

# Condition Analysis of Electrical Machines by Thermovision

**Abstract.** This article deals with problems of prophylactic measurement and condition of electrical machines using thermovision diagnostics. It examines the basic principles and uses non-contact temperature measurement. The knowledge of the problems of diagnostic of electrical machines in service without disassembly enables us to use more efficient thermo-diagnostic methods and to localize the failures that determine the quality of electrical wiring and equipment. The degradation of insulation materials due to temperature puts increased demands on precise knowledge of the thermal conditions in a given electrical machine. In the article are presented thermovision experimental measurements on asynchronous motor, transfer power transformer 242 kV and high-voltage generator 220 MW. Except for analysis of failures of listed power devices, thermovision technology was also used for checking of electric machines and devices for detecting of the temperature on the pick-up systems and excitation systems of generators, power parts of electric machines, detecting of the temperature differences on the semiconductor valves in individual parallel branches of equipment.

**Streszczenie.** W artykule zaprezentowano wykorzystanie termowizji do profilaktyki i diagnostyki maszyn elektrycznych. Metoda pozwala na ocenę stanu uzwojeń i wykrywanie błędów bez przerywania pracy urządzenia. Badano silnik asynchroniczny, transformator i generator. **Diagnostyka maszyn elektrycznych z wykorzystaniem termowizji**

**Keywords:** thermovision, electrical machines, temperature, failures

**Słowa kluczowe:** diagnostyka, maszyny elektryczne, termowizja

## Introduction

Technical diagnostics can be defined as a process for detecting the current technical state of objects. There is based for objective evaluation of the symptoms detected by means of the measuring technique. Requirements for the production growth and in particular on its quality, however, are closely related to reliability requirements of manufacturing equipment. [1]

Early diagnostics and monitoring of the technical condition of the equipment also result in an early detection of a malfunction (early stage malfunctions) which could cause relatively large damage during operation (e.g. early replacement of the bearing prevents it from burning or prevents the accident for electric motors, generators, transformer ventilators and the like.). [2]

One of the modern methods of screening that can be used, for example, in developing of an experimental component in research and development work, is the application of industrial thermovision, thus the method of mapping of temperature fields. For sensing of two-dimensional imaging are currently the most preferred decomposition infrared measuring systems operating in real time. These systems are attractive especially when watching fast dynamic phenomena. [3]

Fundamental for a non-destructive diagnostics of electrical equipment using thermovision systems, is the ability to record and to work infrared radiation (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, detect a failures (defect). [3]

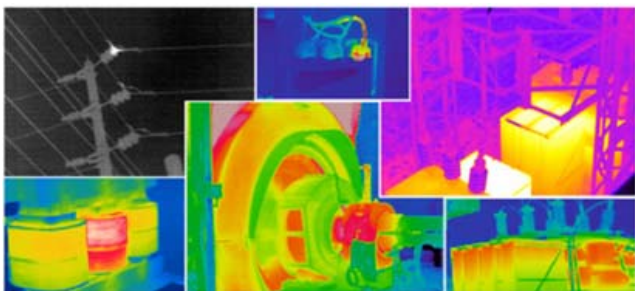


Fig. 1. Thermogram of electrical equipment

Radiation of hot sources acts (in respect of surrounding conditions), like visible light. To display temperature fields we can use visualization techniques used in optics. The only differences are materials used for elements of visualization systems, size of values which are derived from the wavelength of radiation, and also sensitivity of sensors for recording the signal.

