CHAPTER «ENGINEERING SCIENCES»

INCREASING THE EFFICIENCY OF ELECTRIC DRIVES WITH PERIODICAL LOADING BY USING COMPREHENSIVE MATHEMATICAL MODELING MEANS

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Abstract. The mode of operation of induction motors (IMs) affects their performance. In most cases, motors are optimally designed for steady state operation. When operating in other modes, additional attention is required to the problems of energy efficiency. Induction motors are the most common type of electromechanical energy converters, and a significant part of them operate under conditions of periodic changes in the load torque.

The work is devoted to solving the problem of increasing the energy efficiency of asynchronous motors of electromechanical systems with a periodic load, including pumping and compressor equipment. The traditional solution to this problem for compressor equipment is the optimal design of an IM under static conditions, as well as the use of flywheels, the use of an IM with an increased slip value and controlled IM with a squirrel-cage rotor and with frequency converters.

In this work, the modes of operation of asynchronous motors with periodic loading are investigated. For this, complex mathematical models are developed in the simulation system. Such models are effective in modeling taking into account periodic load changes: repetitive transient processes, their possible asymmetry and non-sinusoidality, increased influence of nonlinearity of electromagnetic parameters. In complex

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mathematical modeling, the mutual influence of the constituent parts of the electromechanical system is taken into account. Simulation allowed quantifying the deterioration in energy efficiency under intermittent loading, in comparison with static modes. Criteria for evaluating quasi-static modes have been developed and areas of critical decrease in efficiency have been determined.

The paper proposes and demonstrates a methodology for solving this problem. For this purpose, tools have been created for the optimal design of asynchronous motors as part of electromechanical systems with periodic loading. These tools include: complex mathematical models of electromechanical systems with asynchronous motors with periodic load, mathematical tools for determining the parameters of quasi-steady-state modes, the methodology of optimal design based on the criterion of the maximum efficiency of processes under quasi-steady-state modes of operation.

The possibilities, advantages and prospects of using the developed mathematical apparatus for solving a number of problems to improve the efficiency of electric drives of compressor and pumping equipment are demonstrated. It is shown that by taking into account quasi-static processes, the use of complex mathematical models for the optimal design of asynchronous motors with a periodic load provides an in-crease in efficiency up to 8 ... 10%, relative to the indicators of motors that are designed without taking into account the quasi-static modes.

The areas of intense quasi-steady-state modes are determined using the developed criterion. In these areas, there is a critical decrease in efficiency compared to continuous load operation. A decrease in efficiency is associated with a decrease in the amount of kinetic energy of the rotating parts compared to the amount of electromagnetic energy. In connection with the development of a frequency-controlled asynchronous drive of mechanisms with a periodic load, the relevance of design taking into account the peculiarities of quasi-static has increased significantly. For example, a variable frequency drive of a refrigerator compressor or a heat pump can increase energy efficiency up to 40%, but at low speeds, due to a decrease in kinetic energy, the efficiency can decrease to 10 ... 15%, unless a special design methodology is applied. This problem can be solved by using the complex mathematical modeling tools developed in the article.

1. Introduction

The energy efficiency of machines and mechanisms is an important aspect of engineering research. Increasing the energy efficiency of production processes and ensuring life support is very important for: increasing economic performance reducing thermal pollution of the environment and, consequently, curbing the rate of negative climatic changes due to global warming; reducing the consumption of energy resources, which reduces the required volume of mining and the use of installations for the use of renewable energy sources. The latter reduces the area of land plots that are removed from the territories of agricultural use, natural environments.

Induction electrical machines of alternating voltage are the most powerful con-sumer of electrical energy resources, both in everyday life and in production. The capacities of these machines range from units to millions of watts. Induction electric motors consume approximately half of all generated electrical energy. Therefore, the indicators of the energy efficiency of states significantly depend on the efficiency of these engines. Mechanisms that create a periodic (variable) load of motors are widely used with induction electric drive. Pumping and compressor equipment belongs to this type of mechanism. They are widely used in industry, transport, utilities and household appliances.

The absence of steady operating modes is a feature of the operating modes of electric drives with intermittent load. In this case, repetitive transients occur under the main operating conditions. Such regimes are characterized as quasi-steady. In general, the energy efficiency in quasi-steady-state modes decreases in comparison with the operation of the electric drive in static modes (when all the parameters of the operating mode: rotation speed, effective current value, useful motor torque are unchanged). Such a decrease can reach 10 ... 15%.

