ANALYSIS OF THERMAL PROCESSES IN OIL POWER DISTRIBUTION TRANSFORMERS

Miroslav GUTTEN   Daniel KORENCIAK
Department of Measurement and Applied Electrical Engineering,
Faculty of Electrical Engineering, University of Zilina, Univerzitna 1, 01026 Zilina
mail: richard.janura@fel.uniza.sk, miroslav.gutten@fel.uniza.sk, daniel.korenciak@fel.uniza.sk

Abstract: *Paper deals with the analysis of thermal processes in oil power distribution transformers. By means of the mathematical analysis and experimental measurements it is possible to diagnose of distribution oil transformers in terms of mechanical strength of winding. Analysis of warming at varying loads is very importance, since allows determining the load capacity and overload of the transformer under various operating conditions and respecting the variable ambient temperature. By means of the practical test, diagnostics, measurements and subsequent analysis it was proved that thermovision plays an important role in diagnostics of power oil transformers in terms of winding mechanical strength.*

Key words: *transformer, temperature, winding, measurement, thermovision*

1. Introduction

Loss of electric energy during transformer operation is triggered by alteration of alternating current and is mostly transformed into heat in windings, magnetic circuit and in other segments of transformer. As a consequence, trans-former's temperature increases and its particular components may reach much higher temperature comparing with the one in surroundings. Heat in transformer grows with its increasing strain and with related heat losses and thus also dependents on cooling down of windings, magnetic circuit and other segments of transformer.

Various insulating materials utilized in transformers respond diversely to temperature increases. Paper insulation plays the basic role in the present construction of transformers and belongs to the least heat resistant insulators. In the long run, 95 – 105 °C is the maximum temperatures that this kind of insulation withstands in oil medium without critical negative change of its insulating properties.

Considering heat properties, transformer acts as inhomogeneous body. Metal plates of magnetic circuit are described by the huge thermal conductivity and rather low thermal capacity. They are separated by insulation layers which have low thermal conductivity. Transformer windings are composite structure of copper or aluminum and together with insulating material, form up huge thermal conductivity. This material serves as both, electrical and thermal insulation.

2. Analysis of thermal processes in oil

During transformer's performance, the metal plates of magnetic circuit and copper winding constantly act as heat sources. By means of thermal conductivity, the heat in magnetic circuit and winding is consequently interchanged from inner segments towards the outer surface where the heat is conducted away.

Magnetic circuit and winding of oil trans-formers are immersed in oil, whose level significantly exceeds the top part of magnetic circuit. Oil particles (fig.1) which are close or touching the hot surfaces of winding and magnetic circuit increase their temperature, ascend and transfer warmth through the sides and top of tank to surroundings. Cooled down particles descend and so are replaced by heated ones. The transfer of warmth thus happens by convection. Between transformer parts (magnetic circuit and winding) and oil, steady temperature difference is attained. On the other hand, temperature of oil and other parts of transformer container in its several heights varies. Fig. 1 documents characteristic behavior of temperature variation in relation to the transformer's height.

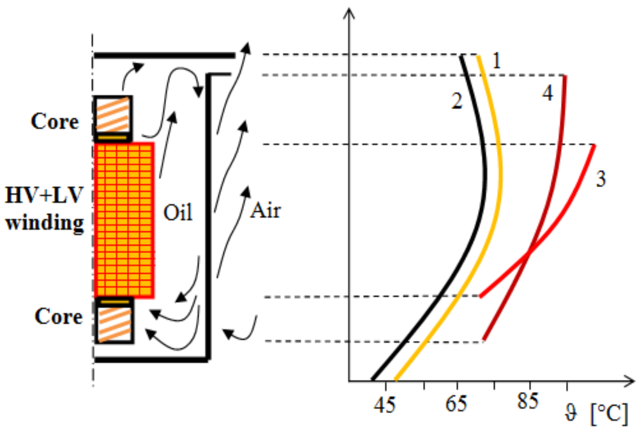


Fig. 1. Typical temperature curve in relation to the transformer height (1 – oil temp., 2 – tank temp., 3 – winding temp., 4 – core temp.)

Heat progresses through the wall of transformer tank by means of conduction. Transfer of warmth from the tank surface is enabled by convection (by movement of heated air particles) as well as by radiation. Temperature difference between the tank and surrounding atmosphere reaches several tenths of degrees. Fig. 2 demonstrates characteristic temperature distribution in oil transformer (horizontal section) [1].

