INVESTIGATION OF THE HEATING PROCESSES AND TEMPERATURE FIELD OF THE FREQUENCY-CONTROLLED ASYNCHRONOUS ENGINE BASED ON MATHEMATICAL MODELS

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Abstract

The study of the temperature field of the engine for non-stationary modes is done. A numerical simulation of a non-stationary thermal process using dynamic EHD, the characteristic of the rate of rise of temperatures is done. An increase in the temperature of individual parts in the idle interval, when the power of heat release is significantly reduced, is established, and the reverse of the heat flow through the air gap is established. It is shown that the EHD method, in contrast to the FEM, is self-sufficient, which determines its practical value. In various parts of the speed control range in the implementation of various laws of regulation. At the same time, the main electrical, magnetic and additional losses associated with the fundamental voltage harmonics (FVH), and mechanical losses, as well as additional electrical and magnetic losses associated with the higher voltage harmonics, change. When using serial asynchronous engines as frequency-controlled. Permissible under the conditions of heating power is significantly reduced by the power of serial engines. Depending on the synchronous speed, the reduction is from 10 % to 20 %. Given the additional overheating due to higher voltage harmonics, as well as the deterioration of the cooling conditions when adjusting the rotational speed "down" from the nominal, it seems very relevant.

Keywords: thermal control of an electric engine, equivalent e circuits of temperature processes in an electric engine

1. Introduction

The peculiarity of frequency-controlled asynchronous engines is work on different parts of the rotation speed control range when implementing various control laws. At the same time, the main electrical, magnetic and additional losses associated with the fundamental voltage harmonics (FVH), and mechanical losses, as well as additional electrical and magnetic losses associated with the higher voltage harmonics, change.

When using serial asynchronous engines as frequency-controlled, the power allowed by the heating conditions is significantly reduced by the powers of the serial engines. Depending on the synchronous speed, the reduction is from 10 % to 20 %.

Thus, the task for non-stationary modes, taking into account additional overheating due to higher voltage harmonics, as well as deterioration of cooling conditions when adjusting the rotation frequency "down" from the nominal one, seems to be very relevant.

The analysis of the state of the problem of asynchronous frequency-controlled engines under various laws of regulation, load values and types of power sources made it possible to formulate the main objectives of the study.

The solution of the tasks will allow to objectively predict the power sources in stationary.

Taking into account the gained experience and analyzing the latest achievements in this field, it is necessary to conclude that the creation of a mathematical model is relevant.

The problem of diagnostics and prediction of thermal processes in variable frequency asynchronous engines is the subject of many scientific papers. Works on the study of heating processes and on the basis of mathematical models are displayed in scientific works on the optimization of energy consumption [1], which requires quite serious material costs and cannot be used as a universal tool. Other work to optimize the control of the temperature characteristics of the engine [2] is aimed at solving one existing problem and does not cover the problem as a whole. In [2], the authors' attention is directed to finding solutions for monitoring current temperature parameters when using a thermal model of an induction machine. The findings in [2] show that it is necessary to create a general mathematical model for monitoring engine temperature parameters.

In [3], it is proposed to use sensors for monitoring the temperature parameters of the engine, when combined with the existing model for calculations. Studies show that the universal component that allows to solve this problem does not exist and is necessary for each specific engine. Especially when it concerns the experimental part of the study, where each sensor is configured separately and requires special, individual parameters.

Simulation programs [4], compiled thanks to the obtained mathematical models, make it possible to more accurately describe the thermal processes taking place in a running engine and can serve as a good tool for designing new types of electric engines. However, the existing types of engines used in urban electric transport, which work in conjunction with the control system and are largely dependent on engine speed control technologies, require the compilation of mathematical models for the system as a whole.

The considered methods for controlling temperature characteristics [5] allow more precise control of heating processes and obtaining accurate data from sensors. It should also be noted that the proposed new methods with network sensors with replacement grids make it possible to conduct experiments more optimally, but the disadvantage of such methods is rather expensive equipment and the necessary experimental base.

In [6], it is shown how to optimally control the output parameters of electric engines. Special attention should be paid to the output parameters in the digital version. These converters allow to most accurately describe the processes and temperature changes in the engine. Display and analysis of the received information, which allows to collect statistical data on the operation of the electric engine and on the basis of this information to predict the work as a whole.

But the existing variety of engines does not allow to fully apply these techniques. Although this material is necessary for further research.

