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Development of a Microprocessor Control System for a Multi-Motor Asynchronous Electric Drive of a Trolley Travel Mechanism

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Abstract

Most of the technological processes in modern industrial production are realized with the help of mechanical energy, which is most conveniently obtained by means of an electric drive. In the metallurgical, machine-tool and other industries, it is advisable to use a multi-motor asynchronous electric drive for general industrial mechanisms such as overhead cranes (trolley movement mechanism), conveyors, rolling mills, taking into account technological requirements and operating modes. This requires the use of more sophisticated control methods for electromechanical systems, since two or more electric motors must work in concert for a single load. This, in turn, entails the use of a new element base, power and control, which makes it possible to implement these technological work cycles. The constant development of technology places increased demands on the electric drive regarding the accuracy of movement, both in statics and dynamics, speed and reliability. At the present stage, all these requirements can be achieved using specialized high-speed microprocessors as the basis of a control system for a twin-motor asynchronous electric drive, which opens up wide opportunities for creating technically advanced adjustable drives. At the same time, due to the intensive development of electronics and semiconductor technology, it is necessary to reduce the cost of electric drive control systems.

Keywords: two-motor asynchronous electric drive; pulse automatic control; microprocessor technology; digital control system; mathematical apparatus; automatic Miles; Boolean algebra

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1. Introduction

1.1. Initial Positions

The increasing complexity of regulated asynchronous electric drives containing an analog part, various digital devices [1], communication devices and information form transformation devices, the increasing complexity of control laws and mathematical description of the system [2], the need to perform many functions, including those previously performed by service personnel, require new technical means for implementing these systems [3].

The current stage of automation is characterized by an increase in the degree of integration of semiconductor technology and the transition from relay-contactor control [4] and protection of electromechanical systems [5,6] to power electronics - microcontrollers - with a built-in set of specialized peripheral devices, which leads to a trend of replacing analog drive control systems with direct digital control systems [7].

One of the main criteria for designing an automatic control system is the rational use and organic combination of the capabilities provided by microprocessor (MP) technology with the properties of controlled objects. A microcontroller can act as the basis of a set of technical means that can implement the main functions of the control system: to perceive and analyze information about the state of the control object; to compare the received information with the management goals and form appropriate control actions based on the results of this comparison [8]. However, the most effective in each case is obviously a technical tool, the architecture of which corresponds to the class of problems to be solved [9,10].

1.2. Pulse Automatic Control of a Two-Motor Asynchronous Electric Drive

To increase the reliability and level of automation of the electric drive, pulsed automatic control of a two-motor asynchronous electric drive in the rotor circuit was developed [11,12].

The principle of operation of the developed pulse automatic control of a two-motor asynchronous electric drive in the rotor circuit consists in the fact that, in accordance with the information received from stator current sensors and voltage sensors, the current parameters of the stator current and voltage modules are converted into digital codes, on the basis of which a pulse is calculated and generated that provides a change in speed, The pulse is fed through the galvanic isolation units to the power valves of the control switches [13].

The functional diagram of the developed pulse automatic control of a two-motor asynchronous electric drive, shown in Figure 2.1, contains [14]:

– three-phase electric network; asynchronous electric motors with a phase rotor – M1, M2; rectifiers – UZ1, UZ2; throttles smoothing ripples – L1, L2; resistances – R1, R2; switches – S1, S2; galvanic isolation units – GIU1, GIU2; input port – IP; analog-to-digital converter – ADC; central processor – CPU; timer – T; output port – OP; random access memory – RAM; permanent storage device (permanent memory) – ROM; pulse width modulator – PWM; internal bidirectional bus – IBB; liquid crystal screen – LCS; control buttons – CB; stator circuit current sensors – SCCS1, SCCS2; stator current matching blocks – SCMB1, SCMB2; voltage sensors – VS1, VS2; voltage matching blocks – VMB1, VMB2.

The microprocessor control system is made in the form of a single-chip microcontroller containing an input port, an analog-to-digital converter, a central processor, a timer, an output port, a random-access memory device, a permanent storage device, a pulse-width modulator, the main nodes and devices are connected by an internal bidirectional data bus.

The central processor is made in the form of electronic circuits based on triggers and contains an arithmetic logic unit (ALU), memory, an input/output control circuit, general-purpose registers, an interrupt controller, a clock pulse generator and connections between them. An input/output ports are based on parallel write registers and bus drivers. The analog-to-digital converter is made in the form of a digital circuit. The random-access memory device is based on static cells. The timer is made in the form of digital counters. Permanent storage device – made on the basis of large integrated circuits (LSI) ROM.

The pulse width modulator (PWM) is based on electronic circuits and includes a reference voltage generator, a threshold device, and a control pulse generator. The internal bus (IB) is made in the form of a wired communication line.

Galvanic isolation units - GIU1, GIU2 are optocouplers, which are switched on by applying a high-level signal to the optocoupler’s photo-emitter, under the influence of light radiation, the photodetector opens and a control effect passes through the circuit, and optocouplers also provide reliable galvanic isolation between the power circuit of the switches – S1, S2 and the microprocessor.

Pulsed automatic control of a two-motor asynchronous electric drive in the rotor circuit is implemented as follows.

