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Direct Measurement of Transformer Winding Hot Spot Temperature and its Significance

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ABSTRACT: One of the most important parameter that governs the transformer ageing or life expectancy, is the winding hot spot temperature, hence it is imperative to measure the real time winding hot spot temperature with accuracy to assess the transformer ageing. This paper investigates the relevance of direct measurement of the winding hot spot temperature of power transformer over conventional indirect measurement methods being used largely even today and also depicts some of the measurement principles of direct measurement using optical fibre with temperature sensor working in varying principle.

KEYWORDS: Power Transformer, Winding Temperature, Oxidation, Temperature measurement, TUP (Thermally Upgraded Paper), Fibre-optic Sensor.

I. INTRODUCTION

Measurement of transformer winding hot spot temperature accurately is an important concern for every operator as the insulation ageing of transformers are directly related to the winding hot spot temperature during operation, which allows the operator to plan out short term and emergency overloading of the transformer above its nameplate rating without compromising the design life of the transformer. Therefore in order to optimally use the transformer for short term overloading, measuring the winding hot spot temperature accurately is very important. The conventional traditional methods of measuring transformer winding temperature, which is also being used very widely today, is an indirect way of measurement, that is calculated value based on thermal imaging proportional to load current. It fails to provide correct hot spot temperature particularly for dynamic loading conditions due to its very high time constant, thus the actual ageing of transformer insulation is not taken into consideration for planning overloading, highlighting a need to develop some method and instrument for direct real time measurement of winding hot spot temperature.

In the 1980s and 90s, various optical fiber sensors were introduced operating with different principles. Initially, the major issue was of dielectric failure and fragile equipment resulting in breakage during handling or installation. It has since been modified appropriately and it has now been established as a reliable and accurate instrument to instantly provide the real time winding hot spot temperature, so the transformers can be optimally overloaded to meet the fluctuating load demand without compromising or degrading its design life

II. WINDING HOT SPOT TEMPERATURE AND IT's ROLE

It has been recognized that transformer ageing is primarily a time function of three parameters: temperature, moisture, and oxygen content. Oxidation of mineral oil results in degrading of transformer life and the oil oxidation is a function of moisture and oxygen content in oil. With a modern oil preservation system (such as atom seal breather in conservator) and anti-oxidant inhibitor in oil, moisture and oxygen contribution to the transformer ageing is very much controlled or minimized, thereby leaving winding hot spot temperature the only important controlling parameter for transformer ageing. Let us look at what happens to the transformer while the winding hot spot temperature exceeds the design limit.

At this point, it is imperative to look at the temperature rise limits specified in IEC -60076.
IEC – 60076 Temperature Limits:

- Yearly Average Temperature – 20 °C

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- Maximum Ambient Temperature – 40 °C
- Top Oil Temperature Rise – 60 °C
- Average Winding Temperature Rise – 65 °C
- Average Winding Temp. Rise (OD cooling) – 70 °C
- Ageing Rate of 1.0 for normal Paper – 98 °C
- Ageing Rate of 1.0 for TUP (Thermally Upgraded Paper (TUP)) – 110 °C

During short time emergency loading exceeding its nameplate rating, gas bubbles would generate in the mineral oil if the winding hot spot temperature exceeds 140 °C. This happens with moisture content of 2% in the paper. Should the moisture content be higher, the gas bubble would start generating even at lower temperatures. This would obviously reduce the dielectric property and may lead to dielectric failure. Hot spot temperature is linked to ageing of the insulation. The normal design life of cellulose paper insulation is obtained at operating winding hot spot temperature of 98 °C, while it is 110 °C for thermally upgraded paper. For long term emergency loading, the main concern is transformer ageing. Table 1 under shows statistics for a typical transformer with a design life of 30 years.

Table 1: Transformer expected design life at different winding hot spot temperature.

Winding Hot Spot Temp. in ^{0}C	Aging Rate (insulation) with normal Cellulose Paper	Expected Life Span (years) with Cellulose paper	Aging Rate of the insulation with TUP	Expected Life Span(years) with TUP
98	1	30	0.282	106
104	2	15	0.536	56
110	4	7.5	1	30
116	8	3.75	1.83	16
122	16	1.875	3.29	9
128	32	0.937	5.8	5

As shown in Table 1 above, every 6 °C rise in winding hot spot temperature, the lifespan gets reduced by half. The same is true on the reverse side, too. If the transformer is operated at a winding hot spot temperature of 92 °C (104 °C for transformer with TUP), the design life goes up to 60 years. Therefore, in view of the dynamic load/demand changes on the transformer, the transformer can be optimally & intelligently overloaded considering the actual hot spot temperature of the transformer without any degradation of design life. However, the temperature limits specified in Table 4 of the IEC-60076-07 must be considered while loading the transformer above the nameplate rating under emergency loading to ensure the winding hot spot temperature does not exceed the specified limit.
Therefore, the winding hot spot temperature is a prime concern for the operators. It gives the operator an idea of transformer aging, so the operator can assess the risk of short term overloading without degrading design life.