## Theory thermal radiation

The surface of the measured object 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 emission coefficient  $\varepsilon(\lambda, T)$  and temperature  $T$  of radiation source [4].

$$(1) \quad H(\lambda, T) = \varepsilon \sigma T^4$$

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

Heating is defined by the relationship  $\alpha/\varepsilon$ , where  $\alpha$  is the absorption coefficient of energy and  $\varepsilon$  is the emission coefficient (emissivity) of the measured body. [4]

Ratio of intensity radiation of actual body and ideal black body at the same temperature is defined by spectral coefficient of emissivity: [5]

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

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

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

where  $dH(\lambda, T)$  are 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 - Planck constant,  
 $k = 1,38054 \cdot 10^{-23}$  - Boltzmann constant,  
 $c$  - speed of light,  
 $T$  - absolute temperature of black body in °K. [6]

Spectral radiant flux density of black body surface depends on the length of the wave and temperature. Plank's law is a function of spectral distribution of values

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

Real objects generally do not behave as black bodies. No-black bodies absorb only a part of  $\alpha(\lambda) \Phi$  (incident radiation), part of the reflected radiation  $\varepsilon(\lambda) \Phi$  and part  $\tau(\lambda) \Phi$  is transient radiation. Coefficients  $\alpha(\lambda)$ ,  $\varepsilon(\lambda)$ ,  $\tau(\lambda)$  is selective and depend on the wavelength. If the system is in thermodynamic equilibrium Fig. 2, under the law of conservation of energy reflected and transient energy is equal to the energy absorbed.

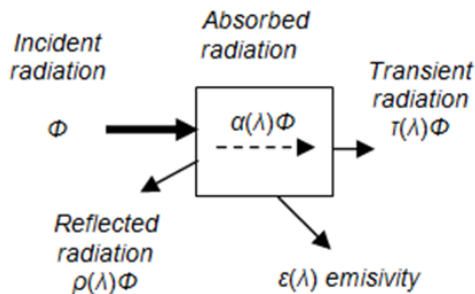


Fig. 2. Distribution of the incident radiation

Emissivity  $\varepsilon(\lambda)$  (coefficient of radiation), compensates absorption coefficient  $\alpha(\lambda)$  then  $\varepsilon(\lambda) = \alpha(\lambda)$ . It follows that:

$$(5) \quad \varepsilon(\lambda) + \rho(\lambda) + \tau(\lambda) = 1$$

Spectral radiant flux density of any object is bound to spectral radiant flux density of black body, therefore [6]

$$(6) \quad \frac{dH(\lambda, T)}{d\lambda} = \varepsilon(\lambda) \frac{dH_{\varepsilon, T}(\lambda, T)}{d\lambda}$$

Radiated power in the range  $\Delta\lambda$  of the body surface with area  $S$  at a temperature  $T$  is defined as:

$$(7) \quad H = \int_{\Delta\lambda} \varepsilon(\lambda) \frac{dH_{\varepsilon, T}(\lambda, T)}{d\lambda} S d\lambda$$

Object's own radiation is defined by its temperature. Deriving the Planck's equation:

$$(8) \quad \frac{\partial(dH(\lambda, T)/d\lambda)}{\partial T} = \frac{hce^{(hc/\lambda kT)}}{\lambda kT^2(e^{hc/\lambda kT} - 1)} \cdot \frac{\partial H(\lambda, T)}{\partial \lambda}$$

We need together 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  $\varepsilon_0(\lambda)$ .

Difficulties arise when the body is surrounded by other objects, which have high temperature and these temperatures are higher than the examined object. [8]

In this case, its own radiation depends on the  $T_0$  and  $\varepsilon_0$  affected by reflected radiation error caused by parasitic (surrounding) objects with a temperature  $T_e$  and emissivity

$\varepsilon_e$ . If the reflection coefficient is measured as  $\rho_e$  - radiation error, then the part characterizing the error is proportional to  $T_e$ ,  $\varepsilon_e$  and  $\rho_e$ ,  $T_e$ , Fig. 3.

