Winding temperature monitoring on transformer with OLTC

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Transmission network transformers are typically provided with on-load tap changers (OLTC) to regulate the voltage delivered to customers and to adjust power flow in the system. By virtue of OLTC operation, per unit (p.u.) currents are bound to be different on the HV winding and LV winding.

Usually the rated current is established for both windings at the mid-tap position, and this leads to a transformer with a reduced rated power on some taps. When such transformers are requested to operate under overload conditions during system contingency, the on-load tap changer typically moves from the normal operating position to the end of the tapping range to compensate for the voltage drop taking place on the system. Depending on transformer design, the winding hottest spot may well move from the high-voltage winding to the low-voltage winding or vice versa. Most transformers are provided with a single winding temperature indicator, which does not allow for a direct control of temperature on each winding.

In order to take full advantage of transformer loading capabilities during emergency conditions without jeopardizing reliability of the unit, accurate evaluation of temperature on both windings is needed. Limitations of the classical thermo-mechanical Winding Temperature Indicator (WTI) are discussed along with difficulties related to the installation of an additional system for the monitoring of the second winding. As an alternative, a simple digital device, capable of monitoring temperature on three windings, is proposed. Field experience is reported demonstrating the accuracy of the thermal model and the capabilities to provide control functions for the cooling system and protection functions to trip the transformer if a winding reaches excessive temperature.

Limitations of traditional winding temperature indicator

For many decades it has been a standard practice to install on new power transformers a winding temperature indicator. This device typically comprises a temperature-sensing bulb inserted in a well in the top layer of the insulating oil. Surrounding the bulb is a heater element to which a sample of the load current is applied as shown in Fig. 1. This current causes the temperature bulb to read the oil temperature plus a temperature rise from the heater which is intended to be the same as the winding hottest temperature rise above top-oil temperature. The fluid in the bulb expands through a capillary tube connected to a dial gage equipped with switches that can be adjusted to any temperature within the operating range. These mechanical devices provide accuracy of 3 to 5°C, assuming that the transformer designer has properly evaluated the winding hottest-spot temperature. These devices can be used for cooling control temperature alarm and they are sufficiently rugged to be used for protection purpose if the recommended maintenance is carried out at regular intervals. WTI’s are offered by several manufactures and provide dependable winding temperature indication at a cost effective price.

A single WTI is fine for a transformer without tap changer because the calibration circuit allows for the simulation of the hottest winding even if the current is measured on a different winding. For instance if the CT feeding the heating elements is on the LV winding and it is known from heat run test and design reviews that the HV winding is the hottest, then the HV gradient can be used to calibrate the winding temperature simulator.

The situation is different on a transformer with a tap changer as the ratio between primary and secondary currents varies continuously with changes in tap position. In this case the WTI cannot be used to monitor the temperature on the primary side if the CT is on the secondary winding. Common practice requires the winding hot-spot temperature indicator to be fed by a CT on the LV winding. This provides a good control over the temperature of low-voltage winding regardless of the transformer load. For the HV winding the situation is not so clear.

Let’s consider a 47 MVA transformer, 120/26,4 kV, wye/delta connection, with a tap changer of 8 steps in the neutral of the HV winding. Each step changes the rated voltage on the primary by 2,25 kV or 1,875 % of the rated
voltage in the neutral position. On these transformers the tap changer is intended to regulate the voltage on the secondary side (26.4 kV). Therefore the voltage and current variations can be depicted as shown in Fig. 2.

On tap positions between 1 and 9, the current in the HV winding is less than the rated value for the neutral position; therefore this winding will be cooler than the rated value. If the tap position is between 9 and 17, the HV winding will be carrying more current and will be at a higher temperature than the rated value at neutral position, although this situation will not be revealed by the WTI. When the transformer in designed to deliver full MVA on any tap, the HV winding has to be enlarged by a value close to the tapping range to be capable of carrying the extra current on tap 17.

In most cases, the maximum load losses are to be found on tap position 17; therefore this is the tap position that will be used to carry out the temperature rise test. Since the winding temperature rise is known in position 17 and the winding temperature indicator is fed by a CT on the secondary winding, the winding temperature simulation, on any tap position, will be realistic for the LV winding and conservative for the HV winding.

