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OTI & WTI – What they measure?

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1.0 Introduction

Temperature rise is one of the critical parameters specified during procurement of transformers. During testing at manufacturer's works, the observed temperature rise is compared against guaranteed values for compliance. This article addresses the underlying concepts involved and clarifies what OTI (Oil Temperature Indicator) and WTI (Winding Temperature Indicator) readings represent.

2.0 Specification

The temperature rise as specified by typical Utility, IS and IEC are compared in Table 1.

Table 1

Item	Utility A	IS-2026	IEC-60076
Yearly weighted ambient temperature	32°C	32°C	20°C
Top oil temperature rise	40°C	50°C	60°C
Average winding temperature rise	45°C	55°C	65°C
Top oil temperature	72°C	82°C	80°C
Average winding temperature	77°C	87°C	85°C

Since India is relatively hot compared to Europe, yearly weighted ambient temperature has been raised by IS to 32°C compared to 20°C as per IEC. Oil and winding temperatures as per IS & IEC are nearly same. This is achieved by lowering the allowable temperature rise by 10°C compared to IEC. Typical utility specification results in very conservative design. The temperature rise limits are 10°C lower than that specified in IS.

3.0 OTI & WTI

Among the two, Oil temperature indication is directly measurable. In majority of cases, winding temperature indication is a calculated value using a formula based on thermal imaging. In some cases, fibre optic sensors are embedded between the discs of the windings to directly measure the winding temperature.

The only stage when the winding temperature is actually measured is during the temperature rise test of transformer. The temperature rise is basically due to losses in the transformer which acts like a heater immersed in oil. The test is done by applying

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low voltage on HV side with LV shorted and power input is equal to the sum of guaranteed no load loss and load loss. This is illustrated with an example.

Transformer Rating: 125 MVA, 220 / 33 kV. Tapping range is +5% to -10%.

The guaranteed total losses = 375 kW

At extreme negative tap,

Rated voltage $= 220 \times 0.9$

$= 198$ kV

Rated current $= \dfrac{125{,}000}{\left(\sqrt{3} \times 198\right)}$

$= 365$ A

Short circuit impedance $= 14.53\%$

Impedance voltage $= 0.1453 \times 198$

$= 28.8$ kV

Since the test is done at low voltage, the no load loss will be lower than at rated voltage. To inject guaranteed total losses, during heat run, applied voltage is slightly higher than impedance voltage. In this case, the injected current will be higher than rated current. Increased load loss will compensate for reduction in no load loss to maintain guaranteed total loss as input. Since the no load loss is only about 20% to 30% of total loss, the increase in current is marginal during testing. After the temperature has stabilized, the applied voltage is reduced to pass exactly rated current in the winding. Then the supply is cut off and immediately the resistance of the winding is measured.

The above complex procedure is adopted due to the limitation of test set up. At manufacturer's work, it is difficult to pass rated current at rated voltage. Hence the only option is short circuit test method. To measure temperature rise, it is necessary to inject the guaranteed losses. But to measure winding temperature, it is necessary to inject rated current. The hot winding temperature measured at works (by extrapolating at zero time) is 'Average winding temperature'. This is because the temperature is 'calibrated' based on the DC resistance of the whole winding.

It must be emphasized that during entire heat run test, only the Oil temperature is continuously monitored and measured. Winding temperature is measured indirectly *only at the end of heat run test*. During heat run test healthiness of OTI, if mounted, can be checked. But soundness of WTI readings can not be checked during heat run. Calibration of WTI itself is possible only after the end of the test and 'Average winding temperature' is evaluated which leads to estimation of winding gradient. Hence during heat run, entering WTI readings periodically has no practical utility.

In this context, it is very pertinent to point out that the following statement is sometimes made in technical offer or test reports – 'guaranteed temperature rise of X°C *over an ambient of* Y°C'. This statement is fallacious as temperature rise is independent of ambient temperature. For the same total loss, temperature rise is same in summer or winter.

There is no confusion in guaranteed oil temperature rise as it is directly measured quantity both at works during testing as well as in service during running. Hence OTI reading does not pose conceptual problems. But the significance of guaranteed winding temperature rise ends almost with the heat run test. This corresponds to 'Average winding temperature', whilst during service what WTI measures is the 'Hot spot temperature' of the winding.

4.0 Winding Hot Spot Temperature

In Fig 1, winding immersed in oil is shown.

