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Adaptive Automatic System of Controlling Acceleration Characteristics of Electromechanical Converters with an Observing Identification Tool

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***Abstract*—The operating modes of the automatic control system for electromechanical converters for synchronization of rotor speeds have been developed and investigated. The proposed automatic speed control system allows adjusting the slave engine to the master one in a wide range from 0 to 6000 rpm. To improve the synchronization accuracy an adaptive algorithm is proposed that allows to increase the synchronization accuracy by 3-4 times. The proposed model of an adaptive automatic control system with an observing identification tool makes it possible to minimize the error in the asynchrony of the rotation of the rotors of two electromechanical converters.**

***Keywords*—electromechanical converters; adaptive system; control systems; identification**

I. INTRODUCTION

THE electromechanical converters (EM) operating in motor mode (induction motors, DC motors, etc.) are the main means of driving various mechanisms in modern industrial production. In practice there often arises the task of developing systems for controlling acceleration characteristics of electromechanical converters for synchronizing rotation frequencies of several EM, for example, when rolling metals or roughing diamonds. The main point of this task is to ensure relative synchronicity in terms of rotation frequency, as well as ensuring high accuracy and synchronization performance.

In the context of the development of computing and digital technology, the capabilities of automatic control systems (ACS), tracking and stabilization are expanding, which leads to the emergence of new structural solutions. Along with it, the requirements for reliability and an increase in the service life of the developed systems are growing. This brings up the task of identifying the parameters and monitoring the technical condition of EM, signalling their malfunction and automatic adjustment of the EM rotor angular velocities [1-5]. There are lots of tracking systems that differ in the principle of operation, structure, elements, the principle of actuator control, the kind of power sources, etc.

According to the methods of signal comparison, tracking systems can be analogue, in which the asynchronous rotation of E-M converter rotors is distinguished by different methods in the analogue form; and digital, in which the master device is a microprocessor, and the asynchronous rotation signal is allocated digitally in the form of a code; as well as mixed – digital-analogue.

By structure, tracking systems can be one- and two-channel (multichannel), with one or more receiving devices, with serial or parallel correction devices, simple and interconnected complex [6, 7]. In practice, single-channel tracking systems are the most common. However, for metal rolling machines, thread and paper winding, as well as for roughing diamonds, we need two-channel (multi-channel) ACSs with increased requirements for the accuracy of synchronization of the rotation frequencies of the EM rotors. An increase in accuracy is possible due to the development of an adaptive synchronization algorithm and an observing identification tool that will allow reproducing the states of the EM parameters and identifying external actions that are not directly measurable.

An ACS for controlling asynchronous rotation of EM rotors should ensure synchronization of rotational frequencies both in static and dynamic modes of operation, automatically monitor the rotational frequencies of the master and slave EM with subsequent auto- regulation, as well as identify other EM parameters that significantly affect the process of asynchronous rotation of the rotors.

Therefore, the development and research of an adaptive automatic control system with an observing identification tool that will synchronize the rotational speeds with high accuracy is a task of current research concern Its solution will significantly improve the quality of products.

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II. AUTOMATIC CONTROL SYSTEM FOR ACCELERATION CHARACTERISTICS OF ELECTROMECHANICAL CONVERTERS

There are works [8-12] in which DC electromechanical converter control systems are considered under the condition of the same load on the motors, which do not allow operating at frequencies up to 5000 rpm and at the same time provide high precision control of the E-M converter rotor rotation speed. The frequency controller proposed to be used in the control system provides a smooth start of an E-M converter without starting currents or mechanical shocks, which reduces the load on electric motors and related mechanisms [8, 9]. The built-in microprocessor PID controller allows implementing a high-quality electromechanical converter automatic control system. For discrete adjustment of EM rotation speed, it is appropriate to proceed from the continuous structure of the PID controller described in detail in [9, 10].

