UDC 621.384.3

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MATHEMATICAL MODEL TO DIAGNOSE OPERATING POWERFUL ELECTRICAL MACHINE INSULATION STATE USING THERMAL IMAGE

The paper presents both the approach and the mathematical model to find a possible powerful electrical machine windings insulation damage place, from the points inaccessible for thermal viewing.

Keywords: *thermal camera, mathematical model, electrical machine.*

Initial conditions and task setting

Non-contact methods for controlling over the thermal state of the object are widely used in different spheres of technical activities. [1-3]. Such a tendency also takes place in power industry, where the application of non-contact controlling is especially important for determining the failures with operating equipment. [4, 5].

It is known, that the controlling over thermal fields of electric equipment, including the equipment with rotating parts, requires the usage of thermal imager of general and special application. [6, 7]. But not in all the cases their usage allows to make a decision as for the working ability of the object under control. If, for example, inside the powerful electric machine there appears the local sphere with higher temperature in the result of insulation weakening in the coil wire, which is located in the rotor or stator slot, it is possible then to detect the development of the damage by television methods only on temperature increase in the end winding part of electric machine, where the wires are connected to the coils.

But such an information, received by thermal imager, does not allow to prognosticate the place of possible insulation damage.

The above stipulated for the objective of the paper to develop the approach for detecting of the places for possible damage of coils insulation of electric machines by measured thermal fields in its end winding parts.

Solution of the task

Let us consider the wire, located in the channel of the rotor or stator of the operating electric machine.

Let’s assume, that in any place of this wire with the length l there appears the insulation damage, causing the wire temperature increase due to influence of micro currents, which allows to suppose that the heat is supplied to the wire in this place.

Thermal balance in the place which accounts for heat supply and abstraction , we illustrate graphically (fig.1), where $Q_{пд}$ – quantity of heat supplied to the wire per time unit; Q_{c} – quantity of heat abstracted to the steel surface of stator or rotor during the same time; $Q_{п}$ –quantity of heat, emitted into the air space during the same time; $Q_{пр1}$, $Q_{пр2}$ – quantity of heat disseminated in both direction from the place of heating along the wire during the same time.

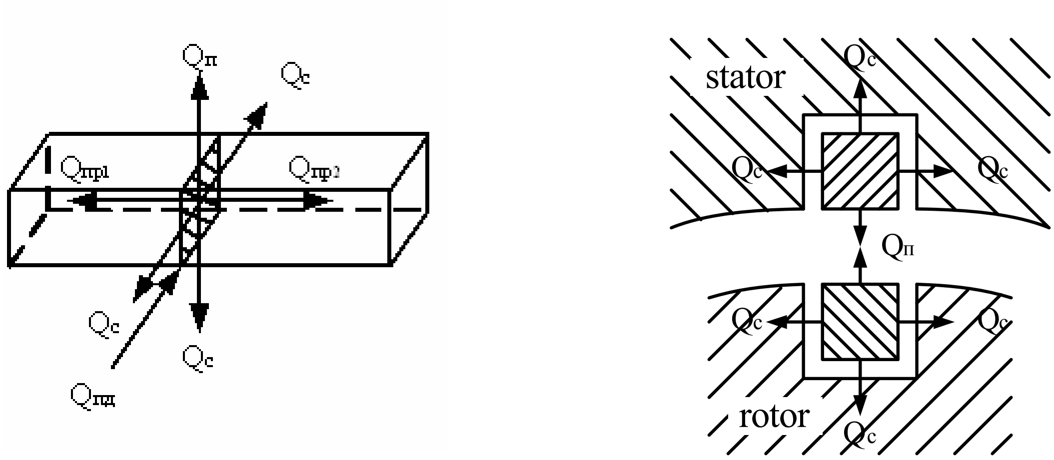

Fig. 1. Illustration of supply and abstraction of heat from the wire

The equation of thermal balance for the task under consideration will look like:

$$Q_{\text{пд}} = 3Q_{c} + Q_{\text{п}} + Q_{\text{пр}1} + Q_{\text{пр}2}. \tag{1}$$

We assume that along the wire length, located in the rotor or stator slot, the heat is supplied to the steel surface with equal intensively. The analogical conclusion we make on that quantity of heat which is equally emitted along the whole length of the conductor to the air place.

So we can omit some parts of the equation (1) leaving it as

$$\Delta Q_{\text{пд}} = Q_{\text{пр}1} + Q_{\text{пр}2}. \tag{2}$$

Papers [8, 9] prove that during the research of heat dissemination character in the stem, the excessive temperature ϑ changes according to the law, which has the exponential character and is described by the expression

$$\vartheta = C_1 e^{mx} + C_2 e^{-mx}, \tag{3}$$

Where C_1, C_2 –constant factors, x – continuous-flow coordinate, along which the temperature changes, m – constant factor, value of which depends on geometry of conductor, factor of heat dissipation and thermal conduction factor.