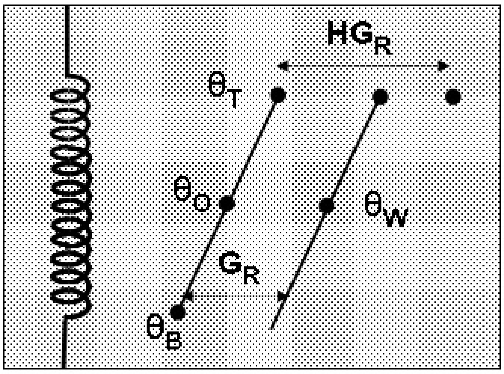

Fig 1

θ_T: Top oil temperature

θ_B: Bottom oil temperature

Average oil temperature $\theta_O = (\theta_T + \theta_B) / 2$

Average winding temperature θ_W is derived from resistance measurement when the winding was carrying rated current just before disconnection of power supply.

Average winding gradient = $\theta_W - \theta_O$.

This is the temperature gradient between conductor (copper) and surrounding oil. It is a function of heat flux generated within the conductor (watts/m^2), temperature drop across paper insulation and heat carried away by oil. The heat flux is directly proportional to copper (I^2R) loss within the conductor and the surface area presented to oil for heat dissipation. Two important facts follow from the above: (a) It is not true that LV winding gradient is always greater than HV winding gradient. The gradient is function of copper loss per m^2 of surface area for each winding. (b) Winding gradient is not influenced by core loss.

Typical average winding gradient is 10°C to 20°C.

As per IEC – 60076,

Hot spot gradient Hgr = 1.3 x Average winding gradient

WTI is calibrated based on the following equation:

$$\theta_{WH} = \theta_T + Hgr \left(\frac{I}{I_{RAT}} \right)^n \quad \text{..........(1)}$$

θ_{WH} : Hot spot temperature as indicated by WTI

θ_T : Top oil temperature

Hgr: Hot spot gradient

I: Actual current as measured by CT and given as feedback to measurement instrument

I_{RAT} : Rated current

n : exponent (between 1.6 to 2)

The WTI measurement thus is a 'calculated' value based on Eqn (1) and depends on Hgr (Hot Spot Gradient) value fed into the measurement device. For old transformers test records may not be available. In such cases, only an estimated value of Hgr is input to the device. As a conservative option, higher value of Hgr (say 25°C) is used.

5.0 OTI & WTI Measurement – Conventional and Modern

In conventional OTI / WTI, one or two thermo-well pockets are provided on the transformer tank cover. They are typically 150 mm long. In the pocket oil is filled and a bulb with temperature sensing element like a RTD (PT100) is inserted. RTD measurement is taken as Top Oil Temperature. To get winding temperature, current proportional to rated current of transformer is passed through standard resistance of WTI. The temperature rise due to I^2R represents the hot spot gradient. For the selected R, the rated current could be 1A, 1.6A, 2A. etc which produces the temperature corresponding to desired gradient. If the rated current of protected winding is 2092A (25 MVA at 6.9 kV), the CT ratio for WTI is chosen as, say, 2092/1.6A. Thus, we end up with odd CT ratio for WTI where the primary current is the rated current of winding and secondary current is the rated current of resistor.

But in modern microprocessor based stand-alone OTI/WTI or Digital RTCC which has inbuilt OTI/WTI, 3 wire PT 100 signal from thermo-well pocket is wired to the device for OTI measurement. In addition current and voltage signals from conventional CT and PT are also wired to the device. The winding rated current, CT and PT ratios, hot spot gradient at rated current, exponent 'n' in Eqn (1), set points for alarm and trip are all settable through HMI. The device internally generates WTI reading based on Eqn (1) through software. The device generates OTI / WTI readings and alarm / trip signals and communicates to local RTU on Modbus, IEC 103 or IEC 61850 protocols. The device can also generate (4-20) mA signals for OTI and WTI for use in local indication in transformer marshalling box. The device detects any open circuit in PT100 signal and inhibits OTI / WTI operation.

6.0 OTI & WTI Alarm & Trip settings

If the transformer has been designed for a specified top oil temperature rise of 40°C, the actual temperature rise at site at rated current is found to be less than 30°C in majority of the cases and between 30°C and 35°C in a few cases. Assuming the maximum ambient temperature as 45°C with coincidental rated current in transformer, the OTI reading at extreme case could be 80°C. With a margin, OTI alarm setting could be 85°C. The WTI alarm setting should preferably be slightly less than OTI alarm setting plus Hot spot gradient (Hgr). If Hgr used in device is 15°C, WTI setting could be 95°C ($<$ 85+15).

With the above alarm settings, WTI alarm will mostly denote over load. Only in case of cooling circuit failure, OTI alarm will come first even in case of part load operation. OTI and WTI trip setting could be 10°C more than alarm setting. i.e. 95°C and 105°C respectively.

For normal cyclic loading, IEC-60076 recommendations for OTI and WTI trip settings are higher, i.e., 105°C and 120°C. Thus, the suggested OTI and WTI trip settings of 95°C and 105°C are conservative and on safer side.

