rules given above. For separate cooler bank arrangement (distance of at least 3 m from the transformer tank) 4 numbers sensors shall be used to measure the ambient temperature.

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.

Total loss injection

The Contractor before carrying out this test shall submit detailed calculations showing losses on various taps and for the three types of ratings of the transformer and shall recommend the combination that result in highest temperature rise for the test. The Temperature rise type test results shall serve as a "finger print" for the units to be tested only with short term heat run test.

2-Winding Transformer

Load Loss measurement for HV-LV connection and at Normal & extreme taps) shall be carried out. For 2-winding transformer, total losses to be fed during temperature rise test shall be **2-Winding Loss at tap corresponding to maximum measured loss and No load loss.**

2-Winding Loss = [HV-LV] (Max MVA)

The total losses to be injected during the first part of the test shall be equal to the highest value of total loss appearing at any tapping (corresponding to the particular tapping). 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.

3-Winding Transformer

Load Loss measurement for all combinations (HV-IV, HV-LV, IV-LV and at Normal and extreme taps) shall be carried out. The temperature rise test shall be conducted at a tap for the worst combination of loading (3-Winding Loss) for the Top oil of the transformer. Total losses to be fed during temperature rise test shall be **3-Winding Loss and No load loss.**

3-Winding Loss = HV (Max MVA) + IV (Max MVA) + LV (Max MVA)

The injection of total loss for the determination of liquid temperature rise may be made in an approximate manner by not short-circuiting or closing certain windings. The total losses shall be fed to HV or IV while LV winding is left open and raise the current until the correct total loss is obtained.

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 4 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.

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 15 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 (IEC 60076-2 clause 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. In the similar way winding hotspot, average winding rise etc. shall be measured for tertiary winding for various cooling.

Determination of liquid temperatures

Top-liquid temperature

The top-liquid temperature (θo) 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.

Bottom and average liquid temperatures

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

Average liquid temperature (θom) is used for the calculation of the average winding gradient and correction of certain temperature rise test results. The average liquid temperature is:

$$\theta om = (\theta o + \theta b)/2$$

Determination of top, average and bottom liquid temperature rises

The top-liquid temperature rise (Δθo) shall be determined by difference between the top-liquid temperature measured at the end of the test period with total losses (θo) and the external cooling medium temperature at the end of the test period with total losses (θa), 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 4.2 and the external cooling medium temperature (θa), 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 (θb) defined according to clause 7.4.2 of IEC 60076-2 and the external cooling medium temperature (θa), that is:

$\Delta\theta b = \theta b - \theta a$

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 ($R1,\theta 1$) of all winding resistances is made with the transformer at ambient temperature, in a steady-state condition (see IEC 60076-1).

When the resistance ($R2$) is measured after disconnection of the power supply, extrapolated to the instant of shutdown, this yields the temperature value:

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

Where $\theta 2$ is the average temperature of the winding at the instant of shutdown. In the formula, the temperatures are expressed in Celsius degrees.

Determination of winding resistance at the instant of shutdown

The winding resistance ($R2$) 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.

The detailed execution of the measurement are given in IEC 60076-2 Annex C. Resistance shall be measured for atleast 30 minutes.

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. The corrected winding average temperature rise of the winding ($\Delta\theta w$) is:

$\Delta\theta\ w = \theta 2 + \Delta\theta\ ofm - \theta\ a$

where $\theta 2$ is the average winding temperature at the instant of shutdown, θa is the external cooling medium temperature at the end of the test period with total losses, $\Delta\theta ofm$ the fall of the temperature of the average liquid during the 1 h test at rated current.

The detailed execution of the measurement are given in IEC 60076-2 Annex C. The calculation details, Graph with Annexure C (duly filled) shall be submitted with temperature rise test result.

After hot resistance measurement of HV and IV winding, Tertiary winding shall be loaded at rated MVA (of LV) for 1 hour. After it, hot resistance measurement shall be carried for LV winding. The above sequence shall be followed for all cooling combinations (ONAN/ONAF/OFAF as applicable).

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 ($\theta 2$) and the average liquid temperature θom at shutdown:

$g = \theta 2 - \theta om$.

Determination of the hot-spot winding temperature rise

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.

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 θh 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 θa the ambient temperature at the end of the total loss test period.

Determination by calculation

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 ($\Delta\theta om$).

$(g) = (\Delta\theta w) - (\Delta\theta om)$.

