Thermal diagnostic model of induction motor operating in steady state mode

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***Abstract* — The paper considers a thermal diagnostic model of an induction motor operating in steady-state thermal mode. The mathematical description of the heat transfer processes in the machine is presented. Parametric identification of the diagnostic model and method of analysis of the engine thermograms for this operating mode are presented.**

Keywords — diagnostic model, induction motor, thermography, maintenance

I. INTRODUCTION

The reliability and safety of the electrical equipment of industrial consumers are related to timely and quality maintenance consisting of scheduled repairs and preventive tests performed in accordance with regulations. When maintaining electrical equipment, the lowest possible labor and material costs should be ensured. Also, the opposite task is relevant - providing the greatest reliability with the available labor and material resources. The productivity of the industrial units and the quality of the products obtained from them largely depend on the organizational and technical measures, among which the measures for preparation and carrying out of planned, unplanned, and emergency repairs play an important role.

The research, and the analysis of the faults in the electrical equipment, in the different spheres of the industry, allow the drawing the following conclusions:

- the system of planned preventive repair and maintenance, which has received the widest application, is not able to ensure the fault-free operation of the elements of the technological units in the modern conditions of production intensification;
- systems for monitoring the technical condition of electrical equipment are not effective enough in solving the problem of operational diagnostics of faults in the elements of electric drives and elements of power supply systems at an early stage of development of defects.

This proves the need for development of systems for monitoring the technical condition of electrical equipment in the infrastructure of industrial complexes. In order to increase the level of operational reliability of the electrical equipment, it is necessary to supplement the existing approaches and methods for technical diagnostics with new systems, providing timely diagnostics and localization of defects in the early stages of their development; organization of regular preventive works in accordance with the current technical condition.

Currently, one of the leading operational methods for monitoring the technical condition of electrical equipment is the method of thermographic diagnostics (TD), which is characterized by high information content, technical and regulatory coverige [1].

The purpose of thermographic diagnostics is to determine the actual technical condition of the equipment during under-load operation, which allows to monitor and analyze all changes in the diagnostic parameters that characterize the occurrence and development of a defect.

The attention of the specialists is focused on the analysis of the obtained thermograms for localization of the occurring faults. In the process of thermal imaging diagnostics, the technical condition of the equipment is usually assessed by the diagnostic parameter - surface temperature of the object being examined. In most cases, the diagnostic parameters only show the possibility of detecting equipment defects. Here it should be borne in mind that only when the reliability of technical diagnostics is determined with a certain probability, we can talk about the criteria of the boundary condition. This is only possible in the presence of developed diagnostic models, as the increase in temperature itself does not yet indicate the presence of a specific defect or fault [2].

Also, a topical issue is the analysis of the relationship between the observed temperature field of the object and the possible external or internal damage and defects according to the quantitative data from the thermographic studies. The complexity of determining the faults in electrical equipment is due to the fact that the literature contains a limited number of thermal diagnostic models needed to solve the main task of technical diagnostics - determining the type and location of the fault [3].

II. MATHEMATICAL DESCRIPTION OF HEAT TRANSFER PROCESSES IN ELECTRIC MOTORS

To solve the problem of determining the technical condition of the electrical equipment of individual enterprises in the industry, it is necessary to create diagnostic models for the individual types of equipment. The diagnostic model allows to calculate the parameters of the technical condition based on the analysis of the spatial distribution of the temperature field of the object of study.

It is known that the processes of thermal conductivity in a homogeneous body are described by the differential equation:

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$$div\left(\lambda\, grad\ \tau\right)+q_{in}=\rho c\frac{\partial\tau}{\partial t}\,, \qquad (1)$$

where: q_{in} is the thermal energy released inside the body;

λ - thermal conductivity ;

ρ and c are density and specific heat capacity of the material.

The heat flux is distributed in the stator frame of the electric machine due to the thermal conductivity of the metal and the heat transfer to the surface of the fins and the ventilation channels in the individual directions, as shown in Fig. 1.

