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Starting modes of asynchronous motors control by the supply voltage amplitude

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Abstract. Electric drives with asynchronous electric motors with a squirrel-cage rotor are quite widespread due to their operational reliability and fairly high energy characteristics. The article proposes a method for further improving the energy characteristics of an asynchronous electric motor in starting modes controlling by the amplitude of the supply voltage. Based on the mathematical model of a generalized electric machine in fixed axes α and β, an algorithm has been developed that allows reducing electrical energy losses in the windings of an asynchronous electric drive in starting modes. Using the maximum principle and the Newton-Raphson method, the optimal functional dependence of the amplitude of the supply voltage of an asynchronous motor on the time of the transient process is determined. The minimum square of the voltage supplying the electric motor was chosen as the optimization criterion. Based on the calculation results, graphs of currents changes, electromagnetic moment of rotation angular frequency and electrical losses in the asynchronous motor windings under optimal control actions were obtained. The possibility of the starting time reducing of asynchronous motors with optimal control action was investigated. Practical recommendations on the application of the optimal control algorithm are given.

INTRODUCTION

Asynchronous motors with a squirrel-cage rotor have become widely used in all areas of human activity where the conversion of electrical energy into mechanical energy is required. The modern trend in the use of asynchronous motors is that an increasing number of them are used as part of a controlled electric drive. [1-3]. Requirements for improving the energy and weight-size parameters of electric drives, expanding the range of regulation of operating speeds, increasing speed, reliability are constantly increasing, and the element base of the frequency converter is being updated, new items appear in circuit solutions [4–11]. Intensive work is underway to further improve the control laws of an asynchronous frequency electric drive [12–17]. There are quite a few areas of application for asynchronous motors where they often operate in starting modes. These are various types of metalworking equipment, robotic execution of technological operations in mechanical engineering, traction drives of vehicles and others. It is known that in these dynamic starting modes, as well as the transition from one rotation frequency to another, the efficiency of asynchronous motors is significantly lower than in the nominal mode. The heat generated in the windings and magnetic circuit significantly limits the intensity of use of the electric motor. Efficiency in starting modes can be increased by optimally adjusting the supply voltage parameters.

Among the methods for regulating the rotation frequency of asynchronous motors, the most effective is the frequency control method, in which both the frequency and the amplitude of the supply voltage change [18-20]. Less commonly used is a control method in which only the amplitude of the supply voltage changes while the frequency remains constant. This changes the motor slip. This control method is classified as parametric. Parametric control is inferior to frequency control in energy efficiency and is used mainly for soft starting of powerful asynchronous motors, or for regulating the rotation speed in a narrow range near the nominal value [21]. The practical implementation of the parametric method of controlling asynchronous motors is simpler and cheaper than frequency control. The parametric method of controlling the AM can be used to organize starting modes in combination with optimization algorithms, which will allow obtaining high energy indicators.

Optimization algorithms used in the field of electric drives have proven their effectiveness in practical implementation [22-25]. The maximum principle has become widely used in the optimal control of AC and DC electric drives. [25-27].

This article proposes an algorithm for optimal parametric control of starting asynchronous motors, in which the amplitude of the supply voltage changes so as to ensure a minimum of the following functionality:

$$\Phi = \int_0^{\mathrm{T}} u^2\, dt \Rightarrow min \quad (1)$$

where u– is relative supply voltage (the ratio of the current voltage value to the base value); t – is the time, T – the period of time during which the transition process takes place.

Minimization of functionality (1), as further calculations showed, allows to significantly reduce electrical losses in the stator and rotor windings of asynchronous motors, which in the processes of starting and braking make up the majority of all losses emitted in the electric motor.