H = Hotspot factor = 1.3 (As per existing practice) and also furnish the design calculate of this factor in line with IEC. Derive winding hotspot rise based on above factors and values should not exceed the guaranteed parameters for both the cases.

Hotspot temperature rise shall be measured by direct FO sensors and shall be recorded for reference only.

Calculation of Hotspot factor as per IEC 60076-2 shall also be furnished during design review.

The format of measuring parameters is attached at Annexure-I.

ANNEXURE-I

TRANSFORMER SR. NO.			
TRANSFORMER RATING : COOLING :			WNDING
The top-liquid temperature (θo)	(θo)	^{o}C	
The bottom liquid temperature (θb)	(θb)	^{o}C	
External cooling medium temperature at the end of the test period with total losses (θa)	(θa)	^{o}C	
The average liquid temperature θom	$= (\theta o + \theta b)/ 2$	^{o}C	
The top-liquid temperature rise ($\Delta\theta o$)	$\Delta\theta o = \theta o - \theta a$	^{o}C	
The average liquid temperature rise ($\Delta\theta om$)	$= \theta om - \theta a$	^{o}C	
Winding			
Average winding temperature at the instant of shutdown, $\theta 2$	$\theta 2$	^{o}C	
Fall of the temperature of the average liquid during the 1 h test at rated current , $\Delta\theta ofm$	$\Delta\theta$ ofm	^{o}C	
The corrected winding average temperature rise of the winding $\Delta\theta w$	$= \theta 2 + \Delta\theta ofm - \theta a$	^{o}C	
The average winding to average liquid temperature gradient (g) (Uncorrected)	$g = \theta 2 - \theta om$	^{o}C	
Temperature reading at shutdown by fiber optic sensor (direct reading), θh	θh	^{o}C	
The top-liquid temperature during the 1 h test at rated current, $\Delta\theta of$	$\Delta\theta of$	^{o}C	
The average winding to average liquid temperature gradient (g) (corrected)	g =g (uncorrected)+$\Delta\theta ofm$	^{o}C	
The hot-spot winding temperature rise ($\Delta\theta h$)	$= \theta h + \Delta\theta of - \theta a$	^{o}C	
The average thermal gradient of Winding, (g)	= ($\Delta\theta w$) - ($\Delta\theta om$)	^{o}C	
Calculated Hotspot rise ($\Delta\theta h$) [where Hotspot factor, H = 1.3]	$= \Delta\theta o + H g$	^{o}C	
Hotspot rise ($\Delta\theta h$) [where design Hotspot factor, H = to be furnished by manufacturer]	$= \Delta\theta o + H g$	^{o}C	
Top liquid temperature rise		^{o}C	
HV Winding average temperature rise		^{o}C	
The hot-spot winding temperature rise ($\Delta\theta h$) by fiber optic sensor (reference purpose)		^{o}C	
The hot-spot winding temperature rise ($\Delta\theta h$) by conventional method		^{o}C	
The hot-spot winding temperature rise ($\Delta\theta h$) considering design hotspot factor and measured top oil rise.		^{o}C	

9. Overload testing in short-circuit method

The test shall be carried out on the tapping position that will cause the highest current under normal conditions. Hot spot temperature measurement shall be done by using temperature probes or sensors in approved locations.

The transformer shall be fully erected as for service with all cooling equipment.

I. Testing option 1:

Pre-load the unit with 100% of full load current for a period long enough to stabilise the top oil temperature with cooling as for service conditions.

- Increase the loading to 120% overload rating. Forced cooling shall be activated as per service conditions.
- Scan and record infra-red images of all four sides and the top of the transformer at the interval of every one hour.
- Hold the overload current for a period of 4 hours.
- Measure and record the hotspot temperatures (by resistance method & fiber optic sensors).

II. Testing option 2:

Pre-load the unit with 100% of full load current for a period long enough to stabilise the top oil temperature with 100% cooling as per service conditions.

- Increase the loading to 130% overload rating.
- Scan and record infra-red images of all four sides and the top of the transformer every 30 minutes.
- Hold the current at 130% for a period of 2 hours.
- Measure and record the hotspot temperature (by resistance method & fiber optic sensors).

III. Acceptance criteria:

Winding hotspot temperatures shall not exceed 130°C for option 1 and 135 °C for option 2.
The temperature rise recorded by infra-red shall be not more than 10°K above top oil temperature or 15°K above the local oil temperature.
The rate of gas development as determined from oil samples shall be determined. Samples shall be taken before and after the test and acceptance criteria shall be in accordance with IEC/IEEE guidelines.