When voltage is applied from a symmetrical AC network to the stator windings of electric motors – M1, M2, EMF is induced in the rotor windings [14]. The voltage of the rotor windings is supplied to the inputs of the rectifiers - UZ1, UZ2 and the rectified current passes through the rotor circuit. Measurement information about the current values of parameters, from the corresponding sensors - SCCS1, SCCS2 of the stator current, through the current matching blocks - SCMB1, SCMB2, voltage sensors - VS1, VS2, through the voltage matching blocks - VMB1, VMB2, enters the microprocessor control system through the input port - IP, to the analog-to-digital converter - ADC. An analog-to-digital converter (ADC) converts the input voltage value into a digital code, and the converted data is displayed on the internal bidirectional bus - IB. The central processing unit – CPU - reads digital data from the internal bus and initiates the operation that the system needs to perform, and the information is sent to the PWM via the internal bidirectional bus. In a pulse-width modulator – PWM - the input coordinate in the form of a binary code is converted to the coordinate – γ_1, γ_2 – the duty cycle of switching on the valves. The conversion occurs as follows: the reference voltage generator generates a sawtooth reference voltage, the threshold device compares the input voltage signal with the reference voltage and receives a mismatch signal, the control pulse generator compares the mismatch signal coming from the output of the threshold device with a linearly increasing sawtooth voltage, which generates the reference voltage generator and generates width-modulated pulses. Control pulses, via the internal bidirectional bus – IBB –, output port – OP, through the galvanic isolation units – GIU1, GIU2 are supplied to the power valves of the switches – S1, S2. Switches S1, S2 are implemented by switching on and off the gate switches – thyristors – the duty cycle set using PWM. Changing the pulse duration leads to a change in the time of the switched-on state of the power thyristor switches S1, S2 and, consequently, to a proportional change in the output voltage, that is, changing the duty cycle of the supply voltage pulses, or the duty cycle of changing the values of the motor parameters, you can adjust its rotation speed, and with the help of a microprocessor device, the motor speed is regulated automatically.

The converted received data is recorded by the central processing unit – CPU – in a random-access memory device – RAM, which performs the function of data storage, and also displays current and speed values received from sensors on a liquid crystal display – LCD.

The developed pulse automatic control of a two-motor asynchronous electric drive in the rotor circuit allows you to adjust the speed of the electric drive system automatically, regardless of the difference in their parameters, which achieves installation accuracy, and by changing the time of switching on thyristor switches, you can adjust the pulse duration, which allows you to expand the range of speed control of the electric drive.

Along with the above, the use of pulsed automatic control of a two-motor asynchronous electric drive in the rotor circuit makes it possible to ensure uniform loading of the system's electric motors, which increases the reliability and level of automation, and therefore leads to easier maintenance of electrical equipment.

2. Materials and Methods

2.1. Investigation of Mechanical Parameters of a Two-Motor Asynchronous Electric Drive

Due to the complexity of determining electromechanical connections with rectified current in the rotor circuit and independent connection of rectifiers, in the absence of mechanical and electrical connections, we assume that $R_{equivalent}$ is the total changing rotor resistance [15].

To determine the currents and torques of a two-motor asynchronous electric drive that includes two asynchronous motors, we use the functional diagram (Figure 1) and its T-shaped substitution scheme, which is shown in Figure 2, where are respectively denoted [16]:

U – mains voltage;

$I_{1\,I}$, $I_{1\,II}$, $I_{2\,I}$, $I_{2\,II}$ – stator and rotor currents M1 and M2;

$r_{1\,I}$, $r_{1\,II}$, $x_{1\,I}$, $x_{1\,II}$ – active and inductive resistances of the stator windings M1 and M2;

$r_{2\,I}$, $r_{2\,II}$, $x_{2\,I}$, $x_{2\,II}$ – active and inductive resistances of the M1 and M2 rotor windings;

$x_{0\,I}$, $x_{0\,II}$ – inductive resistances of magnetization circuits;

R_{equiv} – equivalent varying resistance in the rotary circuit;

S – sliding;

θ– angular shifts of the rotors in electrical degrees.

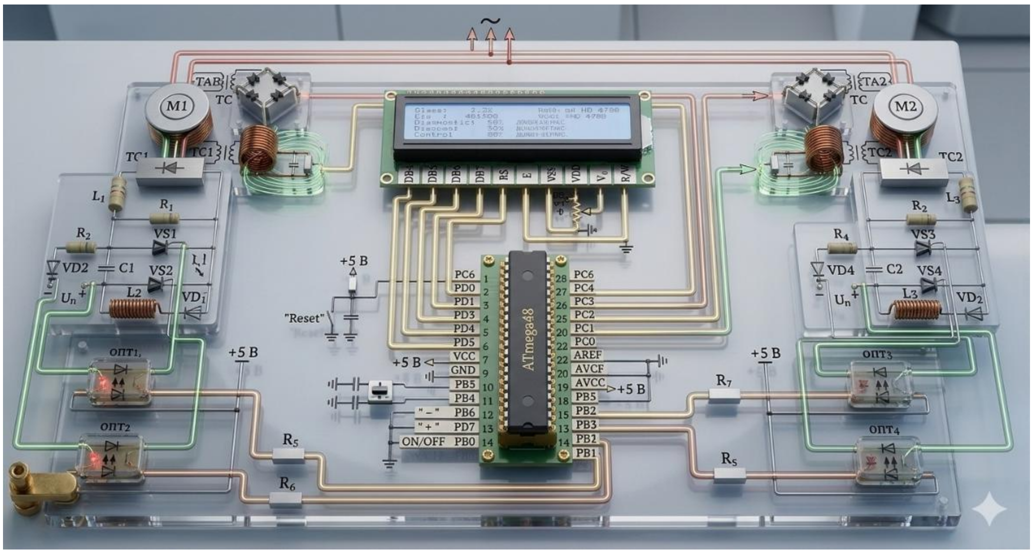

Figure 1. Functional diagram of pulse automatic control of a two-motor asynchronous electric drive.