7.0 Relevance of OTI & WTI in different systems

In case of power plants, the transformers (Generator Transformer, Station Transformer, Unit Auxiliary Transformer) are designed based on worst loading criteria. In these cases, the loading on the transformer can not exceed the rated value unless the design itself is faulty. For example, typical capacities of GT for different unit sizes are given in Table 2.

Table 2				
Unit Size (MW)	250	300	500	600
GT Size (MVA)	315	370	600	750

The probability of the current through GT exceeding the rated current is very small. In this case, only OTI is more relevant, as oil temperature might rapidly rise, even under part load, in case of cooling circuit failure. WTI has no practical significance as there is very little chance of transformer overloading. In Eqn (1), (I/I_{RAT}) is always less than unity. The same arguments hold good for Station Transformer and Unit Auxiliary Transformer in power plants.

In transmission systems, transformer loading is as per power flow dictated by network conditions and load-generation geometry. In distribution systems, power flow through transformers is as per downstream load requirements. In both cases, the chances of transformer overloading are present. OTI and WTI are both relevant in these cases.

8.0 Oil Volume

There is a misconception that transformer with higher oil volume capacity is inherently superior from cooling point of view. Two transformers, say 100 MVA rating, can have oil capacity of 40 Kilolitres and 50 Kilolitres but both can satisfactorily meet temperature rise requirements. It should be emphasized that the oil volume plays a significant part when the transformer is heated from the cold as in ‘heat run test’ at works. Transformer with a higher volume may take more time to reach steady state value. Typical heating curve, from heat run test, is shown in Fig 2. From the tangent drawn at origin, the thermal time constant can be evaluated. Incidentally, to accurately estimate thermal time constant, the initial temperature readings during heat run test shall be taken at frequent intervals, say every 10 minutes in the first one hour. Typical thermal time constant of oil could be 1 to 3 hours while that of winding (which is a metal – copper) could be 3 to 5 minutes.

A well designed cooling system consisting of pumps, fans and heat exchangers like radiators can take care of limiting the temperature rise for a given oil volume in steady state operation. Of course, oil volume will not be absurdly low, as it is determined by physical dimensions of core-coil assembly and clearance with tank.

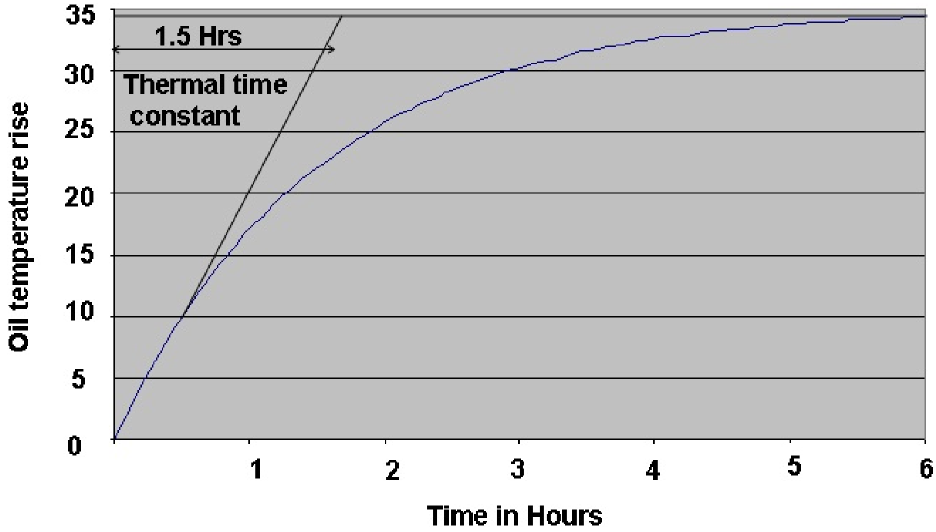

Fig 2

9.0 Insulation Life

The age of transformer is synonymous with that of insulation. The loading of transformer is reflected as winding temperature. The effect of winding temperature on insulation life is discussed in detail in Ref [2]. The relative rate of using life in hours for normal Kraft paper is shown in Fig 3.

