UDC 621.313.333.1
DOI: 10.15587/1729-4061.2021.251232

DEVELOPMENT OF MATHEMATICAL DESCRIPTION OF MECHANICAL CHARACTERISTICS OF INTEGRATED MULTI-MOTOR ELECTRIC DRIVE FOR DRYING PLANT

Sultanbek Issenov
Corresponding Author
PhD, Associate Professor, Dean
Department of Energy*
E-mail: isenov_sultan@mail.ru
Ruslan Iskakov
PhD, Associate Professor
Department of Agrarian Technique and Technology*
Kazhybek Tergemes
PhD, Associate Professor
Department of Power Supply of Industrial Enterprises
Almaty University of Power Engineering and Telecommunications
Baytursynuli str., 126/1, Almaty, Republic of Kazakhstan, 050013
Zhanat Issenov
Master of Technical Sciences
Department of Electrical Power
Toraighyrov University
Lomov str., 64, Pavlodar, Republic of Kazakhstan, 140008
*S. Seifullin Kazakh Agro Technical University
Zhenis ave., 62, Nur-Sultan, Republic of Kazakhstan, 010011

More than 60 % of electric energy in industry and agriculture is consumed by an electric drive. In a number of production mechanisms, machines and aggregates of various industries, synchronous rotation of several electric motors connected to each other mechanically, electrically or technologically is needed. This requires the use of more complex methods of controlling electromechanical systems, since two or more electric motors must work in concert for one load, which, in turn, entails the use of a new element base, power and control, allowing to implement these technological cycles of work.

The object of research is a three-motor electromechanical system interconnected and operating according to the "electric working shaft" (EWS) system. The main fundamental difference from earlier works is that they consider a system of coordinated rotation of only two asynchronous motors, respectively, only one misalignment angle between two asynchronous motors was taken into account. At the same time, the conclusions of the moments and currents of the motors were significantly simplified.

In the proposed study, the number of consistently (synchronously) rotating motors from three and above is taken into consideration. In this case, the number of misalignment angles is assumed to be equal to the number of engines, that is, three involved in rotation.

The analytical expressions of the basic electromechanical relations of the "electric working shaft" system with the regulation of the supply voltage are developed. A method is proposed for calculating the statistical characteristics of the regulated EWS system, which is easy to use and allows calculations in a wide range of rotor misalignment angles at various engine loads

Keywords: multi-motor electric drive, electric working shaft, experimental mechanical characteristics, mathematical model, drying, technological process, synchronizing moment, additional resistance, rotor link, misalignment angle

Received date 12.11.2021
Accepted date 21.12.2021
Published date 28.12.2021

How to Cite: *Issenov, S., Iskakov, R., Tergemes, K., Issenov, Z. (2022). Development of mathematical description of mechanical characteristics of integrated multi-motor electrical drive for drying plant. Eastern-European Journal of Enterprise Technologies, 1 (8 (115)), 46–54. doi: https://doi.org/10.15587/1729-4061.2021.251232*

1. Introduction

Currently, a multi-motor electric drive, in which electric motors work together for a common mechanical load, is widely used in industry and agriculture. In such an electromechanical system, a group of electric motors is united by a common control system and set in motion individual working bodies of a machine or installation [1].

Asynchronous motors are most often used as electric motors. First of all, because asynchronous motors are characterized by simplicity of design and maintenance, low cost, low weight and size indicators, high efficiency and reliability, good dynamic performance due to a lower moment of inertia, as well as acceptable adjustment properties, which are provided by the use of semiconductor converters.

The control of a multi-motor electric drive provides for a certain order of switching on and off individual electric motors, as well as maintaining the operating speed (synchronous rotation), torque and other parameters with a given accuracy. Unstable maintenance of working electromechanical parameters leads to incorrect operation of the entire installation, occurrence of emergency situations, increased wear and destruction of mechanisms, premature failure of electric motors.

Examples of machines and mechanisms with multi-motor asynchronous electric drives are: rolling mills; carding machines – control of synchronous thread tension; bridge cranes – control of the mechanism for moving the crane trolley; combined metalworking machines; walking excavators; drying machines for grinding and drying feed; crushing and mixing machines for preparing feed; paper machines; drive roller supports, conveyors; drive trams and drawbridges [2, 3].

Therefore, given the variety of machines and mechanisms with a multi-motor asynchronous electric drive, the development of a new circuit solution, the study of analytical expressions of moments, currents are relevant and have important social and economic significance.

2. Literature review and problem statement

Regulation of the coordinates of an asynchronous electric drive, both in two- and multi-motor electric drives, is possible with frequency and parametric (phase and pulse) controls in the stator circuit and with parametric (phase and pulse) control and in case circuits in the rotor [3].

Frequency control provides smooth speed control over a wide range. However, it also has disadvantages. So the current at the output of the converter has a non-sinusoidal shape. In converters with a DC link, double energy conversion is carried out, which reduces the total efficiency of the drive system. The disadvantage of direct frequency converters is the use of a large number of thyristors. In addition, the maximum frequency at the output of the rectifier is 10–12 Hz and is limited by the frequency of the supply network. Currently, the use of this control method is justified when, according to the requirements of the production mechanism, the environment, etc., it is necessary to use a reliable, cheap and maintenance-free asynchronous motor with a short-circuited rotor [3, 4].

Phase control of an asynchronous motor is one of the most developed and most widely used in industry, compared to other parametric methods. In this case, the asynchronous motor is connected to the supply network via a thyristor voltage regulator [3–5].

This electric drive system has a significant drawback, which is as follows. When the voltage on the stator windings decreases, the flow and torque of the motor decrease, and when the static moment of resistance on the shaft is constant, achieving a new steady-state mode is possible only by increasing the stator current, which leads to significant heating of the motor. The reduction of heating can be achieved by choosing an over-powered motor, or by using an engine with a phase rotor by including additional resistors in the rotor circuit and taking part of the electric losses outside the motor. Both options worsen the technical and economic indicators. The first – due to an increase in the cost and weight and size of the drive system, the second – due to the complexity of the control circuit of the electric drive associated with the need to simultaneously control the stator and rotor circuits. The disadvantage of this system is also a lower power factor than in a conventional switching circuit, due to the shift of the main voltage harmonic relative to the mains voltage and due to the influence of higher harmonics, which also leads to an increase in engine heating [5].