III. WINDING TEMPERATURE MEASUREMENT METHOD

A. Conventional Method (Top Oil)
This is the conventional method which we normally find in most of the transformers in use. The rated winding hot spot rise above top oil is usually derived from the temperature difference between the average winding and the average oil temperature. This difference is then multiplied by a hot spot factor to account for additional losses toward the end of the winding. This hot spot factor is normally estimated using factory heat run test results. For a given load current, the difference between the average oil temperature and the average winding temperature is assumed to remain constant at all operating conditions, which may not be true. This method and the exponent used for different cooling conditions is universally used and specified in both IEC and IEEE.
The measurement method assumes the following:

- The oil temperature inside the tank increases linearly from the bottom to the top of the core/coil assembly.
- The temperature rise of the conductor at any position up the winding is assumed to increase linearly, parallel to the oil temperature rise, with a constant difference between the straight lines.

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- The hot spot temperature rise is higher than the temperature rise of the conductor at the top of the winding to make allowance for stray losses, local oil flow losses, etc.

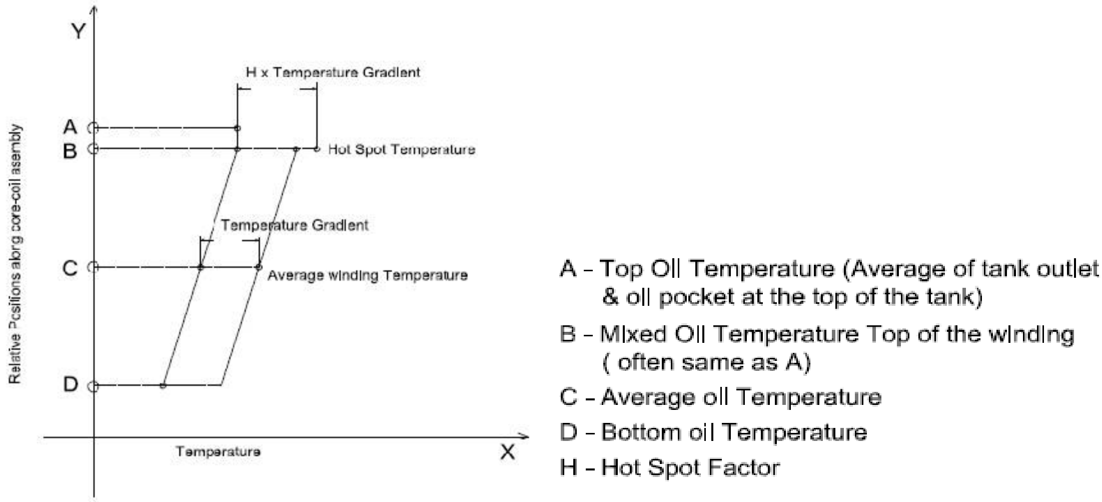

Figure 1: Oil and winding temperature bottom to top along the core coil assembly.

The Hot Spot Factor (H) depends on various factors such as winding type and design, short circuit impedance, transformer size, etc. It is either evaluated during a temperature rise test or calculated. The value of H can be anything between 1.1 to 2.0. For distribution transformers, it is assumed to be 1.1, while it can be assumed to be 1.3 for (medium & large size) power transformers.
The temperature element, the thermo-bulb, is placed inside a thermo-well filled with top oil. To simulate the winding temperature gradient, the thermo-well is additionally fitted with a heater element, fed by a bushing mounted CT input, with current directly proportional to the load current. The bulb is filled with a liquid with a large coefficient of thermal expansion and is connected through a capillary tube to a spiral wound burden tube in the measurement device (dial gauge). When the burden tube expands due to increased temperature, the burden tube will unwind, thereby moving the pointer over the scale in the dial gauge.