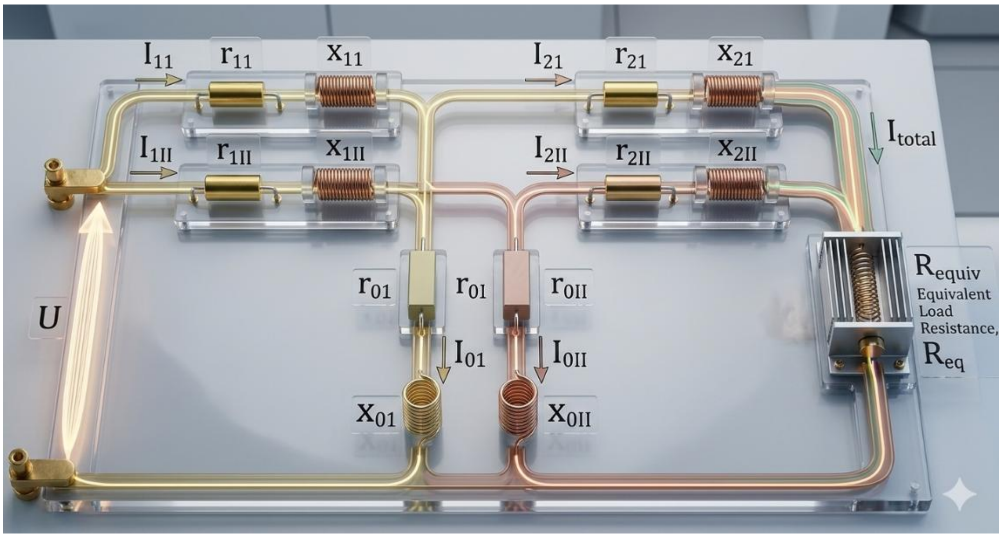

Figure 2. T-shaped replacement circuit of a two-motor asynchronous electric drive.

Denoting the complex resistances of the stators and rotors when sliding S through Z_1, Z_2, taking into account the identity of the motor parameters and the reduction of the rotor resistances [16]. Based on this, we get:

$$\begin{cases} Z_1 = r_{1\,I} + j\left(x_0 + x_{1\,I}\right); \\ Z_2 = r'_{2\,II}/S + j\left(x_0 + x'_{2\,II}\right), \end{cases} \tag{1}$$

where $r'_{2\,II}$ и $x'_{2\,II}$ – the reduced active and inductive resistances of the rotors.

Using the principle of superposition according to the substitution scheme, it is possible to write the voltage equations for the stator and rotor circuits of each motor in the form:

$$\begin{cases} U = I_{1\,I}\, z_1 - I_{2\,I}\, jx_0; \\ U = I_{1\,II}\, z_1 - I_{2\,II}\, jx_0; \end{cases} \tag{2}$$

$$\begin{cases} \left(I_{1\,I}\, jx_0 - I_{2\,I}\, z_2\right)e^{j\theta} = \dfrac{R_{экв}}{S}\left(I_{2\,I}\, e^{j\theta} + I_{2\,II}\, e^{j\theta}\right); \\ \left(I_{1\,II}\, jx_0 - I_{2\,II}\, z_2\right)e^{j\theta} = \dfrac{R_{экв}}{S}\left(I_{2\,I}\, e^{j\theta} + I_{2\,II}\, e^{j\theta}\right). \end{cases} \tag{3}$$

Having transformed Equations (1)–(3), we determine the currents of the rotors and stators of the motors of the electric drive system, taking into account the identity of the formulas for determining currents and moments that differ in the corresponding indices and angular mismatches, in the future we specify formulas only for the first motor. The rotary current of the first motor has the form [16,17]:

$$I_{2\,I} = \frac{jx_0\left\{x_0^2 + z_1\left[z_2 + \dfrac{R_{экв}}{S}\left(2 - e^{j\theta}\right)\right]\right\}}{\left[x_0^2 + z_1\left(z_2 + \dfrac{2R_{экв}}{S}\right)\right]\left(x_0^2 + z_2 z_1\right)} \cdot U; \tag{4}$$

$$I_{1\,I} = \frac{U}{z_1} + \frac{jx_0}{z_1} I_{2\,I} = \frac{x_0^2\left[z^2 + \dfrac{R_{экв}}{S} e^{j\theta}\right] + z_1 z_2\left(z_2 + \dfrac{2R_{экв}}{S}\right)}{\left[x_0^2 + z_1\left(z_2 + \dfrac{2R_{экв}}{S}\right)\right]\left(x_0^2 + z_2 z_1\right)} \cdot U. \tag{5}$$

Given the input correction factor and designations 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

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

neglecting the smallness of the ratio $\dfrac{r_1}{x_0}$, Equations (4) and (5) after transformations are written as:

$$I_{2\,I}=\frac{z_1+\frac{\sigma R_{экв}}{S}\left(2-e^{j\theta}\right)}{z\left(z+\frac{2R_{экв}}{S}\sigma_1\right)},$$

$$I_{1\,I}=I_{0\,I}+\frac{1'}{\sigma_1}\cdot\frac{z+\frac{\sigma_1 R_{экв}}{S}\left(2-e^{j\,\theta}\right)}{z\left(z+\frac{2R_{экв}}{S}\sigma_1\right)}U, \tag{7}$$

where is $I_{0\,I}$ the idling current of the first motor.

Using Euler's formulas, we obtain the equations of moments for the first engine

$$M_{1\,I}=\frac{U^2}{2\sigma_{1\,I}}\left\{\frac{r_{2\,I}\sigma_{1\,I}/S\left[2-\cos\theta\right]}{\left(\frac{r_{2\,I}\sigma_{1\,I}}{S}\right)^2+x^2}\right\}+\frac{\frac{\left(r_{2\,I}+2R_{экв}\right)\sigma_{1\,I}}{S}\cdot\cos\theta}{\left[\frac{\left(r_{2\,I}+2R_{экв}\right)\sigma_{1\,I}}{S}\right]^2+x^2}. \tag{8}$$

When the engines are running on a natural characteristic, the maximum torques developed by the engines are equal to

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

and the critical slip corresponding to this moment

$$S_m=\frac{\left(r_2+2R_{экв}\right)\sigma_1}{x_1+x_2\sigma_1}. \tag{10}$$

When the rotors are switched on to an equivalent resistance $R_{экв}$, the critical slip is

$$S'_m=\frac{\left(r_2+2R_{экв}\right)\sigma_1}{x_1}=S'_m\left(1+\frac{2R_{экв}}{r_2}\right). \tag{11}$$

Taking into account (9-11), the moment equation has the form:

$$M_{I,\,II}=\frac{M_m}{2}\left\{\frac{2-\left[\cos\theta+S/S_m\sin\theta\right]}{S/S_m+S_m/S}+\frac{\left[\cos\theta+S/S_m\sin\theta\right]}{S/S'_m+S'_m/S}\right\}, \tag{12}$$

Or

$$M_{I,\,II}=M_{I,\,II\,асин}+M_{I,\,II\,син}=\frac{M_m}{2}\left[\frac{2-\cos\theta}{S/S_m+S_m/S}+\frac{\cos\theta}{S/S'_m+S'_m/S}\right]+$$

$$+\frac{M_m}{2}\left[\frac{S/S_m\sin\theta}{S/S_m+S_m/S}-\frac{S/S'_m\sin\theta}{S/S'_m+S'_m/S}\right]. \tag{13}$$

The currents and torques of the second motor are determined similarly and differ only in the angular positions of the rotors.

