Calculation and Analysis of the Thermal State of the Frequency-Controlled Induction Motor Pump Unit

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Abstract: The article presents the results of the application of a method for calculating the thermal state of a frequency-controlled induction motor of closed design in steady-state heating mode. The study analyzes the excess temperature of thermal bodies, particularly the stator winding of the frequency-controlled induction motor installed in the pumping unit. Previous studies on regulated electric drives based on induction motors have focused on low-voltage induction motor drives for general industrial purposes. However, high-voltage induction motors have distinct specific features in terms of design and operation. The study of thermal processes in such motor drives is mainly based on three research methods: the method of heating thermal parameters, the method of the temperature field, and the method of equivalent thermal circuits. The analysis of these methods of thermal calculation showed that the most acceptable method of thermal calculation of regulated high-voltage induction motors is the method of equivalent thermal circuits (ETC). Based on the analysis of the excess temperature of thermal bodies, in particular the stator winding of the frequency-controlled induction motor installed in the pumping unit, it is shown that the optimal frequency control range lies within 30-50 Hz, that is, the frequency reduction causes an increase in temperature in all thermal bodies of the engine.

1 INTRODUCTION

As is known, most of the studies of electrical, energy and thermal characteristics of the regulated electric drive on the basis of induction motors at different values of mechanical loads on their shaft in order to obtain technical solutions that improve their parameters related to low-voltage induction motor drives for general industrial purposes [1-8]. Despite the fact that high-voltage induction motors have much incommon with low-voltage induction motors in terms of design, they have their own distinct specific features, both in terms of design and operation. The study of thermal processes in such motor drives is mainly based on three research methods: the method of heating thermal parameters, the method of the temperature field and the method of equivalent thermal circuits [9]. The analysis of these methods of thermal calculationshowed that the most acceptable method of thermal calculation of regulated high-voltage induction motors is the method of equivalent thermal circuits (ETC). The essence of this method is to replace the solution of the one-dimensional stationary Laplace equation to such a transformation of the element size, which would contribute to the achievement of the desired numerical result, as well as to obtain two-dimensional solutions by adding the thermal conductivities of one- dimensional, based on the equivalence of thermal circuits with linear electric circuits.

2 METHODS AND MATERIALS

The article presents the results of studies of the main thermal parameters of high-voltage induction motors obtained by the proposed method of calculating the thermal state by drawing up graph models for each thermal body – the active parts of the motor [10] for the steady-state heating of the frequency-controlled induction motor (IM) of closed design. In this case, the resulting power loss between the source and the temperature of the thermal bodies equivalent transmission have a dimension of thermal resistance [11] and therefore they will be called the total thermal resistance of the thermal bodies R_{ii} , as well as thermal resistance between the thermal bodies R_{ij} (where i and j – the order numbers of the thermal bodies), then the final form of the solution of the steady-state heating will take the following form (1)

$$\left.\begin{aligned}\Theta_{1f} &= R_{11f}P_{1f} + R_{12f}P_{2f} + R_{13f}P_{3f};\\ \Theta_{2f} &= R_{21f}P_{1f} + R_{22f}P_{2f} + R_{23f}P_{3f};\\ \Theta_{3f} &= R_{31f}P_{1f} + R_{32f}P_{2f} + R_{33f}P_{3f};\end{aligned}\right\} \tag{1}$$

where $R_{11f} = \dfrac{\Lambda_{11f}\Lambda_{22f}\Lambda_{33f}}{(\Lambda_{11f}\Lambda_{33f} - \Lambda_{13f}\Lambda_{31f})(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})}$;

$$R_{12f} = \frac{\Lambda_{13f}\Lambda_{12f}\Lambda_{22f}}{(\Lambda_{11f}\Lambda_{33f} - \Lambda_{13f}\Lambda_{31f})(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})};$$

$$R_{13f} = \frac{\Lambda_{22f}(\Lambda_{11f}\Lambda_{33f} + \Lambda_{12f}\Lambda_{21f})}{(\Lambda_{22f}\Lambda_{33f} - \Lambda_{23f}\Lambda_{32f})(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})};$$

$$R_{21f} = \frac{\Lambda_{21f}\Lambda_{33f}\Lambda_{11f}}{(\Lambda_{11f}\Lambda_{33f} - \Lambda_{13f}\Lambda_{31f})(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})};$$