SOLVING THE OPTIMAL CONTROL PROBLEM

For the mathematical description of an asynchronous motor, the equations of a generalized electric machine were used, written in the following form [28]:

$$\begin{bmatrix} i'_{s\alpha} \\ i'_{r\alpha} \\ i'_{s\beta} \\ i'_{r\beta} \end{bmatrix} = \begin{bmatrix} -cR_s & dR_r & \omega dL_{sr} & \omega dL_r \\ dR_s & -bR_r & -\omega bL_{sr} & -\omega bL_r \\ -\omega dL_{sr} & -\omega dL_r & -cR_s & dR_r \\ \omega bL_{sr} & \omega bL_r & dR_s & -bR_r \end{bmatrix} \times \begin{bmatrix} i_{s\alpha} \\ i_{r\alpha} \\ i_{s\beta} \\ i_{r\beta} \end{bmatrix} + \begin{bmatrix} c & 0 \\ -d & 0 \\ 0 & c \\ 0 & -d \end{bmatrix} \times \begin{bmatrix} u_{s\alpha} \\ \\ \\ u_{s\beta} \end{bmatrix},$$

$$\omega' = \frac{pP_б}{\nu_б{}^3 J}\left[L_{sr}\left(i_{s\beta} i_{r\alpha} - i_{s\alpha} i_{r\beta}\right) - \mathrm{M}_c\right], \quad (2)$$

The following notation is used in equations (2)

$$b = \frac{L_s}{L_s L_r - L_{sr}{}^2};\quad c = \frac{L_r}{L_s L_r - L_{sr}{}^2};\quad d = \frac{L_{sr}}{L_s L_r - L_{sr}{}^2};\ P_б = \frac{3}{2} u_б i_б,$$

where $i_{s\alpha}, i_{r\alpha}, i_{s\beta}, i_{r\beta}$ – projections of stator and rotor currents of an asynchronous motor onto fixed coordinate axes α and β; $\frac{di_{s\alpha}}{dt}, \frac{di_{r\alpha}}{dt}, \frac{di_{s\beta}}{dt}, \frac{di_{r\beta}}{dt}$ – time derivatives of the projections of stator and rotor currents along the coordinate axes α and β; R_s, R_r – active resistances of the stator and rotor; p – number of pole pairs; ω – angular rotation frequency; L_s, L_r– stator and rotor inductances; L_{sr}– mutual inductance between stator and rotor; M_e– electromagnetic moment; M_s– static moment of resistance on the shaft of the asynchronous motor, J– moment of inertia of the rotor.

The projections of the supply voltages on the stator and rotor windings along the coordinate axes α and β were calculated from the expressions:

$$u_{s\alpha} = U_m u\, cos(\,\omega t);\quad u_{s\beta} = U_m u\, sin(\,\omega t), \quad (3)$$

The electromagnetic moment was calculated using the formula:

$$M_e = M(i_{r\alpha} i_{s\beta} - i_{r\beta} i_{s\alpha}) \quad (4)$$

Electrical losses in the transient process for the time from 0 to T were calculated using the expression:

$$\mathrm{P}_e = \int_0^{\mathrm{T}} i_{s\alpha}{}^2 R_s dt + \int_0^{\mathrm{T}} i_{sb}{}^2 R_s dt + \int_0^{\mathrm{T}} i_{ra}{}^2 R_r dt + \int_0^{\mathrm{T}} i_{rb}{}^2 R_r dt \quad (5)$$

The transformation of the projections of the stator currents of the asynchronous motor $i_{s\alpha}, i_{r\alpha}, i_{s\beta}, i_{r\beta}$ in the coordinate axes α and β into phase currents i_{a}, i_b, i_c is performed using the following formulas [18]:

$$i_{\mathrm{a}} = i_{s\alpha};\quad i_b = -\tfrac{1}{2} i_{s\alpha} - \tfrac{\sqrt{3}}{2} i_{s\beta}\quad i_b = -\tfrac{1}{2} i_{s\alpha} + \tfrac{\sqrt{3}}{2} i_{s\beta}. \quad (6)$$

Calculations of variables were performed in relative units. The following basic values are adopted:

$$\omega_б = 2\pi f_н;\, P_б = (3/2) i_б u_б;\, M_б = P_б/\omega_б;\, L_б = x_б/\omega_б;\, J_б = M_б/\omega_б;\, t_б = 1/\omega_б.$$

In the mathematical modeling of asynchronous motors, assumptions were used that correspond to the concept of a “generalized electric machine” [28].