Taking into account the transformation equations [13-17] which describe the operation of asynchronous motors (AM) and the EM mechanical part, the EM model for controlling the frequency of the stator will be written in the form of transfer functions (Fig. 1):

$$\frac{\Delta\bar{M}(p)}{\Delta\bar{\omega}_1(p)-\Delta\bar{\omega}(p)}=\left(\frac{\gamma}{\nu}\right)^2\frac{(T_{el}p+1)-\frac{(S/S_{cr})^2}{1+(S/S_{cr})^2}(T_{el}p+2)}{(T_{el}p+1)^2+(S/S_{cr})^2}\text{; (1)}$$

$$\frac{\Delta\bar{\omega}(p)}{\Delta\bar{M}(p)-\Delta\overline{M}_o(p)}=\frac{1}{T_m p} \qquad (2)$$

where $T_m = J\Omega_{0n}/M_{st}$ is the EM mechanical time constant; $T_{el} = L_2''/R_2'$ is the induction motor electromagnetic time constant; $S_{cr} = R_2'/L_2''\Omega_1$ is the critical slip; R_2' denotes active resistance of the rotor windings; $S = (\omega_1 - p_n\omega)/\omega_1$ is the slip; p_n is the number of induction motor pole pairs; ω_1 denotes stator angular speed; M_{st} – starting torque nominal value; $\Omega_{0n}=\Omega_{1n}/p_n$ – nominal angular velocity of the synchronous motor; Ω_1 - nominal angular frequency of the induction motor stator; J – induction motor inertia moment; ΔM_o is the increase in the moment of resistance relative to the initial value; $(\Delta M/M_{st}) = \Delta\bar{M}$ is the increase in the electromagnetic moment relative to the initial value; $\Delta\omega_1$ is the increase in angular velocity relative to the initial value ω_1.

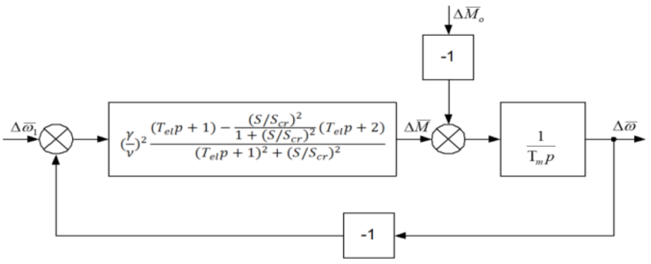


Fig. 1. Model of an asynchronous EM

The system of automatic control of rotational frequencies by electromechanical converters (EM) works as follows (Fig. 2): using the frequency setter (FA), the signal U_1 through the frequency controller FC_1 sets the frequency of rotation of the EM; the angular velocity signals of the master EM_1 and slave EM_2 are measured using tachometric sensors (ω_1/f_1 and ω_2/f_2), the output signals of which are amplified and transmitted to a microcontroller (μC), which calculates the current EM rotational speeds and automatically tracks the resulting difference (asynchrony) of rotation. If the speed difference between the master EM_1 and the slave EM_2 exceeds the preset one (20 rpm), then the MC automatically generates a U_2 signal for the frequency controller (FC_2), which reduces or increases the angular velocity of the slave EM_2. With simultaneous operation of the adjustment circuits, the slave EM synchronously occupies the position

$$U_2 = U_1 \pm \Delta U \qquad (3)$$

where ΔU - values of the deviation of the speed of rotation of the leading EM from the driven one.

To simulate the operation of an automatic control system with synchronization of EM rotation frequencies, a 4A50 type induction motor was used, with the following parameters: nominal voltage Un=220V; nominal current I_n=0.27 A; synchronous rotation speed Ω_0 = 3000 rpm; angular frequency of the stator ω=314rad/s; the master converter inertial moment J_1=0.0389 kg·m^2; the slave converter inertial moment J_2=0.038 kg·m^2; the master E-M converter load torque M_{o1}=15.38 N·m; the slave E-M converter load torque M_{o2}=14.39 N·m; number of pole pairs p=2; the master stator resistance R_1=152.9 Ω; the slave stator resistance R_2 = 192 Ω; main flow inductance L_m = 2.66 H; the master stator inductance L_1 = 3.175 H.