In practice, motors are often designed, and the optimal values of their electromagnetic parameters are determined using software for steady-state operating modes.

The effect of complex design decreases with increase of rotor kinetic energy. However, there are such standard sizes of IM for the design is not effective under in-controlled conditions, but effective at frequency control (taking into account that the kinetic energy decreases in proportion to the square of speed). Moreover, the consideration of periodically changing load torque can significantly increase the energy efficiency. The use of controlled electric drives (induction motors with frequency converters (FC), etc.) for refrigeration compressors is an efficient way to increase their energy efficiency [1; 2; 3; 4; 5]. Therefore, the task of complex designing of their IM taking into account the periodic change in the load torque is a topical one. At the same time, the determination of dynamic parameters and criteria for effective controlled IM with PC is of importance.

At the same time, there is an urgent question, to what extent the energy efficiency can be increased if the design synthesis of drive motors with periodic load changes is carried out using software that takes into account the features of real operating modes? This work is based on research at the Institute of Electrodynamics of the National Academy of Sciences of Ukraine.

The purpose of this work is to substantiate the need for the development and use of tools for complex mathematical modeling for research, modernization and optimal design of IM of electromechanical systems with a periodic load.

The stages in achieving this goal are as follows:

1. Development and software implementation of refined mathematical models of elements of an electromechanical system of equipment with a periodic load of asynchronous motors.

2. Development and software implementation of complex mathematical models of such electromechanical systems, when the mutual influence of the system elements is taken into account in the process of modeling the operating modes.

3. Development of criteria (and mathematical means of calculating them) for evaluating the effectiveness of quasi-steady-state operating modes and optimal design using complex mathematical models.

4. Comparative study of steady-state and quasi-steady-state modes of operation of asynchronous electric drives under constant and periodic load.

5. Formation of recommendations for improving the energy efficiency of asynchronous drives of mechanisms with a periodic load and determination of the scope of these recommendations.

2. Requirements and description of mathematical models for the study of quasi-static modes

Mathematical models and their software implementation for a project for the synthesis of induction motors with quasi-steady-state modes of operation must comply with the specifics of the requirements due to the features of these modes.

In quasi-steady-state regimes, repetitive transient processes take place. Therefore, mathematical models of dynamics, for example, simulation models of the MATLAB system, are advisable to use. This system of mathematical modeling has the following advantages: taking into account the mutual influence of the components of the electromechanical system; the ability to integrate mathematical models of various technical devices (in the form of standard system blocks) into a single software product; the ability to develop refined mathematical models of the research object and integrate them into a complex mathematical model of the system

The mathematical model of induction motors of electric drive systems with intermittent load must satisfy a number of requirements.

1. The change in the magnitude of the electromagnetic parameters of the motor should be taken into account when changing the parameters of the operating mode. This ensures the accuracy of mathematical modeling, which is determined by the synthesis of design tasks.

2. Possible asymmetry of processes in motor phases, their spatial and temporal nonsinusoidality should be taken into account to adequately take into account the features of energy conversion processes in quasi-steady-state and transient modes of asynchronous motors of electric drive systems of mechanisms with periodic loading.

3. Changes in the connection diagrams of the stator winding branches with each other and with the elements of the external circuit of the motor should be taken into account in mathematical modeling to take into account the peculiarities of quasi-steady-state modes in controlled electric drive systems.

The mathematical model of induction motors of electromechanotronic systems [6; 7] meets these requirements. This model in the simulation system (Figure 1 shows an example of modeling a two-pole 550 W motor with a load such as a single-cylinder compressor) is presented in the form of blocks of stator winding branches with their input and output terminals (n1-k1, n2-k2, n3-k3).

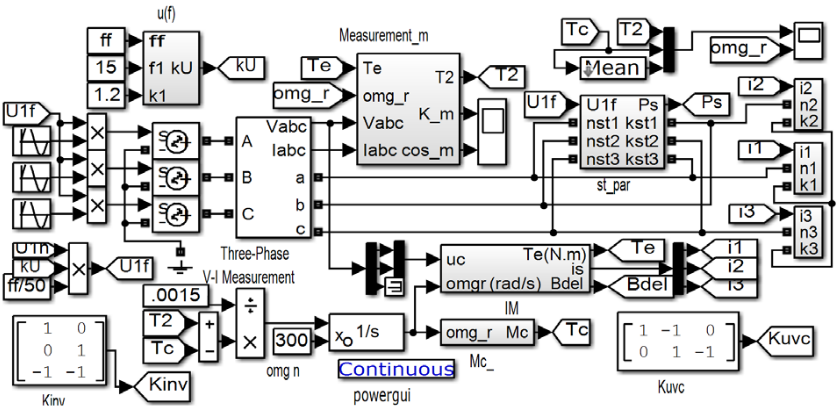


Figure 1. Simulation mathematical model of an induction motor with a periodic load