As shown in [7], the method for analyzing heat losses in AC machines, where they are taken into account using sensors and information processing tools, makes it possible to more accurately describe the processes occurring inside the engine. But this technique is limited to those processes that are hidden from the field of the observer.

Analyzing the literature sources described above, we can conclude that this direction is not fully developed and requires more detailed research, in particular, this concerns equivalent thermal replacement schemes for asynchronous electric engines.

The aim of research is improvement of the mathematical model of heating processes. To achieve this aim it is necessary to solve the following objectives:

– investigate the moving modes of heat exchange of the engine parts at the initial cycles;

– establish the range of oscillations within one cycle in a quasi-stationary mode with intermittent mode;

– theoretically substantiate using the proposed model of non-stationary modes.

2. Materials and methods of research
2. 1. Application of the investigation of the heating process of the electric engine

The heat generated in the active elements [8] is distributed throughout the volume of the machine and transferred to the cooling medium using the cooling system. Thus, in the volume of the machine there are heat flows and temperature differences between the individual elements of

the structure. In this case, a stationary heat process is distinguished, characterized by the constancy of heat fluxes and temperatures at any point of the machine, and a non-stationary heat process characterized by a continuous change in heat fluxes and temperatures [9].

A feature of thermal processes in engines is the presence of additional electrical losses. The values of these losses depend on the type of power source, the regulation factor and the law of regulation and can reach up to 20 % of the main engine losses in the nominal mode. The presence of additional electric losses changes the relations between components of losses that are usual for unregulated engines and leads to a change in the structure of the temperature field of the engine. Particularly significant impact of additional losses in the field of small engine loads [10].

2. 2. Investigation of the moving mode of heat exchange of engine parts at the initial cycles

The most reliable and well tested in the practice of designing and researching series and individual asynchronous engines. For example, the analysis [10] is carried out using the EHD method, this also applies to [11]. Let's note that the proposed EHD is composed with very substantial assumptions:

– rotor core and short-circuited winding are considered as one body, but thermal connection with the shaft;

– engine cooling is symmetrical; the drive and fan sides are combined into one element;

– continuously varies from heating the air along the length of the fins, equivalent to the use of average values along the length of the fins;

– influence of "through" heat fluxes is not taken into account [3–5].

The difference between the temperatures of the internal air and the bearing shields on the drive side and on the fan side reaches 10–15°.

In this regard, EHD of the closed blown engine [9] was adopted as the base, which we adapted to the working conditions.

2. 3. Establishing the range of temperature fluctuations

Sources of heat EHD, including the main electrical and magnetic losses, mechanical losses, real additional losses and additional losses associated with higher voltage harmonics:

P_4 – magnetic losses in the teeth of the stator core, including the main magnetic losses, the real additional losses associated with the FVH, additional magnetic losses associated with the AVH;

P_6 – magnetic losses in the back of the stator core, which include the main magnetic losses, real additional losses associated with FVH, additional magnetic losses associated with AVH.

The real additional losses associated with FVH, as shown by experimental studies [5–10], are significantly higher than the standard (0.5 %, P_{st}), which is taken into account with the aid of the coefficient of additional losses, K_d. In this case, it is assumed that half of the real additional losses are included in the magnetic losses of the teeth and the back of the stator core (separation is proportional to their masses), half of the real additional losses are included in the electric losses of the rotor winding:

P_7 – including the main electrical losses and additional electrical losses associated with AVH;

$P_8 = P_9$ – including the main electrical losses and additional electrical losses associated with AVH;

$P_{10} = P_{11} = 0,5 P_{vent}$, where P_{vent} – ventilation losses, determined by the results of the hydraulic calculation of the internal cooling circuit;

P_{14} – losses in the rotor, including the main, half of the real additional losses, additional magnetic losses in the teeth of the rotor core, additional electrical losses in the rotor winding. The last two components of additional losses are associated with AVH;

P_{16} – additional magnetic losses in the back of the rotor core from the action of AVH.

To account for changes in the heat transfer coefficient of the finned case, the latter is divided in length into three parts: the "hanging" part of the case on the fan side, the part of the case in

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contact with the stator core, the "hanging" part of the case on the drive side. The heat transfer coefficient averages for each part of the body were determined according to [8–11] taking into account the quality factor of the fins. Resistances R_{01}, R_{02}, R_{03} are the thermal resistance of the heat transfer of the finned blown body.