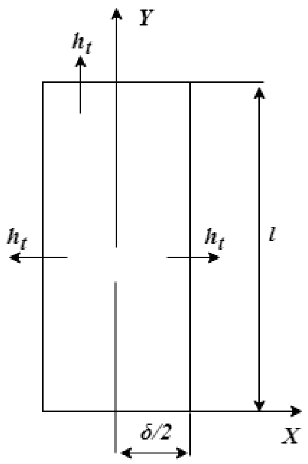

Fig. 1. Fin with a rectangular profile

The differential equation of the two-dimensional thermal conductivity of the fin with a rectangular profile has the form:

$$\frac{\partial^2\tau}{\partial x^2}+\frac{\partial^2\tau}{\partial y^2}=0\,, \qquad (2)$$

the solution of equation (2) imposes the following boundary conditions:

$$\left.\begin{array}{c}\partial\tau/\partial x=0, \quad for \quad x=0;\, 0\le y\le l\\ -\lambda\partial\tau/\partial x=h_t\vartheta, \quad for \quad x=\delta/2;\, 0\le y\le l\\ -\lambda\partial\tau/\partial y=h_t\vartheta, \quad for \quad 0\le x\le\delta;\, y=l\\ \tau=\vartheta_s \quad for \quad 0\le x\le\delta;\, y=0\end{array}\right\}, \qquad (3)$$

where: h_t is the generalized heat transfer coefficient;

ϑ – temperature difference;

ϑ_s – temperature difference between the machine frame and the environment;

δ and l are the thickness and height of the fin.

The solution of the system of equations (2) and (3) for the two-dimensional problem of thermal conductivity in a stator frame with ribs with a rectangular profile is presented in [4, 5]:

$$\frac{Q_{l,0}}{h_t\tau_f\,\delta}=\sum_{j=1}^{\infty}\frac{2Bi}{\mu_j(\mu_j^2+Bi+Bi^2)}\left[\frac{\mu_j\, th(\mu_j\,\frac{l}{\delta/2})+Bi}{\mu_j+Bi\, th(\mu_j\,\frac{l}{\delta/2})}\right], \qquad (4)$$

where: $Q_{l,0}$ is the heat flux emitted by a unit length of the fin;

$Bi=\frac{h_t\delta}{2\lambda}$ – Biot number;

τ_f - temperature at the base of the fins;

μ_j – roots of the equation $ctg\,\mu_j=\frac{\mu_j}{Bi}$.

Fig. 2. shows an image of the distribution of the heat flux in a section of the ribbed surface of the stator frame, for which q_s is the transverse density of the heat flux entering the stator frame; δ_f - the thickness of the stator frame; q_{f1} - transverse heat flux density in the ventilation channel space; q_{f2} - longitudinal heat flux density along the frame; $Q_{l,2}$ - the heat flux emitted per unit length of fins from the stator frame.

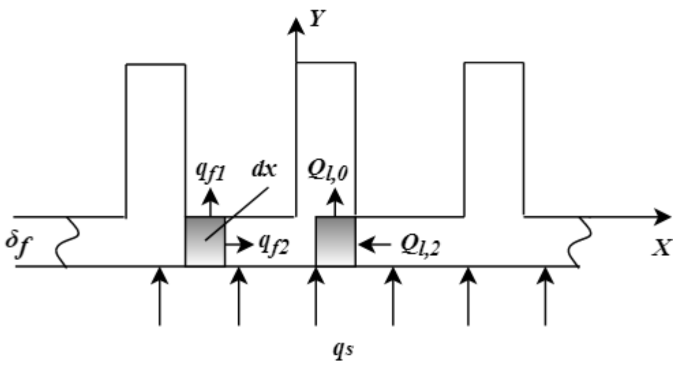

Fig. 2. Schematic representation of the heat flux distribution in the ribbed wall of the stator frame in steady state mode

Assuming that the heat flux approaching the inner surface of the stator frame is parallel to the surface of the fins (ie the temperature of the frame changes only on the x-axis and the temperature of the fins only on the y-axis), the differential equation of stationary thermal conductivity for the presented structure yields the form:

$$\lambda\delta_f\,\frac{\partial^2\tau}{\partial t^2}-h_t\tau+q_s=0\,, \qquad (5)$$