In a multi-motor asynchronous electric drive, the required adjustment characteristics can also be obtained by the addition of mechanical characteristics of motors operating in various modes, the use of a mechanical differential, the use as one of the drive motors with a rotary stator. These drive systems are of very limited use due to obvious significant drawbacks and are not considered further [6, 7].

In a multi-motor asynchronous electric drive, control can be carried out both from one common converter and from individual converters for each motor. Depending on the specific technical requirements, both options are used.

When controlling both the stator circuits and the rotor circuits by a multi-motor drive, in the absence of communication between the shafts, from individual converters, in order to ensure the load equality of the motors, it is necessary to control the load of each motor and control the converters in such a way as to ensure a sufficiently uniform load distribution between the motors [7, 8].

When powering a multi-motor asynchronous electric drive from a common converter or directly from the mains, as noted earlier, the uniform load of the motors will not be ensured and additional devices are required to achieve the latter. So, to ensure an acceptable load distribution, it is proposed to reduce the supply voltage on a more loaded engine, electromagnetic sliding couplings and an equalizing transformer are used, which redistribute voltage among the motors. Analysis of these solutions shows that these and similar drive systems have a significant disadvantage, since expensive equipment is used only to ensure uniform load [8–10].

In this respect, drive systems with control in the rotor circuit are more advanced – cascade circuits and pulse regulation in the rectified current circuit of the rotor, in which this problem is solved much easier [11, 12].

Both when controlling an asynchronous motor in valve helmets and with pulse control in the rectified current circuit of the rotor, an uncontrolled three-phase bridge rectifier is connected to the rotor circuit. This creates an additional advantage in a multi-motor drive, since there is no need for phasing the rotors, both when installing the electric drive and when starting up, because the motors are already interconnected along the rectified current circuit of the rotors and the previously noted disadvantages associated with equalizing currents are not manifested here. When using these control principles of a multi-motor asynchronous electric drive, the following options for connecting rectifiers are possible [3, 5, 13, 14]:

a) sequential, when one common speed control device is used, to which rectifiers are connected in series;

b) parallel, when one common speed control device is used, to which rectifiers are connected in parallel;

c) independent, when the output of each rectifier is connected to an individual speed control device, either an inverter driven by a network, or a pulse regulator.

A distinctive feature when connecting rectifiers in series, when using one common speed control device, is that in this drive system, the majority of motor loads are already embedded in the drive power circuit and no additional equipment is required. Such connection of rectifiers is used in a multi-motor valve-machine cascade, in an asynchronous valve cascade (AVC), with rheostatic regulation, as well as with pulse regulation [3, 5, 13, 14].

One of the positive qualities of electric drive systems in cascade circuits for switching on an asynchronous motor with a phase rotor is high efficiency due to the recovery of the amount of energy released in the rotor circuit during regulation into the supply network. The use of cascade circuits for medium and especially high-power drives, including multi-motor ones, can give a significant economic effect. In low-power drives, which are most widely used in industries, especially with a small speed control range or with a short operating time at a reduced speed, that is, when the sliding energy released in the rotor is insignificant, this system loses its advantages and, as a rule, does not find application. This electric drive system, as well as the phase-controlled system, has a low power factor. This is due to the use of a static converter (inverter), which leads to the appearance of higher harmonics. Another, more significant reason is an increase in the consumption of reactive power by the system, which is necessary not only for the engine, but also for the inverter [13, 14].

The use of AVC for the serial connection of rectifiers, in addition to the noted positive qualities, has significant drawbacks. So, when adjusting the angular velocity in the range from zero to nominal, the voltage for which the inverter should be designed is doubled. This can lead to an increase in the cost and weight and size of the inverter and the drive system as a whole.

The variant according to the scheme with parallel connection of rectifiers is the most widely used, both in two-motor and multi-motor electric drives to ensure the matching of the high speeds of the motors [3, 5, 13, 14].

The drive system with the parallel connection of rectifiers was used in crane movement mechanisms. Due to the agreement of the angular velocities of the engines, it is possible to ensure the movement of the crane with fewer distortions, which leads to a decrease in mechanical stresses in metal structures and an increase in the reliability of the crane mechanisms [13, 14].

The use of the circuit with the serial connection of rectifiers in mechanisms without mechanical connection of the motor shafts is associated with certain difficulties associated with ensuring uniform load distribution between the motors.

The drive system according to the scheme with parallel connection of rectifiers, without mechanical connection of the motor shafts, in some cases may be unacceptable. Due to the spread of motor parameters, the voltages at the outputs of the rectifiers may be different and such a ratio between them will be maintained when the angular velocity is regulated due to the lack of mechanical coupling of the motors. In this case, the entire load will be borne by the motor, which has a higher voltage at the output of the rectifier, and, consequently, it will be unacceptably overloaded [13, 14].

The drive system, in which the rectifiers are connected independently, has no such a drawback. An electric drive system, in which an option with an independent connection of rectifiers is used, where the output of each rectifier is connected to an individual speed control device, should be used in the mechanisms where it is necessary to ensure the required ratio of speeds, for example, the speeds of individual sections, or to create an electric drive through an electric shaft system when there is no electric connection between the motors. In this case, the alignment of angular velocities is carried out along the control circuits of individual converters. Independent connection of rectifiers is currently the most common and promising, due to the fact that the output of each rectifier is connected to an individual control device, introducing feedback at a given coordinate. A targeted effect on the individual control device is possible if one of the motors is not operating in nominal mode, which contributes to the formation of the necessary mechanical characteristics [3, 5, 8, 15, 16].