III. RELATED STUDIES REVIEW

Taking into account the PID controller model, the model of two (master and slave) asynchronous EM (Fig. 1) and closing them into a system for automatic control of the EM rotation frequencies, we receive a model of the control system shown in Figure 2. Modelling of the control system with different loads on their shafts was carried out in MATLAB - SIMULINK mathematical package.

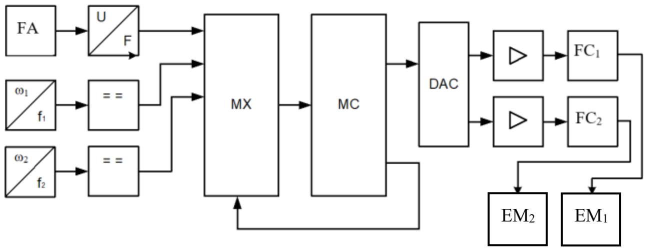
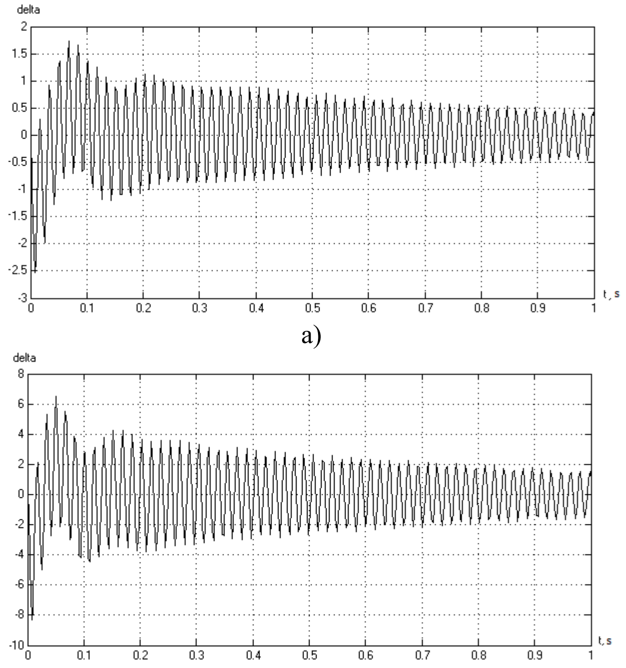


Fig. 2. Control system for EM rotation frequencies synchronization

The results of the simulation of the automatic control system for synchronizing the EM rotation frequencies are shown in Fig. 3. They indicate that in the developed control system the E-M converter rotation frequencies arte automatically synchronized, i.e. the slave EMP_2 adjusts to the master EMP_1 (Fig. 3). The difference in rotation frequencies that takes place during automatic synchronization due to changes in the load on the shaft of one of the AMs is shown in Figure 3b.



a)

b)

Fig. 3. Asynchrony of two EM rotation with their automatic control: a) – with nominal EM parameters; b) – with deviation from nominal EM parameters

As can be seen from Fig. 3 a, the asynchrony (difference) of rotation between the two EM in the dynamic mode is 4.3 rpm, while in the static mode – 1 rpm.

It is also known that over time, the EM parameters like inertia moment, resisting moment, and the stator active resistance change, but insignificantly; and a change in these parameters leads to a change in electromagnetic and mechanical component time constants. If in the EM model these parameters are changed (Fig. 1), the asynchronous rotation of the EM will increase (Fig. 3b). As can be seen from Fig. 3b, in the dynamic mode, the asynchrony of rotation makes approximately 15 rpm, while in the static mode – an average of 4 rpm.

As a result of the research, the following peculiarities have been established: the EM rotation frequency control system allows adjusting the slave EM to the master EM (synchronizing rotation speeds) in a wide range – from 0 to 5000 rpm; the asynchrony of EM rotation differs according to electromagnetic and mechanical parameters, as well as properties of mechanisms during performance.