From (12) and (13) it can be seen that the torques developed by the first and second motors are the sum of two components: the synchronizing one, which supports the coordinated rotation of the motors, acting on both motors, depending on the angular misalignment of their rotors

$$M_{\text{син (I, II)}} = \frac{M_m}{2}\left\{\frac{2-\cos\theta}{S/S_m + S_m/S} + \frac{\cos\theta}{S/S'_m + S'_m/S}\right\}, \qquad (14)$$

and the asynchronous component

$$M_{\text{асин (I, II)}} = \frac{M_m}{2}\left\{\frac{2-\cos\theta}{S/S_m + S_m/S} + \frac{\cos\theta}{S/S'_m + S'_m/S}\right\}. \qquad (15)$$

The sign and magnitude of the synchronizing moments depend on the sign and magnitude of the misalignment θ .

The maximum values of the first components occur at the angle of misalignment $\theta = \pm 90^0$ and are equal to each other

$$M_{\text{синI}} = M_{\text{синII}}, \quad M_{\text{син I, II}} = \frac{M_m}{2}\left\{\frac{2\cdot S/S_m}{S/S_m + S_m/S} + \frac{2\cdot S/S_m}{S/S'_m + S'_m/S}\right\}. \qquad (16)$$

From the expressions of the moments obtained, it follows that when two machines rotate synchronously

$$M_{\text{I, II}} = \frac{2M_m}{S/S_m + S'_m/S}\ . \qquad (17)$$

At the same time, both machines operate on rheostatic characteristics, with twice the additional resistance 2 R $2\,R_{\text{экв}}$, and the synchronizing moments are zero.

2.2. Development of an Algorithm and Mathematical Model for Automatic Pulse Control of a Two-Motor Asynchronous Electric Drive

To ensure automatic stable operation in the low-speed zone, smooth regulation and consistent rotation of electric motors, it is necessary to develop an algorithm and mathematical model of an automatic pulse control device for a two-motor asynchronous electric drive.

To perform the task of automatic control of a two-motor asynchronous electric drive, as well as information input and output, monitoring and protection, based on the functional scheme shown in Figures 1 and 2, it is necessary to develop an algorithm and mathematical model of an automatic pulse control device for a two-motor asynchronous electric drive [18].

Obtaining a mathematical model of an automatic pulse control device for a two-motor asynchronous electric drive will allow conducting research (modeling) of the logical-temporal behavior of the device under development, obtaining comparative estimates of various variants of the device structure. Based on the simulation results, it is possible to determine the final mathematical model of the device, which will be used as the basis for the software.

The analysis of methods of mathematical description of digital computing machines has shown that the most effective methods are those of automata theory, which allow synthesizing rather complex models of computing devices for certain applied problems. Elements of Boolean algebra, graph theory, and algorithms are used in the process of mathematical description of the automatic pulse control device of a two-motor asynchronous electric drive [19].

Discrete automata are devices used to transform discrete information. Discrete automata use the standard binary number system alphabet. Therefore, discrete automata are usually called digital. The main quality that distinguishes discrete automata is the presence of a discrete (in real automata, always finite) set of internal states and the properties of a jump-like transition of an automaton from one state to another. The jumpiness of a transition defines such a transition as instantaneous, which, moreover, occurs directly, bypassing any intermediate values. Such an abstraction describes quite well the basic properties of real digital automatic devices (first of all, electronic computers) and is therefore accepted for constructing the theory of digital automata [19,20].

Changes in the states of a digital automaton are caused by input signals that occur outside the automaton and are transmitted to the automaton by a finite number of input signals. Two assumptions are made about the input signals of digital automata: first, for any digital automaton, the number of different input signals is finite, and second, the input signals are considered as the reason for the transition of the automaton from one state to another and relate to the time points determined by their corresponding transitions. Under this assumption, the input signal is considered instantaneous, although in reality it has a finite duration [21].

The result of the operation of a digital automaton is the output of output signals transmitted from the automaton to external circuits via a finite number of output channels. For the output signals, assumptions are made that are similar to those made for the input signals. First, the number of different output signals for any digital machine is always finite. Secondly, each non-zero moment of the automaton time has its corresponding output signal. The actual physical output signal w(t) assigned to time t, always appears after the input signal z(t) corresponding to the same time.

The signal w(t) may actually appear either earlier or later than the moment t when the automaton transitions from state a(t–1) to state a(t). In the first case, it is assumed that the output signal w(t) is uniquely determined by the input signal z(t) and the state a(t–1) of the automaton at the previous time; in the second case, the signal w(t) is uniquely determined by the pair (a(t), z(t)). Digital automata in which the output signal y(t) is determined by the pair (a(t–1), z(t)) are called automata of the first kind, and automata in which the signal w(t) is determined by the pair (a(t), z(t)) are called automata of the second kind.

A digital automaton (of the first or second kind) is called correct if the output signal w(t) is determined only by its state (a(t–1) or a(t)) and does not explicitly depend on the input signal z(t).

Since the state a(t) in any digital automaton is uniquely determined by the pair (a(t-1), z(t)), then any automaton of the second kind can be considered as a special case of automata of the first kind. Thus, automata of the first kind are the most general type of digital automata. Automata of the first kind are usually also called Mile automata, after the American scientist who first began their systematic study.

The general theory of automata is divided into two parts: abstract automata theory and structural automata theory, the difference between which lies in the fact that abstract theory does not consider the structures of either the automaton or its input and output. Input and output signals are received as letters of two fixed alphabets for this automaton – input and output.