As due to the above assumptions the appearance of damage place in the conductor causes the exponential kind of heat dissipation character, we accept the law of temperature change t, which is described by the expression

$$\begin{cases} t_1 = k_1 \cdot e^{b_1 x}, \\ t_2 = k_2 \cdot e^{b_2 x} \end{cases} \tag{4}$$

during the temperature dissemination in both direction, from the place of damage, where k_1, b_1, k_2, b_2 –constant factors which characterize the dependence t = f(x), t_1, t_2 – dependences, which describe the temperature character corresponding both to the left and right from the damage point.

It is obvious that the graph of distribution by the temperature along the conductor with damaged insulation in any place will look as shown on a fig. 2, and the character of temperature decrease is equal in both sides from the place of heating of conductor.

Scanning thermal field of electric machine allows to determine the temperature on the ends of the conductor. Assuming the possibility to measure the temperature of the conductor on the specific distance from its ends, let us formulate the task of prognostics the place of conductor insulation damage.

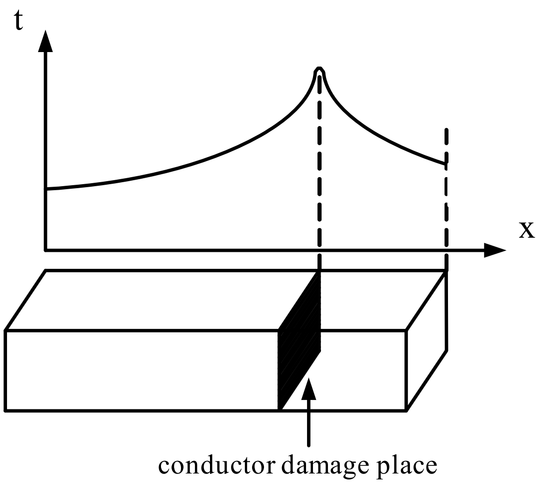

Fig. 2. Illustration of temperature distribution along the conductor with damage.

The value of the temperature t_1 is known, and is measured on the conditional beginning of the conductor ($x_1 = 0$), and value of temperature t_2, measured on the end of the conductor ($x_2 = l$). The value of the temperature t_3 is also known and measured on distance δ from the beginning of conductor($x_3 = \delta$), and meaning of temperature t_4, measured on distance δ from the end of the conductor($x_4 = l - \delta$).

Lets reflect the known parameters graphically (fid. 3).

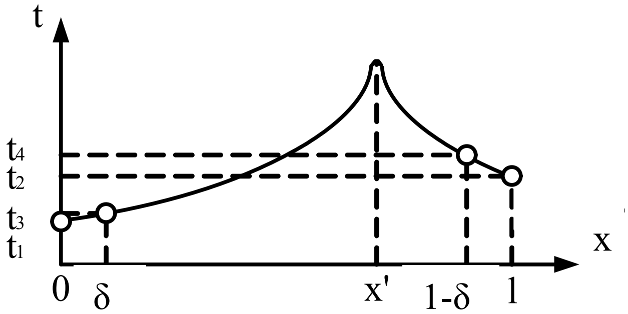

Fig. 3. Graphical reflection of the known parameters

Let's compose the two systems of equations according to (4)

$$\begin{cases} t_1 = k_1 \cdot e^{b_1 \cdot 0}, \\ t_3 = k_1 \cdot e^{b_1 \cdot \delta} \end{cases} \tag{5}$$

and

$$\begin{cases} t_2 = k_2 \cdot e^{b_2 \cdot l}, \\ t_4 = k_2 \cdot e^{b_2 \cdot (l-\delta)}. \end{cases} \tag{6}$$

Lets assume that the factors b_1 and b_2 are equal on absolute value in both sides of equation system and differs only by the indication, as temperature descending graphical is systematical as for the heating place.

Having solved the system of equations (5) and (6), we find the unknown factors k_1, k_2 and b_1.

Lets substitute the found factors in the equation system (4) and, changing x within the range $\overline{0,l}$, we receive the point of crossing of two graphics which allows to find the highest temperature of conductor in the point of prognosticated insulation damage x′ (fig. 3).

