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Thermal Measurement and its Application for Diagnostics of Distribution Oil Transformers

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Abstract. In the first part of the paper the theory of infrared radiation and the use of non-destructive measurement of electrical devices by means of thermovision are under analysis. In the second part of paper basic principles and application of non-contact temperature measurement are examined. In the third part of paper thermal processes in distribution oil transformer – temperature in dependence on height of oil transformer and temperature distribution in sectional plan of oil transformer – are considered. In the fourth part of paper, by means of the experimental measurements and subsequent analysis, practical thermal imaging and contact thermal measurements by optical detectors for the diagnosis of distribution oil transformers in the field of mechanical strength of windings are shown. In this paper, we wanted to show out the possibility of using thermal measurements in this field of analysis and detection of quality of winding for distribution oil transformer. It is possible to use these methods to localize places of faults, and they are also applicable for the diagnosis and detection of disorders of the quality of materials and other anomalies during operation of the equipment. By means of the experimental measurements followed by diagnostic analysis the practical use of thermovision and optical sensors for diagnostics of power oil transformers in field mechanical strength and quality of winding is demonstrated.

Keywords: thermovision, emissivity, radiation, temperature, diagnostics, transformer

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Тепловое измерение и его применение для диагностики масляных трансформаторов распределительных сетей

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Реферат. Статья посвящена анализу теории инфракрасного излучения и применения неразрушающего контроля с помощью электрических приборов и тепловизионного оборудования. Изложены основные принципы использования бесконтактного измерения температуры. Проанализированы тепловые процессы в силовом масляном трансформаторе: температура

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в зависимости от его высоты и распределение температуры в секционном плане масляного трансформатора. Рассмотрены экспериментальные тепловизионное и контактные тепловые измерения оптическими детекторами для диагностики механической прочности обмоток силовых масляных трансформаторов. Также показана возможность использования тепловых измерений для анализа и определения качества обмотки масляного трансформатора. Эти методы позволяют локализовать места неисправностей и могут использоваться для диагностики и выявления нарушений качества материалов и других аномалий в ходе эксплуатации оборудования. Путем экспериментальных измерений с последующим анализом определено практическое применение тепловизионных и оптических датчиков для диагностики силовых масляных трансформаторов в части механической прочности и качества обмоток.

Ключевые слова: термовидение, излучательная способность, излучение, температура, диагностика, трансформатор

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Introduction

Basic diagnostics for a non-destructive measurement of electrical devices using thermovision is the opportunity to record infrared radiation in the form of real thermal pictures of measured objects, and, on the basis of overheating of certain surround, for a detection of a fault (defect).

With non-contact measurement it is possible to verify the temperature distribution on the surface of measured objects using sensitivity measuring of a few Kelvin (or °C) decimal [1].

Infrared radiation is generated as a result of various physical processes that take place in the object of radiation; vibration in crystal lattice, moving atoms, molecules and transition of electrons from one energy level to another. The basic source of infrared radiation is elevated temperature of the radiation source.

Radiation of thermal sources acts like (in respect of ambient conditions) visual light. For thermovision, it is important to identify materials used for elements of visualization systems, the size of values that are derived from the wavelength of material radiation, and, also, sensitivity of sensors for recording the signal.

Precision of thermal measurement for thermovision diagnostics is impacted by following factors:

- incorrect determination of emissivity – a radiation coefficient of measured object $\varepsilon(\lambda, T)$;
- low current load of measured electric equipment because current load plays a relevant role for assessment of warming being measured; influence of other hot objects close to objects being measured and inaccurate determination of surrounding temperature can cause changes of an emission coefficient;
- incorrectly interpretation of values of warming being measured;
- various surfaces (the surface may be chromatic ones, oxidized surfaces and peeled paint on materials) may cause wrong evaluation of results.

For diagnostics of infrared radiation by thermovision of internal transmission and distribution of electric power, it is necessary to take into account many relevant factors affecting the measurement accuracy [2].

Fundamental for a non-destructive diagnostics of electrical devices using thermovision systems is the ability to record and to work infrared radiateon (thermal radiation) to the form of real thermal images (Fig. 1), of measured objects, and on the basis of overheating of certain parts diagnosed objects, to detect a fault (defect).

The analysis demonstrates that the method based on recognition of thermal images may be profitable for technical engineers [3].

