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The ways for the improvement of the information value of the thermal image control of electric machines with long mean time between failures

Abstract. *The paper deals with the substantiation of the prospects of the use of the methods and means for the thermal image control to determine the state of the internal structural units of electric machines with long time between failures. We determined the interrelations of the basic types of the structural unit defects with their thermal manifestation, which made it possible to formulate the special features and problems of the current thermal image control of electric machines under the operation conditions.*

Streszczenie. *Artykuł prezentuje uzasadnienie perspektyw użycia metod I środków sterowania obrazu termalnego w celu określenia stanu wewnętrznych jednostek konstrukcyjnych maszyn elektrycznych z długim czasem między awariami. Określono wzajemne relacje podstawowych typów defektów jednostek konstrukcyjnych oraz ich obrazowania termicznego. Umożliwia to sformułowanie specjalnych właściwości i problemów bieżącego obrazowania termicznego maszyn elektrycznych w specjalnych warunkach działania.* ***(Sposoby polepszania wartości informatywnych obrazowania termicznego maszyn elektrycznych z długim średnim czasem miedzy awariami).***

Keywords: electric machine, structural unit, defect, thermal process, thermal image control.
Słowa kluczowe: maszyna elektryczna, jednostka konstrukcyjna, defekt, proces termiczny, obrazowanie termiczne

Introduction

To provide the reliable operation of electric machines (EM) it is necessary to have trustworthy information about their current state [1]. Its presence will enable both the assessment of their operation conditions and the forecast of the residual life for their timely withdrawal to repair or maintenance.

In this case, the main problem consists in the impossibility to use many of the most accurate and advanced methods of diagnostics, as the current monitoring of EM condition is performed in most cases with operating equipment with limited access to EMs and their basic structural units [2].

The above said substantiates the use of such methods of measuring, control and diagnostics that minimize the possible preparatory procedures and even eliminate their influence on operating EM, including various distant methods [3].

According to the existing statistic data, most EM failures result from the winding or bearing units breakage preceded by the growth of their temperature. Thus, the diagnostic methods allowing additional assessment of the thermal condition of both separate units and EM on the whole are sufficiently informative [4, 5].

Their application is especially topical in the determination of the deviation of the temperature of the basic structural elements in complex dynamic operation modes and in the assessment of EM condition in the course of aging.

The posed problem can be solved with the use of the methods and means of thermal image control (TC), along with the following digital processing of the obtained images. However, the problems of the accurate interpretation of separate sources of heating and the assessment of the intensity remain unsolved. The present paper settles these problems.

Theory

The direct application of TC to EM is a rather complicated and ambiguous problem nowadays. First, it is explained by the impossibility of the direct assessment of the state of the internal structural units as windings, cores, bearing units, etc.

The units with easier access are an exception. They include commutator brushes in direct current machines, current pickup units in induction motors with a wound rotor and synchronous machines, terminal boxes.

Besides, all the external surfaces of EM are accessible for direct research, including rotating shafts, the points of attachment to the bottom and/or technological equipment as well as the components of the ventilation systems and the points of the EM external heatsink.

Apart from this, one should keep in mind certain problems at the interpretation of TC results, as, in terms of heat, EM is a rather complex and inertial object, which prevents the adequate assessment of the thermal modes from the side of the winding.

Besides, a number of important signs, confirming the presence and localization of the internal sources of the local heat do not reveal due to the balance of heat dissipation via the aluminum case used in low-power EM.

We propose to take into account the presented features of the thermal processes in EMs in the following way.

1. It is proposed to use the approach described in [6] for the assessment of the manifestation of overheating of the internal structural units. It implies the determination of the change of the structural unit temperature during heating and cooling as a result of the solution of the system of homogeneous differential equations of thermal condition. As the process of heating or cooling is transient practically at every statement of the problem, the corresponding dependences for the change of the temperature of the considered unit at its heating $\theta_{hi}(t)$ or cooling θ_{ci} will be of the form:

$$\theta_{hi}(t)=\theta_{sti}\left(1+\sum_j a_{hij}\,exp\left(-t/T_{hij}\right)\right); \quad (1)$$

$$\theta_{ci}(t)=\theta_{sti}\sum_j a_{cij}\,exp\left(-t/T_{cij}\right), \quad (2)$$

where θ_{sti} - the steady value of the unit temperature; a_{hij}, a_{cij}, T_{hij}, T_{cij} - the coefficients of the specific weight and the time constants of heating and cooling exponents, respectively.