IV. A MODEL OF AN AUTOMATIC CONTROL SYSTEM FOR ELECTROMECHANICAL CONVERTERS WITH AN OBSERVING IDENTIFICATION TOOL

In electromechanical converters, as a rule, unpredictable changes in mechanical characteristics, such as resistance, inertia and electromagnetic moments take place. Observing means that reproduce the state variables of EM parameters can also identify external impacts and unknown EM parameters that are not directly measurable. In this case, the observing means are performed with self-tuning according to the identifiable parameters due to the input of integrators, whose input signals represent the difference between the measured and estimated values of the variable components of an EM. Such adaptive automatic control systems (ACS) of parameters are convenient in cases when the necessary parameter of a non-stationary object needs to be continuously adjusted by changing the system transfer coefficient.

It is convenient to consider the procedure for identifying unknown EM parameters using an adaptive ACS with an observing means on the example of an object with one input u(t) and one output y(t) signals. The EM can be characterized by a transfer function, the degree of the numerator of which is at least one less than the degree of the denominator:

$$W_{EM}(s) = \frac{y}{u} = \frac{B_0 s^{n-1} + B_1 s^{n-2} + \ldots + B_{n-1}}{s^n + A_1 s^{n-1} + \ldots + A_n}. \quad (4)$$

where A_i and B_i – unknown coefficients.

When the numerator and denominator of the transfer function (4) are divided by a polynomial of the (n–1)th degree $(s+\lambda_2)(s+\lambda_3)\ldots(s+\lambda_n)$, in which $\lambda_2, \lambda_3, \ldots, \lambda_n$ are real and negative roots, and the numerator and denominator are decomposed into simple fractions, we obtain a transfer function in the form:

$$\frac{y}{u} = \frac{b_1 + b_2 \dfrac{1}{s+\lambda_2} + \ldots + b_n \dfrac{1}{s+\lambda_n}}{s - a_1 - a_2 \dfrac{1}{s+\lambda_2} - \ldots - a_n \dfrac{1}{s+\lambda_2}}, \quad (5)$$

where $b_1 = B_0$; $a_1 = (\lambda_2 + \ldots + \lambda_n) - A_1$.

Other coefficients b_i and a_i are connected by complex polynomials with A_i, B_i and λ_i; and in this case there is no need to introduce them.

The EM stator current is taken as a controlling action on the unsteadiness of the system, and the angular velocity of the EM – as the initial value. For simplicity, we will assume that in a closed loop tracking system, the feedback on the electromotive intensity of an electromechanical converter can be neglected, and the moment of resistance remains invaried. Then the EM transfer function can be written as:

$$W_{EM}(s) = \frac{y}{u} = \frac{c_{cc}\Psi}{Js} = \frac{b}{s}, \quad (6)$$

where $y = \omega$ (ω is the angular velocity); $u = i_{sc}$ (i_{sc} is the EM stator current); Ψ denotes the EM magnetic induction; $c_{cc} = \frac{N p_п}{2\pi a}$ is the design factor of EM; N is the number of stator winding bars; p_n is the number of pairs of poles, and a denotes the number of pairs of parallel coils. Thus, the parameter $b = (c_{cc}\Psi)/J$ will be subject to identification.

When (6) is compared with the transfer function (5), and the corresponding transformations are performed, we obtain

$$\begin{cases} b_1 = b; \\ a_1 = a_2 = \ldots = 0; \\ \overline{a_1'} = a_1 + \lambda_1 = 0 + \lambda_1 = \lambda. \end{cases} \quad (7)$$

Taking into account (7), we will construct a block diagram of the observing identification tool shown in Figure 4.

