

Diagnosis of Thermal Processes in Motors of the Electrical Objects

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Abstract. The authors have proposed a candidate solution by the example of identification and synthesis of the system of measuring system performance indicators required to evaluate the electric power quality in this system and, as a consequence, performance quality. The approach proposed in the paper eliminates the need for a wire or radio channel to estimate the temperature of the electric drive in the offshore constructions and to improve the operational reliability.

1. Introduction

The problem of diagnostics of the ship equipment is very relevant. The article presents a review and a partial solution to the problem of the diagnosis and energy complex. In the case of overheating of the drive motor, the recovery of machine efficiency is associated with its replacement under severe environmental conditions. This results in significant installation costs as well as losses due to operational delays in the whole object. In connection with this, assessment of the drive motor windings temperature is an urgent task in order to create a gentle mode of operation.

2. Analysis of published data and the problem statement

This problem may be solved by various methods [1]. The best known methods are based on the use of thermocouples, resistance sensors, capacitors with a capacity depending on the temperature, using one of the motor windings as a primary element. It is proposed to use wire and radio communications to transfer the data. There are indirect methods of measuring the temperature of the eclectic devices based on the use of mathematical models of the process of heating windings of electric motors [2, 3-6]. However, the implementation of computational algorithms proposed earlier, could not provide a sufficiently high accuracy and performance due to the imperfect hardware, which did not allow the handling of large arrays of information in a short period. This led to the need for simplifying the calculations, with the loss of accuracy.

Thus, in particular, two important practical problems remain unresolved: an increase of the accuracy of calculations; exclusion of wire and radio channels for transmitting the data required to estimate the temperature of the windings, the wear rate of the motor insulation in the complex mechanisms.



3. The purpose and objectives of the research

The aim is to improve the quality of the process of diagnosis of the thermal state of the motor windings by developing algorithms for indirect estimation of the temperature in the windings of electrical drives of the complex objects in order to prevent their failure due to drives overheating.

Materials and research techniques.

In the case of electric motors, the design of which cannot accommodate the sensor to measure the temperature, this problem must be solved by calculation. Computational capabilities of modern personal computers allow making such an approach acceptable from a practical point of view.

In order to measure the induction motor winding temperature indirectly, it is necessary, first of all, to develop a mathematical model of the heat transfer. This model should be presented in a form suitable for implementation by means of its microprocessor technology. In addition, the model should allow a simple interpretation and practically acceptable procedure to determine its basic and variable parameters.

Motor winding is a non-uniform heat transfer system from conductors through several layers of insulation to the boundary separating mechanism and the external environment. The high thermal conductivity allows the winding to prevent the absence of significant temperature gradients in some of its points. Thus, despite heterogeneity of heat transfer, it may be considered that the average winding temperature differs slightly from the temperature in each of its points. Parameters of the process of heat transfer may be treated as average. The heat capacity of the environment is infinite; the ambient temperature is constant.

4. Research results

In view of the above comments, the scheme of heat transfer in the system can be reduced to a one-dimensional model of heat transfer through a multilayer wall (Fig. 1).

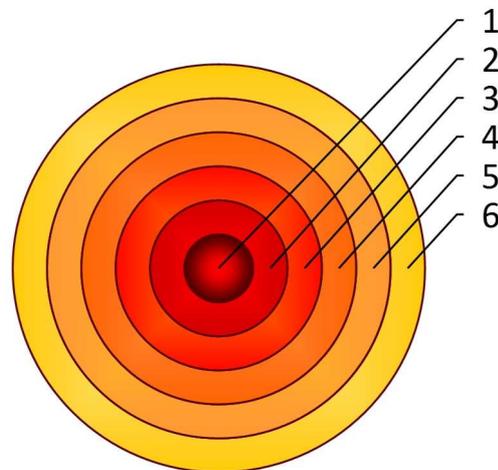


Figure 1. The chart of the heat transfer from the motor windings to the external environment (1 - Electric motor winding; 2 - Electric motor insulation; 3 - Electric motor frame; 4 - The internal part of the mechanism; 5 - Mechanism case; 6 - Ambient environment.).