$$R_{22f} = \frac{\Lambda_{33f}\Lambda_{11f}\Lambda_{22f}}{(\Lambda_{11f}\Lambda_{33f} - \Lambda_{13f}\Lambda_{31f})(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})};$$

$$R_{23f} = \frac{\Lambda_{12f}\Lambda_{11f}\Lambda_{33f}}{(\Lambda_{22f}\Lambda_{33f} - \Lambda_{23f}\Lambda_{32f})(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})};$$

$$R_{31f} = \frac{\Lambda_{12f}\Lambda_{33f}\Lambda_{11f}}{(\Lambda_{22f}\Lambda_{11f} - \Lambda_{12f}\Lambda_{21f})(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})};$$

$$R_{32f} = \frac{\Lambda_{13f}\Lambda_{22f}\Lambda_{11f}}{(\Lambda_{11f}\Lambda_{22f} - \Lambda_{12f}\Lambda_{21f})(\Lambda_{22f}\Lambda_{33f} - \Lambda_{23f}\Lambda_{32f})};$$

Further, in Figure 1 the changes of total thermal resistances for IM of A4-457-UH-8UZ type at frequency control in the range of 30-50 Hz are presented. As can be seen, the total thermal resistance of thermal bodies of IM with a decrease in the frequency have the character of increasing. The total thermal resistance of the stator winding and the stator steel (R_{11f} and R_{22f}) with a decrease in the frequency value increases slightly, but the total resistance of the rotor R_{33f} increases at a sufficiently high rate, which is associated with a deterioration in the intensity of the airflow.

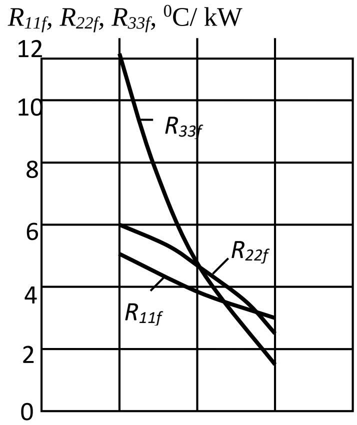

Figure. 1: The change of the total thermal resistances of the thermal bodies of frequency-controlled IM of A4-457-UH-8UZ type in frequency function.

In Figure 2, the changes of thermal resistances between thermal bodies of IM of A4-457-UH-8UZ type at frequency control in the range of 30-50 Hz are presented. As can be seen from the Figure 2, the thermal resistance between the thermal bodies of IM also has an increasing character, but their increases are insignificant. In (Figure 3), the changes of power losses of thermal bodies of IM of A4-457-UH-8UZ type at frequency control are presented, when the law of frequency control in the range of 30-50 Hz for the fan type of load is realized.

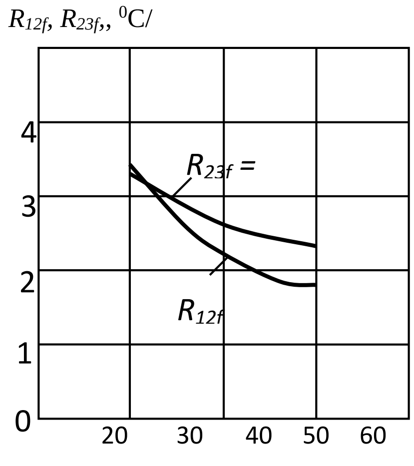

Figure 2: Changes of the thermal resistances between the thermal bodies of frequency-controlled IM of A4-457-UH-8UZ type in frequency function.

All the power losses of thermal bodies of this IM with a decrease in the frequency (respectively the decrease of mechanical power on the motor shaft in proportion ω^2) are also reduced according to the nonlinear law [11, 12, 13].

3 RESULTS AND DISCUSSION

Patterns reduce the loss of heat capacities of all thermal bodies are almost identical. Since in the frequency range 30-50 Hz, the power losses of the rotor IM P3f vary, due to the fact that they consist of electrical losses of the rotor winding (with a decrease in the load, respectively, the current decreases, and electrical losses decrease in proportion to the square of the relative change in the nominal value) as well as losses in the bearings (mechanical losses are associated with a quadratic rate of change) and therefore both losses decrease with a decrease in frequency [14,15].