In practice transformers with on-load tap changers are commonly designed with a reduced capacity for some parts of the tap range. This is a practice well recognized in Standards [1]. A transformer similar to the one described above but with reduced capacity on some taps can be represented as shown in Fig. 3. The full capacity is available from tap 1 to tap 9 but from tap 9 to tap 17 there is a progressive reduction of capacity because the current is limited by the capacity of the primary winding.

For transformers with full capacity on any tap, the position showing maximum load losses is tap 17. For transformers with reduced capacity on some taps, the highest losses are found on tap 1 and this is the connection that will be used for the temperature rise test. This situation makes it more difficult to monitor with confidence the HV winding hot-spot temperature from a measurement of the secondary winding current. Although test results normally show a lower temperature rise for HV winding it is clear that between tap positions 9 and 17, the primary winding will reach its temperature limit long before the secondary winding. The difference between the temperature patterns for the two types of transformer is illustrated in Fig. 4. It is assumed that both transformers show a winding hot spot temperature rise at the limit of 80°C comprising 55°C for the top oil rise and 25°C for the winding rise above top oil.

It can be seen that for a full capacity transformer tested on tap 17, the HV winding is always the limiting factor. But for transformers with reduced capacity and tested on tap 1, the highest temperature may shift from one winding to another depending on the tap position.

This limitation of the traditional practice of monitoring only the low-voltage winding temperature can be deemed acceptable for loads up to nameplate rating but this situation becomes unacceptable when overloading is considered. It can be shown that for a few hours at 150% overload the temperature difference can exceed 20°C.

Thermal protection of transformers is normally provided by the winding temperature indicator. The HV transformer overcurrent protection could provide a partial thermal backup depending on the relay setting. If the overcurrent protection setting is raised to allow for overload conditions, the winding temperature indicator must be considered as the main thermal protection for the transformer. Hence it is not acceptable anymore to rely on the traditional devices, which monitor only one winding of the power transformer.

One option would be to add a winding temperature indicator on the second winding so that both windings would be protected independently whatever the tap changer position. If not already available this would require the installation of an additional CT on one of the HV bushings to monitor the HV current. It is generally not practical to add a CT on existing bushings. Therefore this option is applicable only on new units where the additional CT can be provided at a competitive price.

**Digital transformer temperature controller**

The preferred method implies the use of a fully electronic device that can calculate separately the temperature on primary, secondary and eventually tertiary windings using as inputs the measured top oil temperature and the current in each winding as shown in Fig. 5.

The winding temperature is calculated as recommended in the IEEE Loading Guide [2]. For the HV winding hottest spot, the ultimate value of temperature rise above top oil is given by:

\[
\Delta \Theta_{HV} = \Delta \Theta_{HR} \left( \frac{I_{HV}}{I_{HR}} \right)^{2m}
\]
The response of the winding to a sudden load increase is not instantaneous. Considering the winding time constant $\tau_w$, the actual winding hot-spot temperature rise above top oil at time $t$ is given by:

$$\Delta \Theta_{(n)}(t) = \left( \Delta \Theta_{(n)}(0) - \Delta \Theta_{(n)}(t) \right) (1 - e^{-t/\tau_w}) + \Delta \Theta_{(n)}(t)$$

where:

- $\Delta \Theta_{(n)}(0)$ is the ultimate HV winding hot-spot temperature rise above top oil
- $\Delta \Theta_{(n)}(t)$ is the HV winding hot-spot temperature rise above top oil at time $t$
- $\Delta \Theta_{(n)}(t)$ is the rated HV winding hot-spot temperature rise above top oil
- $I_{(n)}$ is the load current in the HV winding
- $I_{(n)}$ is the rated value of load current in the HV winding
- $\Delta t$ is the time increment used in the calculation

A similar set of equations allow for calculation of winding temperature rise above top oil for LV windings and tertiary windings. This winding rise is then added to the measured top oil temperature. This calculation method has shown to be sufficiently accurate for reliable monitoring of the winding temperature and the insulation aging. Test results on a converter transformer [3] equipped with fiber optic sensors inserted in the winding insulation have shown a good correlation even when the unit was subjected to rapid load changes as shown in Fig. 6.