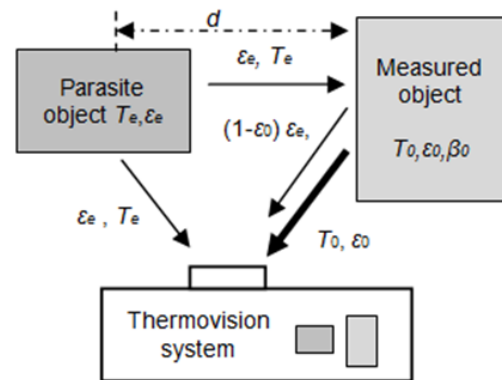


Fig. 3. Influence of other radiating object

### Experimental measurement

The current progressive development in the field of rotating (but also non-rotating) electric machines forces us to continuously apply higher and more active materials, and thus the requirements for insulating systems are increasingly tightened. [9]

The degradation of insulation materials due to temperature puts increased demands on precise knowledge of the thermal conditions in a given electrical machine. The frame of asynchronous motors, which uses the cover IP 54, IP 55, crucially influences the transfer of losses into the cooler and thus also the temperature of the insulation winding.

Measured experimental results of asynchronous motor, with a ribbed frame, showed relatively good distribution of heat in the axial direction. From the thermal image, we could see the very good thermal arrangement (reduction) of the ribs in the radial direction, Fig. 4.

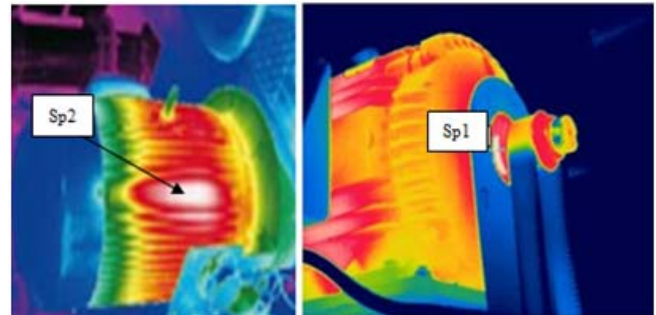


Fig. 4. Temperature field distribution of asynchronous motor

In order to increase the thermal conductivity of the skeleton to the surrounding space, for example, the surface of the skeleton is enlarged (the so - called "ribbing") and at the same time heat transfer value to the ambient (air) through the introduction of forced ventilation.

On the relative conductivity of the material of skeleton, on the geometric dimensions of the skeleton (i.e., height, length, rib thickness, etc.) and also on heat transfer coefficients from the skeleton surface, depend then the heat distribution in the radial and axial direction.

Larger warming of the central part of the electric motor (Sp2 - 64 °C at 35% current load) may probably be caused by the stator currents in the coils of stator or by the bearing temperature at the frontal part (Sp1 - 55 °C) larger loading by the radial force, than the bearing located at the rear. When evaluating winding warming from current load, the

measured warming must be converted to 100 % current load. The failure was caused by the degradation of stator winding insulation.

When applying the thermovision systems on the transformers, it is checked if some parts of the transformer are not warming up, the transformer bushings are checked, but also the temperature distribution on the transformer vessels. It is confirmed that the combination of thermovision diagnostics, oil chromatography and other diagnostic methods creates very good conditions for the implementation of high quality defectoscopy of the mentioned machines [9-11].

The measurement was carried on Transformer ŠKODA 250 MVA, 242 kV  $\pm$  5 %/15.75.

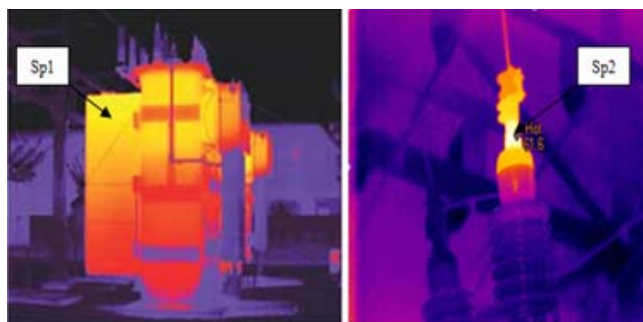


Fig. 5. Thermovision diagnostic of transformer

Transformer T1 was measured at an ambient temperature of 18 °C. During the measurements were in operation all fans (4 left and 4 rights). The transformer temperature according to the installed thermometer was 54 °C.

The metal tube passing through the area of the outlet of encapsulated conductors between the phases L2 and L3 (the extreme left and the middle phase as seen from the 15.75 kV side) is heated by eddy currents up to 103 °C (confirmed by thermovision measurement), Fig. 5.