The mathematical model takes into account fast-moving electromagnetic transient processes in asynchronous motors. The presence of the equation of motion in the mathematical model makes the entire system of equations (2) quite rigid, since the time constants of electromagnetic and electromechanical transients differ significantly. Rigid mathematical models require choosing an integration step that is consistent with the smallest time constant.

The maximum principle was used to solve the optimization problem. The Hamilton function H is defined:

$$H = u^2\psi_0 + i_{s\alpha}^{/}\psi_1 + i_{r\alpha}^{/}\psi_2 + i_{s\beta}^{/}\psi_3 + i_{r\beta}^{/}\psi_4 + \nu^{/}\psi_5 \quad (7)$$

In equation (7) we take $\psi_0 = -1$.

Differential equations for auxiliary functions are compiled $\psi_1 - \psi_5$:

$$\begin{bmatrix}\psi_1^{/}\\ \psi_2^{/}\\ \psi_3^{/}\\ \psi_4^{/}\end{bmatrix} = \begin{bmatrix} cR_s & -dR_s & \omega dL_{sr} & -\omega bL_{sr}\\ -dR_r & bR_r & \omega dL_r & -\omega bL_r\\ -\omega dL_{sr} & \omega bL_{sr} & cR_s & -dR_s\\ -\omega dL_r & \omega bL_r & -dR_r & bR_r\end{bmatrix} \times \begin{bmatrix}\psi_1\\ \psi_2\\ \psi_3\\ \psi_4\end{bmatrix} + \begin{bmatrix} \alpha\psi_5 L_{sr} \end{bmatrix} \times \begin{bmatrix} i_{r\beta}\\ i_{s\beta}\\ i_{r\alpha}\\ i_{s\alpha}\end{bmatrix}$$

$$\psi_5^{/} = (\psi_3 d - \psi_4 b)(L_r i_{r\alpha} + L_{sr} i_{s\alpha}) - (\psi_1 d - \psi_2 b)(L_r i_{r\beta} + L_{sr} i_{s\beta}). \quad (8)$$

The optimal control action – the relative amplitude of the supply voltage u^* is found from expression $\frac{\partial H}{\partial u} = 0$ according to the maximum principle.

$$u^* = \frac{U_{\text{н}}}{2}[(\psi_1 - \psi_2 d) \times cos(\omega t) + (\psi_3 c - \psi_4 d) \times sin(\omega t)]. \quad (9)$$

The initial conditions of the auxiliary functions in differential equations (8) are not known in advance. $\psi_1 - \psi_5$ in differential equations (8) are unknown in advance. To determine them, the Newton-Raphson method was used from the condition of obtaining the desired rotor speed of an asynchronous motor at the end of the transient process [19]. The advantage of the Newton-Raphson method over other optimization methods is its quadratic convergence near the desired solution. However, there is a disadvantage - a small convergence region (smaller than that of the gradient method). The influence of this drawback on the convergence process can be eliminated by using an iterative transition from the initial convergence region, determined by arbitrary values of auxiliary functions, to the convergence region with a predetermined rotor speed at the end of the transient process.

The expressions defined by the Newton-Raphson method for determining the initial conditions of the auxiliary functions $\psi_1 - \psi_5$ have the following matrix form:

$$\psi^{j+1}(0) = \psi^j(0) - [K^j]^{-1}[y^{j+1}(\text{T}) - y^j(\text{T})], \quad (10)$$

where $\psi^{j+1}(0)$– initial conditions of auxiliary functions at the subsequent iteration; $\psi^j(0)$– initial conditions of auxiliary functions at the previous iteration; $y^{j+1}(\text{T})$– values of currents and rotation frequency $i_{s\alpha}, i_{r\alpha}, i_{s\beta}, i_{r\beta}, \omega$ at the end of the transient process at the subsequent iteration; $y^j(\text{T})$– values of currents and rotation frequency $i_{s\alpha}, i_{r\alpha}, i_{s\beta}, i_{r\beta}, \omega$ at the end of the transient at the previous iteration.