Both phase and pulse regulation in the rotor, as well as rheostatic regulation, provide for the conversion of sliding energy into heat losses and their allocation to additional resistors included in the rotor circuit. However, when using these systems in drives with low-power motors, these losses can not be considered, especially if the cycle time at reduced speed is small.

There are quite a lot of phase-controlled circuits in the rotor circuit when thyristors are connected to the alternating current circuit of the rotor. In these circuits, no additional nodes are required for artificial switching of thyristors, since in this case natural switching is carried out when the current passes through zero. As other positive properties, it is necessary to note the simplicity of the power circuit, especially in those circuits where only three thyristors are used, small weight and size indicators and cost. The rotation current is regulated by changing the opening angle of the thyristor relative to the point of natural opening. The peculiarity of these systems is that when the speed changes, the frequency of the rotor current does not remain constant, but changes proportionally to the slip [4, 7, 8].

It follows that the control of thyristors must be carried out with a sliding frequency, and this leads to a noticeable complication of the electric drive control system. In addition, when the drive is operating in the nominal speed range, i.e. at low slip values, and hence at a low switching frequency of thyristors, large amplitudes of speed fluctuations can occur, especially at a small moment of inertia of the mechanism.

Pulse regulation in the rectified current circuit of the rotor in comparison with the phase one has a number of positive qualities. The control system is fundamentally simpler and has only one control channel. The switching frequency of thyristors is not limited by the frequency of the alternating current of the rotor, but is limited by the switching capabilities of the thyristors themselves, and is selected depending on the permissible pulsation of the drive speed and on the electromagnetic time constant of the rotor circuit [3, 7, 8].

In a multi-motor asynchronous electric drive, control is carried out by a common thyristor switch connected to the outputs of parallel rectifiers. Since this drive system, as noted earlier, is used as a working electric shaft or with semi-rigid mechanical coupling, the load on the shaft of each motor will be different and may change during operation. To obtain the required static and dynamic characteristics of the drive, it is necessary to use feedback on coordinates that can be measured by available means. However, the question arises, according to the coordinates of which engine to control, when their values for engines can differ greatly. If the weight is controlled by a less loaded engine, then when operating in the rated load area, the second engine will be overloaded. Such a solution would lead to a decrease in the reliability of the drive. It follows that the control must be carried out according to the most loaded engine, i.e. so that it is the master, and the other, less loaded, the slave [4, 13, 14].

Consequently, the introduction of speed sensors and speed isolation units of a loaded engine into the electric drive makes it possible to increase the accuracy of speed control compared to the use of reverse communication over the rectified voltage of the motor rotors by increasing the accuracy of the signal for the speed of the most loaded engine.

The existing electric drive systems of this mechanism provide for the regulation of the speed of movement by a stepwise change of additional resistances included in the circuit of the parallel-connected rotor windings. An analysis of the operation of this system and its long-term operation in production conditions revealed significant shortcomings and inconsistency with the requirements:

– uneven load of engines, due to the lack of the possibility of purposeful impact on each engine separately;

– insufficient reliability, due to the large number of electric drive inclusions necessary to ensure the technological process;

– does not provide a stable reduced adjustable speed of movement of the trolley;

– significant impacts of the electromagnetic moment, both during start-up and during speed control.

Therefore, it is necessary to improve the multi-motor electromechanical system in order to eliminate the noted shortcomings.

3. The aim and objectives of the study

The aim of the study is to develop a multi-motor asynchronous electric drive for synchronous rotation of the drying unit with the determination and analysis of electromechanical relations to optimize the operating modes of the electromechanical system.

To achieve the aim, the following objectives were accomplished:

– to apply a circuit design and a T-shaped equivalent circuit when calculating electromechanical parameters;

– to determine the currents and moments of the "electric working shaft" system;

– to develop analytical electromechanical relations with varying equivalent resistance in the rotor circuit and impulse control in the rotor circuit.

4. Materials and methods

The above predetermines the formulation and solution of the task – the improvement and development of analytical expressions of moments, currents based on a three-motor T-shaped equivalent circuit, a system of coordinated rotation of asynchronous motors with a common rheostatic resistance in the rotor windings of motors. Investigation and analysis of the obtained data on the torques of three electric motors, at different misalignment angles of the engine rotors of the system were conducted.

In the process of performing the research, the methods of the theory of electric drives, electric machines, and valve converters were applied.

The validity and reliability of scientific provisions, conclusions and recommendations are confirmed by: selection of significant processes; accepted levels of assumptions in the mathematical description of phenomena; the validity of the premises arising from the fundamental laws of natural sciences and the theory of electric drive; a sufficient amount of experimental research.

5. Results of research of electromechanical parameters of a multi-motor electric drive

5. 1. Application of a T-shaped equivalent circuit in the calculation of parameters of a multi-motor asynchronous electric drive

When calculating electromechanical parameters, a circuit solution (Fig. 1, *a*) and a T-shaped equivalent circuit (Fig. 1, *b*) were used for a multi-motor asynchronous electric drive.

To define the currents and torques of the EWS system comprising three asynchronous drives (Fig. 1, *a*), we use its equivalent-T shown in Fig. 1, *b* that designates [4, 5]:

– U_1, U_2, U_3 – network voltages for each engine;

– I_{11}, I_{12}, I_{13} and I_{21}, I_{22}, I_{23} – stator and rotor currents of the machines;

– r_{11}, r_{12}, r_{13} and x_{11}, x_{12}, x_{13} – active and inductive resistances of the stator windings of the respective EWS system's engines;

– r_{21}, r_{22}, r_{23} and x_{21}, x_{22}, x_{23} – active and inductive resistances of rotor windings;

– x_{01}, x_{02}, x_{03} – inductive resistances of excitation contours;

– Rd – multiplier resistance in rotor circuit;

– S – slip;

– φ_1, φ_2, φ_3 – angular shifts of rotors in electric degrees in relation to the accepted axis of reference.