In this case the exponent time constants are conditionally divided into three groups: small (up to 1 min), characterizing the winding copper heating; medium (up to 10 min), characterizing the heat exchange via the insulation and air gaps and big ones determining the external heat emission.

In the considered case, the small and the medium time constants are most informative as they characterize respectively the intensity of the heating source (windings) and the specific features of the heat transfer to the body. In this case, the small time constant is actually determined by the winding type and can be easily recalculated for homogeneous EMs when the similarity principles are observed in the design. The average time constant can be recalculated in an analogous way provided the coefficients of the heat transfer and heat emission for the basic structural materials and units are constant.

As the exponent specific weight coefficients are different for each of the structural units and take into account their temperature in a certain way, when assessing the change of $\theta_{hi}(t)$ and θ_{ci}, it is possible both to divide the external manifestation of their heating and to forecast the change of their condition, also locally, e.g. for the cores. However, in the latter case the required result can be obtained only with the use of low-inertia thermal imagers with high discrimination ability.

2. The defects of the units adjacent to EM body parts, e.g. bearings, can be determined directly by the results of the thermal image control. In this case, if it is necessary to determine their type or localization, the information about the initial dynamics of the thermal image change at the start of EM is required. If the defect details are unnecessary, it is sufficient to take measurements in the steady operation mode.

3. To compensate for the influence on the results of the distribution of the temperature of the aluminum body it is necessary to transfer from the temperature energy parameter proportional to energy ($\theta \sim W$), which, in its turn, is an integral value, to the power of the emission energy flow *P*:

$$P = \frac{dW}{dt}. \tag{3}$$

This transfer, along with the increase of the speed of the control procedure, allows the direct analysis of power *P* that may have instantaneous values and be a quantitative sign of temperature according to the Planck law [7]:

$$\frac{dR(\lambda,T)}{d\lambda} = \frac{2\pi hc^2\lambda^{-5}}{exp(hc/\lambda kT)-1}, \tag{4}$$

where $dR(\lambda,T)/d\lambda$ – the spectral surface density of the emission flux, i.e. emission power; λ – the length of the wave; h,k – the Planck and Boltzmann constants; c – the light speed.

In this case, as expression (4) demonstrates, $dR(\lambda,T)/d\lambda$ depends on the wave length and temperature, determining the growth of the temperature via the decrease of the wave length and the increase of the emission intensity. It enables the decrease of the inertia of the temperature measuring method and obtaining the real distribution of the body heating under the aluminum body due to the use of the spectral analysis of the information instead of the integral methods of its processing.

4. It is possible easily assess the general level of EM heating by the external temperature of the body and the bearing caps or, if the access inside EM is available, by the excess of the temperature of the internal cooling air. However, in any of the considered cases, the obtained information is sufficient only for the determination of the possible overheat or the general assessment of the design quality for new EMs with the use of their calculated thermal models.

Thus, as the results of the performed research revealed, the promising ways of the improvement of the reliability and information value of the method for the assessment of the EM thermal condition consist in obtaining additional information during the process of thermographing the transient modes of EM operation (heating and cooling). The use of high-sensitivity and high-speed TC devices, taking into account the change of the character of the body temperature distribution, the transfer to the spectral characteristics of heating processes and the subsequent use of the results in the thermal models of corresponding EMs.

A complex application of the mentioned approaches allows the determination of the state of the internal units and EM overall with the accuracy sufficient for the practical use of the method.

Experimental research

The purpose of the performed experimental research consisted in the approbation of the theoretic points of the paper by the example of general-purpose serial squirrel-cage-rotor induction motors (IM) with the range of the power on the shaft of 0.5 – 5.5 kW.