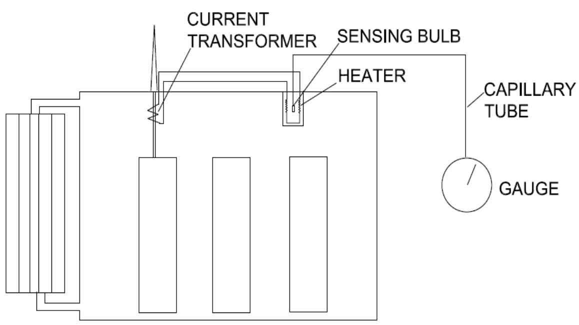

Figure 2: Transformer Winding CT with Temperature Sensing Bulb for Temperature Monitoring

Thus, the winding hot spot temperature is simulated by the actual top oil temperature plus a factor proportional to the load. This assumes that the temperature of the oil at the top of the cooling duct is the same as the top oil temperature measured in an oil filled thermos-well near the top of the tank. This is, however, where inaccuracy gets introduced.
This model, widely used around the world and described in IEC/IEEE, is not adequate to correctly simulate the winding hot spot temperature, particularly under dynamic loading conditions. The main reasons for this include:

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- The oil temperature in the cooling duct could be much higher than the top oil temperature, which is used as the base temperature for deriving the hot spot temperature. So, the hotspot temperature could be different than calculated above.
- The time constant of the oil in the cooling duct could be much higher than the top oil. Under step loading, the hot spot temperature derivation could be inaccurate.

B. Bottom Oil Temperature Measurement Method

The IEEE loading guide (c57-91) is presently under revision to recommend the approach based on the bottom oil temperature over the top oil temperature. The bottom oil methods takes consideration of oil duct temperature into winding hot spot temperature derivation.

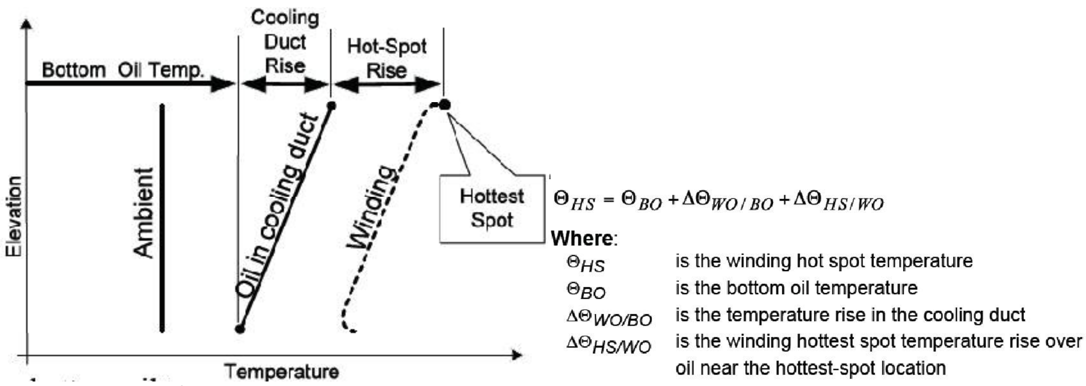

Figure 3: Transformer winding hot spot temperature based on bottom oil temperature measurement

In this method, the losses and temperature rise quantities are adjusted by accounting for the changes in winding resistance and the oil viscosity with the oil temperature. This would give a more accurate hot spot temperature.
Although the bottom oil measurement principle presented above would provide accurate information on winding hot spot temperature data, it still fails to account for the following:

- Eddy losses and stray losses in the hot spot area.
- Oil flow rate at hot spot area.
- Oil temperature at hot spot area.
- Oil time constants.
- Adjustment of the values at different tapings.

The hot spot temperature simulated or calculated this way would be comparatively lower than the actual temperature.

Therefore, a direct measurement for hot spot temperature has become necessary. Optical fibre direct measurement came into use during the 1980s. The dielectric withstand ability and fragility was a major concern initially but developments, improvements, and experiences have made these probes highly reliable. May be in times to come these will be used as standard winding measurement method.

IV. DIRECT MEASUREMENT

Several measurement principles are in use to measure the winding hot spot temperature using fiber optics probe.
Since the sensing probe would be embedded into the high voltage winding spacer, essentially it must have following features to suit the requirement;

- Good dielectric property
- Robust enough to handle and install
- Immunity to EMI and RFI
- Suitable for operating at high temperatures
- Compatible with mineral oil

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- Highly accurate
- Highly reliable
- Small, light, and capable of withstanding vibration

The most widely-used fiber optic temperature probe consists of a Gallium Arsenide (GaAs) semiconductor crystal mounted on the end of an optical fiber. The band gap of the crystal changes based on temperature. The GaAs crystal is fixed on the tip of the fiber and the position of the band edge is temperature dependent. It shifts about 0.4 nm/°C. Light is directed through the optical fiber to the crystal, generally LED light is used, where the light gets absorbed partially and part of that reflects back. A spectrometer measures the spectrum and the position of the band edge, which is temperature specific. Further, the light intensity does not have any role in temperature measurement, and it is an advantage.