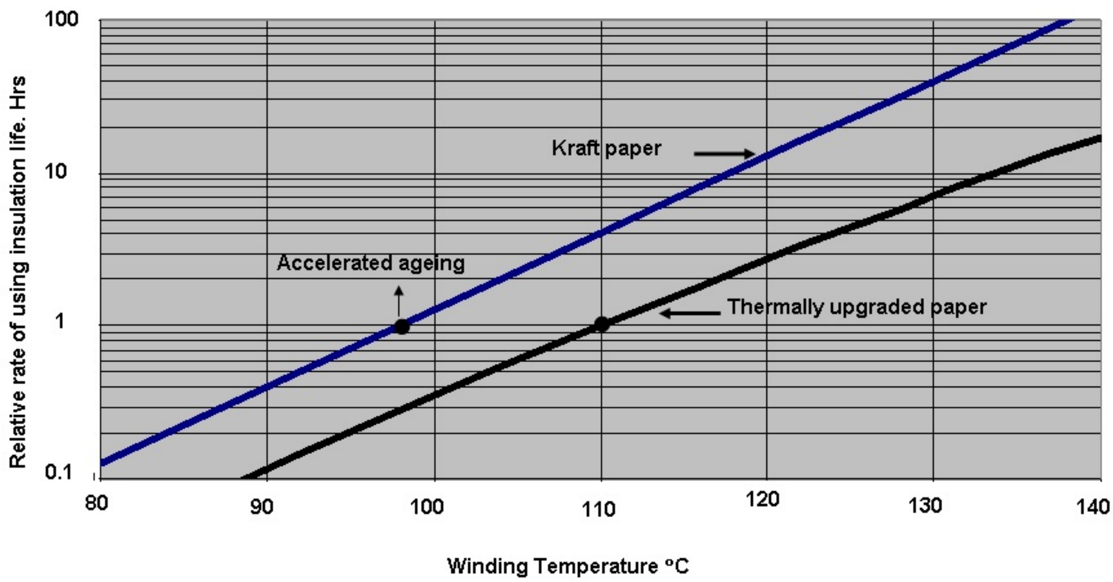

Fig 3

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It can be seen that below 98°C, the ageing is normal but above 98°C, accelerated ageing sets in. Hence over the long run, the winding hot spot temperature should not exceed 98°C. In Table 3, tested values for 125 MVA transformer are given under column 3. The expected values under increased loading conditions (141 MVA – 113%) are given under column 4. Upto 113% loading, normal ageing is obtained (hot spot temperature is within 98°C). This is the basis for the popular perception that, generally 10% over loading of transformer even at frequent intervals is allowed without degrading insulation life.

Table 3

Sr No	**Item**	**Base Load 125 MVA**	**Increased load 141 MVA**
1	Average gradient °C	17 (*1)	21.6 (*2)
2	Hot spot gradient °C (*3)	22.1	28.1
3	No load loss KW	65(*1)	65
4	Load loss KW	325(*1)	414 (*4)
5	Total Loss KW	390	479
6	Top Oil Temp Rise °C	31(*1)	38.1 (*5)
7	Yearly Average ambient temperature °C	32	32
8	Hot spot temperature °C (7 + 6 + 2)	85.1	98

*1: Obtained from type test at works

*2: $(141/125)^2$ x 17 = 21.6°C (exponent 2 – for forced directed air flow)

*3: Hot spot gradient = 1.3 x Average gradient

*4: $(141/125)^2$ x 325 = 414 KW

*5: (479/390)*31 = 38.1°C

Thermally upgraded paper, if used instead of conventional Kraft paper, permits higher hot spot winding temperature. In the former case, the accelerated aging starts only after 110°C as against 98°C for Kraft paper. In this case, OTI and WTI alarm and trip levels can be set much higher.

10.0 Fibre Optic Sensors for WTI

The new trend has been to specify the use of fibre optic sensors for direct reading of winding temperature. Usually 8 channels are used, one for Top Oil, 3 for HV winding (R, Y, B phases), 3 for LV winding (R, Y, B phases) and one for core. It must be emphasized here that accuracy per se is not sacrosanct in WTI measurement. If true value of WTI is above 98°C, transformer is not going to fail immediately. It might lead to loss of insulation life but this is negligible if the WTI value is below 98°C for most of the time.

For transformers in power plant applications, where the winding currents are not expected to exceed rated values as explained in Cl 7.0 fibre optic sensors do not have any value addition. In transmission and distribution systems, where load variations can be erratic and sudden, it can be applied on a trial basis. Fibre optic sensor is not the panacea for transformer trouble diagnostics. The supreme tool in this regard is DGA done at periodic intervals.

11.0 Conclusion

The main tenet of this article is to clarify the basic concepts with respect to temperature rise of oil and winding of transformer. The subtle differences between OTI and WTI are explained. The relevance of OTI and WTI for transformers in generation, transmission and distribution systems is brought out. The effect of temperature on insulation life and over load capability of the transformer are described in brief. The material presented here will enable the practicing engineers to operate the transformers to the maximum capacity without sacrificing life.

12.0 References

[1] IEC 60076-7: Loading guide for oil immersed power transformers

[2] ‘Overload protection of electrical equipment’, K Rajamani, IEEMA Journal, June 2004, pp 30-34.