III. Diagnostic Model of an Induction Motor in Steady-State Thermal Mode

A. *Thermographic image analysis of the induction motor frame*

Fig. 3 shows a thermographic image of the studied induction motor, on which the LNSOPR zone is plotted, which conditionally characterizes the location of the stator magnetic core. Fig. 4 and Fig. 5 show the histograms of the obtained temperature values on the lines AD and FM. The thermographic image was taken in the steady-state thermal mode of operation of the engine, 60 minutes after the start of the measurement. It can be seen that the ribbed surface of the motor frame is characterized by inhomogeneity of the thermal field in the directions of the X and Y axes. Analysis of the temperature distribution in the area marked by the LNOP rectangle shows that the surface temperature varies within 34.5 - 39.6° C at ambient temperature τ_0 = 22.5° C.

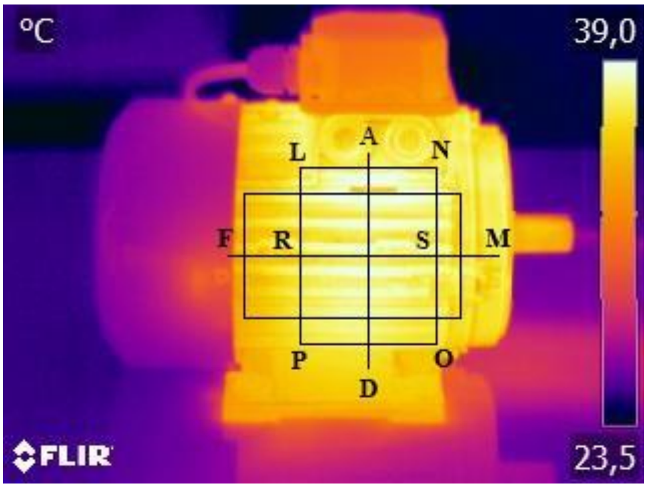

Fig. 3. Thermographic image of the induction motor with marked zones for recording temperature data

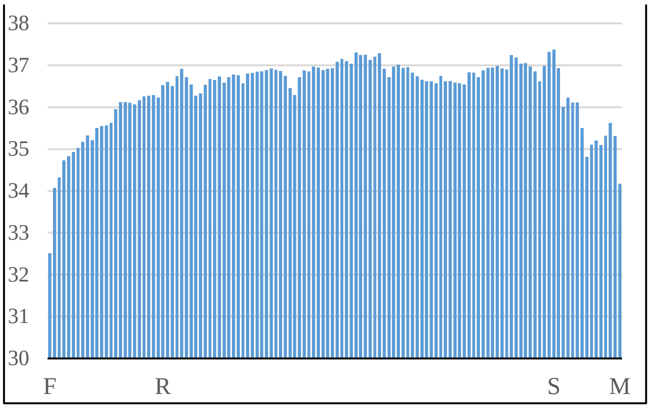

Fig. 4. Histogram of the temperature in the line FM

Analysis of the change in surface temperature along the line FM (representing the Y-axis) shows that the highest temperatures are characteristic of the central part of the motor frame corresponding to the location of the stator magnetic core (the range between the points R and S).

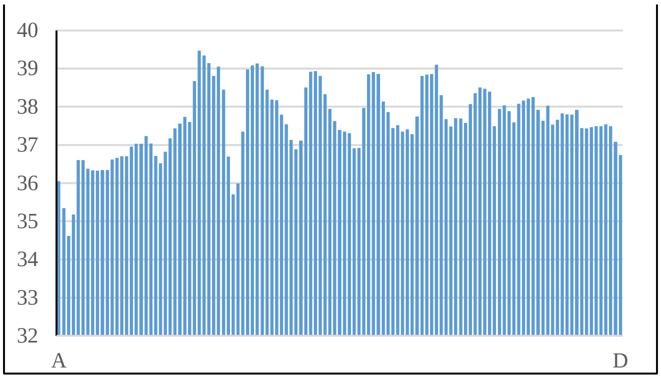

Fig. 5. Histogram of the temperature in the line AD

On the line AD (transverse to the fins, corresponding to the X-axis), the highest temperatures are observed between the fins, and the lowest - at the tops of the fins.