The temperature of nodes 4 and 6 (the teeth and the back of the stator core) are determined by their own losses and the "through" heat flow from the rotor. Resistances $R_{4.5}$ and $R_{2.6}$ are thermal resistances of the teeth and the backs of the stator core, while the thermal resistance of the contact, due to the presence of an equivalent air gap in the contact, is included in $R_{2.6}$ and resistances $R'_{4.14}$ and $R_{5.6}$ are included in the EHD to take into account the "through" heat flux [5].

2. 4. Theoretical substantiation of the use of the technique

The thermal connection between the teeth and the back of the stator core is reflected by the $R_{4.7}$ resistances and $R_{5.7}$, accordingly, these resistances include the internal resistances of the winding, the resistance of the slot insulation, and the resistance of the air layers.

Axial thermal resistances of the stator and rotor windings – $R_{7.8}=R_{7.9}$ and $R'_{10.14} = R'_{11.14}$, respectively.

Thermal resistances from $R_{8.10}=R_{9.11}$ and $R''_{10.14} = R''_{11.14}$, respectively. In this case, resistances $R_{8.10}=R_{9.11}$ are considered as parallel-connected resistances of the outer (facing the body) and inner layers of the frontal parts.

Thermal resistances $R_{1.10}=R_{3.11}$ and $R_{10.12}=R_{11.13}$ reflect the thermal connection of the internal air with the "hanging" parts of the body and with the bearing shields from the drive side, and the resistances $R_{12.0}$ and $R_{13.0}$ thermal connection of the outer surface of the bearing shields with the ambient air.

The thermal resistance of the housing and the shaft in the axial direction is reflected by the resistances $R_{1.2}=R_{2.3}$ and $R'_{10.15} = R'_{11.15}$, respectively.

The thermal coupling of the rotor core and the shaft is taken into account by the resistance $R_{16.15}$, which includes the contact resistance due to the presence of an equivalent air gap in the contact.

Preliminary calculations show, and this heat flow could be neglected, especially since with a sinusoidal form in the core of the rotor are practically absent. However, with frequency regulation, magnetic losses occur in the rotor core.

Thermal resistance $R^*_{4.14}$ is the air gap resistance.

The feature of the EHD rotor part is taken into account, namely: the absence of magnetic losses in the rotor core with a sinusoidal power supply of the engine and their presence under the action, the thermal resistance of the metering through flow $R_{14.16}$ is calculated as a lossless wall. Thermal resistance $R_{16.15}$ is similarly calculated.

The calculation of all EHD thermal resistances is carried out in accordance with [4–7].

The calculation results are shown in **Table 1** in K/W. The values of resistances $R_{16.15}$ and $R_{14.16}$ are determined in the presence and absence of AVH additional magnetic losses – R_{magv}.

Table 1

The values of EHD thermal resistance of the investigated engine

$R^*_{0.1}$	$R^*_{0.2}$	$R^*_{0.3}$	$R_{1.2}=R_{2.3}$	$R_{2.6}$	$R_{2.5}$
0,02155	0,02721	0,04071	0,09062	0,00628	0,0058
$R_{5.6}$	$R_{4.7}$	$R_{5.7}$	$R^*_{4.14}$	$R_{7.8}=R_{7.9}$	$R_{8.10} = R^*_{9.11}$
0,004526	0,02665	0,3265	0,1701	0,05157	0,1706
$R_{10.12} = R^*_{11.13}$	$R_{1.10} = R^*_{3.11}$		$R^*_{13.0}$	$R'_{10.14} = R'^*_{11.14}$	$R''_{10.14} = R''^*_{11.14}$
0,1301	0,1209	0,2064	0,4128	0,0245	0,2458
$R_{16.15}$ $P_{magv}=0$	$R_{16.15}$ $P_{magv}\neq0$	$R_{14.16}$ $P_{magv}=0$	$R_{14.16}$ $P_{magv}\neq0$	$R'_{10.15} = R'_{11.15}$	$R''_{10.15} = R''_{11.15}$
0,03943	0,02376	0,0474	0,01618	0,5153	2,03

For all EHD nodes, the heat balance equations are compiled, and the series-connected resistances in the EHD branches are combined. The thermal resistances of the branches are replaced by thermal conductivities, while in the equations of thermal balance distinguish the intrinsic thermal conductivities of the nodes λ_{ii}, equal to the sum of the thermal conductivities of all the branches converging at this node. For example, for the i-th and j-th nodes this is the conductivity of the branch connecting the i-th and j-th nodes, moreover $\lambda_{ij}=\lambda_{ji}$. If there is no thermal connection between the i-th and j-th nodes, then $\lambda_{ij}=\lambda_{ji}=0$, including:

– study of the structure of the engine;

– study of the influence of the engine load voltage;

– study of the influence of the engine regulation law with sinusoidal and stepped voltage forms.