The possibility of arbitrary connection of these output ends with each other and with the external circuit is ensured by the formation of a system of differential equations for the electrical equilibrium of the engine. This system is presented relative to the system of variables in the form of: instantaneous values of independent currents of the stator winding branches and projections of the total spatial complexes of the currents of the rotor circuits for each taken into account harmonic component magneto motive force of the stator winding.

The model of induction motors of electromechanotronic systems makes it possible to study any connection schemes of the stator winding branches. This mathematical model is implemented by means of structural modeling Simulink and integrated into a complex structural mathematical model using the library blocks of controlled current sources of the MATLAB system. The initial information for calculations at the current step of numerical modeling is transferred from the simulation system (in Figure 1 – the MATLAB meter block of the SimPowerSystems library) to the engine model (in Figure 1 – the IM block) in the form of current voltage values.

The calculated instantaneous values of the currents of the stator winding branches are control signals for the stator winding branches, which contain controlled current sources and simulate the stator winding branches. The interconnection of the variable systems of the motor and the external circuit is carried out using the inclusion matrices formed for the investigated winding circuit. They, in accordance with Kirchhoff's laws, establish the interconnection of all and independent currents of the stator winding branches, as well as the voltages of these branches and voltages in the external motor circuit (Figure 1 shows the Kinv, Kuvc matrices for connecting the branches according to the «star» scheme).The st_par block is connected in parallel to the motor input to account for losses in steel (as a function of the frequency of magnetization reversal and induction in the magnetic circuit) and additional losses.

The complex mathematical model of the electromechanical system of the piston compressor drive (Figure 1) contains a block for modeling the moment of resistance on the motor shaft Mc_. Its output signal (Tc in Figure 2) varies as a function of the rotor angle, which is determined by integrating the rotational speed signal. The account of mechanical losses in the motor [8] and the determination of its energy coefficients is carried out in the Measurement_m block.

The simulation results of the quasi-steady-state operation of the compressor drive are shown in Figure 2 for a frequency control system at a frequency of 15 Hz. The moment of resistance, instantaneous and average values of the moment on the motor shaft are shown on the upper oscillogram. The rotor speed is shown in the lower oscillogram. The change in the voltage value as a function of the given network frequency is carried out in the u (f) block.

Increased accuracy of accounting for changes in electromagnetic parameters in modeling is ensured by the use of their nonlinear dependences obtained from the results of field analysis of the engine [9]. The parameters in the form of two-dimensional dependencies in the system of alternating current – slip are presented.

The parameters of quasi-steady-state modes of operation are calculated as follows. The simulation results of the quasi-steady-state regime (Figure 2) illustrate sig-nificant deviations from the dependences of the steady-state regimes.

For example, in Figure 2 it can be seen that the instantaneous values of the rotor rotation speed at certain moments exceed the steady rotation speed of the field (94,25 s-1 at the considered frequency of 15 Hz). An analysis

