

SOLUTION OF OPTIMIZATION PROBLEMS OF HIGH-INERTIAL ASYNCHRONOUS ELECTRIC DRIVE

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Abstract. The method of optimum start-up calculation on computer with use of the principle of a maximum and Newton-Rafson's method for the high-inertial asynchronous electric drive is offered. Based on this technique, optimal dynamic modes of high-inertia frequency-controlled asynchronous electric drive are calculated taking into account thermal processes. Methods of increasing electric motor energy efficiency due to reducing power consumption in dynamic modes are considered.

The problem of the operating modes optimizing of electromechanical systems for a long time is in the center of attention of specialists. Physical processes that occur in electromechanical objects, as a rule, are controlled, they are implemented in various ways depending on the requirements of the technological process. In this regard, the problem arises of finding the best mode on the basis of optimal process control, which provides improved technical and economic indicators of the facility. For example, a performance optimality criterion that achieves a process goal in the shortest time or with minimal energy consumption. Such issues are tasks of optimal control [1-5].

In the sectors of the national economy, a number of asynchronous electric drives operate in heavy start-brake modes. These include high-inertial electric drives, for example, turbomolecular pumps, lifting and transportation mechanisms, balancing machines, high-speed centrifuges, centrifugal separators, gas turbines, mechanical energy accumulators, and others. The peculiarity of such mechanisms is the long start-up process. Due to the large losses in the process of starting high-inertial mechanisms, a significant amount of thermal energy is released, an unacceptable overheating of the asynchronous motor insulation occurs and the engine can break down. In this regard, an important scientific and technical task arises: reducing losses in the transition process and increasing the speed of high-inertial asynchronous electric drives. One promising way to solve this problem is to determine the optimal control effects based on the use of mathematical models and using the theory of optimal control [6-9].

One of the most effective methods of researching problems of optimal control of dynamics of high-inertial automated frequency-controlled electric drives consists in their mathematical modeling on computers, finding optimal control laws for evaluating their limit capabilities and improving the adjustment, energy and operational characteristics of the electric drive.

Let's consider a system of integral equations, describing the joint electromechanical and thermal processes that take place in a high-inertial frequency-controlled asynchronous electric drive and add speed functionality to them:

$$\left. \begin{aligned} \theta_{\theta} &= \int_{t_0}^T \left(\frac{P_h}{C_i} + k_1 \theta_0 - k_2 \theta_a \right) dt \\ \omega &= \int_{t_0}^T \left(\frac{p}{J} (M_e - M_s) \right) dt \\ J_T &= \int_{t_0}^T dt \end{aligned} \right\}, (1)$$

where θ_0 - average temperature, ω - angular speed of shaft rotation, C_i - engine heat capacity, k_1, k_2 - coefficients reflecting the thermal connection of the motor with the environment, p - number of pairs of motor poles, J - inertia torque of rotating parts of asynchronous motor, M_e - electromagnetic torque, M_s - static torque on the shaft.

A generalized mathematical model (1) in which an asynchronous motor is considered as a single homogeneous body, taking into account the mutual influence of all parameters, includes two integral equations: the first is the thermal balance of the asynchronous motor with the environment, the second is the equation of motion of the electric drive. Heat equations in the system of equations (1) are written on the basis of the classical theory of non-stationary heat exchange. [10-14]

Electrical losses in stator and rotor windings of asynchronous motor (P_h) are taken as heat losses during transient process. [15-17]

Convert the system (1):

$$\left. \begin{aligned} \theta_{\theta} &= \int_{t_0}^T \left[m_1 \Phi^2 C_k^2 f_{1H}^2 \frac{(r_1 + \frac{r_1 x_1'}{x_0})^2 \beta^2 + \frac{r_1^2 x_1'^2}{x_0^2} + r_1 r_2 \beta^2}{r_1 (x_2^2 \beta^2 + r_2^2)} + k_1 \theta_0 - k_2 \theta_a \right] dt \\ \omega &= \int_{t_0}^T \frac{p}{J} \left(\frac{p m_1 \Phi^2 C_k^2 f_{1H}^2 r_2 \beta}{\omega_{1H} (x_2^2 \beta^2 + r_2^2)} - M_s \right) dt \\ J_T &= \int_{t_0}^T dt \end{aligned} \right\}, (2)$$

The basis for writing equations (2) was the positions [2].