The system of equations has the form (1).

In the body heat balance equation, the cooling air temperature values (Θ_{01}, Θ_{02}, Θ_{03}) in the respective sections along the length of the case: the "hanging" part from the fan side, the part, "hanging" part from the drive side.

Calculation of temperatures Θ_{01}, Θ_{02}, Θ_{03} and heating of the cooling air $\Delta\Theta_a$ is carried out the values of the total power loss $\left(\sum P + \sum P_{addv}\right)$ in the $\Delta\Theta_a$ calculation.

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\left.
\begin{aligned}
&\theta_1 \cdot (\lambda_{0.1} + \lambda_{1.2} + \lambda_{1.10}) - \theta_2 \cdot \lambda_{1.2} - \theta_{10} \cdot \lambda_{1.10} = \theta_{01} \cdot \lambda_{0.1}; \\
&-\theta_1 \cdot \lambda_{1.2} + \theta_2 \cdot (\lambda_{0.2} + \lambda_{1.2} + \lambda_{2.6}) - \theta_3 \cdot \lambda_{2.3} - \theta_6 \cdot \lambda_{2.6} = \theta_{02} \cdot \lambda_{0.2}; \\
&-\theta_2 \cdot \lambda_{2.3} + \theta_3 \cdot (\lambda_{0.3} + \lambda_{2.3} + \lambda_{3.11}) - \theta_{11} \cdot \lambda_{3.11} = \theta_{03} \cdot \lambda_{0.3}; \\
&\theta_4 \cdot (\lambda_{4.5} + \lambda_{4.7} + \lambda_{4.14}) - \theta_5 \cdot \lambda_{4.5} - \theta_7 \cdot \lambda_{4.7} - \theta_{14} \cdot \lambda_{4.14} = P_4; \\
&-\theta_4 \cdot \lambda_{4.5} + \theta_5 \cdot (\lambda_{4.5} + \lambda_{5.6} + \lambda_{5.7}) - \theta_6 \cdot \lambda_{5.6} - \theta_7 \cdot \lambda_{5.7} = 0; \\
&-\theta_2 \cdot \lambda_{2.6} - \theta_5 \cdot \lambda_{5.6} - \theta_6 \cdot (\lambda_{2.6} + \lambda_{5.6}) = P_6; \\
&-\theta_4 \cdot \lambda_{4.7} + \theta_7 \cdot (\lambda_{7.8} + \lambda_{4.7} + \lambda_{5.7} + \lambda_{7.9}) - \theta_8 \cdot \lambda_{7.8} - \theta_9 \cdot \lambda_{7.9} = P_7; \\
&-\theta_7 \cdot \lambda_{7.8} + \theta_8 \cdot (\lambda_{7.8} + \lambda_{8.10}) - \theta_{10} \cdot \lambda_{8.10} = P_8; \\
&-\theta_7 \cdot \lambda_{7.9} + \theta_9 \cdot (\lambda_{7.9} + \lambda_{9.11}) - \theta_{11} \cdot \lambda_{9.11} = P_9; \\
&-\theta_1 \cdot \lambda_{1.10} - \theta_8 \cdot \lambda_{8.10} + \theta_{10} \cdot (\lambda_{1.10} + \lambda_{8.10} + \lambda_{10.12} + \lambda_{10.14} + \lambda_{10.15}) - \\
&-\theta_{12} \cdot \lambda_{10.12} - \theta_{14} \cdot \lambda_{10.14} - \theta_{15} \cdot \lambda_{10.15} = P_{10}; \\
&-\theta_3 \cdot \lambda_{3.11} - \theta_9 \cdot \lambda_{9.11} + \theta_{11} \cdot (\lambda_{3.11} + \lambda_{9.11} + \lambda_{11.13} + \lambda_{11.14} + \lambda_{11.15}) - \\
&-\theta_{13} \cdot \lambda_{11.13} - \theta_{14} \cdot \lambda_{11.14} - \theta_{15} \cdot \lambda_{11.15} = P_{11}; \\
&-\theta_{10} \cdot \lambda_{10.12} + \theta_{12} \cdot (\lambda_{10.12} + \lambda_{12.0}) = P_{12} + \theta_{01} \cdot \lambda_{12.0}; \\
&-\theta_{11} \cdot \lambda_{11.13} + \theta_{13} \cdot (\lambda_{11.13} + \lambda_{13.0}) = P_{13} + \theta_{01} \cdot \lambda_{13.0}; \\
&-\theta_4 \cdot \lambda_{4.14} - \theta_{10}\lambda_{10.14} - \theta_{11} \cdot \lambda_{11.14} + \\
&+\theta_{14} \cdot (\lambda_{4.14} + \lambda_{10.14} + \lambda_{11.14} + \lambda_{14.16}) - \theta_{16} \cdot \lambda_{14.16} = P_{14}; \\
&-\theta_{10} \cdot \lambda_{10.15} - \theta_{11} \cdot \lambda_{11.15} + \theta_{15} \cdot (\lambda_{10.15} + \lambda_{11.15} + \lambda_{15.16}) - \theta_{16} \cdot \lambda_{15.16} = 0; \\
&-\theta_{14} \cdot \lambda_{14.16} - \theta_{15} \cdot \lambda_{16.15} + \theta_{16} \cdot (\lambda_{14.16} + \lambda_{16.15}) = P_{16}.
\end{aligned}
\right\} \quad (1)
$$