The main design parameters of the tested machine, necessary for the creation of the thermal model, are shown in Table 1.

TABLE I. CONSTRUCTION PARAMETERS OF THE INVESTIGATED MOTOR

Parameter	Designation	Value
Motor shaft height	H, mm	80
External length of the frame	L, mm	170
Fin height	l, mm	11.5
Fin thickness	δ, mm	1.5
Fin length	b, mm	155
Frame thickness	δ_f , mm	5
Distance between fins	s, mm	10
Stator magnetic core length	l_1, mm	90
Outer diameter of the stator magnetic core	D_{n1}, mm	106
Inner diameter of the stator magnetic core	D_1, mm	61
Channel height	h_1, mm	13
Outer diameter of the frame	D, mm	117
Diameter of the magnetic circuit at the bottom of the channel	D_C, mm	88
Frame area	S_F, m^2	0.168

During measurements, the hottest part of the motor stands out in the AD section located approximately in the middle of the magnetic core. The temperature values for this section are measured and taking into account the dependence (3) the temperature rises can be determined as:

$$\left.\begin{array}{r}\vartheta_f = \vartheta_{\max} = \tau_{\max} - \tau_0 \\ \vartheta_l = \vartheta_{\min} = \tau_{\min} - \tau_0 \\ \Delta\tau = \tau_{\max} - \tau_{\min}\end{array}\right\}, \tag{6}$$

where: ϑ_f is the temperature rise of the frame in the ventilation channel spaces;

ϑ_l – temperature rise of the fins;

$\tau_{\max}$ and $\tau_{\min}$ are the maximum and minimum temperature values for the ribbed area of the frame.

B. Diagnostic thermal model

When estimating the magnitude of the heat flux based on quantitative data from thermography, the base task is to calculate the heat transfer coefficient from the surface of the frame h_t of an electric machine at arbitrary points on the surface.

The propagation of the heat flux along an arbitrary fin - parallelepiped with length ΔH is described by the ratio::

$$\begin{array}{l} ch(m\Delta H) = \vartheta_f / \vartheta_{\Delta H} \\ m = \sqrt{\dfrac{h_t u}{\lambda f}} \end{array}, \tag{7}$$

where: u is the perimeter of the cross section of the investigated element;

f – cross section of the investigated element.

Based on the thermographic study, the temperatures are determined and the experimental value of the ratio $\vartheta_f / \vartheta_l$ is calculated. In this case, taking into account the dependence (7) and the constructive parameters given in Table 1, the following dependence can be written for experimental determination of the m_{exp} coefficient:

$$m_{\exp} = \frac{arcch(\vartheta_f / \vartheta_l)}{l'}, \qquad (8)$$

where: $l' = l + \delta / 2$.

The experimental value of the heat transfer coefficient $h_{t\_\exp}$ on the surface of the fins in the studied surface area is calculated as:

$$h_{t\_\exp} = m_{\exp}^2 \lambda f / u . \qquad (8)$$

The value of the heat flux density q_{s_r} that enters the fin and propagates radially along the r axis is determined by the expression [6]:

$$q_{s\_r} = \frac{h_{t\_\exp}\vartheta_l}{k}, \qquad (9)$$

where: $k = \dfrac{Bi_l + \sqrt{Bi_f}\, thN_f}{\sqrt{Bi_l}\, thN_l + \sqrt{Bi_f}\, thN_f}$.

The values of the Biot numbers Bi_l and Bi_f, as well as the characteristic dimensions N_l and N_f relating to the fins and ventilation channels are determined by the following dependencies:

$$\begin{aligned} Bi_l &= \frac{h_{t\_\exp}\delta}{2\lambda} \\ Bi_f &= \frac{h_{t\_\exp}\delta_f}{2\lambda} \\ N_l &= l\sqrt{\frac{2h_{t\_\exp}}{\lambda\delta}} \\ N_f &= \frac{s}{2}\sqrt{\frac{2h_{t\_\exp}}{\lambda\delta_f}} \end{aligned}, \qquad (10)$$

C. Determining the temperature of the motor windings

The temperature of the stator winding is calculated by the method of thermal resistances. Such a technique is used for calculations in solving the inverse problem for known values of the parameters of the studied machine and the magnitude of the heat flux passing through the layers of the structure: the machine frame, the air gap between the frame and the stator, the magnetic core of the stator, and channel insulation, which all have thicknesses respectively δ_f, δ_{ag}, h_s and b_1.