Abstract theory studies the transitions that an automaton undergoes under the influence of input signals, and the output signals that it outputs. In contrast to abstract theory, structural automata theory is aimed at studying the structure of both the automaton itself and its input and output signals.

In structural theory, methods of constructing automata from elementary automata, methods of encoding input and output signals with elementary signals transmitted over real input and output channels are studied. Structural automata theory is a proposal and further development of an abstract theory.

The mathematical model of any digital device is an abstract automaton, which is defined by a set of six elements [21–23]

$$S = \{A, Z, W, \delta, \lambda, a_1\}, \quad (18)$$

where $A = \{a_1, \ldots, a_m, \ldots, a_M\}$ – set of states (alphabet of states);

$Z=\{z_1,\ldots,z_f,\ldots,z_F\}$ – multiple input signals (input alphabet);

$W=\{w_1,\ldots,w_g,\ldots,w_G\}$ – multiple output signals (output alphabet);

δ – a transition function that implements the display of a set $D_\delta \subseteq A\times Z$ в $A[a_s=\delta(a_m,z_f)], a_s \in A;$

λ – an output function that implements the display of a set $D_\lambda \subseteq A\times Z$ на $W[w_g=\lambda(a_m,z_f)]$;

$a_1 \in A$ – the initial state of the machine.

An abstract automaton has one input and one output and operates in discrete time, taking integer non-negative values t = 0, 1, 2, ... At each moment t of discrete time, the automaton is in a certain state a(t) from the set of states of the automaton, and at the initial moment t = 0 it is always in the initial state a(t) = a1. At the moment t, being in the state a(t), the automaton is able to perceive the letter of the input alphabet at the input

$$z(t)\in Z, \tag{19}$$

According to the function of the outputs, it outputs at the same time t the letter of the output alphabet

$$W(t)=\lambda[a(t); z(t)], \tag{20}$$

and according to the transition function, it will switch to the following state

$$a(t+1)=\delta[a(t); z(t)]. \tag{21}$$

If, letter by letter, a sequence of letters of the input alphabet z(0), z(1), z(2), ... is applied to the input of the automaton installed in the initial state a1 – is the input word. The letters of the output alphabet w(0), w(1), w(2),... – the output word will appear sequentially at the output of the machine.

In the class of synchronous automata, two types of automata are considered mainly: the Mili automaton and the Moore automaton. There is a correspondence between the Mili and Moore automata, which makes it possible to transform the law of functioning of one of them into the other or vice versa. The Moore automaton can be considered as a special case of the Mile automaton, bearing in mind that the sequence of states of the outputs of the Mile automaton is one clock cycle ahead of the sequence of states of the outputs of the Moore automaton, i.e., The difference between the Mealy and Moore automata is that in the Mealy automata, the exit state occurs simultaneously with the input state causing it, while in the Moore automata it occurs with a delay of one clock cycle.

The most common digital automaton is the Mile automaton, whose law of operation is given by the equations:

$$a(t+1)=\delta(a(t),z(t));\quad w(t)=\lambda(a(t),z(t));\quad t=0,1,2,\ldots. \tag{22}$$

The synthesis of the digital finite automaton Mile is reduced to the following actions:

– building a graph of a finite automaton;

– compilation of a structural transition table for a given graph;

– drawing up a logical circuit of the machine.

The graph diagram of the algorithm reflects a set of rules for the transition of an automaton from one state to another, depending on the input information and internal states of the automaton. When constructing graph diagrams of the algorithm, a certain set of graphic symbols connected by lines is used. The symbols indicate the operations being performed, and the arrow lines indicate the sequence of their execution. The symbol can be initial, final, operator, or conditional. The operator symbol is indicated by a rectangle in which the symbol of the operator implemented at this step of the algorithm fits. An operator symbol means performing some operation or group of information processing operations. A logical symbol means choosing the direction of the algorithm execution depending on whether or not some logical condition is fulfilled, the designation of which fits into a diamond. If the condition is met, then branching occurs along the outgoing line, indicated by “1” with the symbol “yes”, otherwise along the outgoing line, indicated by “0” or the word “no”.

Based on the above, a graph diagram of the algorithm and a graph of the Mile automaton (Figure 3), an automatic pulse control device for a two-motor asynchronous electric drive, have been developed [18,24].