The performed research included:

– the experimental determination of the time constants of heating and cooling of the stator winding;

– the assessment of the thermal image mapping of the bearing units defects;

– the research of the specific features of the manifestation of the structural unit internal overheat in transient conditions;

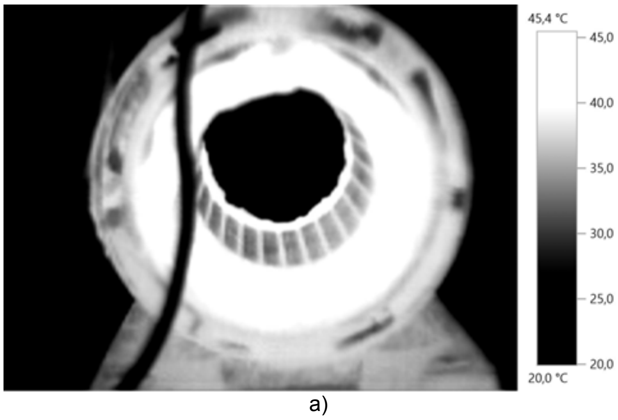
– the identification of the explicit defects causing essential decrease of IM operability.

In accordance with the above recommendations for the thermal image control of the researched EM we used thermal imager Testo 881-2 with the function of Super Resolution and thermal sensitivity of 0.05 ^{o}C in the set range of measurements of -20…100 ^{o}C

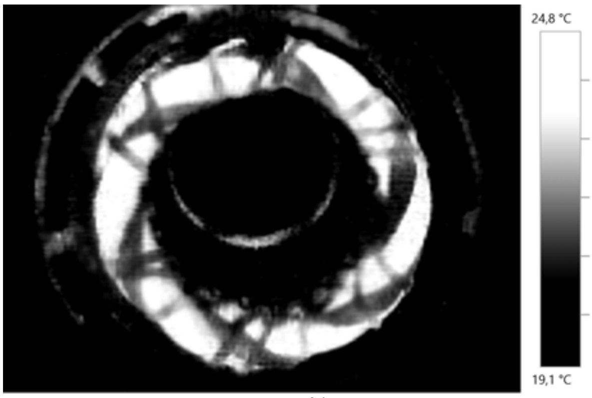
We determined the time constants of the stator winding heating and cooling under the conditions of its partial heating by the rated current with the following cooling for IM with a removed rotor (Fig. 1 a, b).

Later we used the obtained results for analogous lap and random windings of IMs of the researched power range due to the observance of the similarity principles.

The purpose of the assessment of the bearing unit defects consisted in the determination of the correlation between the thermal image of the unit with an open and a shut bearing cap (Fig. 2, a, b).

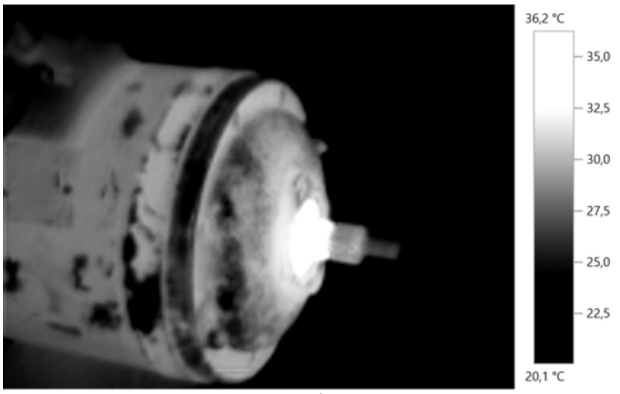


a)

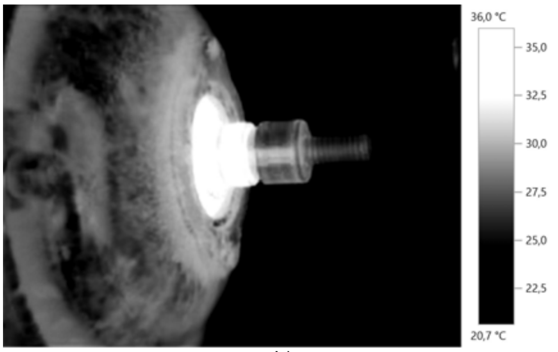


b)

Fig. 1. The determination of the time constants of the stator winding heating and cooling: a) a partially heated winding; b) a partially cooled winding



a)