The calculations were performed for the АИР80В4У3 electric motor with a power of 1.5 kW with the following parameters of the equivalent circuit in relative units:

$$R_s = 0{,}098; R_r = 0{,}06; L_{sr} = 2{,}1; L_s = 2{,}176; L_r = 2{,}23. \quad (11)$$

Calculations were performed for starting an asynchronous motor up to the rated rotation speed with a direct connection to a 380 V supply voltage source with a frequency of 50 Hz. The results of calculations without load on the shaft are shown in Fig. 1. The nominal rotation speed was achieved in 8.3 relative units (r.u.), the electrical losses in the stator and rotor of the asynchronous motor Pe, determined from expression (5), amounted to 22.9 r.u.

Fig. 2 shows the results of calculations for the optimal start of an asynchronous motor up to the rated rotation speed. The optimal amplitude of the supply voltage was determined from expression (9). Electrical losses in the stator and rotor amounted to 13.4 r.u. or 58.5% of the losses during start-up without optimization of the supply voltage (Fig. 1). As can be seen from Figure 2, the amplitude of the supply voltage at the beginning and end of the start is significantly less than the nominal value.

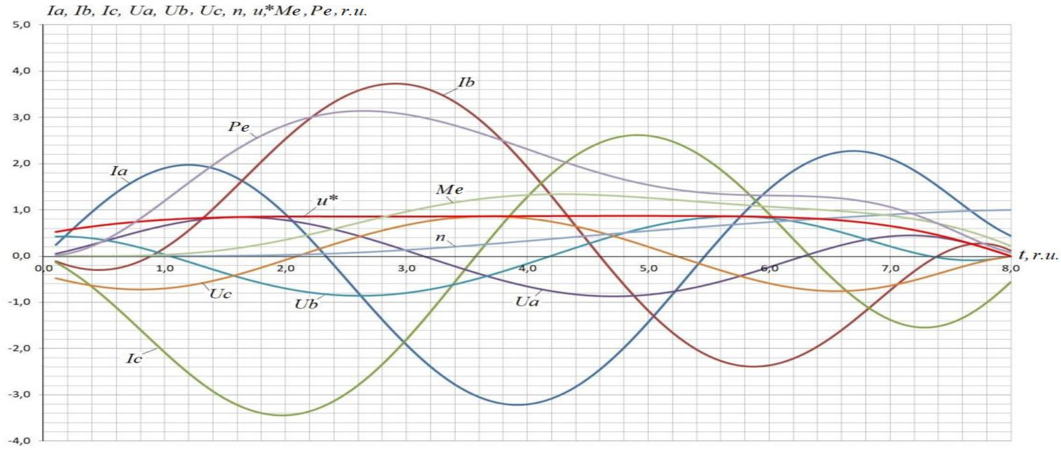

FIGURE 1. Direct start of the asynchronous motor

Such a significant reduction in electrical losses in the stator and rotor of an asynchronous motor occurred for the following reasons. It is known that when directly connected to an alternating current network, in the first period of the supply voltage, significantly more energy enters the electromagnetic circuit of an asynchronous motor than the increase in mechanical energy as a result of electromechanical conversion over the same period [28]. For this reason, an oscillatory process of energy exchange occurs between the power source and the electromagnetic circuit of the asynchronous motor. This in turn leads to an increase in electrical losses in the windings of the asynchronous motor.

A distinctive feature of optimal parametric control is the smooth increase in the amplitude of the supply voltage in the initial period of the starting mode to the nominal value. This allows for optimal dosing of the energy supply from the source to the electromagnetic circuit of the active part of the asynchronous motor, followed by electromechanical energy conversion.