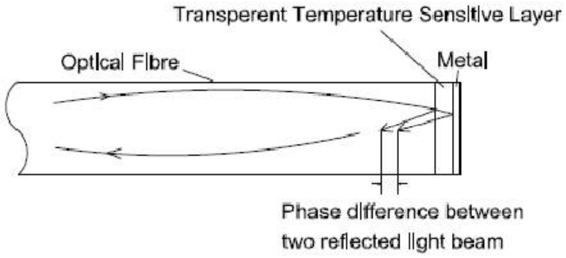

Figure 4: Optical Fibre - Phase Difference of light beam temperature dependent

There are other sensing technologies that use spectrally based sensors in which the light wave is modulated by temperature, as in the blackbody sensor where an end of the fiber is placed in a blackbody cavity so that the wavelength profile of the light emitted by the cavity depends on the temperature.

The Optical Time Domain Reflection (OTDR) principle of optics is also used for measurement in some probes. The principle of temperature measurement is based on the fact that when the laser pulse couples into the optical fiber, excited photons scatter and collide. On the time domain, the interval of backscattering photons can be measured which is temperature dependent.

Another principle used for direct measurement is the use of Fluoroptic optical sensor technology, based on the fluorescence decay time of a special thermo-sensitive phosphorescent (phosphor) sensor located at the end of a fiber optic cable. Light at the appropriate wavelength generated by an excitation LED is routed through a probe extension and connectors, where it falls on the phosphor sensor located at the probe tip. The Luxtron phosphor sensor emits light over a broad spectrum in the near infrared region, as shown in Figure 5. The time required for the fluorescence to decay is dependent on the sensor's temperature. After the LED is turned off, the decaying fluorescent signal continues to transmit through the fiber to the instrument, where it is focused onto a detector. The signal from the detector is amplified and sampled after the LED is turned off.

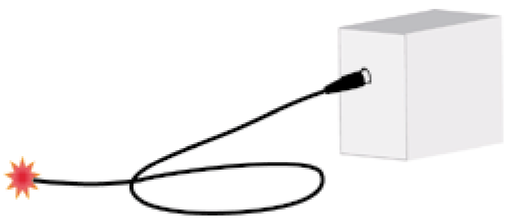

Figure 5: Phosphor Sensor at the End of the Fiber Optic Probe excited by an LED in the Instrument

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The measured decay time is then converted to temperature by the instrument's software using a calibrated conversion table. Different calibration tables are used depending on the temperature range and application, but the overall temperature range capability of this optical sensor technology is currently –200 °C to 330° C.
The fact that the excitation light signal and the fluorescent decay signal pass along the same optical path means that the fiber optic probe and sensing tip can be relatively small. This is particularly important in medical research applications, where fiber optic probes as small as 0.5mm diameter (STB probe) are available. Other probe configurations and customized fiber optic temperature sensors are also available.
The advantage of this system is that no periodic calibration is required and it is independent of light intensity, so the temperature measurement is not affected even if the LED emits lower intensity light.

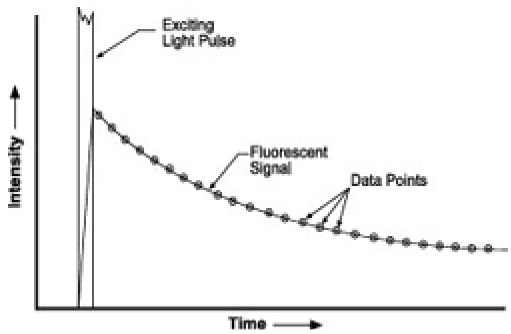

Figure 6: light from the sensor decays at a rate that varies precisely with temperature.

Irrespective of the principles described above for sensing the temperature, the components of the winding hot spot measurement systems generally include the following:

- FO probes embedded in isolation spacers in between winding. Generally, these probes are placed in the spacer between the first or second coil from the top, which is considered to be the hot spot point. At least two or more probes are placed in each phase.
- A well designed and sealed tank wall feed through.
- FO Cable.
- Converter to convert the light signal to an electrical signal located outside, generally on the main tank wall.

V. CONCLUSION

The technology of direct winding hot spot temperature measurement has been in use for more than 20 years and has undergone several modifications and improvements to make it more reliable and affordable. So far, the major drawback preventing its use has been the high initial cost.
It is for sure that the conventional, indirect way of measuring the winding temperature through thermal imaging would be obsolete someday in the near future and direct optical fiber sensors would be used by default in all transformers. By using this technology to acquire the actual real time hot spot temperature, it is possible to optimally use the transformer capacity by overloading the transformer above its nameplate rating without compromising or degrading the transformer design life.

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