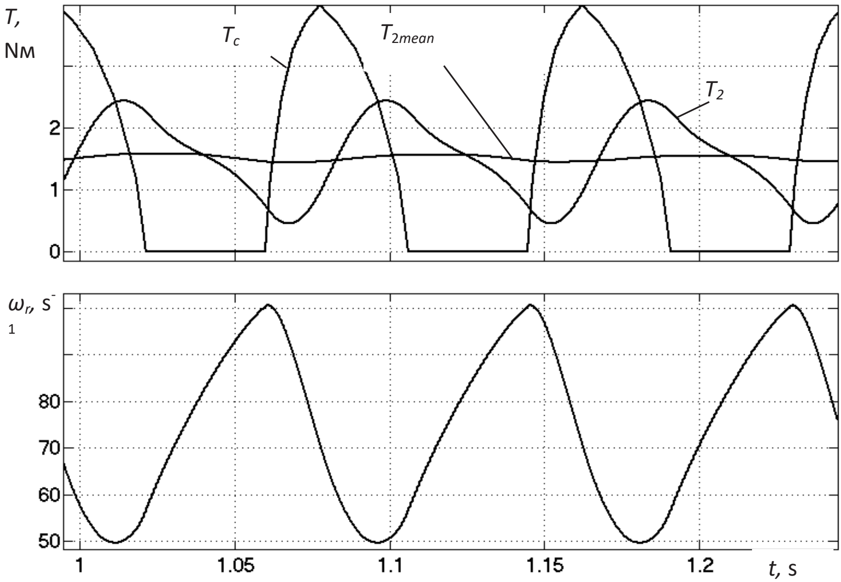


Figure 2. Simulation results for a quasi-steady-state compressor drive

taking into account the features of quasi-steady-state modes requires refined approaches to fixing and calculating the parameters of such operating modes.

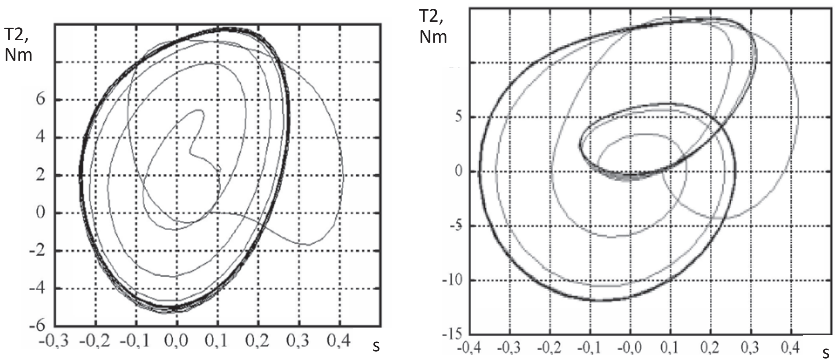
Dependencies Figure 2 were obtained by calculating the transient process for the moment corresponding to the repeatability of the time dependences. In this case, the repetition period T_r can be distinguished and the values of the operating mode parameters can be determined integrally. In the general case (with asymmetry of the motor, power supply parameters, in the presence of a mechanical gearbox, multi-pole stator winding), the repeatability period is greater than the mains period.

To illustrate the process of entering a quasi-steady mode, the dynamic dependences of the useful torque of the motor 4A80A6У3 of a two-cylinder reciprocating compressor on the instantaneous value of the rotor slip $s = 1 - p\omega_r / (2\pi f)$, where p – the number of pole pairs, f – the network frequency, are shown in Figure 3a. A similar dependence for a single-cylinder compressor is shown in Figure 3b.

The averaged integral values of the quasi-steady-state regime are determined over the repeat period. In this case, the operating current I_{1q}, usful power P_{2q}, rotation speed ω_{rq} are calculated in accordance with the following expressions

$$I_{1q} = \sqrt{\frac{1}{mT_r}\sum_{k=1}^{m}\int_{t}^{t+T_r} i_k^2(t)dt};\ P_{2q} = \frac{1}{T_r}\int_{t}^{t+T_r} \omega_r(t)\cdot T_2(t)dt;\ \omega_{rq} = \frac{1}{T_r}\int_{t}^{t+T_r} \omega_r(t)dt, \quad (1)$$

where m, i_k – the number of phases and the current of the k-th phase of the motor power supply system.



a *b*

Figure 3. Dynamic mechanical characteristics of the 4A80A6У3 engine of the compressor drive: ***a – two-cylinder; b – single-cylinder***

In the presence of information on the values of the phase voltages u_k of the motor, the power consumption in the quasi-static mode is determined by the expression

$$P_{1q} = \frac{1}{T_r}\int_{t}^{t+T_r}\sum_{1}^{m}(u_k(t)\cdot i_k(t))dt. \quad (2)$$

In the absence of access to the zero point of the motor, the power consumption is calculated from the line voltages and phase currents. For example, for a three-phase network – in accordance with the method of two wattmeters

$$P_{1q} = \frac{1}{T_r}\int_{t}^{t+T_r}(u_{1,3}(t)\cdot i_1(t) + u_{1,2}(t)\cdot i_2(t))dt. \quad (3)$$

The efficiency η is determined by the ratio of the power at the output and the input of the motor. The power factor α, in accordance with the S. Fryze theory, is determined by the ratio of the minimum possible line current (capable of transmitting a given active power at a given voltage) to the current (instantaneous current in this mode):

$$\eta = \frac{P_{2q}}{P_{1q}}; \tag{4}$$

$$\alpha = \frac{P_{1q}}{3U_f I_{1q}}, \tag{5}$$

where U_f – the value of the phase voltage of the network, subject to its symmetry. With this assumption, this expression of the power factor is valid for any asymmetry and non-sinusoidality of the processes [9; 10].