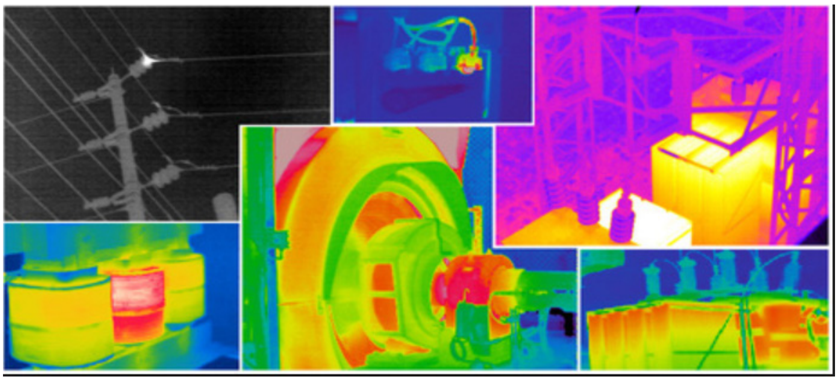

Fig. 1. Thermograms of electrical equipments

The theory of infrared radiation

The surface of the object being measured in a state of thermodynamic equilibrium emits electromagnetic radiation, and the radiated power depends on the thermodynamic temperature and properties of the object surface. Radiation power (intensity) $H(\lambda, T)$ is the only parameter that is measured by infrared receiver and is a function for an emission coefficient ε (λ, T) and temperature T of radiation source [4]

$$H(\lambda, T) = \varepsilon\sigma T^4. \tag{1}$$

This uncertainty (the value of one parameter is the subject of another parameter) is one of the problems of measuring the infrared radiation. An emission coefficient are too much dependent on the direction from which the radiation is recorded, on the temperature and, also, on the surface of material.

Heating is defined by the relationship α/ε, where α is an absorption coefficient of energy and ε is an emission coefficient (emissivity) of the body being measured [5].

Fig. 2 presents the dependence of spectral density – intensity of radiation to wavelength.

Ratio of intensity radiation of the actual body and the ideal black body at the same temperature is defined by a spectral emissivity coefficient [6].

$$\varepsilon_\lambda(\lambda, T) = \frac{H_\lambda(\lambda, T)}{H_{0\lambda}(\lambda, T)}. \tag{2}$$

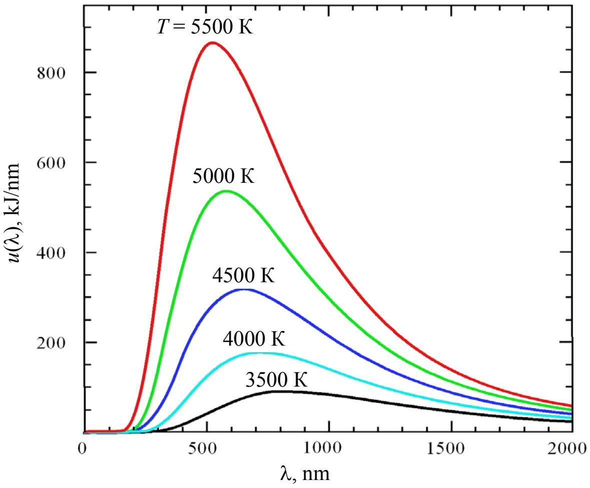

Fig. 2. Dependence of spectral density – intensity of radiation to wavelength

A coefficient of spectral emissivity is equal to a spectral absorption coefficient. The research on issues of radiation of solid bodies is based on the knowledge of absolute black body; an object which is able to fully absorb the full spectrum of radiated energy. According to Kirchhoff's law the black body is an ideal emitter. Plank defines the spectrum of black body radiation

$$\frac{dH(\lambda,T)}{d\lambda}=\frac{2\pi hc^2\lambda^{-5}}{e^{\frac{hc}{\lambda kT}}-1},\tag{3}$$

where $dH(\lambda, T)$ is spectral radiant flux density surface, i. e. radiated power, which is emitted by a unit surface of the black body in an interval of wave length; $h = 6.625 \cdot 10^{-34}$ J·s is the Planck constant; $k = 1.38054 \cdot 10^{-23}$ J·K^{-1} – Boltzmann constant; c – speed of light; T is absolute temperature of black body, K [7].