Let us consider the temperature values at the discrete points evenly distributed in the depth of the multilayer wall, as it is shown in Fig. 1. The principle of assessing the temperature of the motor windings is based on evaluating the energy that is delivered to the motor from the power supply and temperature conditions of the deep-water mechanism operation. The problem is somewhat simplified in that the temperature at the depth varies little throughout the year, and the amount of energy supplied

to the motor may be measured on the surface. The heat transfer equations were obtained by using the heat energy supplied to the motor and consumed across the surface of the mechanism. Let us first consider a simplified model of the heat transfer process for two points: the motor winding and the border of the water surface. The boundary conditions at the left extreme point are represented by equation

$$\frac{dT}{dt} = B_1 V - B_2 (T_1 - T_2) \quad (1)$$

where V is control function (electric power supplied to the motor winding), W ; T_1 and T_2 are temperatures of the winding and the water surface border, respectively, $^{\circ}C$; t is current time, c .

$$B_1 = \frac{1}{C_0 \cdot m_0} (1 - \eta),$$

where C_0 is the specific heat in the winding, $J/^{\circ}C \cdot kg$; m_0 is the winding net weight, kg ; η is the motor efficiency.

$$V = U \cdot I \cdot \cos\varphi,$$

where U is voltage of the supply mains of the motor, V ; I is the current of the motor, A ; $\cos\varphi$ is the coefficient of the motor output.

$$B_2 = (C_0 \cdot m_0)^{-1} \cdot \Lambda \cdot S \cdot l^{-1},$$

where Λ is the thermal conductivity of the gap winding-motor weight, $W/^{\circ}C \cdot m$; S is the square area of the heat transfer section, m^2 ; l is the width of the wall of the motor case, m .

The process of the thermal conductivity is described by equation

$$\frac{dT}{dt} = a \frac{d^2T}{dx^2} \quad (2)$$

where a is the coefficient, $m^2/^{\circ}C \cdot s$.

$$a = \frac{k_i}{c_i \cdot \rho_i},$$

where k_i is the coefficient of the thermal conductivity of the i^{th} section of the ambient environment; c_i is the specific heat of the the i^{th} section of the ambient environment, $J/^{\circ}C \cdot kg$; ρ_i is the density of the the i^{th} section of the ambient environment, kg/m^3 .

Border conditions $T(x, t)$ for the temperature are present in every present i -point. Let us express the above-mentioned model of the heat transfer represented by equations (1) and (2) in a discrete form. Let us take the first index in the notation as the number of the point in the multilayer space; the second index is the number of momentum in the present time. We assume the thermal process in the motor winding with relatively slow integration pitch ΔT . Then, applying to (1) Euler's method, we obtain:

$$T_{1,k+1} = T_{1,k} + (B_1 V_k - B_2 (T_{1,k} - T_{2,k})) \Delta t$$

Equation (2) in the finite differences is

$$T_{2,k+1} = R_2 T_{2,k} + q_2 (T_{1,k} + T_{3,k}),$$

$$T_{3,k+1} = R_3 T_{3,k} + q_3 (T_{2,k} + T_{4,k});$$

$$T_{n,k+1} = R_n T_{n,k} + q_n (T_{n,k} + T_{n,k}).$$

In a more compact form, it is

$$T_{1,k+1} = T_{1,k} + (B_1 V_k - B_2 (T_{1,k} - T_{2,k})) \Delta t; \tag{3}$$

$$T_{j,k+1} = R_j T_{j,k} + q_j (T_{j,k} + T_{j,k}) \quad j = 2, n,$$

where $T_{1,k+1}$ is the right boundary condition; $T_{1,k}$ is the left boundary condition for each interval n along coordinate x ; $R_j = 1 - 2\Delta t \cdot a_j h^{-2}$, for the k^{th} at the time moment; $q_j = \Delta t \cdot a_j \cdot h^{-2}$, for the k^{th} at the time moment. Values R_j and q_j were obtained by applying the Euler's standard procedure of transition from differential equations to linear equations.

Equations (1), (2), (3) include a large number of factors, analytical determination of which is impractical. In practice, the shape of each layer is different from that adopted by the ideal contact, but it is not ideal. The value of equations (1), (2), (3) is presented in their quality content. Specific values of the coefficients can be reliably determined experimentally.

Experimental assessment of the coefficients of system (3) can be produced during pilot scale tests and a process of calibration of the computational algorithm for a specific type-size complex mechanism. After the calibration, coefficients assessed are stored in the processor memory, being used to calculate the temperature of the motor windings. The main objective of this study is the closest assessment of the model general equation regardless of the number of points of the x -axis partitioning and the number of layers. For the sake of reducing the dimension of the problem in this paper, we take the number of partition points along the x -axis to be equal to four [7-11].

If to apply Z-transformation in the system of equations (3) (for $n + Y = 4$) and to solve it with respect to T_1 (winding temperature), T_4 (right boundary value - ambient temperature) and V (supplied to the motor power), we obtain:

$$P(Z^4, Z^3, Z^2, Z^1, Z^0) T_1 = P(Z^1, Z^0) T_4 + P(Z^3, Z^2, Z^1, Z^0) V, \tag{4}$$

where $P(Z^4, Z^3, Z^2, Z^1, Z^0)$ is a polynomial in the parameter Z - transformation.