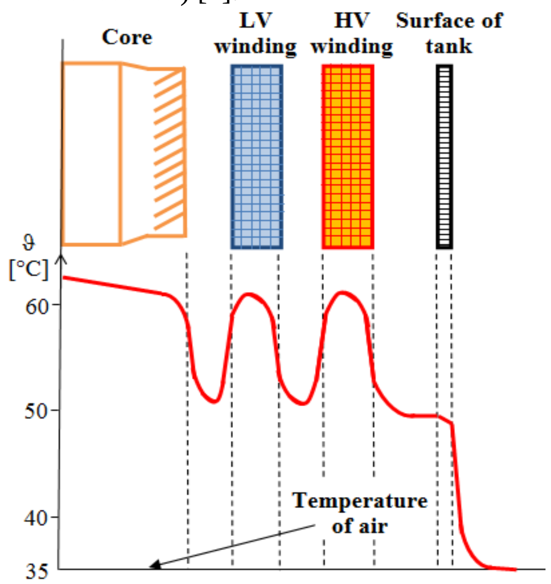


Fig. 2. Typical temperature distribution in sectional plan of the oil filled transformer

3. Mathematical analysis of thermal processes in the oil

Thermal energy $\Delta P \cdot dt$ emerging in the body during given time interval dt results in partial temperature increase of the body by $d\vartheta$. Remaining energy is transferred to the surrounding.

There is a balance among accumulated and transferred thermal energy which is described by differential equation:

$$\Delta P \cdot dt = C \cdot d\vartheta + \alpha \cdot \Delta\vartheta \cdot dt \,, \tag{1}$$

where C represents total thermal capacity of the body,

$\Delta\vartheta$ stands for temperature difference between the body and surrounding, α is the heat dissipated by the cooling-top per unit of time at a temperature drop of 1 °C between the surface and the environment.

If at stable thermal conditions warming of the body exceeds temperature of surrounding, following equation applies: $C \cdot d\vartheta = 0$. Based on that heat originated the body is transferred away through the surface and following applies

$$\Delta P = \alpha \cdot \theta \,, \tag{2}$$

where θ is steady-state value of warming.

Substituting ΔP from equation (2) to an equation (1), following is valid

$$\theta \cdot dt = \frac{C}{\alpha} \cdot d\vartheta + \Delta\vartheta \cdot dt \,, \tag{3}$$

where the expression C/α had a time dimension $T = C/\alpha$.

Adopted in the equation an equation (3), following relation is formed up

$$dt = \frac{T}{\theta - \Delta\vartheta} \cdot d\vartheta \,. \tag{4}$$

Result from this equation is the next formula

$$t = -T \cdot ln(\theta - \Delta\vartheta) + A \,. \tag{5}$$

Integration constant A is obtained from initial conditions. Let us assume that the $t = 0$, warming $\Delta\vartheta = \theta_0$. For this reason is valid

$$A = T \cdot ln(\theta - \theta_0) \,. \tag{6}$$

Appointed from an equation (6) to the equation (5) we obtain

$$\frac{t}{T} = ln \frac{\theta - \theta_0}{\theta - \Delta\vartheta} \,. \tag{7}$$

From this equation is result

$$\Delta\vartheta = \theta_0 + (\theta - \theta_0) \cdot \left(1 - e^{-t/T}\right) . \tag{8}$$

Equation (8) enables to define temperature difference $\Delta\vartheta$ for warming as well as for cooling scenario. Warming of the body is represented by the upper curve in Fig. 3, where $\theta > \theta_0$, applied in equation (8).

In case of cooling, there is $\theta < \theta_0$ and the cooling process follows the lower curve in Fig. 3.

As stated by [1], time constant for warming of the overall transformer against the sur-rounding air is determined as follows

$$T_t = \frac{\sum c \cdot m \cdot \theta}{\Delta P_j + \Delta P_{Fe}} \,, \tag{9}$$

where numerator is defined by the product of several parameters: specific heat of particular transformer components c, their weight m and warming of individual components above the air temperature θ due to losses in winding and core $\Delta P_j + \Delta P_{Fe}$.