Let's take:

$$
\left.
\begin{aligned}
\Theta_{01} &= \Theta_{amb}, \\
\Theta_{02} &= \Theta_{01} + \frac{\Delta\Theta_a}{2}, \\
\Theta_{03} &= \Theta_{01} + \Delta\Theta_a,
\end{aligned}
\right\} \quad (2)
$$

where Θ_{amb} – ambient temperature.

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The calculation results are shown in **Table 1** of the regulation coefficient.

For all values of α and all laws of regulation let's take $\Theta_{01}=\Theta_{amb}=25°$.

3. Non-stationary modes

In thermal terms, an electric machine in a non-stationary mode, while significantly complicating the decision. If refuse to consider the temperature fields inside each individual element of the electric machine, the non-stationary thermal process can be described. In our case, the number of bodies equals the number of EHD nodes. For each body (node) is compiled [9].

$$\left.\begin{array}{l} C_1 \dfrac{d\Theta_1}{dt} = \left(-\sum_{i=2}^{m} \lambda_{i1}\right) \cdot \Theta_1 + \sum_{i=2}^{m} \left(\lambda_{i1} \cdot \Theta_i\right) + P_1 \\[2ex] C_2 \dfrac{d\Theta_2}{dt} = \left(-\sum_{i=1}^{k(i\neq 2)} \lambda_{i2}\right) \cdot \Theta_2 + \sum_{i=1}^{k(i\neq 2)} \left(\lambda_{i2} \cdot \Theta_i\right) + P_2 \\[2ex] \ldots \\[1ex] C_n \dfrac{d\Theta_n}{dt} = \left(-\sum_{i=1}^{q(i\neq n)} \lambda_{in}\right) \cdot \Theta_n + \sum_{i=1}^{q(i\neq n)} \left(\lambda_{in} \cdot \Theta_i\right) + P_n \end{array}\right\}, \tag{3}$$

where C_1–C_n – heat capacity of the nodes; Θ_1–Θ_n – node temperatures; λ_{i1}–λ_{in} – thermal conductivities from one of the neighboring nodes i to this node 1–n; P_1–P_{1n} – heat generation power in the given node 1–n; t – the current time.

Here m – the number of bodies having thermal connection with the first body ($n=1$); k – the number of bodies having a thermal bond with the second body ($n=2$).

Taking into account the accepted terminology $\sum_{i=2}^{m} \lambda_{i1}$ is the intrinsic thermal conductivity of the first node, and λ_{i1} in the second term of the right side of the first equation there are mutual thermal conductivities of the first node with all m nodes having a thermal connection with the first node different from zero.

Thus, the proposed EHD of the closed, blown calculation of non-stationary (dynamic) thermal states, but each node must be supplemented with the corresponding heat capacity. Hereinafter, EHD will be called "dynamic EHD", in contrast to the previously considered "stationary EHD".