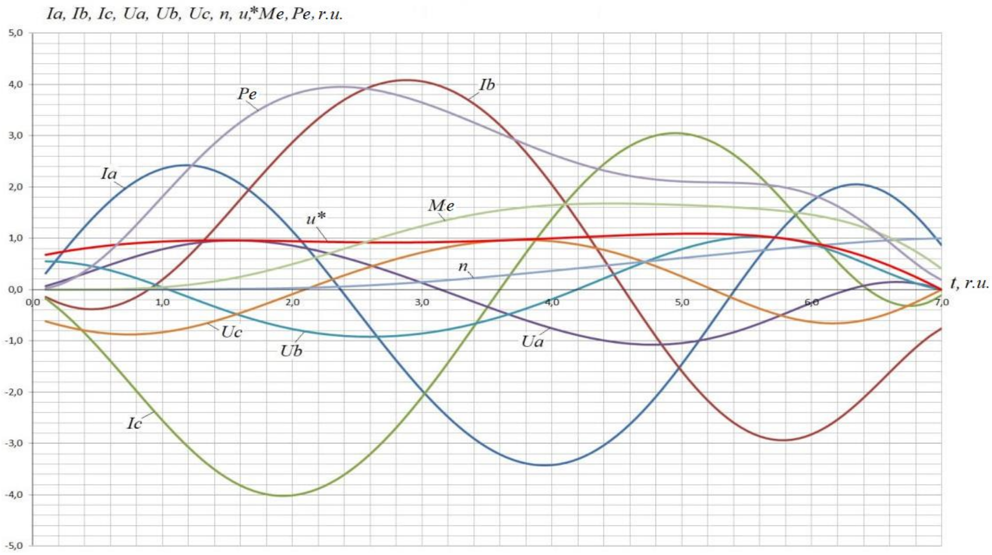

FIGURE 2. Optimal start of the asynchronous motor with a time of 8 r.u.

Optimal parametric control allows starting an asynchronous motor in a shorter time. Figures 3 and 4 show the results of calculations of the optimal start of an asynchronous motor to the rated speed in 7 r.u. and 6.1 r.u., respectively. When the starting time is reduced, electrical losses in the stator and rotor windings of the asynchronous motor increase. Electrical losses (Fig. 3) are 14.1 r.u. or 61.6% of the losses during start-up without optimization.

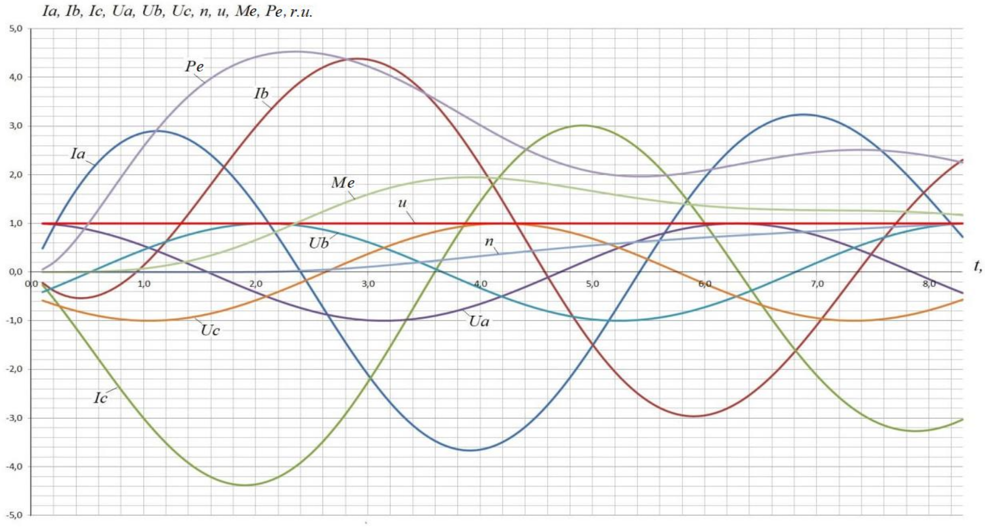

FIGURE 3. Optimal start of the asynchronous motor with a time of 7 r.u.