The linear thermal resistances of the individual layers of the structure are determined by the following expressions:

$$\begin{aligned} R_{L\_f} &= \frac{\ln[(D_{n1} + 2\delta_{ag} + 2\delta_f)/(D_{n1} + 2\delta_{ag})]}{2\lambda_f} \\ R_{L\_ag} &= \frac{\ln[(D_{n1} + 2\delta_{ag})/(D_{n1})]}{2\lambda_{ag}} \\ R_{L\_s} &= \frac{\ln[D_{n1}/(D_{n1} - 2h_s)]}{2\lambda_s} \\ R_{L\_ins} &= \frac{\ln[D_C/(D_C - 2b_1)]}{2\lambda_{ins}} \end{aligned}, \qquad (11)$$

where: λ_f, λ_{ag}, λ_s and λ_{ins} are the coefficients of thermal conductivity of the materials from which the respective elements are made.

Since the value of the heat flux density q_s in different parts of a cylindrical structure is determined by the radius *r*, if we assume that the value of the linear heat flux density q_l is not dependent on the coordinate in the radial direction, it can be determined by the equation:

$$q_l = \pi D_{n1} q_{s\_r}, \qquad (12)$$

When the heat flux with density q_l passes through the structural elements (stator magnetic core, motor frame, channel insulation) the following relations are fulfilled:

$$q_l = \pi\Delta\tau_f / R_{L\_f} = \pi\Delta\tau_{ag} / R_{L\_ag} = \pi\Delta\tau_s / R_{L\_s}, \qquad (13)$$

$$q_{lw} = \pi\Delta\tau_{ins} / R_{L\_ins}, \qquad (14)$$

$$\begin{aligned} &\Delta\tau_f = \tau_{ag} - \tau_{\max};\ \Delta\tau_{ag} = \tau_s - \tau_{ag}; \\ &\Delta\tau_s = \tau_{ins} - \tau_s;\ \Delta\tau_{ins} = \tau_w - \tau_{ins} \end{aligned}, \qquad (15)$$

where: τ_{ag}, τ_s, τ_{ins} and τ_w are the temperatures of the air gap, the stator magnetic core, the channel insulation and the motor winding;

$q_{lw} = P_{w1} / l_1'$ is the linear heat flux density of the winding;

P_{w1} - power loss in the stator winding;

l_1' - average length of the winding.

Based on the calculated values of the linear thermal resistances and the value of the linear heat flux density of equation (13), it is possible to calculate the temperature changes in each analyzed layer of the structure and finally to determine the value of the winding temperature:

$$\tau_w = \tau_{\max} + \Delta\tau_{ins} + \Delta\tau_s + \Delta\tau_{ag} + \Delta\tau_f . \qquad (16)$$

Table 2 presents the values of the thermal conductivity coefficients of the individual elements and the results of the calculations of the thermal resistances.

The results obtained from the quantitative analysis of the thermographic image of the motor and the calculations of the parameters describing the heat transfer in the motor frame are shown in Table 3. The indicated temperature data refer to the zone with the most significant temperature rise located in the middle of the magnetic core - line AD.