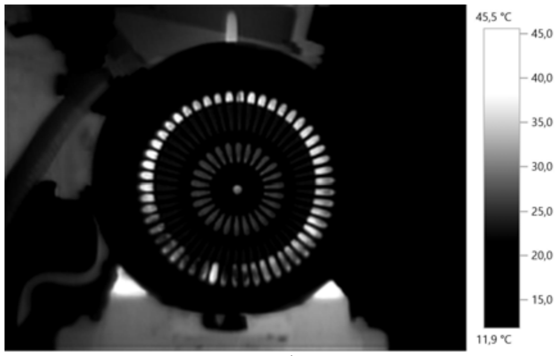


b)

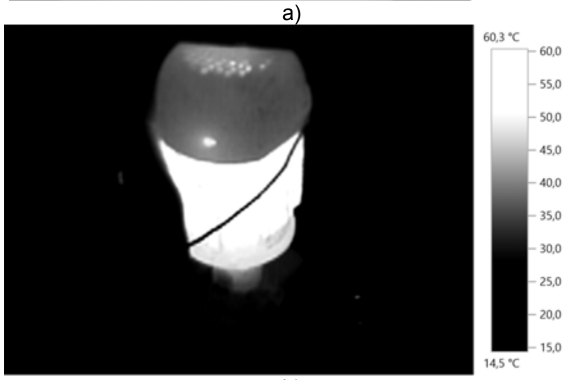
Fig. 2. The thermal images of the defects of IM front bearing: with a shut bearing cap; b) with an open bearing cap

Fig. 3. The thermal image manifestation of IM stator core overheat

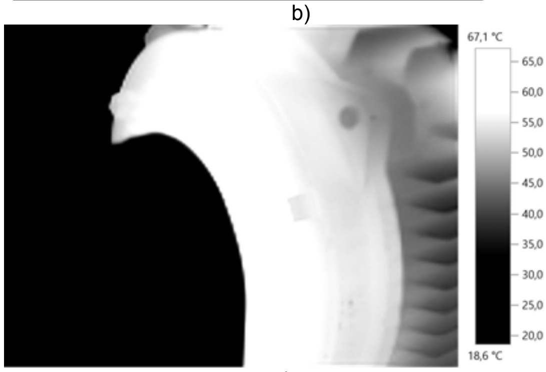
The results of their manifestation, revealed during the performed research, are shown in Fig. 4 (a-d).



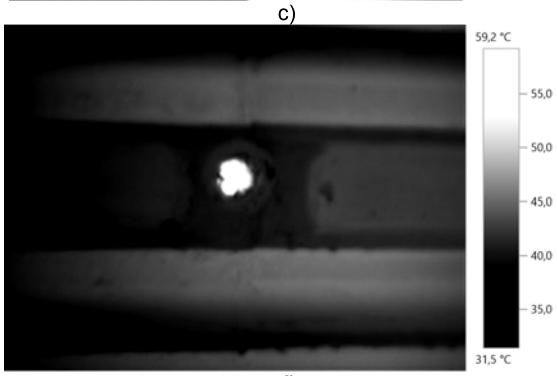
a)



b)



c)



d)

Fig. 4. The thermal images of IM defects with explicit manifestation:
a) poor fixation of EM to the base;
b) obstruction of the air grid;
c) IM incorrectly designed as to thermal modes;
d) overheat of the internal air

The obtained results confirmed the sufficient level of the surface thermal image control sensitivity to the basic types of the defects of the bearing unit races and retainer.

IM with damaged stator core steel was used for the research of the internal overheat. The thermal image of this core, shown in Fig. 3, explicitly manifests in IM external thermal graph on the expiry of the average time constant.

Explicit defects include defects causing the deterioration of IM thermal and vibration condition.

Conclusions

1. The paper deals with the analysis of the specific features of the use of TC method in the problems of the current monitoring of EMs with different mean-time-between failures in the presence of the defects of basic structural units.
2. The conditions and approaches to the determination of the state of the basic internal units and EM overall have been substantiated by TC results.
3. The use of the obtained results makes it possible to assess in the future the operating conditions and to forecast the residual life of EMs of different forms and types including the cases when the basic structural units are damaged.

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