The following designations are accepted here: β - relative parameter of absolute slip, m_1 - number of phases, r_1 - stator active resistance, r'_2 - rotor active resistance, x_1, x_2, x_0 - inductive resistance of stator, rotor and magnetizing circuit, Φ - magnetic flux in air gap, C_k - constructive constant of the asynchronous motor, f_{1H} - nominal frequency of asynchronous motor power supply, ω_1 - angular speed of stator field rotation. We find the coordinates and optimal control effects of the electric drive, while minimizing the average heating temperature of the asynchronous motor [19-21].

We will find coordinates and optimal control effects of the electric drive, while minimizing the average heating temperature of the asynchronous motor.

Minimization θ_0 is associated with minimization of stator and rotor current of asynchronous motor. The electrical losses in these windings in the transient process are the main losses and accordingly equal to $m_1 I'^2_2 r'_1$ and $m_1 I'^2_2 r'_2$. [2] This setting of the task is a development of the law of frequency control to the minimum square of the stator current of the asynchronous motor. [22-23]

Not accounting of saturation of steel of a magnetic conductor of the asynchronous motor leads to essential mistakes in calculations therefore it is necessary to consider saturation. To do this, we use the Arkhangelsk formula, which expresses the flow through the magnetization current [3]:

$$\Phi = A \cdot \arctg B i_0, \quad (3)$$

where A and B - approximation factors. The resistance of the magnetizing circuit x_0 (included in the formulas of the mathematical model) is calculated as follows

$$x_0 = b - c\Phi^2, \quad (4)$$

where b and c - constant coefficients.

To solve the problem (2), first use the principle of maximum [4]. According to the principle of maximum, the equation (2) is supplemented by an auxiliary, so-called conjugate system $\bar{\psi}$. Then we compose the Hamilton intermediate function H. The max H requirement is a prerequisite for optimality.

As controls, take intermediate variables: absolute sliding parameter β and x_0 . To do this, take the partial derivatives from the intermediate function H of β and x_0 , equate them to zero.

If we enter symbols:

$$k_5 = r'^2_1 r'_2 k_3 \psi_1 \left(1 + \frac{2x'_{12}}{x_0} + \frac{r'_{12}}{x_0}\right), \quad k_6 = (x'_2 r'_2 k_4 \psi_2)^2,$$

$$k_7 = -x'_2 k_4 \psi_2,$$

$$a_1 = -\beta(\psi_1 k_3 \beta r'^2_1 + k_4 \psi_2 + r_1 r'^2_2 \beta \psi_1 k_3), \quad a_2 = 0,$$

$$a_3 = \psi_1 k_3 r'^2_1 (x'^2_2 \beta - 2\beta b x'_2 + r'^2_2),$$

$$a_4 = -2r'^2_1 b k_3 \psi_1 (r'^2_2 + \beta^2 x'^2_2),$$

$$F(\bar{A}, \bar{x}_0) = a_1 x_0^3 + a_2 x_0^2 + a_3 x_0 + a_4,$$

$$\bar{A} = [a_1, a_2, a_3, a_4],$$

as a result, it is possible to write a finally edge point-to-point problem, the solution of which will determine the optimal control effects of a frequency-controlled asynchronous motor with constant resistance moment on its shaft:

$$\left. \begin{aligned} \frac{d\theta_0}{dt} &= k_3 \frac{b-x_0}{c} \cdot \frac{(r_1 + \frac{r_1 x'_{12}}{x_0})^2 \beta^2 + \frac{r'^2_1 x'^2_2}{x_0} + r_1 r_2 \beta^2}{r_1 (x'^2_2 \beta^2 + r'^2_2)} + k_1 \theta_0 - k_2 \theta_0 \\ \frac{d\omega}{dt} &= k_4 \frac{(b-x_0)\beta}{x'^2_2 \beta^2 + r'^2_2} - \frac{p}{J} M_s \\ \frac{d\psi_1}{dt} &= k_2 \psi_1 \\ \frac{d\psi_2}{dt} &= 0 \\ \beta^* &= \frac{-k_5 \pm \sqrt{k_5^2 + k_6}}{k_7} \\ F(\bar{A}, x_0^*) &= 0 \end{aligned} \right\} (5)$$

Boundary conditions:

$$\theta_0(t=0) = \theta_{00}; \quad \theta_0(t=T) = \theta_{0T};$$

$$\omega(t=0) = \omega_0; \quad \omega(t=T) = \omega_T.$$

Next, we solve the problem on a computer using the Newton-Raphson method [5]. According to the above algorithm [5], the optimal launches of ADAE92-4 with power of 40 kW, a protected version with a high moment of inertia were calculated in accordance with the criterion of optimality in terms of minimum electrical losses, taking into account saturation. When calculating, the total moment of inertia of the working mechanism and rotating parts of the asynchronous motor was almost 17 times higher than the own moment of inertia of the rotor.