Thermovision technology was also used for checking of electric machines and devices for detecting of the temperature on the pick-up systems and excitation systems of generators, power parts of electric machines, detecting of the temperature differences on the semiconductor valves in individual parallel branches of equipment.

On the 220 MW generator ( $U = 15.75$  kV,  $I = 9500$  A) were measured magnetic circuit of the stator generator at induction heating.

Before the test, several current magnetizing turns (number 17) in the shape of a toroid were wound around the stator sheets. During the measurement, we have located a significant amount of disorders on the magnetic circuit of the machine (The largest measured warming on the tooth compared to the minor teeth was up to 92 °C), Fig. 6.

After two hours of heating, three heat points were localized which clearly indicated the presence of short circuits on the stator plates (the initial stator temperature of the generator just before heating was 19.2 °C). Point SP1 is located as a wrong place at a temperature of 85.9 °C with the temperature difference of  $\Delta T = 66.7^\circ\text{C}$ , point SP 2 is also a wrong place at a temperature of 86.7 °C,  $\Delta T = 67.5^\circ\text{C}$ . A good place is designated by a point SP 3 at 41.3 °C.

Measuring of the temperature of the collection device on rings and brushes has confirmed that the carbons at the positive polarity ring have a higher temperature than the carbons on the negative polarity ring, Fig. 7.

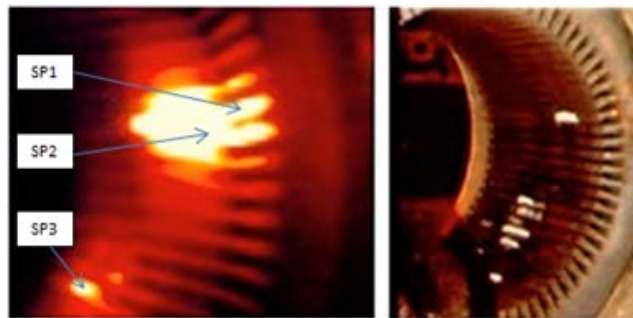


Fig. 6. Disorders on the magnetic circuit of the machine

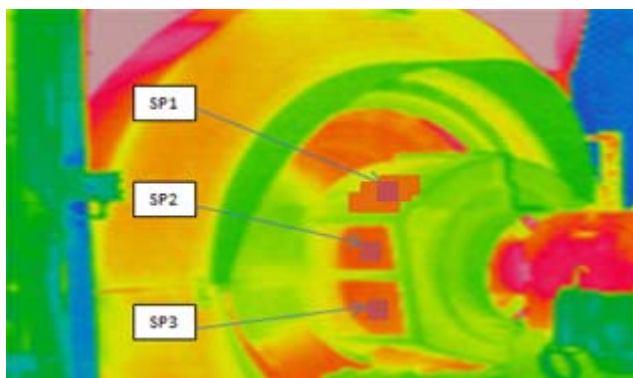


Fig. 7. Positive polarity ring of generator

Higher temperature of the collection device on the positive side is likely due to uneven carbon brushing, which can cause indistinct edges of the grooves of the ring rotor. There were also located brushes that probably did not have sufficient contact with the rings.

The measurement results are shown in Tab. 1 (only thermograms of the first three carbons are given).

Table 1. Measured temperature on carbon contact

Termo gram Spot	Measured temperature		
	Carbon contact	Positive pole	Negative pole
SP1	1	95.6	73.0
SP2	2	115	79.4
SP3	3	115	84.6
SP4	4	116	83.5
SP5	5	113	82.5
SP6	6	103	77.2

## Conclusion

Analyzing fault condition of electrical machines, using the basic methods by standards and also method of thermovision diagnostics, we can adequately evaluate the functionality of the equipment and its individual components.

In some cases, we cannot use the conventional method and therefore it is preferable to proceed to the analysis of temperature fields. This method has limitations in transformers in a metal container.

At the non-contact temperature measurement method the possibilities of using more efficient measurement and diagnostics in locating fault states.