3. Research methodology of operating modes of induction electric drives with variable load

The system of criteria for increasing the efficiency of the EMP in quasi-steady-state modes (and mathematical means for calculating them) has been developed, which includes:

– criteria for assessing quasi-static modes of EMP with variable load;

– criteria for the energy efficiency of EMS in operating modes;

– the criterion for the expediency of modernization of serial IMs and optimal design of motors taking into account quasi-static modes [11];

– criteria for a comprehensive assessment of the energy efficiency of electro-mechanical systems based on IMs [8].

The efficiency criteria for IMs with a variable load torque are determined by the requirements for them from the electromechanical systems. The selection and formation of criteria for motors of specific equipment is carried out taking into account technical, technological and economic requirements.

Important criteria for the efficiency of the IMs for these conditions are the pulsations of the rotor speed and currents, the relative values of which are regulated for the IMs. For example, in the case of closed-type reciprocating compressors (hermetic), they are 20% and 66%, respectively. The criterion for the energy efficiency of the AM in operating modes is the efficiency.

The complex design of induction motors is effective with changing the load torque. However, the efficiency depends on standard sizes and construction of IM. The ratio for heavy quasi-static conditions k_1 is proposed for selection of such uncontrolled IMs for which this method of improving the energy efficiency gives an appreciable effect [11]. The value of k_1 is calculated as a ratio of the mechanical T_{MK} to electromagnetic T_E time constants of IM. In this case, the ratio of the mechanical and electromagnetic energies of IM is taken into account. The efficiency of quasi-static regimes depends on the ratio of these time constants. The resonance phenomena occur for disadvantageous cases. This leads to windings overheating, increased vibrations and IM breakdown. The resonance non-availability is provided when $k_1 = T_{MK} / T_E > 2$ [10]. This can be achieved by choosing the moment of inertia, the number of pole pairs, critical torque and the rotor impedance of electric drive. That affects the critical slip according to the following expression

$$k_1 = \frac{J \cdot (\omega_0 \cdot s_к)^2}{2pM_к}, \tag{6}$$

where J – moment of inertia of electric drive; ω_0 – angular speed of the field in the air gap of IM; $s_к$ and $M_к$ – critical slip and critical torque; p – number of pole pairs.

Thus, to assess the efficiency of the EMP with periodic loading, a complex criterion is needed that will satisfy the requirements for the values of the multiplicity of starting and maximum torques, minimum pulsations of frequency and rotor wrapping, currents and electromagnetic torque of motors, as well as maximum values of efficiency in operating modes.

A number of these questions of increasing the efficiency of quasi-steady-state regimes IMs was solved by us with the help of the proposed mathematical models and means, which include assessment criteria, methods for analyzing the characteristics of the motors of indicators and mathematical means of their calculation.

The research methodology for dynamic and quasi-static modes includes an algorithm for calculating the integral values of the angular frequency of rotation, currents, moments of motors and their pulsations, efficiency taking into account changes in the loading period and a comparative analysis of the results.

According to the algorithm, the calculation of indicators and characteristics of quasi-steady-state modes is carried out in the case, when the average values of the useful moment on the shaft and the moment of the periodic load become equal

$$M_{2mean}(\theta) = M_{cmean} .$$

The analysis of research results is based on a comparison of motor's indicators in quasi-static modes with the results of calculating indicators with a constant load torque, which is equal to the average value of the periodic torque over the repetition period. This approach makes it possible to clarify the features of electromagnetic and electromechanical processes and to increase the adequacy of mathematical modeling of quai-static modes.

According to the methodology, the influence of the design parameters of the IM, the periodic load (of one and two-cylinder compressors), the moment of inertia of the electric drive on the nature (patterns) of changes hour dependences and pulsationes of the rotation frequency, currents, electromagnetic moments and the efficiency of three-phase and single-phase IMs with different power values and the number of pole pairs (from 30 W to 11 kW, p = 1, 2, 3) was investigated.

