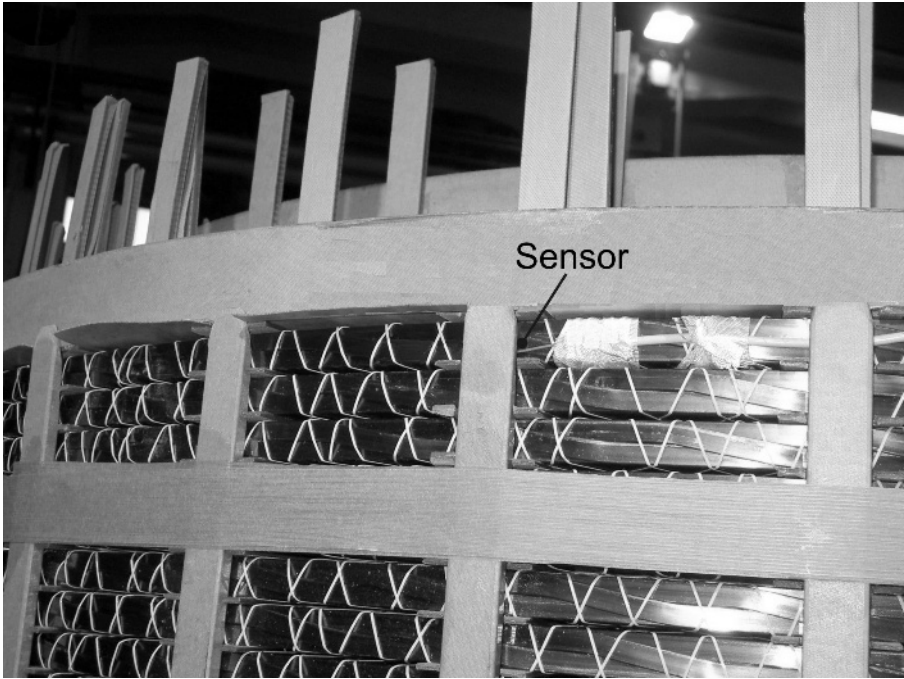
Optical sensors are connected to the measuring instrument by means of optical fibre cables passing through the tank wall or cover.

In principle, optical fibre cables do not disturb the electric field. However, some provisions should be taken about the minimum creepage distance along the cable sheath that could be contaminated when handled during the mounting process.



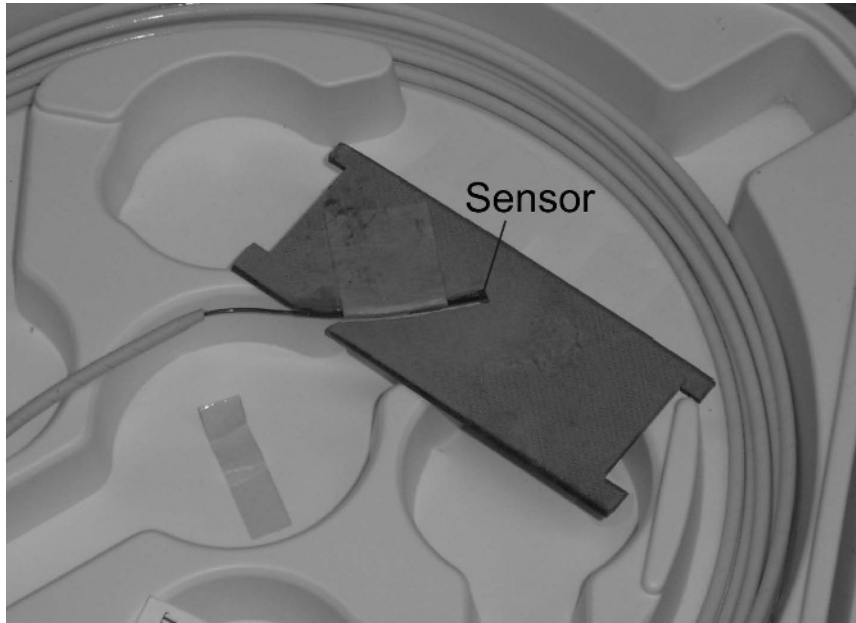
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Figure E.1 – Optical fibre sensor application for a disk winding of core type transformer



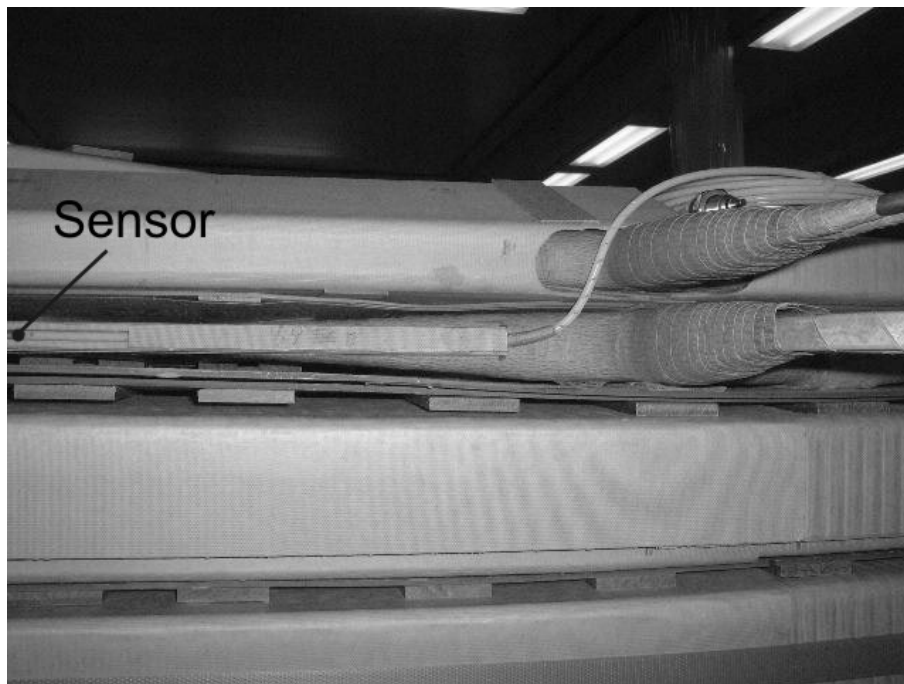
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Figure E.2 – Optical fibre sensor application for a transposed cable of core type transformer



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Figure E.3 – Modality of optical fibre sensor application in the winding spacer of core type transformer



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Figure E.4 – Optical fibre sensor application for high voltage winding of shell type transformer

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