The calculation of the heat capacities of the nodes is carried out by the expression

$$c_i = c_{isp} \cdot m_i, \tag{4}$$

where c_{isp} – specific heat capacity of the material of the i-th node (copper, aluminum, electrical steel, air, structural steel, insulation of grooves); m_i – mass of the material of the i-th node, kg.

All masses are determined based on a known engine design.

Let's note that the heat capacity of the air in the internal cavities of the engine is much less than the heat capacities of the remaining EHD nodes, however, in order to preserve the structure of the equations during the transition from stationary EHD to dynamic, this heat capacity must be taken into account.

When recording EHD nodes, as well as when writing algebraic equations, the thermal resistances are replaced with thermal conductivities, and the thermal connections of all the nodes between them are taken into account. However, if there is no real thermal connection between the i-th and j-th nodes, the thermal conductivity λ_{ij} is taken to be equal to zero.

The equations are written relative to the temperature of the nodes of dynamic EHD. Θ_{01} – ambient temperature, Θ_{02}, Θ_{03} – air temperature in the external circuit with regard to heating.

4. Discussion of the research result

Based on the research and improvement of the mathematical model, stationary and dynamic EHD have been developed, adapted to the working conditions of the IP44, IC0141 version, con-

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taining 16 nodes and allowing, in contrast to the widely used symmetrical EHD of asynchronous engines with a limited number of nodes (from 4 to 8):

– significant irregularity of heating;

– heating of the cooling air in the inter-fin ducts along their length;

– essential asymmetry of heating of internal air, bearing boards and the parties of the drive and the fan;

– presence of additional changes;

– influence of "through" heat fluxes in the back and the teeth of the stator core and in the back of the rotor core;

– change of the convective components of the matrix of thermal conductivities and the law of regulation;

– change in the variable part of the matrix of thermal conductivities.

In non-stationary modes of operation, allowing to investigate the engine in power modes from a source of sinusoidal voltage and from phase voltage at different values of load.

In stationary modes with $\gamma=\alpha=1,0$ and change the load of the engine allowed to establish:

– occurrence in mode A (step-shaped voltage) changes the magnitudes and ratios between the heat release powers of the EHD nodes and the thermal conductivities by mode B (sinusoidal voltage form). This leads to a difference in the values and temperature ratios of EHD nodes;

– additional magnetic losses of P_{magn} are 6 % of the main magnetic losses and the temperature of the engine cores cannot. The difference of these temperatures;

– additional electrical losses of R_{el1n} and R_{el2n} of the engine load, the temperature of the windings is most significant at low loads, when R_{el1n} is commensurate with the basic electrical losses of R_{el1}, and R_{el2n} significantly exceeds the basic electrical losses of R_{el2}. As the engine load increases, the effect of additional electrical losses is significantly reduced, which follows from a comparison of the dependences of the temperature of the windings and engine cores on the useful value. In addition, the presence of R_{eln} in mode A changes the ratio of temperatures between EHD nodes in comparison with mode B. A significant increase in rotor winding temperatures in mode A leads to a decrease in the relative temperatures of the remaining EHD nodes in comparison with their values in mode B;

– the structure of the temperature field of the engine can be reflected using axial and radial temperature distribution along the EHD nodes. Axial distribution: from the shield from the fan side to the shield from the drive side includes a stator winding branch and a rotor branch. Radial distribution: from the shaft to the middle part of the finned hull. It is established that the axial temperature distribution along the stator winding branch has a saddle shape, due to different conditions, a bell-shaped shape along the rotor branch. The latter is due to the presence of intensively cooled ventilation blades at the ends of the rotor, while the winding rods are the most heated part of the engine. This is true for all load values. The radial temperature distribution, being monotonous and uniform at low loads in mode B, undergoes a "jump" in temperatures for "Jump" due to the presence of additional electrical losses R_{el2n} in mode A. As the load increases, the slope of the radial temperature distribution curves increases due to the influence of both the main and the distance from the selection point R_{el1n} and R_{el2n} and their influence weakens and the temperature distribution curves and only slightly differ in the base node Θ_{02} (ambient air in the middle part of the outer cooling circuit);

– one-sided blowout of the finned body leads to asymmetry of temperature distribution along the engine. The greatest degree of irregularity is noted for the finned body and is due to the decrease in the heat transfer coefficient along the length of the fins and the ratio of the thermal conductivities of the paths of heat supply to the body from the internal air and from the stator core. The highest degree of temperature asymmetry is noted for bearing shields, which is due to the significant difference in their heat transfer coefficients from the drive side;

– difference in the temperature of the EHD nodes causes the difference in the heat fluxes, the values of which were determined according to the Fourier law. This difference is most significant for the rotor winding;

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– flows from the finned body to the ambient air q_{k1}, q_{k2}, q_{k3} are 28 %, 54 %, 18 %, respectively, of their sum for both power modes, i. e. finned body with ambient air playing heat flow from the site.