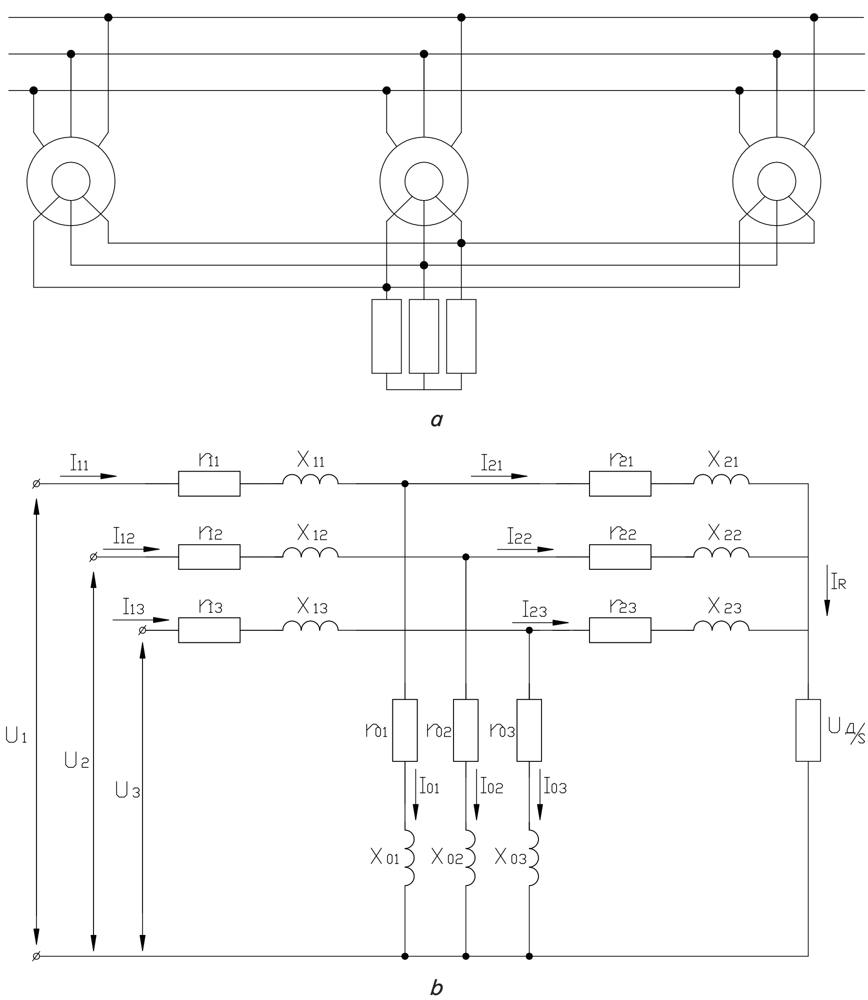

Fig. 1. The main signature: *a* – classical electric working shaft system; *b* – equivalent-T system

5. 2. Calculation of currents and torques for the "electric working shaft" system of a multi-motor asynchronous electric drive

Designating the complex resistances of stators and rotors at slip S through Z_1, Z_2, and accounting for the identity of engine parameters and reduction of rotor resistances, we get:

$$\begin{cases} Z_1 = r_1 + j(x_0 + x_i); \\ Z_2 = r_2'/S + j(x_0 + x_2'), \end{cases} \quad (1)$$

where r_2' and x_2' are reduced active and inductive resistances of rotors.

Resistance equations for stator and rotor circuits can be written using the superposition principle on the equivalent-T as follows:

$$\begin{cases} U_1 = I_{11}Z_1 - I_{21}jx_0; \\ U_2 = I_{12}Z_1 - I_{22}jx_0; \\ U_3 = I_{13}Z_1 - I_{23}jx_0, \end{cases} \quad (2)$$

$$\begin{cases} (I_{11}jx_0 - I_{21}Z_2)e^{j\phi_1} = \\ = \frac{R'}{S}\left(I_{21}e^{j\phi_1} + I_{22}e^{j\phi_2} + I_{23}e^{j\phi_3}\right); \\ (I_{12}jx_0 - I_{22}Z_2)e^{j\phi_2} = \\ = \frac{R'}{S}\left(I_{21}e^{j\phi_1} + I_{22}e^{j\phi_2} + I_{23}e^{j\phi_3}\right); \\ (I_{13}jx_0 - I_{23}Z_2)e^{j\phi_3} = \\ = \frac{R'}{S}\left(I_{21}e^{j\phi_1} + I_{22}e^{j\phi_2} + I_{23}e^{j\phi_3}\right). \end{cases} \quad (3)$$

Based on the equations (1)–(3), we define the rotor and stator currents of the engines in the EWS system after transformations. Considering the identity of the formulae for determining currents and torques that differ in the corresponding indices and angular deviations, we further show formulae only for the first engine. The rotor current of the first engine is as follows:

$$I_{21} = \frac{jx_0\left\{x_0^2 + Z_1\left[Z_2 + \frac{R'}{S}\left(3 - \sum_{i=1}^{3} e^{j(\phi_2 - \phi_1)}\right)\right]\right\}}{\left[x_0^2 + Z_1\left(Z_2 + \frac{3R}{S}\right)\right]\left(x_0^2 + Z_2Z_1\right)} \cdot U_1; \quad (4)$$

$$I_{11} = \frac{U_1}{Z_1} + \frac{jx_0}{Z_1}I_{21} =$$

$$= \frac{x_0^2\left[Z_2 + \frac{R'}{S} i = 1\sum^{3} e^{j(\phi_2 - \phi_1)}\right] + Z_1Z_2\left(Z_2 + \frac{3R'}{S}\right)}{\left[x_0^2 + Z_1\left(Z_2 + \frac{3R'}{S}\right)\right]\left(x_0^2 + Z_2Z_1\right)} \cdot U_1. \quad (5)$$