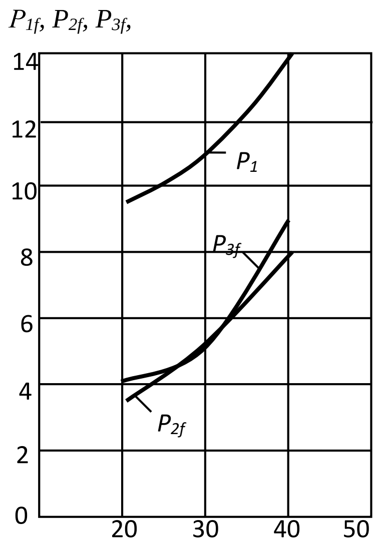

Figure 3: Changes of the power losses of thermal bodies of frequency-controlled IM of A4-457-UH-8UZ type in frequency function.

With the help of the obtained thermal model for each thermal body and solving a system of equations (1), let us determine the excess temperature Θ_{1f}, Θ_{2f}, Θ_{3f} in some parts of the frequency-controlled IM of A4-457-UH-8UZ type in the implementation of the fan nature of the load (Figure 4) [16, 17, 18, 19, 20]. Exceeding the temperature of all thermal bodies of IM at the beginning of the frequency change at a frequency of 40 Hz is reduced, which is associated with a decrease in the power loss of thermal bodies with a decrease in the mechanical load on the motor shaft. At this frequency, there are minor increases in all types of thermal resistances, which especially do not show their effects on the values of excess temperature of thermal bodies, that is, the change in the speed of rotation of the IM has little effect on them. In the frequency range from 30 to 50 Hz due to the decrease in the intensity of the airflow of thermal bodies, a sharp decrease in the power loss occurs, and, despite these excess temperatures of thermal bodies, they reach values corresponding to their nominal values [21, 22. 23, 24, 25, 26].

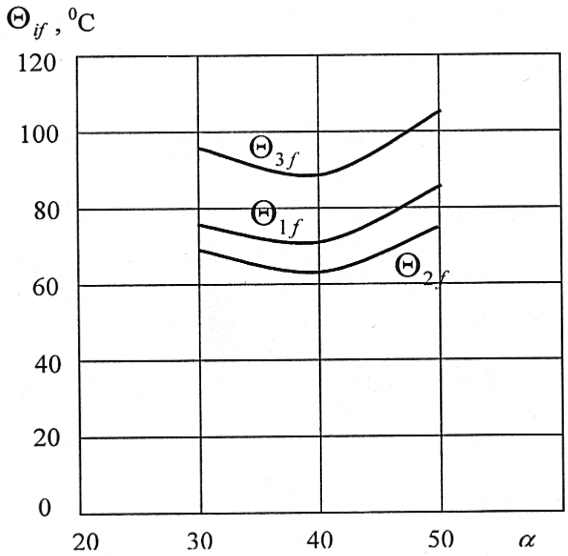

Figure 4: Changes, exceeding the temperature of thermal bodies of frequency-controlled IM of A4-457-UH-8UZ type in the frequency function.

Analysis of the excess temperature of thermal bodies, in particular the stator winding Θ_{1f} of frequency-controlled IM of A4-457-UH-8UZ type (installed in the pumping unit) shows that the optimal frequency control range is 30-50 Hz, that is, a decrease in the frequency cause an increase in temperature in all thermal bodies of the motor. This is due to the design of this type of IM, since this motor having a protected design is blown by a fan located on the shaft of its rotor. Since the performance of the fan is directly related to the speed of rotation of the IM rotor, at low speeds of its rotation, the latter does not contribute to improving the airflow of the motor components.

4 CONCLUSIONS

In order for the IM to work consistently throughout the frequency control range, it is necessary to use an autonomous ventilation system that would allow even at low speed values (rotation frequencies) to improve the degree of air flow of thermal bodies, which in turn will reduce the values exceeding the temperatures of thermal bodies of the frequency-controlled IM pump unit.

Summarizing the above, it can be noted that the developed method for studying the steady-state heating mode of a frequency-controlled induction motor on the basis of a graph model of equivalent thermal circuits allows:

1) To determine the main thermal parameters and the excess temperature of the thermal bodies of the frequency-controlled induction motor;
2) To identify the optimal range of speed control (frequency), taking into account the thermal state of the stator winding.

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