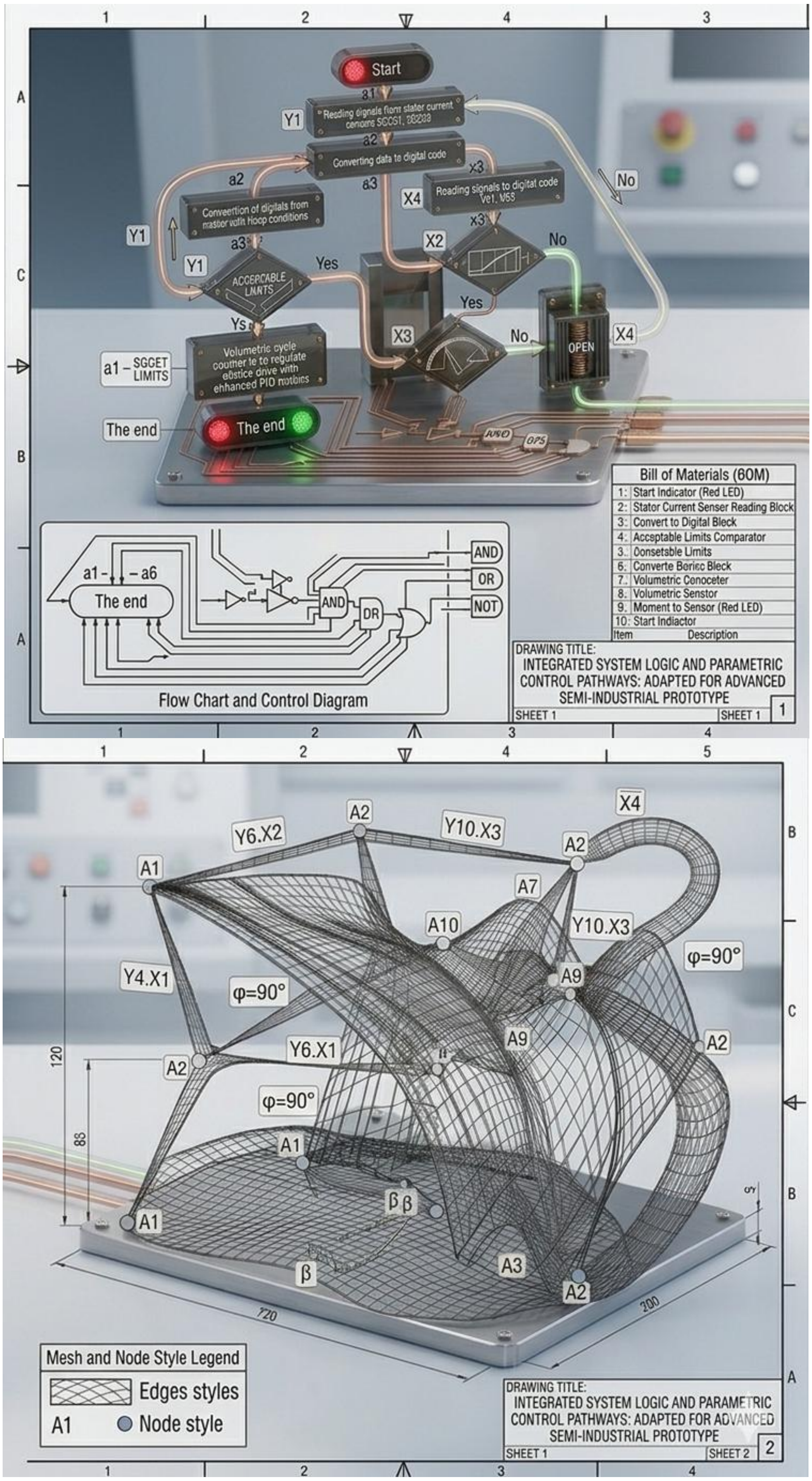

Figure 3. Graph diagram of the operation algorithm and graph of the automatic Mile control device for automatic pulse control of a two-motor asynchronous electric drive.

Since the number of states in the graph of the synthesized model of the Mile control firmware is large, for clarity, a structural transition table of the Mile automatic pulse control device for a two-motor asynchronous electric drive has been compiled (Table 1) [2,18,24,25].

Each row of the table contains: the a_m state from which the transition takes place in the automaton; the a_s state into which the automaton passes from the a_m state where $X(a_m,a_s)$, $Y(a_m,a_s)$, input and output signals at junction (a_m,a_s). If at junction (a_m,a_s) under the influence of multiple input signals $X_{j1}(a_m,a_s),\ldots,X_{jh}(a_m,a_s),\ldots,X_{jH}(a_m,a_s)$, multiple output signals are output $Y(a_m,a_s)=\{Y_1(a_m,a_s),\ldots,Y_j(a_m,a_s),\ldots,Y_j(a_m,a_s)\}$, then all the transition paths are listed sequentially in the table. The codes of the initial state and the transition state are also recorded in the table. $K(a_m)=(\tau_{m1},\ldots,\tau_{m1})$, $K(a_s)=(\tau_{m1},\ldots,\tau_{m1})$, representing a set of states of elementary automata of the memory of a firmware automaton, where $\tilde{F}(a_m,a_s)$, there are many mandatory excitation functions that change the state of memory elements and are generated at the (a_m,a_s) transition.

Table 1. Structural transition table of the control firmware of the Mile automatic pulse control device for a two-motor asynchronous electric drive.

A_m	$K(a_m)$	a_s	$K(a_s)$	$X(a_m, a_s)$	$Y(a_m, a_s)$	$\tilde{F}(a_m, a_s)$
a_1	0000	a_2	0001	1	Y_1	φ_4
a_2	0001	a_3	0010	1	Y_2	φ_3, φ_4
a_3	0010	a_4	0011	1	Y_3	φ_4
a_4	0011	a_5 a_{10}	0100 1001	X_1 $\overline{X_1}$	Y_4 –	$\varphi_2, \varphi_3, \varphi_4$
a_5	0100	a_6	0101	1	Y_5	φ_4
a_6	0101	a_7 a_{10}	0110 1001	X_2 $\overline{X_2}$	Y_6 –	φ_3, φ_4
a_7	0110	a_8	0111	1	Y_7	φ_4
a_8	0111	a_9	1000	1	Y_8	$\varphi_1, \varphi_2, \varphi_3, \varphi_4$
a_9	1000	a_{10}	1001	1	Y_9	φ_4
a_{10}	1001	a_{11} a_1	1010 0000	X_3 $\overline{X_3}$	Y_{10} –	φ_3, φ_4
a_{11}	1010	a_{12}	1011	1	Y_{11}	φ_4
a_{12}	1011	a_1 a_{12}	0000 1011	X_4 $\overline{X_4}$	Y_{12} –	$\varphi_1, \varphi_3, \varphi_4$

According to the structural transition table of the Mile control firmware of the automatic pulse control device for a two-motor asynchronous electric drive, the following results are obtained:

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– a system of Boolean equations of output functions:

$$
\begin{array}{lll}
Y_1 = \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \bar{\tau}_4; & Y_5 = \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_3 \cdot \bar{\tau}_4; & Y_9 = \tau_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \bar{\tau}_4; \\
Y_2 = \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4; & Y_6 = \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_2; & Y_{10} = \tau_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_3; \\
Y_3 = \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \bar{\tau}_4; & Y_7 = \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \cdot \bar{\tau}_4; & Y_{11} = \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \bar{\tau}_4; \\
Y_4 = \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_1; & Y_8 = \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4; & Y_{12} = \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_4.
\end{array}
\tag{23}
$$