Considering the introduced correction factor and symbols from [4] such as

$$\sigma_1 = 1 + \frac{Z_1}{Z_2} \approx \left(1 + \frac{x_1}{x_0}\right) - j\frac{r_1}{x_0},$$

or

$$Z = r_1 + jx_0 + \sigma_1\left(\frac{r_2}{S} + jx_2\right), \quad (6)$$

where

$$x = x_1 + x_2\sigma_1, \quad Z = r_1 + \frac{r_2}{S}\sigma_1 + jx,$$

ignoring the ratio r_1/x_0 in view of its smallness, we write the equations (4), (5) after transformations as follows:

$$I_{21} = \frac{Z_1 + \frac{\sigma R'}{S}\left(3 - \sum_{i=1}^{3} e^{j(\phi_L - \phi_1)}\right)}{Z\left(Z + \frac{3R'}{S}\sigma_1\right)}; \quad (7)$$

$$I_{11} = I_{01} + \frac{1}{\sigma_1} \cdot \frac{Z + \frac{\sigma_1 R'}{S}\left(3 - \sum_{1}^{3} e^{j(\phi_2 - \phi_1)}\right)}{Z\left(Z + \frac{3\sigma_1 R'}{S}\right)} \cdot U_1,$$

where I_{01} is the current of the no-load run of the first engine.

Using Euler formulae, we obtain torque equations for the first engine

$$M_1 = \frac{U_1^2}{3\sigma_1}\left\{\begin{array}{l} \frac{\left(\frac{r_2\sigma_1}{S}\right)\left[3 - \sum_{i=1}^{3}\cos(\phi_2 - \phi_1)\right]}{\left(\frac{r_2\sigma_1}{S}\right)^2 + x^2} + \\ + \frac{\frac{(r_2 + 3R)\sigma_1}{S} \cdot \sum_{L=1}^{3}\cos(\phi_1 - \phi_1)}{\left[\frac{(r_2 + 3R)\sigma_1}{S}\right]^2 + x^2} \end{array}\right\}. \quad (8)$$

The maximum torque achieved by engines that work with the natural characteristic is as follows:

$$M_m = \frac{U^2}{2(x_1 + x_2\sigma_1)\sigma_1} = \frac{U^2}{2x\sigma_1}, \quad (9)$$

and the critical slip corresponding to this torque

$$S_m = \frac{(r_2 + +3R)\sigma_1}{x_1 + x_2\sigma_1}. \quad (10)$$

When rotors are connected to the general external resistance R_d, the critical slip is:

$$S_m' = \frac{(r_2 + 3R_d)\sigma_1}{x_1} = S_m\left(1 + \frac{3R_d}{r_2}\right). \quad (11)$$

With the account of (9)–(11), the torque resistance is as follows:

$$M_1 =$$

$$= \frac{2M_m}{3}\left\{\begin{array}{l} \frac{3 - \sum_{1}^{3}\left[\cos(\phi_L - \phi_1) + S/S_m \sin(\phi_L - \phi_1)\right]}{S/S_m + S_m/S} + \\ + \frac{\sum_{i=1}^{3}\left[\cos(\phi_L - \phi_1) + S/S_m \sin(\phi_L - \phi_1)\right]}{S/S_m + S_m/S} \end{array}\right\}; \quad (12)$$

or

$$M_1 = M_{1asyn} + M_{1syn} =$$

$$= \frac{2M_m}{3}\left[\frac{3-\sum_{i=1}^{3}\cos(\phi_L-\phi_1)}{S/S_m+S_m/S}+\frac{\sum_{i=1}^{3}\cos(\phi_L-\phi_1)}{S/S_m+S_m/S}\right]+$$

$$+\frac{2M_m}{3}\left[\begin{array}{c}\frac{S/S_m\sum_{i=1}^{3}\sin(\phi_L-\phi_1)}{S/S_m+S_m/S}-\\ -\frac{S/S'_m\sum_{i=1}^{3}\sin(\phi_L-\phi_1)\sum_{i=1}^{3}\sin(\phi_L-\phi_1)}{S/S'_m+S'_m/S}\end{array}\right]. \quad (13)$$

Currents and torques of the second and the third engines are determined similarly with the only difference in the angular positions of rotors.

It is apparent in (12), (13) that the torques developed by the first, second and third machines are a sum of two components: the synchronizing component that supports the coordinated rotation of engines impacting all three machines depending on the angular misalignment of their rotors [6]

$$M_{syn(1,2,3)} = \frac{2M_m}{3}\left\{\begin{array}{c}\frac{3-\sum_{i=1}^{3}\left[\cos(\phi_L-\phi_{1,2,3})\right]}{S/S_m+S_m/S}+\\ +\frac{\sum_{i=1}^{3}\left[\cos(\phi_L-\phi_{1,2,3})\right]}{S/S'_m+S'_m/S}\end{array}\right\}, \quad (14)$$

and the asynchronous component

$$M_{asyn(1,2,3)} = \frac{2M_m}{3}\left\{\begin{array}{c}\frac{3-\sum_{i=1}^{3}\left[\cos(\phi_L-\phi_{1,2,3})\right]}{S/S_m+S_m/S}+\\ +\frac{\sum_{i=1}^{3}\left[\cos(\phi_L-\phi_{1,2,3})\right]}{S/S'_m+S'_m/S}\end{array}\right\}. \quad (15)$$

The sign and value of the synchronizing torques depend on the sign and value of misalignment ($\varphi_L-\varphi_{1,2,3}$), and their sum is equal to zero.

The maximum values of the first components occur when the misalignment angles are $\Delta\varphi_{1,2,3}=\pm90°$ and are equal to each other $M_{syn1}=M_{syn2}=M_{syn3}$

$$M_{syn} = \frac{2M_m}{3}\left\{\frac{2\cdot S/S_m}{S/S_m+S_m/S}+\frac{2\cdot S/S'_m}{S/S'_m+S'_m/S}\right\}. \quad (16)$$

The resulting expressions of torques imply that if the rotation of the three machines is co-phase, i.e. when $\varphi_1=\varphi_2=\varphi_3$

$$M_{1,2,3} = \frac{2M_m}{S/S'_m+S'_m/S}. \quad (17)$$

All three machines operate with rheostat characteristics and triple multiplier resistance $3R_d$, while their synchronizing torques are equal to zero.