Plank's law is a function of spectral distribution of values

$$\frac{dH(\lambda,T)}{d\lambda}=f_T(\lambda).\tag{4}$$

Real objects generally do not behave as black bodies. No-black bodies absorb only a part of $\alpha(\lambda)\Phi$ (incident radiation), a part of the reflected radiation $\varepsilon(\lambda)\Phi$ and a part $\tau(\lambda)\Phi$ (transient radiation). Coefficients $\alpha(\lambda)$, $\varepsilon(\lambda)$, $\tau(\lambda)$ are selective and depend on the wavelength.

If the system is in thermodynamic equilibrium (Fig. 3), according to the law of conservation of energy, the reflected and transient energy is equal to the absorbed energy.

Emissivity $\varepsilon(\lambda)$ (coefficient of radiation) compensates absorption coefficient $\alpha(\lambda)$ when $\varepsilon(\lambda) = \alpha(\lambda)$.

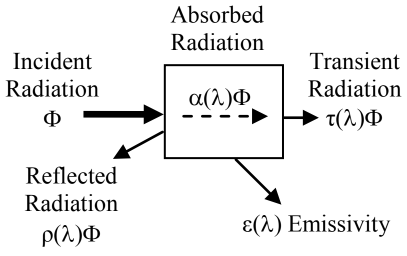

Fig. 3. Distribution of the incident radiation

It follows that

$$\varepsilon(\lambda)+\rho(\lambda)+\tau(\lambda)=1, \tag{5}$$

where $\tau(\lambda)=0,\ \ \varepsilon(\lambda)+\rho(\lambda)=1$ – non-transparent materials; $\rho(\lambda)\to$ high and $\varepsilon(\lambda)\to 0$ – reflective materials; $\varepsilon(\lambda)=1,\ \tau(\lambda)=0,\ \ \rho(\lambda)=0$ – black body; $\varepsilon(\lambda)=\text{const}, \rho(\lambda)=\text{const}$ – black body.

Spectral radiant flux density of any object is bound to spectral radiant flux density of black body; therefore [7]

$$\frac{dH(\lambda,T)}{d\lambda}=\int\limits_{\Delta\lambda}\varepsilon(\lambda)\frac{dH_{b.b.}(\lambda,T)}{d\lambda}. \tag{6}$$

Radiated power in the range Δλ of the body surface with area *S* at a temperature *T* is defined as

$$H=\int\limits_{\Delta\lambda}\varepsilon(\lambda)\frac{dH_{b.b.}(\lambda,T)}{d\lambda}Sd\lambda. \tag{7}$$

An object's own radiation is defined by its temperature. Deriving the Planck equation

$$\frac{\partial(dH(\lambda,T)/d\lambda)}{\partial T}=\frac{hce^{(hc/\lambda kt)}}{\lambda kT^2\left(e^{\frac{hc}{\lambda kT}}-1\right)}\frac{\partial H(\lambda,T)}{d\lambda}. \tag{8}$$

The result of an object's temperature measurement T_0, which is registered in the spectral range of wavelengths Δλ (surface density of radiant flux), is the registered radiant flux density H_{reg} [8]

$$\begin{aligned}H_{reg}=&\int\limits_{\Delta\lambda}\rho_a(\lambda)\left[dH(\lambda,T_a)/d\lambda\right]d\lambda+\int\limits_{\Delta\lambda}\tau_f(\lambda)\left[dH(\lambda,T_f)/d\lambda\right]d\lambda+\\&+\int\limits_{\Delta\lambda}\varepsilon_0(\lambda)\left[dH(\lambda,T_0)d\lambda\right]d\lambda.\end{aligned} \tag{9}$$

We need to gather the values of the first two parts of the equation and emissivity $\varepsilon_0(\lambda)$. When an object is transparent, $\tau(\lambda) = 0$ and if T_0 is much larger than T_a, the first part of the equation is very small. In this case the task is easier, and it is essential to know the value of $\varepsilon_0(\lambda)$.

Difficulties arise when the body is surrounded by other objects, which have high temperature, and these temperatures are higher than that of the examined object [9].

In this case, its own radiation depends on the T_0 and ε_0 is affected by reflected radiation error caused by parasitic (surrounding) objects with a temperature T_e and emissivity ε_e (Fig. 4). If the reflection coefficient is measured as ρ_e – radiation error, then the part characterizing the error is proportional to T_e, ε_e and ρ_e, T_e.