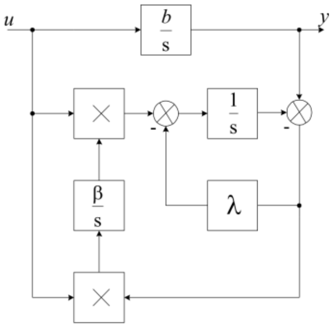


Fig. 4 – Block diagram of the observing identification tool

Accounting for the proposed observing identification tool of the parameter $b = (c_{cc}\Psi)/J$, a block diagram of an adaptive ACS of EM angular velocities was constructed, see Figure 5. As is seen in Figure 5, the observing identification tool is included in the loop of controlling the slave EM, which constantly adjusts to the master EM. In the proposed observing identification tool, β is the gain factor of the adaptation circuit, which is used to optimize the process of identifying EM parameters.

In addition, the block diagram, which is shown in Figure 5, reveals some models that describe the operation of the structural blocks of the control system, which are shown in Figure 2, and also shows how to connect to the automatic control system (Figure 2) the proposed observing identification tool (Figure 4). Figure 5 illustrates the sequence of connecting blocks to create a model of an adaptive speed control system with an observing identification tool in MATLAB-SIMULINK mathematical package.

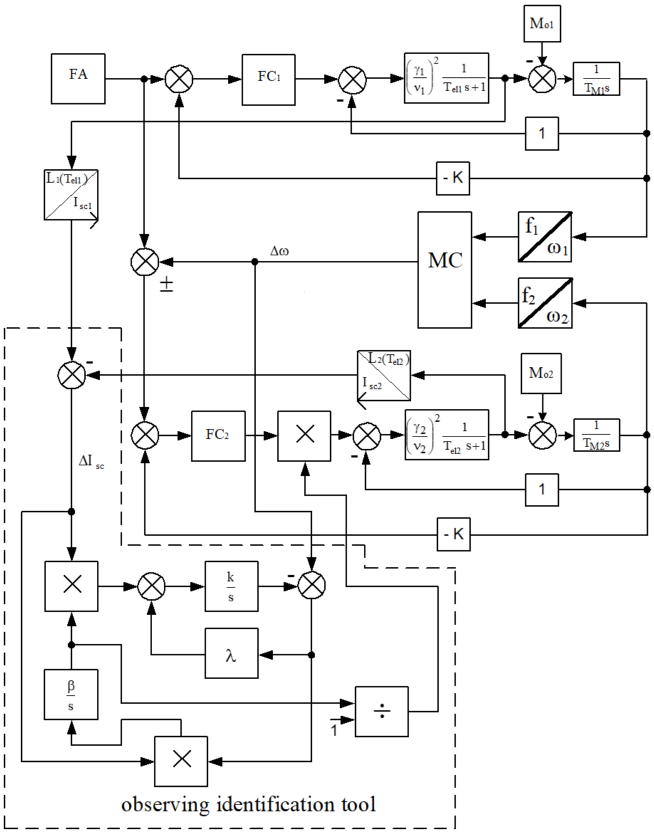


Fig. 5. Adaptive ACS with asynchronous EM rotation with an observing identification tool

The algorithm of the observing identification tool is described by the following expressions:

$$\frac{d\bar{\omega}}{dt} = \frac{\bar{c}_{cc}\bar{\Psi}}{J} i_{sc} + \lambda k(\omega - \bar{\omega}), \tag{8}$$

$$\frac{d(\bar{c}_{cc}\bar{\Psi}/J)}{dt} = \beta \cdot k \cdot i_{sc}(\omega - \bar{\omega}), \tag{9}$$

where k is gear ratio in relation to angular velocity (k=U/ω).

Since the initial operating conditions of the ACS are $\bar{\omega}(0) = 0$ and $(\bar{c}_{cc}\bar{\Psi}/J)(0) = 0$, then if you enter the designation $e = \omega - \bar{\omega}$ and $\nu = c_{cc}\Psi/J - (\bar{c}_{cc}\bar{\Psi}/J)$, and also consider that $d\omega/dt = i_{sc}\, c_{cc}\Psi/J$, the algorithm of the observing identification tool in the coordinates e and ν can be described by the equations:

$$\frac{de}{dt} = \nu i_{sc} - \lambda k e, \tag{10}$$

$$\frac{d\nu}{dt} = -\beta k i_{sc} e. \tag{11}$$

In this connection, the initial conditions are assumed to be e(0)=0 and ν(0)=c_{cc}Ψ/J, and based on the quasi-stationarity hypothesis, it is assumed that during the transient process in the observing device, the c_{cc}Ψ/J parameters do not change.