Research of quasi-steady-state modes with load of single-cylinder reciprocating compressors allowed:

– clarify the relative pulsations of the rotor speed $\delta\omega_r$, stator δi_s and rotor δi_r currents, electromagnetic moments ΔM of motors, to determine the discrepancies in the calculations of these pulsations and KKD ($\Delta\eta$) in comparison with a constant load, which is equal to the average value of the variable moment over the repetition period;

– to reveal the largest values of ripple and $\Delta\eta$, which in this case, correspond to three-phase six-pole IM with a power of 750 W ($\delta\omega_r$ = 81.5%, $\Delta\eta$ =27,3%) and four-pole single-phase IM ($\delta\omega_r$ = 134%, $\Delta\eta$ = 9,6%); the smallest values – single-phase two-pole IM with a sinus winding;

– to substantiate, taking into account the criterion k_1, the possibility of increasing the efficiency in operating modes, to determine, taking into ac-count the characteristics of the load, the corresponding value of the moment of inertia of the drive;

– to substantiate and confirm the need for optimal design of IM (by the example of three-phase and capacitor IM), taking into account the periodic load;

– to determine the areas of critical decrease in efficiency (more than 10%) for non-regulated and frequency-controlled induction motors.

Frequency-controlled y induction motors are important object for reserching the effect of quasi-static modes on the efficiency of processes. This is due to a de-crease in the kinetic energy of the rotating parts in proportion to the square of the speed. In this case, in accordance with criterion k_1 , the efficiency de-creases.

With the help of the developed mathematical support for complex modeling, the regularities of the influence of the frequency of supply of the frequency-controlled IM drive of the piston compressor on its energy efficiency are determined taking into account periodically changing load torque, nonlinearity of electromagnetic parameters, asymmetry and nonsinusoidality of processes. The aggregate of the calculated graphical dependences of the change in the criteria $\Delta\eta$, $\delta\omega_r$, as a function supply frequency of the single-cylinder compressor drive are shown in Figure 4.

The designations of the curves correspond to the degree of load of the motor: the ratio of the average value of the moment of resistance on the motor shaft to its rated torque. At the same time, the area of critical reduction (up to 10%) of the engine efficiency was identified. The permissible ranges of speed regulation are defined for different loading degrees of IMs at 20% regulated speed pulsation level.

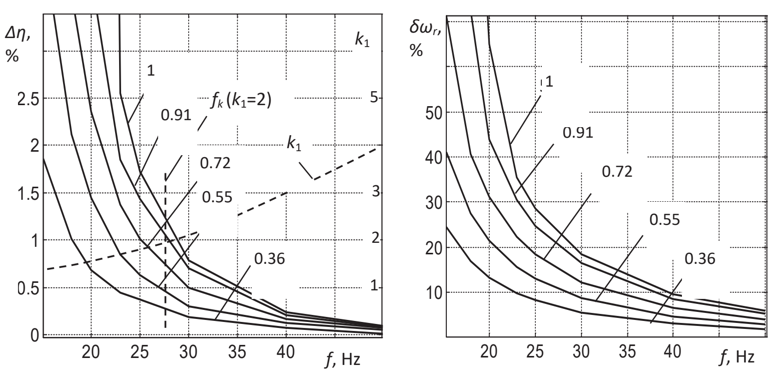


Figure 4. Dependences of the change in the criteria $\Delta\eta$, $\delta\omega_r$ as a function of the supply frequency for the 4A63B2У3 engine of the single-cylinder compressor

4. Optimal design of induction motors with periodical load

The presented studies of induction motors, designed for static conditions, revealed a sharp decrease in efficiency. However, intermittently loaded motors operate in quasi-static modes. To improve efficiency for theeth conditions, there is a need optimal designing of IMs, taking into account quasi-steady modes. In this case, it is necessary to take into account the technical and technological requirements that are presented to motors from the side of electromechanical systems.

The article presents a methodology for the optimal design of electromechanical converters with a periodic load. With its help, it is possible to determine the reserve for increasing the energy efficiency of motors in quasi-steady modes. The methodology is based on the formation of analytical dependences of the criteria for evaluating the efficiency of the EMP in quasi steady state modes depending on the optimization parameters. It includes the following procedures:

1) choice of objective function;

2) choice of optimization parameters $X_1,\ X_2,...X_n$ and ranges of their variation;

3) representation of the given periodic motor load torque as an equivalent constant torque. It is calculated as the average value of the periodic load over the period of repeatability;

4) choice of the plan of the experiment planning method (MPE) and the formation of MPE options, taking into account the variation of their parameters in accordance with the selected plan;

5) researches of quasi-steady modes, calculation of integral values of indicators for each motor variant;