IV. Test records:

Full details of the test arrangements, procedures and conditions shall be supplied with the test certificates and shall include the following:

- Purchaser’s reference number and site designation
- Manufacturer’s name and transformer serial number
- MVA rating and voltage ratio
- Vector group

- Altitude of test bay
- Designation of terminals supplied and terminals strapped
- Colour photographs of the four sides and top of the transformer.

V. Overload test:

A log of the following quantities taken at a minimum of 30-minute intervals:

- time
- voltage between phases
- current in each phase
- power in each phase and total power
- ambient temperature
- top oil temperature
- FO sensors readings

10. Short duration heat run test (Not Applicable for unit on which temperature rise test is performed)

In addition to the type test for temperature rise conducted on one unit, each cooling combination shall routinely be subjected to a short term heat run test to confirm the performance of the cooling system and the absence of manufacturing defect such as major oil flow leaks that may bypass the windings or core.

DGA samples shall be taken at intervals to confirm the gas evolution.

For ODAF or OFAF cooling, the short term heat run test shall be done with the minimum number of pumps for full load operation in order to shorten the temperature build up. Each short term heat run test is nevertheless expected to take about 3 hours.

For ODAF or OFAF cooled transformers an appropriate cross check shall be performed to prove the effective oil flow through the windings. For this purpose the effect on the temperature decay by switching the pumps off/ on at the end of the heat run should demonstrate the effectiveness of the additional oil flow. Refer to SC 12, 1984 cigre 1984 SC12-13 paper by Dam, Felber, Preiniger et al.

Short term heat run test may be carried out with the following sequence:

- Heat run test with pumps running but oil not through coolers.
- Raise temperature to 5 deg less than the value measured during temperature rise test.
- Stop power input and pumps for 6 minutes and observe cooling down trend
- Restart pumps and observe increased cooling trend due to forced oil flow

The cooling down trend shall be observed by recording top and bottom oil temperature and winding resistance.

This test is applicable for the Transformer without Pump also (ONAN or ONAF rating). For such type of transformer test may be carried out with the following sequence:

Arrangement shall be required with pump of suitable capacity (considering the oil velocity) without cooler bank. Raise the oil temperature 20-25 deg C above ambient. Stop power input and pumps for 6 minutes and observe cooling down trend. Restart pumps and observe increased cooling trend due to forced oil flow. FO sensors data shall be recorded during the test.

11. Over excitation test

A routine over excitation test at 1.05 p.u voltage for 12 hours shall be done on the tap position giving the highest flux. This test shall be carried out immediately after the routine short-term heat run test on the transformer. The rate of gas development during the test shall be evaluated using IEEE /IEC/CIGRE guidelines. FO sensors data shall be recorded during the test.

12. Measurement of zero-sequence impedance(s) on three-phase transformers

Standards: IEC 60076-1:2011, IEC 60076-8

General

In the case of transformers having more than one star-connected winding with neutral terminal, the zero-sequence impedance is dependent upon the connection.

The zero-sequence impedance may have several values because it depends on how the terminals of the other winding or windings are connected and loaded.

The zero-sequence impedance may be dependent on the value of the current and the temperature, particularly in transformers without any delta-connected winding.

The zero-sequence impedance may also be expressed as a relative value in the same way as the (positive sequence) short-circuit impedance

Test Procedure

The zero-sequence impedance is measured at rated frequency between the line terminals of a star-connected or zigzag-connected winding connected together, and its neutral terminal. It is expressed in ohms per phase and is given by ($3U/I$), where U is the test voltage and I is the test current. The test current per phase ($I/3$) shall be stated in the test report.

It shall be ensured that the current in the neutral connection is compatible with its current carrying capability.

In the case of a transformer with an additional delta-connected winding, the value of the test current shall be such that the current in the delta-connected winding is not excessive, taking into account the duration of application.

If winding balancing ampere-turns are missing in the zero-sequence system, for example, in a star-star-connected transformer without delta winding, the applied voltage shall not exceed the phase-to-neutral voltage at normal operation. The current in the neutral and the duration of application should be limited to avoid excessive temperatures of metallic constructional parts.

For autotransformers and YY transformers, there are several combinations of tests to perform:
– HV with LV open circuit;
– HV with LV short circuit;
– LV with HV open circuit;
– LV with HV short circuit.
– For YD transformers, the zero sequence impedance is measured from the Y side only.
– Auto-transformers with a neutral terminal intended to be permanently connected to earth shall be treated as normal transformers with two star-connected windings.