– a system of Boolean equations of excitation functions of elementary memory automata:

$$
\begin{gathered}
\varphi_1 = \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_4; \\
\varphi_2 = \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_1 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4; \\
\varphi_3 = \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4 \vee \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_1 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_2 \vee \\
\vee \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_3 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_4; \\
\varphi_4 = \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \bar{\tau}_4 \vee \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4 \vee \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \bar{\tau}_4 \vee \\
\vee \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_1 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_3 \cdot \bar{\tau}_4 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_2 \vee \\
\vee \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \cdot \bar{\tau}_4 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \cdot \tau_4 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \bar{\tau}_4 \vee \\
\vee \tau_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_3 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \bar{\tau}_4 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_4 = \\
= \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \vee \bar{\tau}_2 \cdot \tau_3 \cdot \bar{\tau}_4 \vee \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_1 \vee \\
\vee \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_4 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_2 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \vee \\
\vee \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \bar{\tau}_4 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_3 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_4 = \\
= \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \vee \bar{\tau}_2 \cdot \bar{\tau}_4 \vee \bar{\tau}_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_1 \vee \\
\vee \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_4 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_2 \vee \bar{\tau}_1 \cdot \tau_2 \cdot \tau_3 \vee \\
\vee \tau_1 \cdot \bar{\tau}_2 \cdot \bar{\tau}_3 \cdot \tau_4 \cdot X_3 \vee \tau_1 \cdot \bar{\tau}_2 \cdot \tau_3 \cdot \tau_4 \cdot X_4.
\end{gathered}
\tag{24}
$$

According to the system of equations of minimized functions of output signals and excitation signals of memory elements, a logical circuit of a digital circuit breaker or an automatic pulse control device for a two-motor asynchronous electric drive is compiled, shown in Figure 4.

Based on the graph diagram of the algorithm, a graph of the Mili automaton, a structural transition table, was developed, on the basis of which a system of Boolean equations of output functions, a system of Boolean equations of excitation functions of elementary memory automata, and a logical circuit of the Mili control firmware of an automatic pulse control device for a two-motor asynchronous electric drive were obtained.

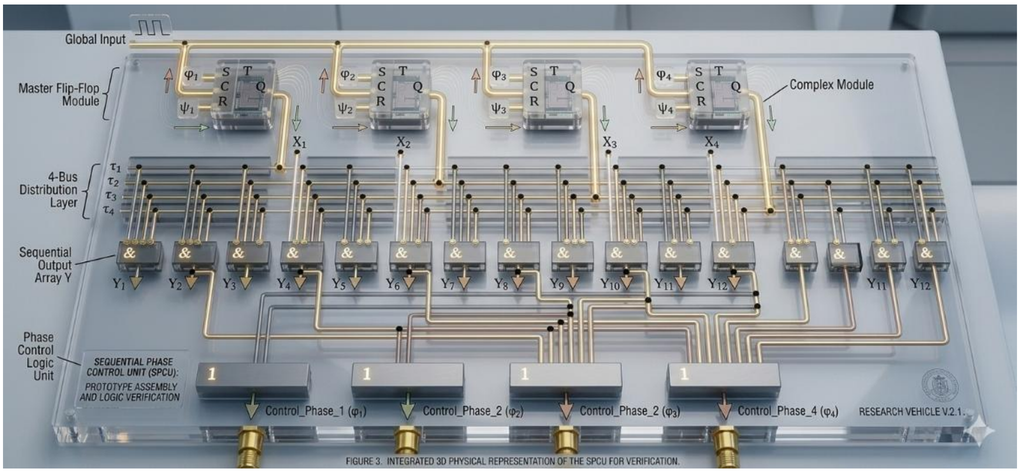


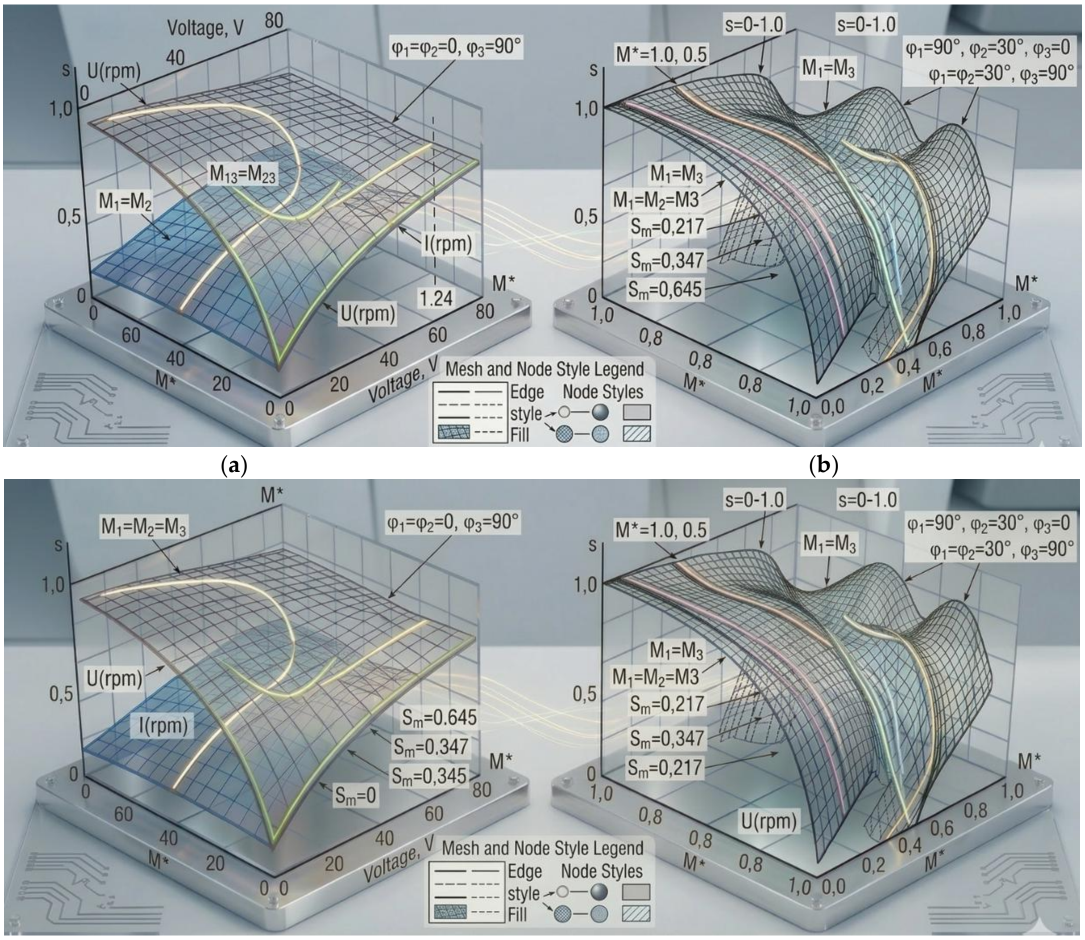
Figure 4. Logical diagram of the control firmware automatic mile control device for automatic pulse control of a two-motor asynchronous electric drive.