The difference equation of model (4) after multiplication by Z^3 in the expanded form may be represented as

$$T_1[n+1] = a_1 T_1[n] + a_2 T_1[n-1] + a_3 T_1[n-2] + a_4 T_1[n-3] + b_1 T_4[n-2] + b_2 T_4[n-1] + C_1 V[n] + C_2 V[n-1] + C_3 V[n-2] + C_4 V[n-3], \tag{5}$$

where a_j, b_j, C_j are constant distribution in terms of physical constants, reflecting the thermal properties of elements of the medium "winding - environment" and electric constants.

In the latter equation, the T -boundary value of the temperature is constant. Thus,

$$b_1 T_4[n-2] + b_2 T_4[n-1] = Q = const. \tag{6}$$

As b_1 and b_2 are not known, Q should be determined.

Let us determine unknown values $a_1 - a_4$, $C_1 - C_3$ in two steps. Moreover, conditions are assumed to measure the temperature of the winding and the environment.

Step 1. We define any value of V for the time period sufficient to heat the motor windings to a certain allowable temperature. The value of the temperature can be measured by one of the available methods

After switching off the motor ($V = 0$), equation (5) takes the following form:

$$a_1 T_1[n] + a_2 T_1[n-1] + a_3 T_1[n-2] + a_4 T_1[n-3] + Q = T_1[n-1].$$

Let us measure winding temperature T_1 at different times, differing in pitch value ΔT . This pitch should be equal to the sample spacing, adopted in the calculation of the winding temperature, according to (5). The measurement results can be represented as a system of linear algebraic equations

$$\begin{aligned} a_1 T_1[4] + a_2 T_1[3] + a_3 T_1[2] + a_4 T_1[1] + Q &= T_1[5]; \\ a_1 T_1[5] + a_2 T_1[4] + a_3 T_1[3] + a_4 T_1[2] + Q &= T_1[6]; \end{aligned} \tag{7}$$

$$a_1 T_1[8] + a_2 T_1[7] + a_3 T_1[6] + a_4 T_1[5] + Q = T_1[9].$$

Based on this system, we determine coefficients $a_1 - a_4$ and Q .

Step 2. Once these coefficients are determined, the members of equation (5) containing T_1 at any stage of the experiment with respect to time may be calculated from respective measured values T_1 . All values, which can be known in the next step, are denoted as follows:

$$F[n] = a_1 T_1[n] + a_2 T_1[n-1] + a_3 T_1[n-2] + a_4 T_1[n-3] - Q. \tag{8}$$

Thus, equation (5) may be represented as follows:

$$C_1 V[n] + C_2 V[n-1] + C_3 V[n-2] + C_4 V[n-3] = F[n].$$

The coefficients $C_1 - C_4$ can be calculated if for each time interval we set different voltage values for the motor U . Then we get a system of linear equations in the unknown C_1, C_2, C_3, C_4 . The value of $F[n]$ is obtained (8) by substituting known values T_1 and Q in this expression.

$$\begin{aligned} C_1 V[4] + C_2 V[3] + C_3 V[2] + C_4 V[1] &= F[1]; \\ C_1 V[5] + C_2 V[4] + C_3 V[3] + C_4 V[2] &= F[2]; \\ C_1 V[6] + C_2 V[5] + C_3 V[4] + C_4 V[3] &= F[3]; \\ C_1 V[7] + C_2 V[6] + C_3 V[5] + C_4 V[4] &= F[4]. \end{aligned} \tag{9}$$

In order to simplify the experiment, we provide the voltage of two values at various intervals. For example, either 1 or 0. Then the matrix of system (9) has the following form:

0	1	0	1
1	0	1	0
0	1	0	1
1	0	1	0

Thence, it seems that the 1st and 3^d, 2nd and 4th columns are pairwise equal. The matrix is singular. Consequently, the experiment cannot be performed in this form. The voltage values should be changed in every interval. However, this does not eliminate the possibility of producing the non-singular matrix.

Let us consider another way of describing the sequence of voltage values. At other intervals $V [j]$ there may be a different integer. Let $V = 1$ at 4-7 intervals.

Then the matrix of system (9) has the following form:

1	0	0	0
1	1	0	0
1	1	1	0
1	1	1	0

This matrix is always non-singular and makes it easy to find a solution. Let us firstly determine $C1 = F [1]$, then $C2 = F [2] - C1$.

The calculations may be simplified if all voltages except $V [4]$ is zero. Then $C4 = F [4]$, then all the values of V , except for $V [4]$ and $V [3]$ are equal to zero. Whereas $C3$ is easy to calculate, etc.

5. Conclusions

1. The results may be used to estimate the values of the motor windings temperature of complex electrical facilities.
2. In developing the algorithm, the heat loss in the power cable has not been taken into account, but the calibration of coefficients of the heat transfer model can consider this drawback in detail.
3. The approach proposed in the paper eliminates the need for the wire or radio channel to estimate the temperature of the electric drive in the offshore constructions and to improve the operational reliability.

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