Including noticed above known values, the analytical expression for finding the coordinate of the damage place, received in MathCAD 7 Pro [10], looks like

$$x' = \frac{\ln\left(\frac{t_1}{t_2}\right)\cdot x_3\cdot x_4 - \ln\left(\frac{t_1}{t_2}\right)\cdot x_2\cdot x_3 - \ln\left(\frac{t_2}{t_4}\right)\cdot x_2\cdot x_3 + \ln\left(\frac{t_2}{t_4}\right)\cdot x_1\cdot x_2}{\ln\left(\frac{t_1}{t_3}\right)\cdot x_4 - \ln\left(\frac{t_1}{t_3}\right)\cdot x_2 - \ln\left(\frac{t_2}{t_4}\right)\cdot x_3 + \ln\left(\frac{t_2}{t_4}\right)\cdot x_1} + \tag{7}$$
$$+\frac{\ln\left(\frac{t_1}{t_3}\right)\cdot x_1\cdot x_4 - \ln\left(\frac{t_1}{t_3}\right)\cdot x_1\cdot x_2 - \ln\left(\frac{t_1}{t_2}\right)\cdot x_1\cdot x_4 + \ln\left(\frac{t_1}{t_2}\right)\cdot x_1\cdot x_2}{\ln\left(\frac{t_1}{t_3}\right)\cdot x_4 - \ln\left(\frac{t_1}{t_3}\right)\cdot x_2 - \ln\left(\frac{t_2}{t_4}\right)\cdot x_3 + \ln\left(\frac{t_2}{t_4}\right)\cdot x_1},$$

which after substitution of the corresponding values, looks like

$$x' = \frac{\ln\left(\frac{t_4}{t_2}\right)\cdot 1 - \ln\left(\frac{t_1}{t_2}\right)\cdot \delta}{\ln\left(\frac{t_4}{t_2}\cdot\frac{t_3}{t_1}\right)}. \tag{8}$$

In case when it is possible to receive only three values of conductor temperature of the electric machine under diagnosing, the solution of the task will be found in the following way.

We assume that temperature values on fig. 4.

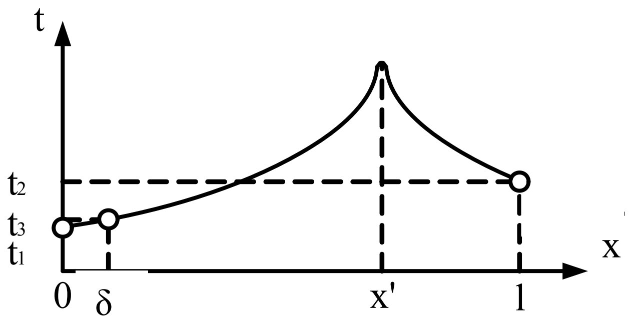

Fig. 4. Graphic illustration of the known parameters for three measured values of temperature.

We make the system of equations analogical to (5), to find factors k_1 and b_1. It is obvious that it is possible to construct a plot which answers the second expression of the equation system(4) and which has to pass through the point with coordinates (l; t_2) (fig. 4).This can be achieved by shifting the plot along the horizontal axis up to the moment of registration with the mentioned point. Having satisfied such a condition we find the point of crossing of both plots (point x′) and the value of the highest temperature of conductor.

Analytical expression which allows to find the ser point, received in MathCAD 7 Pro, looks like

$$x' = \frac{\ln\left(\frac{t_2}{t_1}\right)\cdot x_1 + \ln\left(\frac{t_1}{t_3}\right)\cdot x_2 - \ln\left(\frac{t_1}{t_3}\right)\cdot 1 - \ln\left(\frac{t_2}{t_1}\right)\cdot x_3 + \ln\left(\frac{t_1}{t_3}\right)\cdot x_1}{\ln\left(\frac{t_1}{t_3}\right)}, \tag{9}$$

which after substitution of corresponding values looks like the following expression

$$x' = \frac{\ln\left(\frac{t_2}{t_1}\right)\cdot\delta}{\ln\left(\frac{t_3}{t_1}\right)}. \qquad (10)$$

It should be noted that the suggested method allows to receive only the evaluation of temperature distribution and direction to the detection of the possible insulation damage.

We note that during the solution of the task of searching for place of insulation damage, the factor b_1, which is included into the equation system (4) will acquire different values in both equations. This testifies to the fact that there is more than one insulation damage place in the conductor. It is obvious that such a situation should signal the personnel to assign the electric machine to repair.

Conclusions

The suggested approach serves for the determination of technical state of coils of powerful electric machine in the places with difficult access for thermal imager observation.

There had been developed mathematical model for controlling over the thermal state of coils of electric machine during its operation, application of which allows to determine the places of possible insulation damage with difficult access for research.

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