6) formation of analytical dependences of the objective function, for example, the efficiency of engines, in quasi-steady-state modes (η_q) depending on the coded values of the optimization parameters $(x_1, x_2, ...x_n)$

$$\eta_q = f(x_{1q}, x_{2q}, ...x_{nq}). \tag{7}$$

7) optimization of function (7), determination of the maximum value of efficiency (η_q^*) and optimal parameters in quasi-steady-state modes $(x_{1q}^*, x_{2q,....}^* x_{nq}^*)$

$$\eta_q^*(x_{1q}^*, x_{2q,....}^* x_{nq}^*); \tag{8}$$

8) calculation of the reserve for increasing the energy efficiency of the IMs in quasi-steady-state modes. It is presented in stages:

– calculation of efficiency in static modes for engine options (to point 4) using a mathematical model for calculating dynamic modes. The constant value of the load torque corresponds to point 3;

– obtaining the analytical dependence of the efficiency in static modes (η_c) depending on the optimization parameters (point 2);

$\eta_c = f(x_1, x_{2,....}x_n)$;(9)

– optimization of function (η_c), determination of the maximum value of efficiency (η_c^*) and optimal parameters ($x_{1c}^*, x_{2c,....}^* x_n^*$) in static mode

$$\eta_c^*(x_{1c}^*, x_{2c,....}^* x_{nc}^*); \tag{10}$$

– calculation of efficiency in a quasi-static mode of operation of electromechanical converters with optimal parameters, which are obtained for a static mode (10)

$$\eta_q(x_{1c}^*, x_{2c,....}^* x_{nc}^*); \tag{11}$$

– comparison of the results of calculating the efficiency (7) and (11), determination of the reserve for increasing the efficiency of motors in quasi-static modes using the expression

$$\Delta\eta_p = \eta_q^*(x_{1q}^*, x_{2q,....}^* x_{nq}^*) - \eta_q(x_{1c}^*, x_{2c,....}^* x_{nc}^*). \tag{12}$$

5. An example of improving the efficiency of induction electric drives of reciprocating compressors

The adequacy of mathematical modeling of quasi-steady-state modes on the basis of this model was confirmed by comparing the results of numerical calculations of operating of theeth modes of a three-phase two-pole induction motor with a power of 370 W with experimental data. This was the basis for further scientific research.

An example of the optimal designing three-phase IM for symmetrical three-phase voltage supply for the operation of two-cylinder reciprocating compressors is considered.

The 4A80A6У3 motor with a power of 750 W was selected as the basic. Optimization parameters are the length of the stator package and the number of effective conductors in the stator slot. The intervals of their variation are at the level of 10% of the average values, which correspond to the base induction motor.

The torque on the shaft of an induction motor depends on the angle of rota-tion of the rotor, which is connected to the compressor shaft. This dependence was taken into account when analyzing the parameters of the quasi-steady-state mode and when determining the average value of the torque for analyzing the parameters of the steady-state mode. In both quasi-static and equivalent static modes, the dependences of the change in efficiency were determined when changing the optimization parameters using the experiment planning method.

For quasi-stationary and static modes, a second-order orthogonal central composition plan was used. This provides independence in determining the regression coefficients, sufficient model accuracy and a small number of experiments.

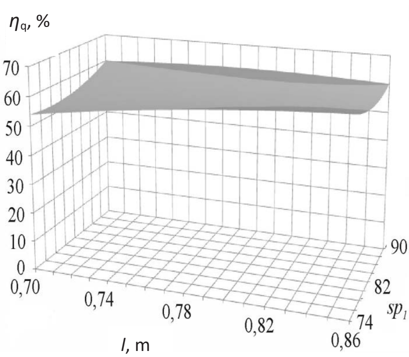
As a result of calculations, analytical dependences of the optimization criterion (efficiency) were obtained: for quasi-static and static modes

$$\eta_q = 58{,}159 + 2{,}668 \cdot x_1 + 0{,}395 \cdot x_2 - 1{,}532 \cdot x_1^2 + 2{,}98 \cdot x_2^2 - 2{,}575 \cdot x_1 \cdot x_2 ; \quad (13)$$