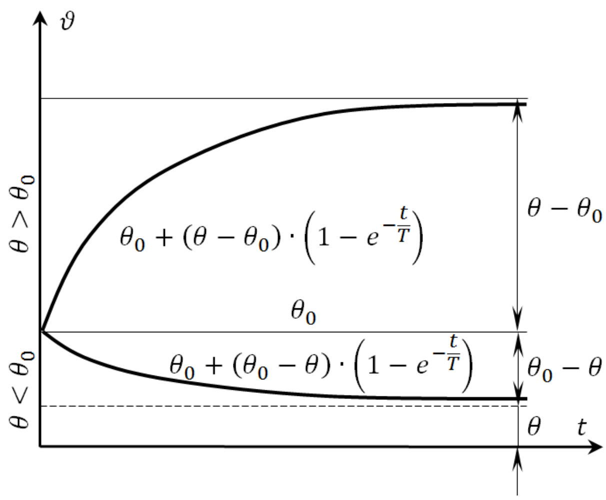


Fig. 3. Ideal warming and cooling of homogenous solid body

4. Experimental measurement

As an example it was decided to analyze thermal processes in transformer utilizing thermovision and method of monitoring of cooling curves. Test was introduced at distributional oil transformer with natural cooling system 22 / 0.4 kV, 30 kV·A, which is established at the University of Zilina, specifically in the Laboratory of Electrical Machine Diagnostics [2].

Two optical detectors with measuring unit Neoptix were installed so as to measure the windings temperature. They were located on top and in the central part of the middle primary phases, seen as white bands in Fig.4.

Fig. 4. Position of the optical detectors covered by white stripe

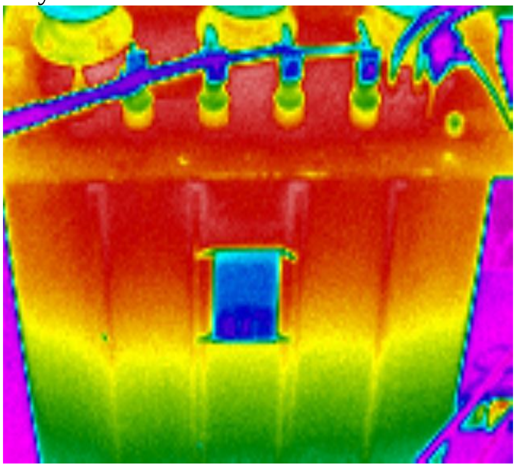
Using extra channel, optical detectors were guided towards the top area of transformer's tank. Further on, from the top, detectors were directed by two optical fibers to the measuring system NEOPTIX T. This measuring system was used to evaluate measured winding temperatures.

Fundamental for a non-destructive diagnostics of electrical equipment using thermovision, is the ability to record and to work infrared radiation (heating) to the form of real thermal images of objects, and on the basis of overheating of certain surround, for a detection of a failure (defect). Thermovision camera supervised the transformer bushings and tank. Decrease of temperature measured in different height of transformer oil is presented in Fig. 5. As observed, significant thermal strain was detected in the top area of transformer.

Based on Fig. 1 it is possible to conclude that temperature difference between tank and winding in the top of oil transformer is approximately 50 %.

Transformer was operated at about 30% load for several months. Temperature data and changes of temperature in time were measured on winding phase after a sudden cut off.

It is important to state that oil in the top of tank and central part of the winding responds diversely to unexpected changes. Due to that we monitored differences in two windings during cooling process after cutting off the device. Decrease in temperature may be influenced by mechanical strength of winding, quality of insulating material as well as viscosity of oil in transformer tank.



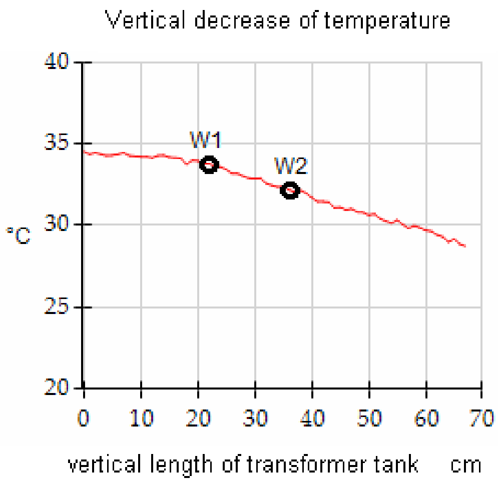


Fig. 5. Distribution of the monitored transformer temperature at 30 % of load

Heated objects with higher temperature near measured objects influences values of measured temperature of these examined electrical equipment, because it is appropriate to use contact method too, for example on transformer winding.