The stability of the observing tool in the identification of parameters c_{cc}Ψ/J can be established on the basis of the second Lapunov method. To test the condition of asymptotic stability of the observing identification tool, the Lyapunov function is considered as a positive definite quadratic form of the error e and the parameter ν:

$$V = \frac{1}{2}e^2 + \frac{1}{2}\frac{\nu^2}{\beta k}. \tag{12}$$

The total derivative of the function (12) in time based on (10) and (11) will be equal to $dV/dt = -\lambda k e^2$.

The dV/dt function must be negatively-defined in the space of variables e and ν, that is $\frac{dV}{dt}(e,\nu)\Big|_{\substack{e\equiv 0\\ \nu\equiv 0}} = 0$. To prove that for $e \equiv 0$ we get $\nu \equiv 0$, we consider the system of equations (10) and (11) with the error e being identically equal to zero. Since thereat the time error derivative is zero, the system of equations (10), (11) will take the form:

$$0 = \nu i_{sc}, \tag{13}$$

$$\frac{d\nu}{dt} = 0. \tag{14}$$

Since i_{sc} is not equal to zero, it is obvious from expressions (13) and (14) that the parameter ν is identical to zero. Consequently, the dV/dt function is negatively-defined and, when constructing an observant identification tool according to expressions (8) and (9), the value $(\bar{c}_{cc}\bar{\Psi}/J)(t)$ asymptotically approaches the c_{cc}Ψ/J parameters. The similarity of the evaluation process depends on the coefficients λ and β, which can almost always be selected from the condition of the evaluation process in the system of the main transient process based on the requirements of the system interference immunity resistance.

The estimation $(\bar{c}_{cc}\bar{\Psi}/J)$ of the parameters c_{cc}Ψ/J is used to automatically adjust the transfer factor of the PID speed controller by multiplying it by the emerging unpredictable deviations of the inertia moment.

V. Empirical Results and Analysis

Modelling an adaptive ACS by asynchronous rotation of EM rotors was performed using the MATLAB package in the SIMULINK environment.

When modelling the operation process of an adaptive ACS by asynchronous rotation of EM rotors with an observing identification tool, we deduced the characteristics of the processes of asynchronous of the EM rotor rotation frequencies, which are shown in Figures 6 and 7.

As can be seen in Figure 6, the asynchrony of rotation of the EM rotors when using an adaptive ACS has significantly decreased compared to the asynchrony shown in Figure 3. The observing identification tool (fig. 5) instantly reacts to deviations in the speed of the slave EM from the master (reconfigures the values of the control signal) and immediately adjusts it to the speed of the master EM. In the steady-state mode, it is almost zero. And with the same deviation of electromagnetic and mechanical parameters from the norms, the characteristic of the process of synchronizing the rotation frequencies of the EM rotors using an adaptive system with an observing identification tool is shown in Figure 7.

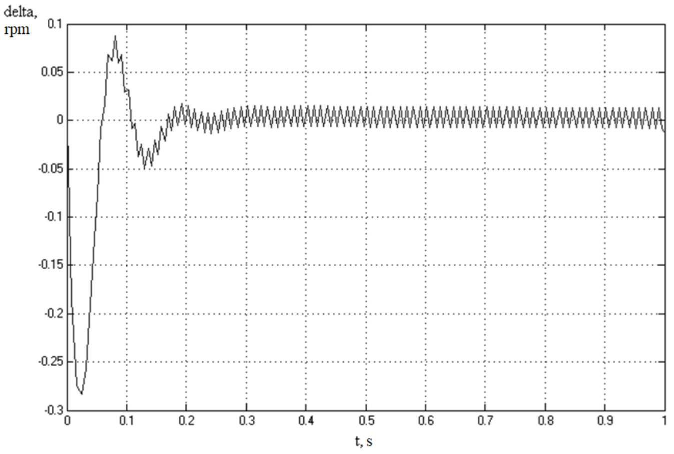


Fig. 6. The process of synchronizing the EM rotor rotation frequencies when using an adaptive ACS with an observing identification tool