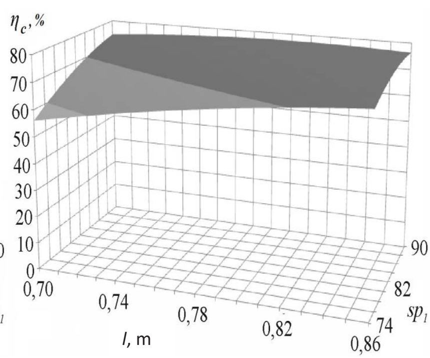
$$\eta_c = 74{,}137 + 4{,}583 \cdot x_1 + 5{,}608 \cdot x_2 - 1{,}95 \cdot x_1^2 - 2{,}395 \cdot x_2^2 - 3{,}625 \cdot x_1 \cdot x_2 . \quad (14)$$

The graphical implementation (response functions) of the dependencies and is presented, respectively, in Figure 5a and Figure 5b. In this case, the maximum values of the efficiency in quasi-static and static modes are η_q = 64.45% and η_c = 77.47%, respectively. Difference of results is 12%.

Having calculated the value of the efficiency in the quasi-static mode with optimal parameters for the static mode (11), we obtain



a



b

Figure 5. Graphs of dependences of the optimization criterion – Efficiency: ***a – for the quasi-static mode; b – static mode***

$\eta_q(x_{1c}^*, x_{2c,....}^* x_n^*)$ = 56.3%. The efficiency increase reserve in accordance with expression (12) is $\Delta\eta_p$ = 8.15%. The results of numerical experiments are presented in Table 1.

Table 1

<table>
<tr><th rowspan="2">Modes of induction motors</th><th colspan="3">Motor parameters</th><th colspan="5">Mode indicators</th></tr>
<tr><th>l, m</th><th>sp_1</th><th>$J \cdot 10^{-3}$, $kg \cdot m^2$</th><th>P_2, W</th><th>P_1, W</th><th>s, %</th><th>I_{sa}, I_{sb} I_{sc}, A</th><th>η, %</th></tr>
<tr><td>Optimal IM for quasi-steady-state mode</td><td>0,0858</td><td>74</td><td>4,6</td><td>325,9</td><td>495,8</td><td>2,50</td><td>1,77, 1,765 1,769</td><td>65,73</td></tr>
<tr><td>Optimal IM for static mode</td><td rowspan="2">0,0803</td><td rowspan="2">84</td><td>∞</td><td>364,7</td><td>477,3</td><td>3,42</td><td>1,313, 1,313 1,313</td><td>76,41</td></tr>
<tr><td>Ouasi-steady-state mode</td><td>4,6</td><td>312,9</td><td>555,7</td><td>3,22</td><td>1,92, 1,94 1,905</td><td>56,31</td></tr>
<tr><td colspan="9">Base motor</td></tr>
<tr><td>Static mode</td><td rowspan="3">0,078</td><td rowspan="3">82</td><td>∞</td><td>388,9</td><td>515,9</td><td>3,425</td><td>1,461, 1,461, 1,461</td><td>75,38</td></tr>
<tr><td>Quasi-steady-state mode $M_c = const$</td><td>4,6</td><td>338,5</td><td>457,4</td><td>2,927</td><td>1,42, 1,42, 1,42</td><td>74,0</td></tr>
<tr><td>Quasi-steady-state mode $M_c = f(\theta)$</td><td>4,6</td><td>315,4</td><td>543,3</td><td>2,918</td><td>1,935, 1,943, 1,920</td><td>58,07</td></tr>
</table>

6. Conclusions

The methodology for optimal design of motors with variable load has been further developed. It is based on the research of transient processes of motors with variable load and the formation of analytical dependences of efficiency in quasi-static modes on the design parameters of motors. The proposed methodology makes it possible to increase the efficiency of induction motors in quasi-static modes in comparison with their optimal design for static modes. The possibility of increasing the efficiency in quasi-static modes up to 8 … 10% on the example of a three-phase six-pole motor with a power of 750 W with a pulsating load is substantiated.

The performed studies are based on the use of complex mathematical models of induction motors, mathematical means of recording indicators of quasi-steady operating modes, criteria for the effectiveness of these modes, complex mathematical models of electromechanical systems based oh induction motors, which drive mechanisms with of periodically changing load torque. Taking into account the dynamics of the mutual influence of the components of the electromechanical system in quasi-steady-state operating modes provided an increase in the efficiency of the design synthesis of induction motors with periodic load changes.

The complex design work should be carried out taking into account the changing range for speed control, loading degree, moment of inertia, the varying voltage and frequency, the structure of frequency-controlled system in order to develop the effective technical solutions for frequency-controlled induction motor drive for piston compressors. Without such complex designing the power efficiency can be decreased by more than 10%.

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