In case of diagnosis of faults in the electrical substations, the degree of defect is determined based on the measured warming. When temperature is measured on winding it is necessary to provide a 50% current load and if it is not possible in some cases it is necessary to recalculate the given warming to 100% current load [12-14].

(9)

$$\Delta T_{100} = \frac{\Delta T}{\left(\frac{I_r}{I_n}\right)^2}$$

where  $\Delta T$  is measured warming,  $\Delta T_{100}$  is warming for 100% current load.  $I_r$  is real measured current load and  $I_n$  is nominal current load.

A very common problem, whether in engineering or other industries, is the determination of a fault when it is still unnecessary to dismantle the machine (diagnostics without dismantling). In this paper, we wanted to point out the possibility of using thermovision in this field of analysis and detection of material and product. This method localized places of faults and it can also serve for the diagnosis and detection of disorders in materials and other anomalies during operation of the equipment.

*This work was partially supported by the Grant Agency VEGA from the Ministry of Education of Slovak Republic under contract 1/0471/20.*

**Authors:** Ing. Milan Šebok, PhD.; Prof. Miroslav Gutten, PhD.; Ing. Matej Kučera; Assoc. Prof. Daniel Korenčiak, PhD; Faculty of Electrical Engineering and Information Technology of the University of Žilina Department of Measurement and Applied Electrical Engineering, Univerzitná 1, 010 26 Žilina, Slovak Republic, E-mail: gutten@fel.uniza.sk.

#### REFERENCES

- [1] Šebok M., Gutten M., Kucera M., Diagnostics of electric equipments by means of thermovision. *Przegląd elektrotechniczny*. 87(2011), No.10, 313-317.
- [2] Kanuch J., Ferkova Z.: Simulation stepping motor with DISC rotor, *International Conference on Low Voltage Electrical Machines*, Brno, 2010
- [3] Simko M., Chupac M., Non-destructive method of measurement of radio transmitters antenna systems, *Elektronika ir elektrotechnika*, 107(2011), No. 1, 33-36
- [4] Toth D., Infrared system helps with energy efficiency, *USA*, 1995.
- [5] Eason G., Noble B., Sneddon I.N., On certain integrals of Lipschitz-Hankel type involving products of Bessel functions, *Phil. Trans. Roy. Soc. London*, A247(1955), 529-551
- [6] Lysenko V., Detectors for noncontact temperature measurement, *Praha*, 2005.
- [7] Benko I., Determination of the Infrared surface emisivity, *Budapest*, 1990.
- [8] Klabacka E., Surface modifications for thermovision measurement, *ČVUT, Praha*, 1998.
- [9] Brandt M., Identification failure of 3 MVA furnace transformer, *DEMISEE 2016, International conference Diagnostic of electrical machines and insulating systems in electrical engineering*, Papradno, SR, 2016
- [10] Brandt M., Experimental measurement and analysis of frequency responses SFRA for rotating electrical machines, *Elektroenergetika 2017*, Stará Lesná, SR 284-288.
- [11] Petras J., Kurimsky J., Balogh J., Cimbala R., Dzmura J., Dolnik B., Kolcunova I., Thermally stimulated acoustic energy shift in transformer oil, *Acta Acustica United with Acustica*, 102(2016), No. 1, 16-22
- [12] Spanik P., Sedo J., Drgona P., Frivaldski M., Real Time Harmonic Analysis of Recuperative Current through Utilization of Digital Measuring Equipment, *Elektronika ir Elektronika*, 19(2013), No. 5, 33-38.
- [13] Hardon, S., Kudelcik J., Rajnak M., Study of Structural Arrangement in Ferrofluid at Various Temperatures by Acoustic Spectroscopy, *Applied Physics of Condensed Matter (APCOM 2018)*, 2018
- [14] Glowacz, A., Glowacz, Z., Recognition of Thermal Images of Direct Current Motor with Application of Area Perimeter Vector and Bayes Classifier, *Measurement Science Review*, 15(2015), No. 3, 119-126.