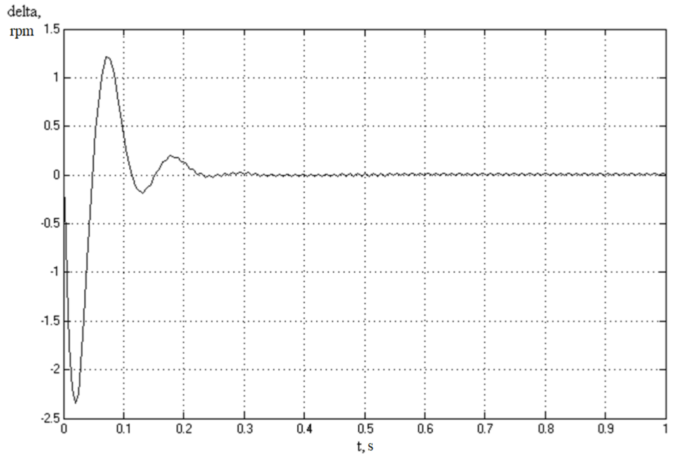


Fig. 7. The process of adaptive synchronization of the EM rotor rotation frequencies with a deviation of electromagnetic and mechanical parameters from the nominal values

As is seen in Figure 7, when the parameters deviate from the nominal values, the asynchrony of rotation of the EM rotors in the static mode has practically not changed compared to Figure 6; but compared to the characteristics of the ACS operation without the use of an adaptive algorithm, the asynchrony of rotation has significantly decreased. The maximum error of asynchronous rotation of EM rotors with an observing identification tool does not exceed 0.4%. The conducted studies indicate that the developed algorithm for adaptive synchronization of EM angular velocities automatically changes (reconfigures) the coefficients of the PID controller when the electromagnetic and mechanical parameters deviate from the norms, that is, adapts.

Thus, the use of an adaptive ACS by asynchronous rotation of the EM rotors with an observing identification tool allows reducing the error of synchronization of angular velocities to a minimum, and thereby increase the accuracy of synchronization and control by 3 - 4 times both in the static and dynamic operation mode with the EM rotation frequencies change from 0 to 6000 rpm.

VI. Conclusions

The developed model of the ACS with the EM acceleration characteristics allows synchronizing the rotational speeds in a wide range – from 0 to 6000 rpm with sufficiently high accuracy. The difference in rotational speeds between the two EM depends on the electromagnetic and mechanical parameters and the properties of mechanisms during operation, therefore, the proposed model of an adaptive ACS with an observing identification tool allows minimizing the error of asynchronous rotation of the rotors of the two EM and correcting when the electromagnetic and mechanical parameters of an EM deviate from their nominal values.

The maximum error of asynchronous rotation of EM rotors with an observing identification tool does not exceed 0.4%. The conducted studies confirm that the developed algorithm of adaptive synchronization of EM angular velocities automatically changes (reconfigures) the coefficients of the PID controller when the electromagnetic and mechanical parameters deviate from the norms, that is, adapts. The observing identification tool, which reproduces the variable state of the EM parameters, also identifies external influences and unknown EM parameters that are not subject to direct measurement. The observing means of identification is performed with self-tuning according to the identifiable parameters due to the input of integrators, whose input signals represent the difference between the measured and estimated values of the variable components of the EM. Such adaptive algorithms for parameter control are convenient in cases when the desired parameter of a non-stationary object needs to be continuously adjusted by changing the transfer coefficient of the system. The adequacy of the proposed mathematical model and adaptive synchronization algorithm is confirmed by the results of mathematical modelling in the Simulink MATLAB environment.

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