Graphs of key parameters of start-up with a nominal frequency and optimum start-up for zero entry conditions of coordinates in relative units are provided respectively on fig. 1 and fig. 2.

Curves 1 in Fig.2 correspond to frequency control for criterion of optimum minimum electrical losses in stator and rotor of asynchronous motor, curves 2 - for criterion of minimum electrical losses only in stator of asynchronous motor.

To give a quantitative assessment to the chosen mode, results of calculation it is comparable to results of the mode of start-up with a nominal frequency. Asynchronous motor parameters are taken as basic parameters in nominal operation mode, except for average temperature. Average heating temperature of asynchronous motor at the end of transient process at starting from cold state to nominal speed of rotation with nominal frequency is taken as basic heating temperature. As can be seen from the graphs (Fig.1, 2) for ADAE92-4, the average temperature of the mode of minimum electrical losses in the stator and rotor of the asynchronous motor can be reduced theoretically by almost 77% with respect to the start of the asynchronous motor at the nominal frequency [24].

Assuming that the transient ends at $\tau = t/t_i = 1$, and the value of all electromechanical and thermal dependencies of the mode according to the minimum electrical losses in the stator and rotor should be taken as 100%, it can be noted that at optimal frequency start-up by minimum of electric losses in stator and rotor upon reaching nominal rotation speed $n=1405$ rpm, relative parameter of absolute sliding β during the same start-up time differs from value β of mode by minimum of electric losses in stator of asynchronous motor by 23.1%; relative supply voltage of the asynchronous motor γ from the mode value γ by minimum electric losses in the stator - by 7.3%; stator current - by 6.6%; relative

frequency of asynchronous motor - by 1.8%; losses in steel - by 15.3%; copper losses and the average temperature of the asynchronous motor - by 67.3% upward. Angular speed of shaft rotation and electromagnetic torques of both modes coincide [25-28]. From the above it follows that the mode of minimum electrical losses in the stator and rotor differs from the mode of minimum electrical losses in the stator by an amount characterizing additional accounting of electrical losses in the rotor winding of the asynchronous motor. Thus, in high-efficiency electric drives with asynchronous motors, accounting for electrical losses in the rotor winding will avoid extremely undesirable overheating of the limiting parts of the asynchronous motor and most fully use the motor by heat.

As can be seen from the graph (Fig.2), the optimal control law assumes the character of the change in rotation speed as monotonous and close to linear. This means that by stabilizing the acceleration in the transition process, high technical and economic performance of the electric drive can be obtained [29-30].

The proposed method and algorithm for calculating optimal launches, and the obtained laws of control actions make it possible to formulate specific requirements for automatic control and control systems of frequency electric drive, which implement optimal dynamic modes.

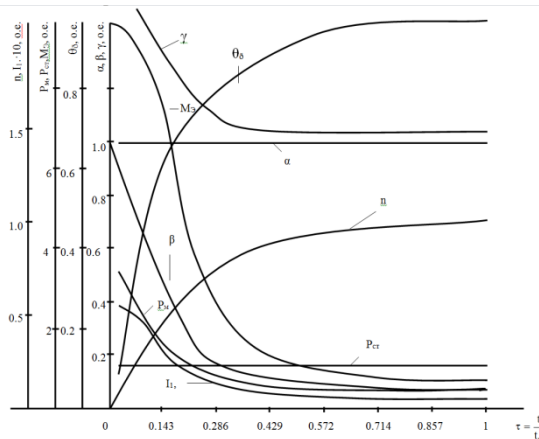


Fig. 1. Start-up ADAE-92-402 at nominal power supply frequency

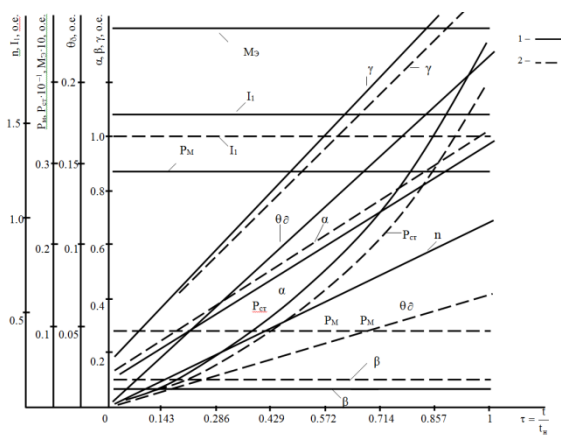


Fig. 2. Curves of optimal ADAE92-4 starts in frequency-controlled electric drive systems

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