TABLE II. VALUES OF LINEAR THERMAL RESISTANCES

Parameter	Designation	Value
Thermal conductivity of air	λ_{air} W/mK	0.0257
Thermal conductivity of the frame	λ_f W/mK	168
Height of the solid part of the stator magnetic core	h_s , mm	11.3
Coefficient of thermal conductivity of the steel of the magnetic core	λ_s W/mK	30
Channel insulation thickness	b_1 , mm	0.5
Thermal conductivity coefficient of channel insulation	λ_{ins} W/mK	0.21
Linear thermal resistance of the frame	R_{L_f} , K/W	0.000267
Linear thermal resistance of the gap between the frame and the magnetic core	R_{L_ag} , K/W	0.073278
Linear thermal resistance of the magnetic core	R_{L_s} , K/W	0.003997
Linear thermal resistance of the channel insulation	R_{L_ins} , K/W	0.027211

TABLE III. RESULTS OF THE THERMAL IMAGE PROCESSING AND THE DETERMINATION OF THE RADIAL DENSITY OF THE HEAT FLUX

Parameter	Designation	Value
Maximum temperature between the fins	$\tau_{\max}$, °C	39,4
Maximum temperature at the top of the fins	$\tau_{\max\_l}$, °C	38,1
Temperature rise at the base of the fin	ϑ_f , °C	16,9
Temperature rise of the tip of the fin	ϑ_l , °C	15,6
Perimeter of the fin	u, mm	313
Fin cross section	f, m^2	0,00025
Adjusted fin height	l'	12,25
Ratio $\vartheta_f / \vartheta_l$	$ch(m\Delta H)$	1,0833
Experimentally obtained value of the coefficient m	m_{exp}	33,099
Value of the heat transfer coefficient	$h_{t\_\exp}$ W/m^2K	147,007
Biot number for the frame	Bi_f	0,00218
Characteristic frame size	N_f	0,09354
Biot number for the rib	Bi_l	0,00065
Characteristic fin size	N_l	0,39281
Coefficient k	k	0,360079
Radial heat flux density	q_{s_r} W/m^2	6368,927

On the basis of the obtained values for the radial density of the heat flux and the thermal resistances, the changes of the temperature in the individual elements of the machine, and hence the temperature of the winding, can be determined. The results of the calculations of the temperature of the individual elements are presented in Table 4.

TABLE IV. RESULTS OF THE DETERMINATION OF THE TEMPERATURE OF THE INDIVIDUAL ELEMENTS

Parameter	Designation	Value
Linear heat flux density	q_l , W/m^2	2120,909
Frame temperature change	$\Delta\tau_f$, °C	0,180576
Temperature change in the gap between the frame and the magnetic core	$\Delta\tau_{ag}$, °C	1,871843
Temperature change in the magnetic core	$\Delta\tau_s$, °C	1,745827
Temperature change in the channel insulation	$\Delta\tau_{ins}$, °C	1,59038
Motor winding temperature	τ_w , °C	43,88863

In order to validate the developed model and to verify its accuracy, a model of the considered motor was created with the software product Motor-CAD, which allows the simulation of different types of fields in electric motors [7]. When simulating the thermal field of the motor, in addition to the exact dimensions of the elements and characteristics of the materials, its operating conditions (load, speed), as well as the parameters of the environment are set. The results of the simulation are shown in Figure 6.

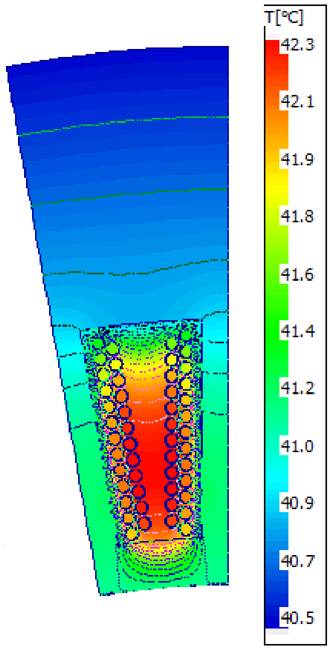

Fig. 6. Result of the thermal field simulation with Motor-CAD

From the data shown in Table 5 and Figure 6 it is seen that the difference between the obtained values of the temperature of the machine winding is 1.57°C, which confirms the accuracy of the developed diagnostic model.

IV. CONCLUSION

There is a significant need to develop thermal diagnostic models of electrical equipment elements to ensure fuller use of the information content of the results of thermal imaging tests.

The developed thermal diagnostic model of an induction motor provides results with accuracy sufficient for the purposes of technical diagnostics based on quantitative thermography.

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