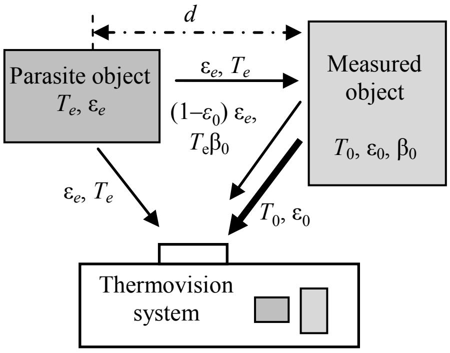

Fig. 4. Influence of other radiating objects

Thermovision addition in diagnostics of power transformers

The temperature measurement by means of a contact (invasive) method is in many cases very difficult to fulfill, and – because of working and safety reasons – is nearly impossible. For this reason, it is necessary to aim at such measuring equipment and methods of temperature measurements which do not require the direct contact with the equipment to be measured. Diagnostics of the equipment~~s~~ satisfying these conditions are based on the radiated infrared energy scanning. Thus, infrared techniques find their application wherever a physical quantity such as temperature gives us information about the technical condition of the equipment in question or about some part of it. An infrared thermograph is a contactless (non-invasive) tool of temperature distribution measurement on the surface of the object being scanned in the infrared area (1–13 μm) of the electromagnetic spectrum.

Infrared measurements can be realized quickly and economically, sparing the minimum time and work as they do not require any adaptations or turning-out of measured equipment. Thermovision techniques are used at the transformers control in order to find out whether the temperature of its some parts does not raise (Fig. 5). Also, the transformer's bushings, thermal field distribution on oil transformer tanks are tested, etc.

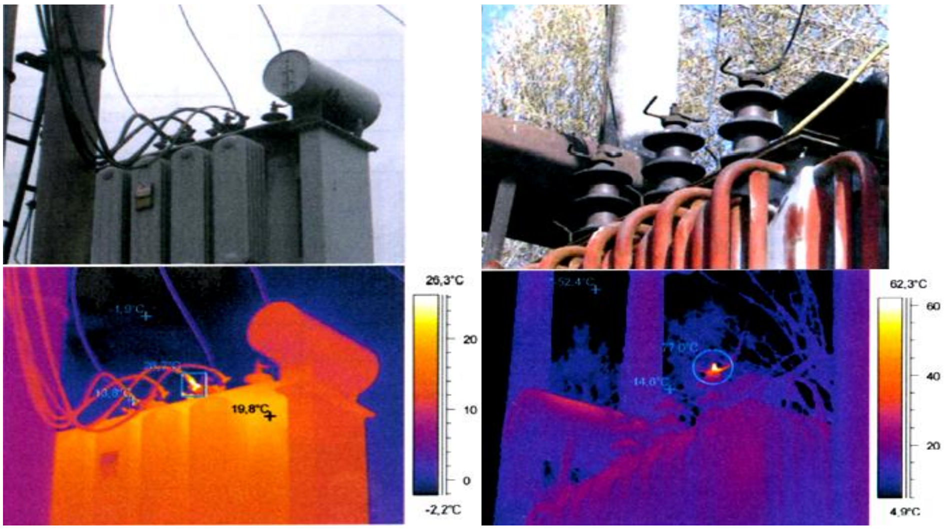

Fig. 5. Real transformer temperature pictures

Thermal processes in distribution oil transformer

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 heats 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, and all these processes depend~~s~~ on cooling winding, magnetic circuit and other heated parts.

As for the 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.

In oil transformers, magnetic circuit and windings are sprayed by transformer oil, where the level is considerably higher than in the highest part of the magnetic circuit. Oil particles (Fig. 6) tangential to the warm surface of the winding and the magnetic circuit are heated, soar up and transfer their heat through the walls and the lid of the container into the surrounding area. Cooled oil particles fall down and leave the space clear for other warmer particles. In this case the share of heat is due to 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 the temperature of the other parts of the transformer tank at different heights are different. Fig. 6 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. 7 [10].