The study of the temperature field of the engine in stationary modes allows to establish:

– thermal condition of the engine;

– when regulating "down" from the nominal rotation speed 1,0≥α≥0,5 with proportional regulation and α=0,5 when the temperature of the engine structural elements Θ_i increase on average by the engine by 29.6 % of their value at α=1,0. With the law of quadratic regulation α=0,5 and at α=0,5 of temperature Θ_i % of their value at α=1,0;

– when regulating "up" from the nominal rotation speed (1,0≥α≥0,5) according to the regulation law at a constant net power and at α=1,5 Θ_i temperature decrease on average by the engine by 28.6 % of their value at α=1,0. At the regulation law at a constant net power and constant voltage and at α=1,5 Θ_i temperature decrease on average by an engine by 16.9 % of their value at α=1,0;

– considered laws of regulation have a different impact on the thermal state of the engine. The greatest changes in temperature in the direction of decrease and increase, starting from the nominal modeγ=α=1,0, take place under regulation according to the laws of quadratic and proportional regulation, respectively;

– effect of additional losses from the higher harmonics of the voltage loss $\sum P_{lossv}$ on the thermal state of the frequency-controlled asynchronous engine depends on the direction of change of the main $\sum P$, additional $\sum P_{lossv}$ losses and the conditions of engine cooling in the process of controlling the rotational speed. This effect is most significant under the law of proportional regulation, with regulation "down" and law of regulation with constant power at regulation "up";

– studies of the temperature field of a frequency-controlled asynchronous engine under various laws of regulation make it possible to assess the thermal "risks" and thermal "reserves" inherent in these laws and thereby ensure, on the one hand, the reliability of the engine required from the heating point of view, and on the other hand, optimal the use of the installed capacity of the electric drive;

– implementation of a predetermined thermal state of the engine during the transition from mode B to mode A is possible due to the correction of the value of the useful power, in accordance with the obtained dependence ΔP_2 %=$f(\Theta_7)$.

The limitations of this study are the limited dependencies created by this model, which allow measurements and prediction of engine operation within certain limits. The reason for this limitation is the insufficient universality of the mathematical model, which is unable to reflect and take into account all the thermal processes occurring in the electric engine. The next research step in this direction should be done in the direction of testing the theoretical results obtained in a more complex diagnostic design using thermal sensors, using the example of a thermal imager, which records temperature changes in a wide radiation spectrum.

An algorithm has been developed for determining the useful power of a frequency-controlled asynchronous engine that is permissible under the conditions of a given heating for various laws of frequency regulation. The algorithm is based on the use of an improved mathematical model of the thermal state.

5. Conclusions

The study of the temperature field of the engine in non-stationary modes allows to establish the following.

When numerically modeling a non-stationary thermal process using dynamic EHD, the characteristic of the slew rate when it is turned on can be the proposed parameter $t_{i(0,95)}$, the proximity $t_{i(0,95)}$, of individual structural elements of an asynchronous engine of IP44, IC0141 has a pronounced local character.

From this study in connection with the tasks, it is possible to formulate the obtained solutions:

– at the interleaved mode $S6$, the heat exchange of the engine parts during the initial cycles differs significantly from the heat exchange in the quasi-steady state. In particular, an increase in

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the temperature of individual parts in the no-load interval, when the heat release power is significantly reduced, is established, the reverse of the heat flow through the air gap is established;

– oscillation range within one cycle in the quasi-steady-state mode with interleaved mode S6 is significantly limited by additional electrical losses from higher current harmonics, since these losses do not depend on the magnitude of the engine load, i.e. equal on load and idle intervals;

– for non-stationary modes, it can be equivalent to heating with a long mode $S1$ modes $S3$–$S8$, which will allow to optimize the use of engines with a nominal mode $S1$ when operating in the above modes.

Thus, the EHD method, in contrast to the FEM, is self-sufficient, which determines its practical value.

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