5. 3. Development of analytical electromechanical relations for a multi-motor asynchronous electric drive with a variable equivalent resistance in the rotor circuit and impulse control in the rotor circuit

The given expressions were used in computation for the integrated multi-motor drive system with the following engine parameters: U_n=220/380 V; IP 44; U_2=153 V; ω_n=960 rpm; I_1=21.4/12.4 A; I_2=12/22.5 A; f_c=50 Hz.

Calculation results are shown in Fig. 2. Design curves of mechanical characteristics have been plotted for various values of multiplier resistances corresponding to critical slips: $S'_m=0.212$; 0.347; 0.645 (*c*, *e*) and misalignment angles $\Delta\varphi_{21}=\Delta\varphi_{23}=90°$ (*e*, *g*), $\Delta\varphi_{12}=60°$, $\Delta\varphi_{13}=90°$ (*a–d*) of engine rotors. Curves with slip $S'_m=0.645$ shown in Fig. 2 are common for the multi-motor electric drive; the value of resistance not clearable from the general rotor circuit is taken as 0.19 Ohm in view of technologically optimal parameters. However, the rigidity of the mechanical characteristic is much lower than that of the characteristics with $S'_m=0.347$ (dash and dot line) and $S'_m=0.212$ (dash line) shown in Fig. 2, *b*.

In this mode (at $S'_m=0.645$), the EWS system is inclined to self-oscillations under static torques over $M_{s\,nom}$.

Under the critical misalignment angles $\Delta\varphi$=90°, the system develops the maximum equalizing torque equal to $M_{eq12}=M_{eq13}$=1.29 M_m, i.e. it can work stably under the values of static torques meeting the following condition: $M_{st1,2,3}$=1.25÷1.26 M_m M_{eq12}, M_{eq13}.

Additionally, it was experimentally determined that unsatisfactory thermal conditions in the system are related to the difference of static loads and inertia masses on the engine shafts that cause significant circulating currents.

Thus, the existing EWS systems in the drives of grinding and drying units, crushing and mixing machines for the preparation of feed, electric heaters, fans designed for convective energy-efficient drying can operate properly when the possible difference of load torques on the machine shafts is not high, and the total rotor resistance of the rotor circuit is not less than $R/R_d\geq0.29$. Reduction of the non-clearable part of rotor resistance or increase in shaft load differences for some reason may result in disruption of synchronous rotation.

The multi-motor electric drive showed high efficiency in the operation of the drying and grinding equipment, where the air supply through the electric heater was optimized using a fan and the rotation of the grinder rotor in accordance with the diagram shown in Fig. 3 [17]. Motors are widely used in waste processing lines [18].

The technical characteristics of the crushing and drying unit, crushing and mixing machines for preparing feed, fans designed for convective energy-efficient drying largely depend on the operation of electric motors [19].

In the scheme shown in Fig. 3, a multi-motor electromechanical system operates that drives the drying unit. Each of the motors is designed for separate equipment and electromechanical process. A multi-motor asynchronous electric drive drives three shafts – the first shaft for crushing; the second shaft for grinding: the third shaft for mixing. The load occurs on impact-cutting elements, impact-splitting elements, blade elements.

It should be noted that a multi-motor electric drive with a uniform synchronous load achieved on each shaft of a separate engine helps to reduce the load on each individual engine of the drying plant (engines for crushing, grinding and mixing).

Reducing the load on each engine entails an increase in the service life of both engines themselves, compared to engines with an uneven load. And, accordingly, an increase in the service life of the entire drying plant, noticeably dependent on the operation of the electric drive. It is also necessary to note the reduction of the noise of the drying unit from the operation of a multi-motor electric drive.