**Temperature controller characteristics**

The temperature controller developed by GE Energy used this winding hot-spot model to provide continuous assessment of temperature of each winding. It comprises analog inputs to measure the top oil temperature and the current in each winding. The computation makes use of these measured values and the configured parameters specific to the transformer, such as the rated current, the rated hot-spot temperature rise for each winding and the thermal time constant for the windings. Simultaneous monitoring of the three windings allows for continuous identification of the insulation hottest-spot temperature even if this hottest spot moves from one winding to another. The calculated hot-spot temperature is used to generate two alarm levels and a third level for tripping the transformer.

The temperature controller is also intended for cooling system control. The controller comprises digital outputs to control the cooling as well as digital inputs to monitor the cooling status and to detect discrepancies between control and status. Starting and stopping the various cooling stages take into consideration the oil temperature, the hottest-spot temperature in the windings and the highest load on the windings.

Because of its sturdiness, this controller qualifies as a protection instrument and can be utilized to trip the transformer in accordance with protection requirements. Efficient packaging allows for installation of the unit in the transformer control cabinet or in a separate NEMA 4X enclosure. The input/output characteristics are summarized in Fig. 7.

Maintenance is significantly simplified. WTI manufacturers recommend calibration verification at regular intervals. It is known that with time, the accuracy tends to degrade due to component oxidation and increased friction. If maintenance is not done in time, it may result in inaccurate measurements, which in turn can lead to the cooling system not being turned on at the correct time. In the temperature controller, sensors are checked continuously and the system carries a self-test twice a month to ensure proper functioning of all components.
Protection vs. monitoring

One important characteristic of this application is the need to provide protection functions in addition to the usual monitoring functions. It is required that the thermal protection be qualified to trip the transformer whenever the critical temperature setting is reached on any winding. This is of special interest for the case of unattended substations where the alarm signal would not have been followed by appropriate actions to reduce the load.

Tripping of a transformer is an event of severe consequences for the customers and should in no case be triggered by false information, electric disturbance in the substation environment, or unusual climatic conditions. In order to carry the tripping duty with confidence, the temperature controller must satisfy stringent requirements usually intended for protection relays. These requirements are well described in the IEC 61000 series covering electromagnetic compatibility. At Hydro-Quebec, requirements and testing procedures for electronic devices and protection material are collated in technical specifications SN 62 1008 and SN 62 210.

This new field of application for monitoring material involves new challenges that had to be met. Below are given examples of some of these requirements specific to protection material.

Processor immunity to electrostatic discharges

For monitoring functions, it is usually acceptable to initiate automatic rebooting when a severe electrostatic discharge occurs. For protection functions however, the device should be capable of sustaining electrostatic discharges up to 6 kV on any input or output terminals without disturbing the operation of the protection device.

Immunity to vibration and shock

For monitoring duty, Hydro-Quebec requires a vibration test with an acceleration of 1 G in the frequency range of 10 Hz to 150 Hz. For the first frequency sweep, the device is energized and operating to check the electrical behavior. The test is repeated 20 times without being energized to check the mechanical behavior.

A protective device needs to withstand these mechanical stresses but it must also be able to sustain severe mechanical shocks. In order to avoid false tripping, especially under earthquake conditions, the trip relay must be very stable. The electrical behavior is demonstrated with acceleration of 10 G applied three times in every axis while the mechanical sturdiness is demonstrated with 15 G impulsions. The resistance to transport stresses is demonstrated with an additional test of 1000 impulsions of 10 G in every axis.

Relay capacity for closing current

For monitoring purposes, the digital output relays usually have light duty such as alarms where a rated current of 1 A is sufficient. In a protective device, the output relay dedicated to circuit breaker tripping will typically have a rated current and breaking capacity of 5 A under a 129 V DC source. In the Hydro-Quebec application, the maximum closing current withstand was set at 30 A for 200 ms.

Conclusions

Transformers with on-load tap changers deserve a special thermal protection scheme especially if the unit is expected to operate properly under overload conditions. Information provided by traditional Winding Temperature Indicator can be misleading if the unit is designed with reduced capacity on some taps. In this case the winding not being monitored could be the hottest one and the underestimation of winding hottest-spot temperature could be very significant during overload occurrence.

Proper thermal protection implies that winding hottest-spot temperature is calculated on both windings. Since it is not practical to install a classical Winding Temperature Indicator on each winding that deserves monitoring, it is found that a good solution is to use a fully digital system. This device calculates the winding hottest-spot temperature using the measured top-oil temperature, the load current on each winding and the winding time constant. The calculation method follows IEEE recommended practices that has been used in the industry for many years.

References


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