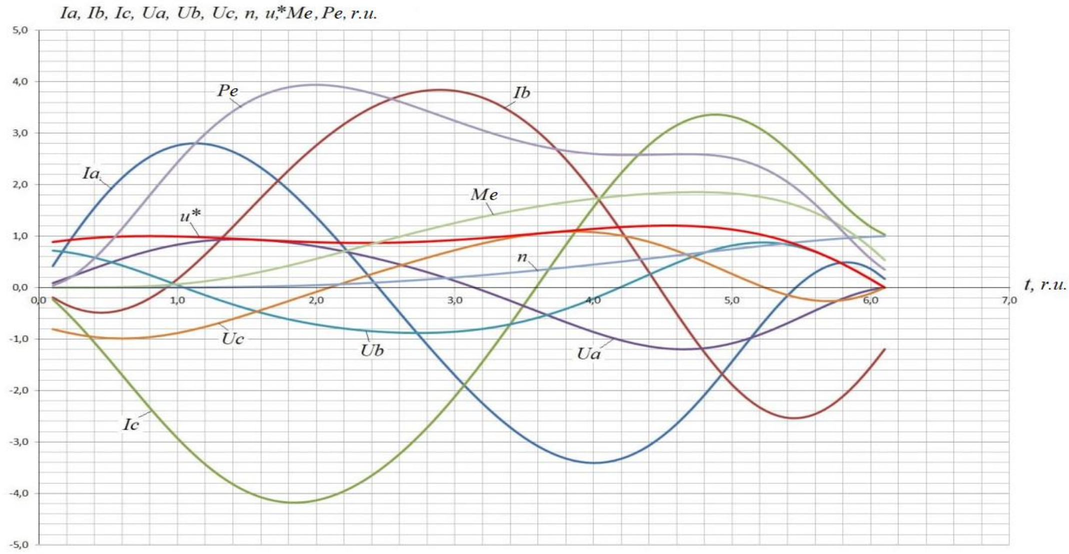

FIGURE 4. Optimal start of the asynchronous motor with a time of 6.1 r.u.

Fig. 5 shows the results of calculations for the optimal start of an asynchronous motor to the rated speed with a constant load on the shaft equal to 15% of the rated value. All other things being equal, compared to the optimal idle start (Fig. 3), electrical losses in the stator and rotor windings increased and amounted to 16.1 r.u. When compared with direct starting without optimization, the electrical losses of the optimal start with a constant load of 15% (Fig. 5) turned out to be lower and amounted to 70.3% of the losses during starting without optimization (Fig. 1).

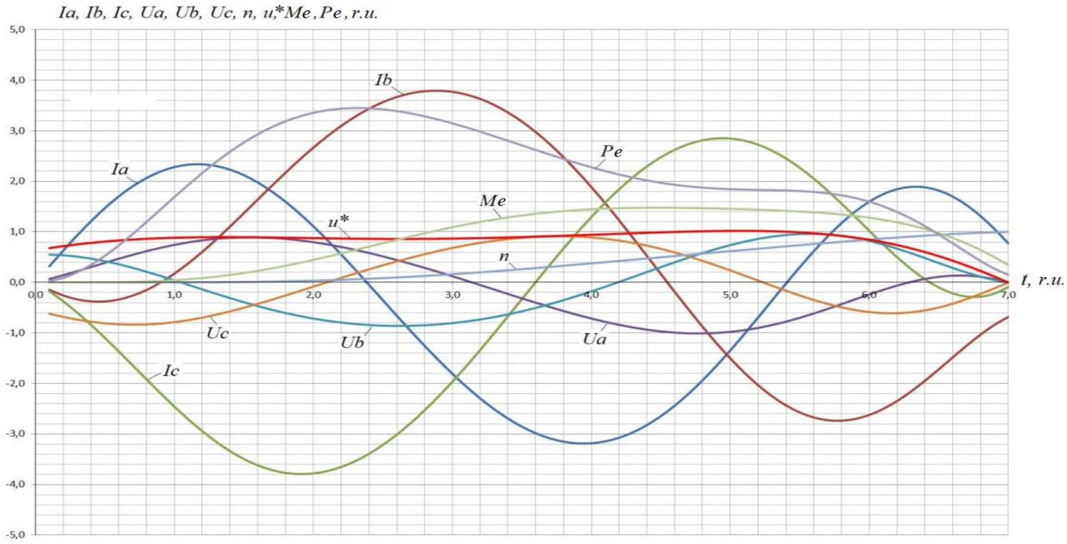

FIGURE 5. Optimal start of an asynchronous motor with a load on the shaft

The table shows comparative data on electrical losses in the stator and rotor of an asynchronous motor based on the calculations performed.