3. Results

3.1. Calculation and Plotting of Experimental Mechanic Characteristics of the Multi-Motor System

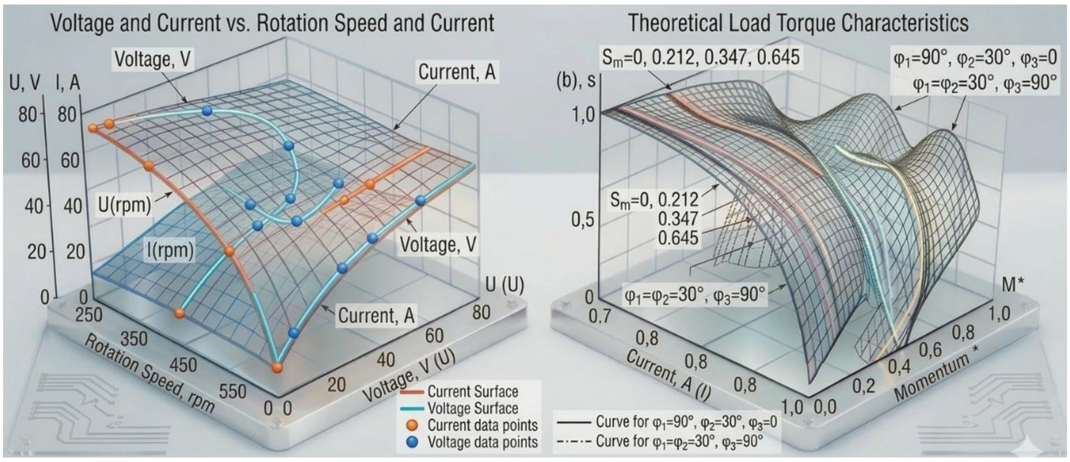
Based on the principal diagram shown in Figure 1 for MTFO12–6 electrical drives, computerized experimental research was done for the integrated multi-motor electrical drive system of with the following engine parameters: U_n=220/380 V, IP 44, U_2=153 V, ω_n=960 rpm, I_1=21,4/12,4 A, I_2= 12/22,5 A, f_c = 50 Hz.

Calculation results are shown in Figure 5 [26].



(a) (b)

(c) (d)



(**e**) (**f**)

Figure 5. Mechanical Characteristics of the Multi-motor System with Various Misalignment Angles and Common Rotor Resistance.

Design curves of mechanical characteristics have been plotted for various values of multiplier resistances corresponding with critical slips: S'_m=0,212; 0,347; 0,645 (c, e) and misalignment angles $\Delta\varphi_{21}=\Delta\varphi_{23}=90^0$ (e, g), $\Delta\varphi_{12}=60^0$, $\Delta\varphi_{13}=90^0$ (a, b, c, d) of engine rotors. Curves with slip S'_m=0,645 shown in Figure 5 are common for the multi-motor electrical 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 Figure 5 (b).

In this mode (at S'_m=0,645), the multi-motor system is inclined to self-oscillations under static torques over $M_{s\,nom}$.

Under the critical misalignment angles $\Delta\varphi$ =90^0, the system develops the уравнительный maximum 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: $M_{st1,2,3}=1{,}25\div1{,}26\ M_m\ M_{eq12}$, M_{eq13}.

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

Thus, the existing multi-motor systems in the drives of industrial machines 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 $R / R_d \geq 0{,}29$. Reduction of the non-clearable part of rotor resistance or increase of shaft load differences for some reason may result in disruption of synchronous rotation.

4. Conclusions

The scientific article contains new scientifically based results that solve an important scientific problem of increasing the reliability and automation level of a twin-motor asynchronous electric drive by studying electromechanical relationships with varying equivalent resistance in the rotor circuit, using pulse control in the rotor circuit; developing mathematical models, an algorithm of operation, and a logical control circuit.

The main scientific results in the article are as follows:

1. A functional scheme of pulsed automatic control of a two-motor asynchronous electric drive has been developed. The schematic solution of the digital control system is described in detail and the principle of operation is described.

2. A study of the mechanical parameters of a two-motor asynchronous electric drive has been carried out. The result of the research was the development of a T-shaped replacement circuit for a two-motor asynchronous electric drive with pulse control via a rotor chain. Using the developed T-

shaped substitution scheme, a system of equations was developed for the torques and currents of the stator and rotor of asynchronous electric motors in a coordinated rotation system.

3. To ensure automatic stable operation in the low-speed zone, smooth regulation and consistent rotation of electric motors, the scientific article develops a graph diagram of the operation algorithm and the graph of the Mile automaton; a structural transition table of the Mile control firmware; a system of Boolean equations of output functions and a system of Boolean equations of excitation functions of elementary memory automata; a logical circuit of the control firmware automatic mile control device for automatic pulse control of a two-motor asynchronous electric drive

Author Contributions: Conceptualization, S.I.; methodology, S.I. and F.B.; software, D.S., J.N.; validation, D.K. and G.N.; formal analysis, S.I., F.B. and G.N.; investigation, D.S. and D.K.; resources, S.I. and G.N.; data curation, F.B., J.N. and G.N.; writing - original draft preparation, S.I., F.B., G.N. and D.S.; writing—review and editing, S.I.; visualization, S.I., D.K., J.N.; supervision, S.I.; project administration, S.I., F.B. and G.N.; funding acquisition, S.I. All authors have read and agreed to the published version of the manuscript.

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