Temperature data from the windings acquired over the defined time period after cutting off the device are presented and compared in Fig. 7. In the top section of windings (W1) the drop down in temperature to 48 °C lasted 75 seconds, in the central windings section (W2) it took only 50 seconds. This behavior was awaited and reflected temperature distribution in oil after cutting the transformer off.

Transformer oil temperature is minimum at the bottom of the tank and gradually increases towards the top, reaching maximum values at about top edge of windings. The maximum temperature is more or less maintained in the entire volume of oil right under the top transformer lid.

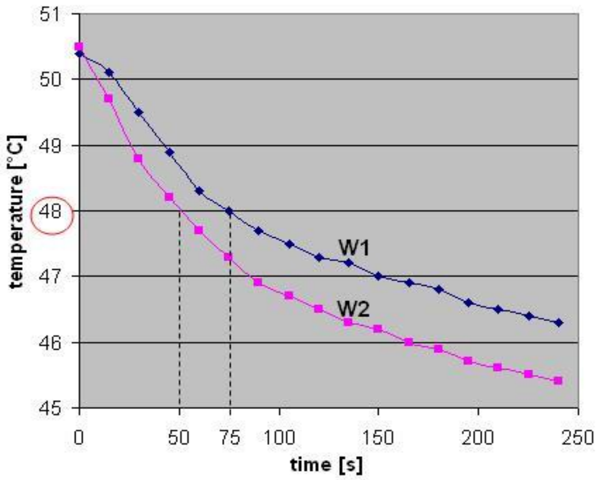


Fig. 6. Measured windings temperature

5. Evaluation of the measured data

Practical measurements and calculations of warming and cooling of transformer require usage of experimentally acquired data which is characterized by transfer of heat from warm surface of winding, magnetic circuit and tank.

If the load at transformer changes in short time intervals, it is necessary to apply equation (8) which determines transitional thermal process in windings, magnetic circuit and in oil of transformer.

In calculation for oil transformer we considered mechanical strength of winding in relation to thermal effect of short current. Their time dependency is similar to cooling curve in Fig. 3.

Measured cooling curves in the top section (W1) and in the central section (W2) of the same winding's phase were compared and following was concluded:

Cooling curves for the mentioned sections are different.

It is mainly due to distribution of temperature in oil as well as on the surface of windings in relation to the surroundings and different height levels of transformer.

Fig. 5 shows 2 °C temperature difference between values obtained by optical sensors W1 and W2, measured by thermovision camera on the surface of tank.

At selected temperature of ϑ = 48 °C (which represents approximately 60% of the exponential curve), the cooling time for W1 t_1 = 75 s and W2 t_2 = 50 s was defined from the cooling curves.

Examining the data by means of equation (2) and (12) it was determined that there is 1.5 times higher stress to mechanical strength in the top part of the windings (W1) than in the central part of the windings (W2). This is mainly due to temperature shocks (short-circuit currents). The above mentioned is also confirmed by the formula:

$$a = \frac{A_1}{A_2} \doteq \frac{t_2}{t_1} = \frac{75}{50} = 1.5\,, \qquad (10)$$

where a is multiple of short-circuit strength, A_1, A_2 are damping coefficients at cooling process and t_1, t_2 are cooling time.

It is evident that the top part of the windings is the most heavily stressed due to temperature decreases during transformer operation or by short-circuit currents.

6. Conclusion

By the experimental measurements and following analysis we showed the practicality of the theory of thermal processes for the windings of oil power transformers. It is obvious that the total temperature into transformer is given by several factors – the grade of the windings mechanical strength, the insulation quality, but also the oil viscosity in the transformer tank. To present the thermal processes in oil transformer, we utilized the degradation of mechanical strength during cooling, triggered by thermal effect of short currents. By the practical test, measurements and subsequent analysis it was proved that thermovision plays an important role in diagnostics of power oil transformers in terms of windings mechanical strength. It is apparent that the overall deterioration due to temperature shock is influenced by multiple factors – state of windings in terms of mechanical strength, quality of insulating material as well as by oil viscosity in the transformer tank.

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