Table 1. Comparison of parameters of optimal parametric control of an asynchronous motor with direct starting

№	**Comparative data**		
	Transient type	***Electrical losses in stator and rotor, r.u.(%)***	***Transition time, r.u.***
1	Direct start at idle speed (Fig. 1)	22,9 (100%)	8.3
2	Optimal idle start (fig. 2)	13,4 (58,5%)	8.0
3	Optimal idle start (fig. 3)	14,1 (61,6%)	7.0
4	Optimal idle start (fig. 4)	15,3 (66,8%)	6.1
5	Optimal start with a load of 15% of the nominal value (Fig. 5)	16,1 (70,3)	7.0

The parameters of an asynchronous motor, such as active and inductive resistances, have a significant impact on the starting processes. Thus, the decrease of L_{sr} corresponds to an increase in the air gap between the stator and the rotor with a constant supply voltage. This leads to a decrease in magnetic flux, an increase in the transient time and, consequently, an increase in electrical losses. Previously conducted studies have shown [28] that there are optimal relationships between the parameters of an asynchronous motor that ensure the most favorable course of transient processes. Optimal control algorithms make transient processes energy efficient.

THE PRACTICAL SIGNIFICANCE OF THE PROPOSED OPTIMIZATION ALGORITHM

The practical significance of the obtained results is that the reduction of electrical losses in the windings of an asynchronous motor with optimal parametric control is an important factor in increasing its energy efficiency.

In practice, the optimal algorithm for starting an asynchronous motor can be implemented using power semiconductor switches. One of the possible ways to implement optimal parametric control is to use pulse-width modulation in an AC power circuit without using an intermediate DC link. With all the variety of circuit solutions for the parametric starting method, the process is characterized by the fact that the change in rotation frequency is achieved by changing the slip at a constant frequency of the supply voltage with the release of slip energy in the form of losses.

The recommended area of practical application of the optimal parametric start of asynchronous motors relates to medium and high power electric motors that often operate in starting modes.

The optimal parametric control algorithm can also be used in soft starters for asynchronous motors, which are mass-produced. The main problems of asynchronous electric motors during starting are:

- starting current, which during direct starting can be 5-8 times greater than the nominal current;
- electromagnetic torque that reaches large values in a fraction of a second, which can damage the actuator and disable the drive kinematic chain;
- low efficiency in transient process.

A soft starter allows you to avoid these problems by accelerating and braking the motor with controlled values of current and electromagnetic torque, eliminating jerks in the mechanical part of the drive. Using the optimal control algorithm will allow the implementation of a built-in energy saving mode.

CONCLUSIONS

An electric drive with asynchronous electric motors uses a significant amount of electricity for its operation. The energy efficiency of electromechanical energy conversion can be significantly increased by using optimal control algorithms built on a mathematical model of an asynchronous electric motor that takes into account fast-moving electromagnetic transient processes. During start-up periods, which are characterized by low efficiency, the proposed algorithm of optimal parametric control allows to reduce electrical losses in the stator and rotor of an asynchronous motor operating as part of various machines and mechanisms.

The presented main parameters of an asynchronous motor during the start-up process (Fig. 1–5): currents and voltages by phases, rotation frequency, electromagnetic torque, total electrical losses in the stator and rotor allow a clear assessment of the physical processes occurring when using the optimization algorithm.

The proposed algorithm of optimal parametric control can be used to improve the energy efficiency of an asynchronous electric drive and is relevant for asynchronous electric drives that operate in frequent starting modes.

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