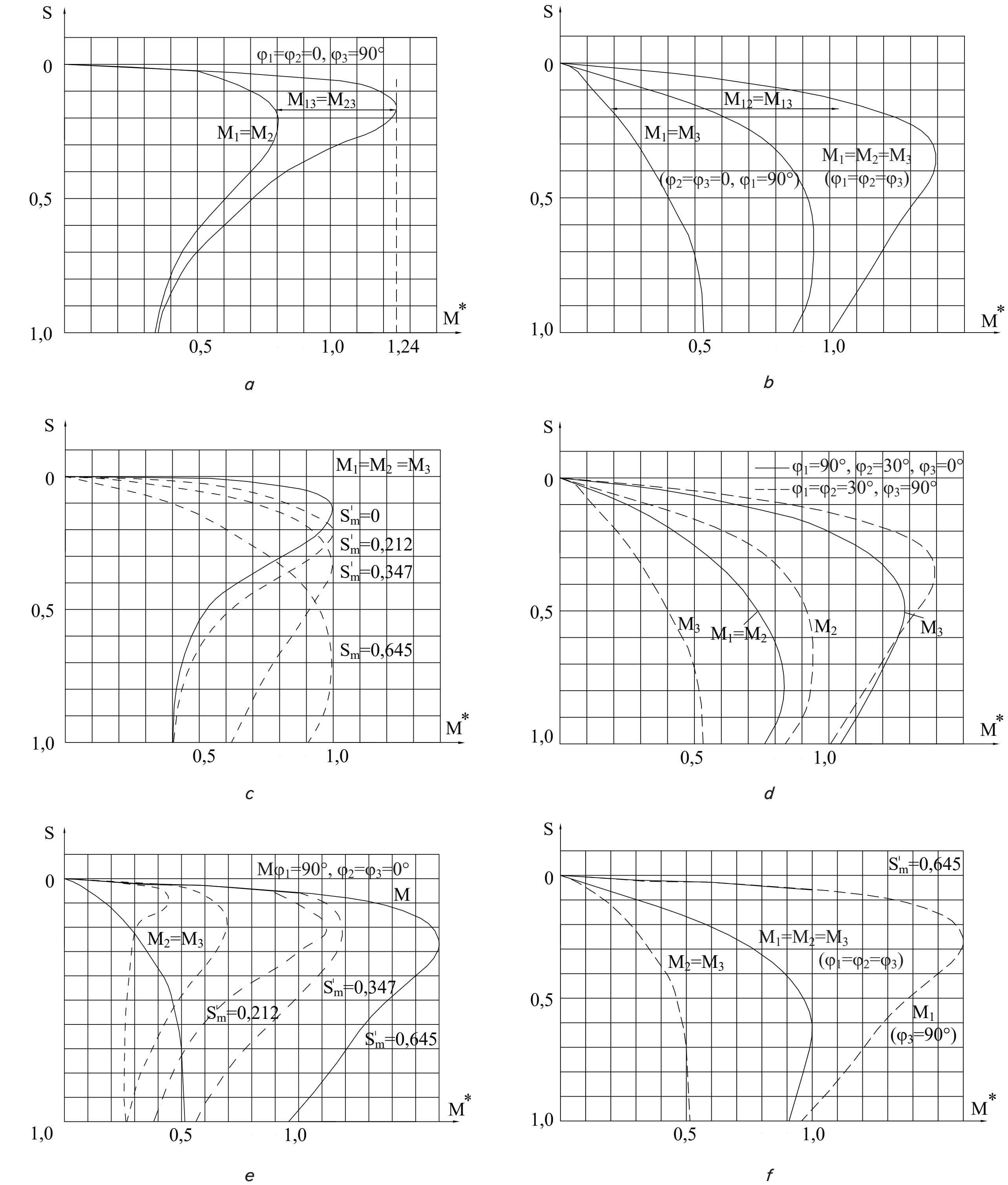

Fig. 2. Mechanical characteristics of the EWS multi-motor system with various misalignment angles and common rotor resistance: *a* – at misalignment angles $\Delta\varphi_{12}$=60°, $\Delta\varphi_{13}$=90°; *b* – at misalignment angles $\Delta\varphi_{12}$=60°, $\Delta\varphi_{13}$=90°; *c* – at critical slip $S'_m = 0.212$; 0.347; 0.645 and misalignment angles $\Delta\varphi_{12}$=60°, $\Delta\varphi_{13}$=90°; *d* – at misalignment angles $\Delta\varphi_{21}$=$\Delta\varphi_{23}$=90°; *e* – at critical slip $S'_m = 0.212$; 0.347; 0.645 and misalignment angles $\Delta\varphi_{21}$=$\Delta\varphi_{23}$=90°; *f* – at critical slip $S'_m = 0.645$ and misalignment angles $\Delta\varphi_{21}$=$\Delta\varphi_{23}$=90°

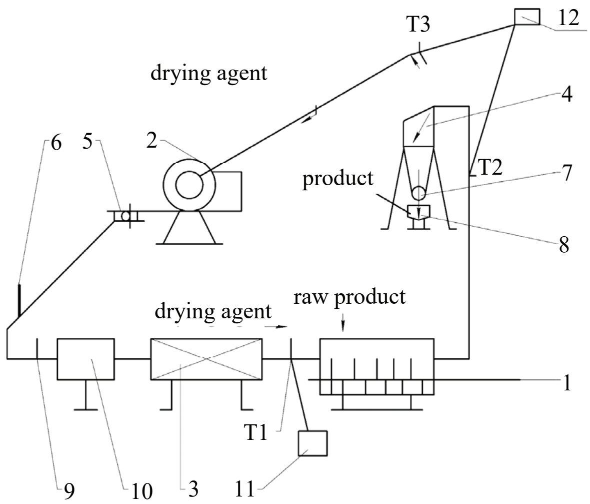

Fig. 3. Diagram of drying installation:
1 — grinding and drying unit; 2 — fan; 3 — electric heating unit; 4 — cyclone; 5 — water remover; 6 — nozzle with flue damper for air delivery; 7 — sluice valve; 8 — tare; 9 — gate; 10 — rotary meter; 11 — automatic maintenance of preset temperature; 12 — potentiometer; T_1, T_2, T_3 — thermocouples

6. Discussion of experimental results of operation of a multi-motor asynchronous electric drive

The results obtained reflect the mechanical characteristics of a multi-motor asynchronous electric drive of the EWS system at various misalignment angles of engine rotors (Fig. 2, *a*, *b*), while in Fig. 2, *b*, the total rotor resistance is greater, that is, the critical slip $S'_m = 0.645$. In Fig. 2, *c*, the angular misalignment of the rotors of this electric drive is absent at various total resistances of the rotors and Fig. 2, *d–f* are also constructed according to the obtained expressions for the torque of a multi-motor asynchronous electric drive and show the correctness of the theoretical substantiation of the expression of the moments of the motors of the "electric working shaft" system.

The theoretical conclusions of the definition of asynchronous torques and synchronizing components of the motor torques were obtained. These conclusions are confirmed by the previously obtained expressions by specialists dealing with the issues of the "electric working shaft" system [1]. The main difference from the earlier works of the authors [1] is that the paper considers a system of coordinated rotation of three asynchronous motors. Accordingly, the number of misalignment angles is assumed to be equal to the number of electric motors, that is, three involved in rotation.

Researchers of the electromechanical ratio of torques and currents of a multi-motor synchronous electric drive have also performed experimental calculations. The calculation results show that approaching the synchronous speed increases the synchronizing components of the motor torques. An increase in the level of active resistances in the equivalent rotor circuit simultaneously with a decrease in the speed of the system increases its synchronizing ability. Negative values of synchronizing torques are due to the difference in loads on the shafts.

At the beginning of the analytical study, the generally accepted restrictions were adopted in (1)–(3), which are widely used in the theory of electric machines.

From the authors' point of view, there are no drawbacks of the theoretically obtained expression, since it repeats the well-known expressions of the moments in multi-motor EWS systems [1].

This research can be continued in the Matlab package of applied programs for solving problems of technical calculations. The mechanical characteristics of the motors of the EWS system can be built and the adequacy of the theoretical conclusions obtained by the previously known equations can be proved.

