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Analysis of thermal processes in oil distribution transformer

Abstract. *Paper deals with the analysis of thermal processes in oil distribution transformers. By means of the mathematical analysis and experimental measurements it is possible to diagnose of power 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.*

Streszczenie. *Artykuł dotyczy analizy procesów termicznych w rozdzielczych transformatorach olejowych. Za pomocą analizy matematycznej I pomiarów doświadczalnych można dokonać diagnozy olejowych transformatorów mocy pod względem wytrzymałości mechanicznej uzwojenia. Analiza nagrzewania się uzwojeń przy zmiennych obciążeniach jest bardzo ważna, gdyż pozwala na określenie nośności i przeciążenia transformatora w różnych warunkach eksploatacji w odniesieniu do zmiennej temperatury otoczenia. (**Analiza procesów termicznych w rozdzielczych transformatorach olejowych**).*

Keywords: transformer, thermal processes, thermovision, windings, temperature.
Słowa kluczowe: transformator, procesy termiczne, termowizja, uzwojenia, temperatura.

doi:10.12915/pe.2014.05.17

Introduction

Electric energy lost in transformer in conversion of alternating current is converted into heat in winding, magnetic circuit and in other parts of the transformer. At the same time transformer heat´s up and the temperature of its individual parts can greatly exceed the ambient temperature. With increasing load and with emerging losses the temperature of the transformer rises, this all depends on cooling winding, magnetic circuit and other heated parts.

As far as temperature, transformer is inhomogeneous element. Sheets of magnetic circuit are characterized by high thermal conductivity and relatively low thermal capacity. They are taking turns with layers of insulation (lacquer etc.), whose thermal conductivity is not large. Similarly, the winding of the transformer is a complex configuration of copper or aluminum, which has high thermal conductivity with insulating material. It consists of electrical insulation as well as thermal insulation.

Thermal processes in oil transformer

In oil transformers, magnetic circuit and windings are sprayed by transformer oil, where the level is considerably higher than the highest part of the magnetic circuit. Oil particles (Fig.1), tangential to the warm surface of the winding and the magnetic circuit are heated, soar upwards and transmitted it´s heat through the walls and the lid of the container into the surrounding area. Cooled oil particles fall down and release their place for other warmer particles. In this case the share of heat happens by convection. Between winding and magnetic circuit on one side and oil on the other side a temperature difference is stabilized. However, the oil temperature and other parts of the transformer tank at different heights are different. Fig.1 shows a typical waveform of temperature changes due to height of the transformer.

Heat passes through the transformer tank wall. Transfer of heat from the surface of the tank is caused by convection, i.e. by the movement of the hot moving particles as well as by radiation of heat. The temperature difference between the tank and the ambient air can reach several dozen of degrees. Typical distribution of temperatures in horizontal cut of oil transformer is shown in Fig.2. [1]

Mathematical analysis of thermal processes

Thermal energy $\Delta P.\mathrm{d}t$ arising in the body for an elementary time interval dt partially contributes to an increase in body temperature of dϑ and partly passed to the surrounding space.

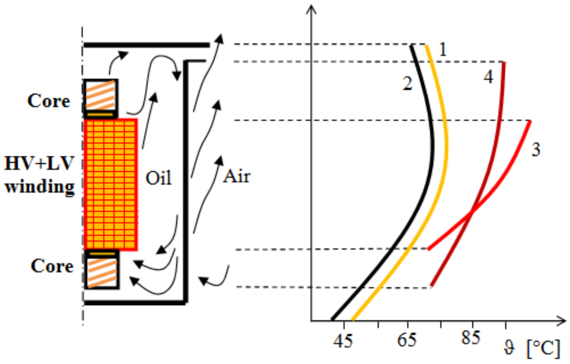

Fig.1. Typical temperature course in dependence on height of oil transformer: 1 – oil temperature, 2 – wall of tank temperature, 3 – winding temperature, 4 – core temperature