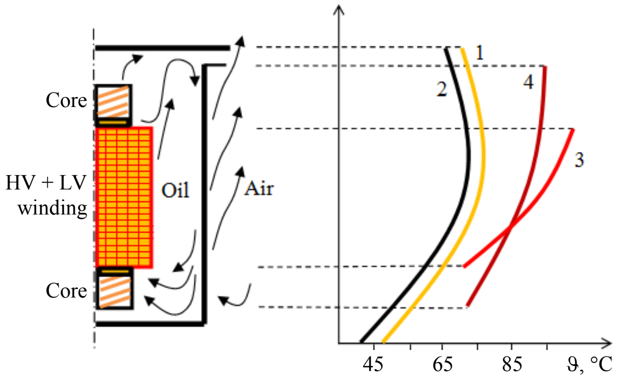

Fig. 6. Typical temperature course depending on height of oil transformer:
1 – oil temperature; 2 – wall of tank temperature; 3 – winding temperature; 4 – core temperature

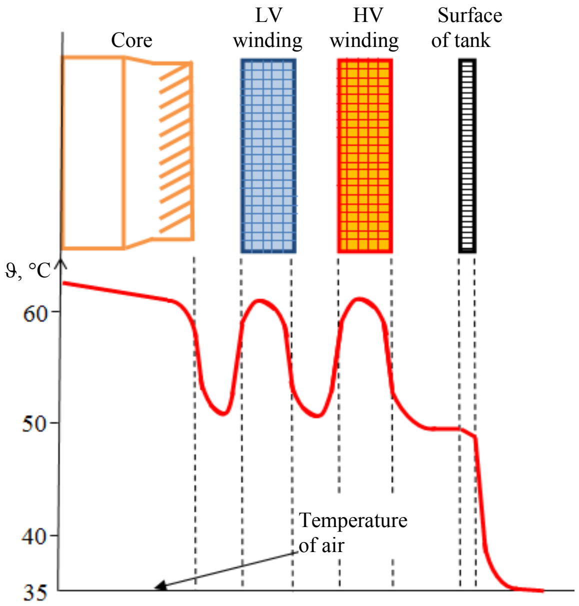

Fig. 7. Typical temperature distribution in sectional plan of oil transformer

Description of experimental measurement

As an example of analysis of thermal processes in transformer by using thermovision and the method of monitoring of cooling curves by optical detectors experimental measurement with distribution oil transformer 30 kV·A, 22/0.4 kV equipped with cooling natural system (Fig. 8) was used. The transformer is located in the Laboratory of electrical machine diagnostics of the University of Zilina.

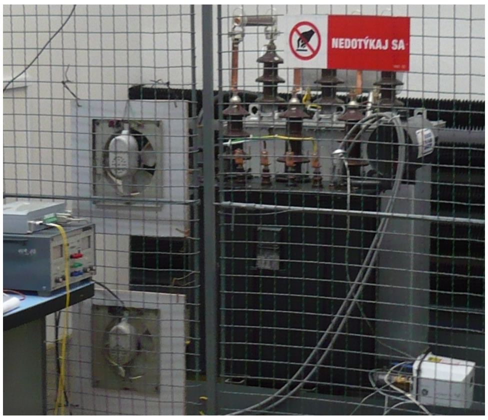

Fig. 8. View of the measured transformer and the NEOPTIX T system

For contact thermal measurement of the transformer winding two optical detectors made of fibers were used. They were led out by a special duct to the top part of the transformer tank and mounted on the middle winding at its top and middle part, and from there they were led to the NEOPTIX T measuring system (in which the measured temperature of the transformer winding was analyzed [11]) via two optical fibers (Fig. 8).

Transformer contacts, bushings and tank were monitored by the FLUKE thermovision camera. In Fig. 9 in its right part vertical decrease of temperature for monitoring transformer winding in top (W1) and middle (W2) part of the coil is shown.

According to [12, 13], thermal deformation is the greatest in the top area of the transformer. Thermal influence of core on surrounding areas of transformer (winding, oil, the tank) is plotted in Fig. 10.

According to Fig. 6, we can assume that temperature difference between the tank and the winding top of the oil transformer reaches about 50 %.

After several months of continuous operation of the transformer at a load of approximately 30 %, the measured temperature values were analyzed as a function of the time when it was suddenly disconnected at the phase of the measured winding.