7. Conclusions

1. Analytical studies were carried out according to the obtained electro-mechanical relations, with varying equivalent resistance and pulse control in the rotor circuit, the consequence of which are expressions for the moments, currents of the rotor and the mechanical characteristics of a multi-motor asynchronous electric drive.

2. From the obtained expressions of moments, it follows that with in-phase rotation of three machines, that is, with $\varphi_1=\varphi_2=\varphi_3$, the moment is $M_{1,2,3} = \frac{2M_m}{S/S'_m + S'_m/S}$. At the same time, all three electric motors operate on rheostatic characteristics with a tripled additional resistance of $3R_D$, the synchronizing moments are zero.

3. The calculation of mechanical characteristics according to the given expressions for various values of equivalent resistance R_{eqv} is made. The calculated curves of mechanical characteristics are constructed for various values of equivalent resistance corresponding to critical slip: S_m=0.212 (Fig. 2, *a*); S_m=0.347 (Fig. 2, *b*); S_m=0, S_m=0.212, S_m=0.347, S_m=0.645 (Fig. 2, *a–d*) and misalignment angles θ=90° (Fig. 2, *a*); θ=60° (Fig. 2, *d*) of engine rotors.

The existing systems of the electric working shaft in the drives of production machines can work satisfactorily when the possible difference of the load moments on the shafts of the machines is small, and the total rotor resistance of the rotor circuit is not less than $R/R_D \geq 0.29$. A decrease in the non-switchable part of the rotor resistance or an increase in the load difference on the shafts for some reason leads to a breakdown in the synchronicity of rotation.

Acknowledgments

This research was funded by the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan (Grant No. AP09259673).

References

1. Sadovskiy, I. M. (1948). Soglasovannoe vraschenie asinkhronnykh dvigateley. Moscow-Leningrad: Gosenergoizdat, 210.
2. Sansyzbaevich, I. S., Sansyzbaevich, I. Z., Nurzhanuly, N. N., Amergalievich, M. S. (2017). Development of algorithm flow graph, mealy automaton graph and mathematical models of microprogram control mealy automaton for microprocessor control device. 2017 International Siberian Conference on Control and Communications (SIBCON). doi: https://doi.org/10.1109/sibcon.2017.7998502

3. Onischenko, G. B. (2018). Teoriya elektroprivoda. Moscow: Infra-M, 384.
4. Tergemes, K. T. (2016). Mnogodvigatel'nye asinkhronnye elektroprivody chesal'nykh apparatov s tiristornymi preobrazovatelyami napryazheniya. Almaty: KazNTU, 108.
5. Chilikin, M. G., Sandler, A. S. (1981). Obschiy kurs elektroprivoda. Moscow: Energoizdat, 576.
6. Donskoy, N. V. (2012). Asinkhronnyy dvigatel' v sistemakh avtomaticheskogo upravleniya. Cheboksary: Izd-vo Chuvashskogo universiteta, 284.
7. Masandilov, L. B. (2012). Mashinostroenie. Entsiklopediya. Vol. 4-2. Elektroprivod. Gidro- i vibroprivody. Kn. 1 Elektroprivod. Moscow: Mashinostroenie, 520.
8. Frolov, Yu. M., Shelyakin, V. P. (2018). Reguliruemiy asinkhronniy elektroprivod. Sankt-Peterburg: Lan', 464.
9. Firago, B. I., Pavlyachik, L. B. (2006). Reguliruemye elektroprivody peremennogo toka. Minsk: Tekhnoperspektiva, 363.
10. Yakunicheva, O. N., Prokof'eva, A. P. (2014). Proektirovanie elektroprivoda promyshlennykh mekhanizmov. Sankt-Peterburg: Lan', 448.
11. Astashev, V. K. (2012). Mashinostroenie. Entsiklopediya. Elektroprivod. Gidro- i vibroprivody. Vol. IV-2. Gidro- i vibroprivody. Moscow: Mashinostroenie, 304.
12. Epifanov, A. P., Guschinskiy, A. G., Malaychuk, L. M. (2016). Elektroprivod v sel'skom khozyaystve. Sankt-Peterburg: Lan', 224.
13. Kisarimov, R. A. (2012). Elektroprivod. Moscow: Radio i svyaz', 352.
14. Nikitenko, G. V. (2013). Elektroprivod proizvodstvennykh mekhanizmov. Sankt-Peterburg: Lan', 224.
15. Novikov, V. A. (2014). Elektroprivod v sovremennykh tekhnologiyakh. Moscow: Academia, 143.
16. Krylov, Yu. A., Karandaev, A. S., Medvedev, V. N. (2013). Energosberezhenie i avtomatizatsiya proizvodstva v teploenergeticheskom khozyaystve goroda. Chastotno-reguliruemyy elektroprivod. Sankt-Peterburg: Lan', 176.
17. Iskakov, R. M., Halam, S., Issenov, S. S., Iskakova, A. M., Beisebekova, D. M. (2013). Heat-and-Moisture Transfer at the Feed Meal Particles Drying and Grinding. Life Science Journal, 10 (12s), 497–502. Available at: https://elibrary.ru/item.asp?id=27889297
18. Iskakov, R. M., Iskakova, A. M., Issenov, S. S., Beisebekova, D. M., Khaimuldinova, A. K. (2019). Technology of Multi-stage Sterilization of Raw Materials with the Production of Feed Meal of High Biological Value. Journal of Pure and Applied Microbiology, 13 (1), 307–312. doi: https://doi.org/10.22207/jpam.13.1.33
19. Iskakov, R. M., Issenov, S. S., Iskakova, A. M., Halam, S., Beisebekova, D. M. (2015). Microbiological Appraisal of Feed Meal of Animal Origin, Produced by Drying and Grinding Installation. Journal of Pure and Applied Microbiology, 9 (1), 587–592. Available at: https://www.scopus.com/record/display.uri?eid=2-s2.0-84930038169&origin=resultslist