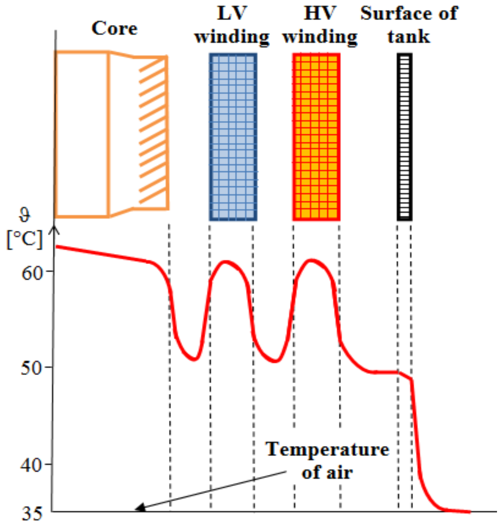

Fig.2. Typical temperature distribution in sectional plan of oil transformer

At any time there is a balance between the fed, stored and extracting thermal energy, expressed by the differential equation

$$\Delta P \cdot \mathrm{d}t = C \cdot \mathrm{d}\vartheta + \alpha \cdot \Delta\vartheta \cdot \mathrm{d}t \ . \tag{1}$$

If is reached limit warming body temperature above ambient environment in the thermal steady state, then is valid $C \cdot \mathrm{d}\vartheta = 0$.

Due to this equation the heat generated by the body is carried off by cooling surface, i.e. applies

(2) $$\Delta P = \alpha \cdot \theta\ ,$$

where θ is steady-state value of warming.

If we appoint to ΔP from equation (2) to an equation (1) we obtain a relation

(3) $$\theta \cdot \mathrm{d}t = \frac{C}{\alpha} \cdot \mathrm{d}\vartheta + \Delta\vartheta \cdot \mathrm{d}t\ ,$$

where the expression *C/α* had a time dimension *T* = *C/α.*

We can write an equation (3) to form

(4) $$\mathrm{d}t = \frac{T}{\theta - \Delta\vartheta} \cdot \mathrm{d}\vartheta\ .$$

Result from this equation is next formula

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

Integration constant A is obtained from initial conditions. Let us assume that the t = 0, warming $\Delta\vartheta$ = θ_0. For this reason is valid

(6) $$A = T \cdot \ln(\theta - \theta_0)\ .$$

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

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

from this equation is result

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

Equation (8) allows determining the temperature difference $\Delta\vartheta$ in the case for global warming, as well as for the case of cooling.

According to [1] time constant warming of the transformer to the surrounding air temperature is determined by the relation

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

where each component of the numerator consists of the product of the specific heat *c* of individual parts of the transformer, their weight *m* and warming the given part over an air temperature θ in electrical losses in the windings and core losses $\Delta P_j + \Delta P_{Fe}$.

Experimental measurement

As an example of analysis of thermal processes in transformer by using the thermovision and method of monitoring refrigerating curves we will introduce experimental measurement with distributional oil transformer with natural cooling system 22/0.4 kV, 30 kVA, which is located in the Laboratory of electrical machine diagnostics of the University of Zilina. [2]

To measure the windings temperature we used two optical detectors with measuring unit Neoptix, which were installed on the top and the middle part of the middle primary phases (Fig.3 – white stripes).

Optical detectors were led out by special duct to the top part of the transformer's tank and from there they were led by two optical fibers further to the measuring system NEOPTIX T, which was subsequently evaluating measured winding temperatures.

Fig.3. View of the optical detectors positioning (covered by white stripes)

Transformer bushings and tank is monitored thermovision camera. In Fig.4 is vertical decrease of temperature for monitoring transformer tank. Thermal strain is the greatest in the top area of the transformer. Thermal influence of core on surrounding areas of transformer (winding, oil, tank) is simulated in Fig.5.

It is necessary to suggest, that according to Fig.1 it attained temperature difference between tank and winding top of oil transformer about 50 %.