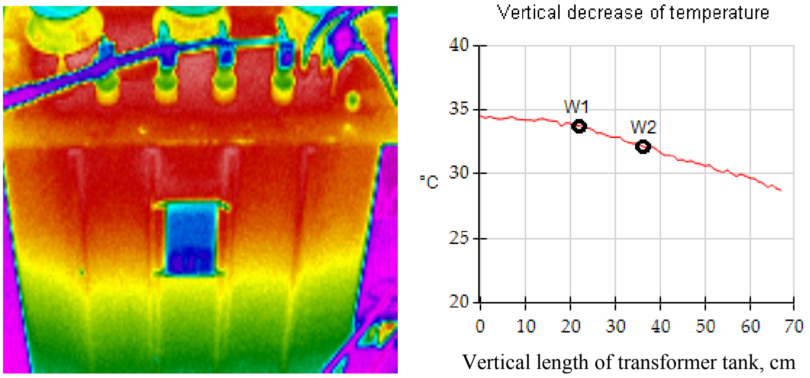

Fig. 9. Decomposition temperature of monitored transformer 22/0.4 kV – 30 % load

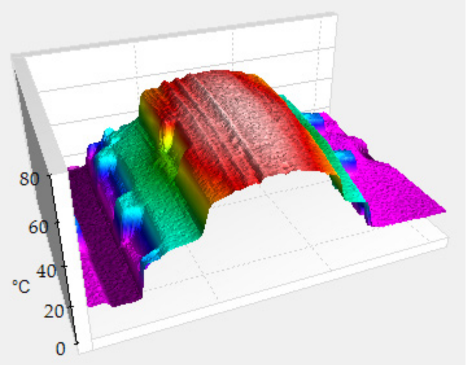

Fig. 10. Thermal influence of core on surrounding areas of distribution transformer

It is necessary to mention that in the 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 cooling process after cutting the device off. Levels of cooling decrease may include the level of winding mechanical strength, insulation quality and viscosity of oil in the transformer tank.

Fig. 11 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 s, and in the middle part (W2) – only 50 s. That corresponds to the expected oil 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 cover of the transformer.

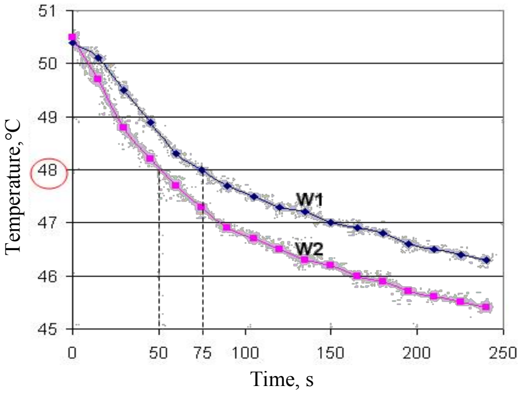

Fig. 11. Dependence of measured values of winding temperature on time

Discussion of the measured data

Some conclusions were made on the base of comparing the measured cooling curves on the top part (W1) and on the middle part (W2) of the same winding phase by optical detectors and thermovision of the transformer tank.

The measured parts of windings showed different dependency of cooling curves. It is mainly caused by the level of distribution of the oil temperature rise and by the winding surface with respect to the ambient along the height of the measured transformer. According Fig. 9, it is temperature difference about 2 °C between optical sensors W1 and W2, that was measured on the surface of the tank by a thermovision camera.

When decreasing the selected measured temperature $\vartheta = 48$ °C, which represents approximately 60 % of the amount of exponential refrigerating curve, it was determined (from the graph plotted in Fig. 11.) that the cooling time for the W1 $t_1 = 75$ s and for the W2 $t_2 = 50$ s.

By comparing these determined values using the equations (10) and others by [11] it was discovered that on the top part of the windings (W1) possible stress of the mechanical strength caused by temperature shocks (short-circuit currents) is up to 1.5 times higher than on the middle part of the windings (W2). That is also proved by the following equation [14]

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

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 would be the most heavily stressed by the effects of temperature degradation caused by operation or by short-circuit currents.

CONCLUSIONS

1. A very important problem relating both to electrical engineering and other industries is the identification of a fault, when it is still unnecessary to dismantle the equipment (diagnostics without dismantling). In this paper, we wanted to show out the possibility of using thermal measurements in this field of analysis and detection of quality of winding of the distribution oil transformer. These methods make it possible to localize places of faults and can also serve for the diagnosis and detection of disorders in material quality and other anomalies during operation of the equipment.

2. By the experimental measurements followed by diagnostic analysis the practical use of thermovision and optical sensors for diagnostics of power oil transformers in the field of mechanical strength and quality of winding was demonstrated. It is obvious that the total mechanical degradation of coil material is determined by several factors, viz. the grade of the winding mechanical strength, the insulation quality of coil, and, also, the oil conductivity and viscosity in the transformer tank.

3. In conclusion important facts are demonstrated, that is, transformers with a large number of short circuits must be analyzed throughout the time interval

of the short-circuit currents, to prevent unpredictable fault during operation. It is necessary to choose the suitable diagnostics, which could foresee such a condition.

Acknowledgments

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