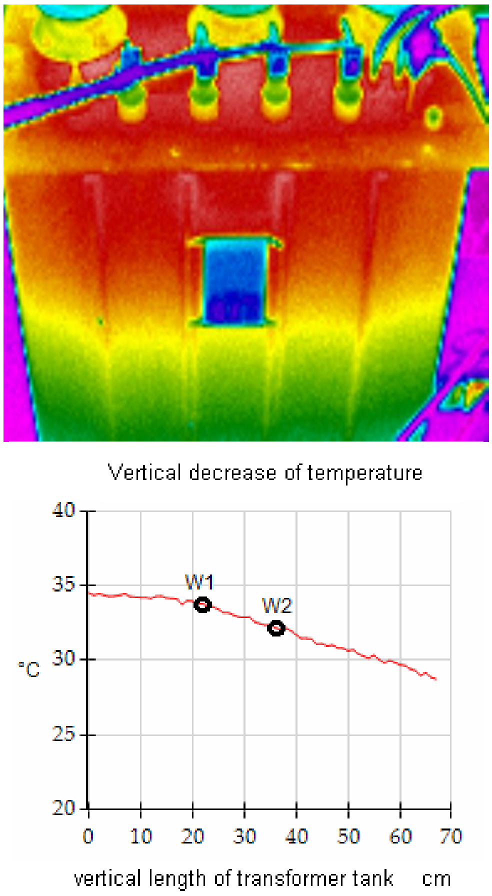

Fig.4. Decomposition temperature of monitored transformer 22/0.4 kV – 30% load

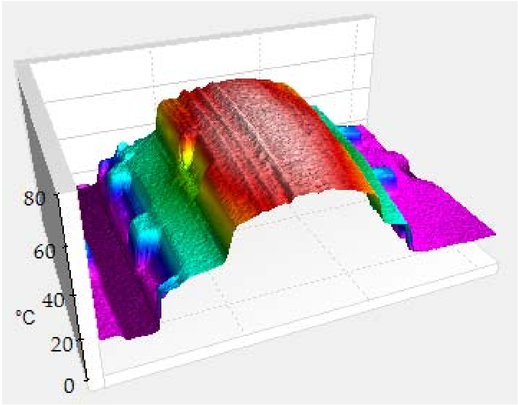

Fig.5. Thermal influence of core on surrounding areas of distribution transformer

After several months lasting operation of the transformer at approximately 30% load the analysis of measured temperature values in dependence on time at its sudden cut off was performed on measured winding phase.

It is necessary to mention that in oil tank the top and the middle part of the winding reacts differently on sudden changes. Thereby we observed possible behavior differences at two winding parts during refrigeration process after cutting the device off. Levels of refrigeration decrease may include level of winding mechanical strength, insulation quality and viscosity of oil in the transformer tank.

Fig.6 shows the comparison of measured windings temperature values in dependency on the time after cutting the device off. The temperature decrease to 48°C in the top part of the windings (W1) took 75 seconds and in the middle part (W2) only 50 seconds. That corresponds to the expected oil's temperature distribution after cutting the transformer off.

The temperature of oil in the transformer tank increases from certain minimum value at the bottom of the tank to the maximum value - approximately to the height of the windings top edge. This maximum temperature is more or less maintained in the whole mass of oil under the top transformer cover.

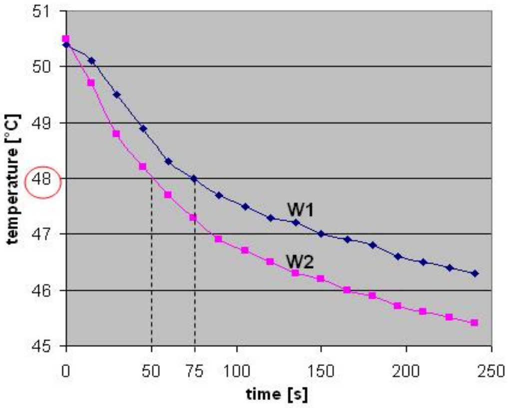

Fig.6. Measured windings temperature values in dependency on the time

Discussion to the measured data

By comparing the measured refrigerating curves on the top part (W1) and on the middle part (W2) of the same winding's phase, we came to some conclusions.

Both parts show different refrigerating curves. It is mainly caused by the level of distribution of the oil temperature rise and the winding's surface with respect to the ambient along the height of the transformer. According to Fig.4 it is temperature difference 2 °C between optical sensors W1 and W2, which was measured on surface of tank by thermovision camera.

When decreasing the selected temperature ϑ = 48°C (which represents approximately 60% of the amount of exponential curve), we determined the cooling time for the W1 t_1 = 75 s and for the W2 t_2 = 50 s from the graph.

By comparing these two values using the equations (2) and (12) we found out on the top part of the windings (W1) 1.5 times higher stress of the mechanical strength caused by temperature shocks (short-circuit currents) than on the middle part of the windings (W2). That is also proved in the following equation:

$$a = \frac{A_1}{A_2} \doteq \frac{t_2}{t_1} = \frac{75}{50} = 1{,}5 \tag{10}$$

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

It is obvious that the top part of the windings will be the most heavily stressed by the effects of temperature degradation by operation or short-circuit currents.

Conclusion

By the experimental measurements and following analysis we showed the practical thermovision for diagnostics of power oil transformers in field mechanical strength of winding. It is obvious that the total temperature shock degradation is given by several factors – the grade of the windings mechanical strength, the insulation quality, but also the oil viscosity in the transformer tank.

This work was supported by the Grant Agency VEGA from the Ministry of Education of Slovak Republic under contract 1/0624/13

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