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STUDYING THE DYNAMIC CHARACTERISTICS OF CLOSED SYSTEM OF GRAVITY CONCRETE MIXER'S ELECTRIC DRIVE BY MEANS OF COMPUTER SIMULATION

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Abstract

Important tasks in the field of improving the quality of concrete and reinforced concrete products, increasing the level and pace of industrial development put serious demands on enterprises in terms of improving technical and economic performance, as well as a clearer and more efficient system of electrical equipment and energy saving.

In this regard, the issues of efficient operation of existing equipment and improvement of its technological characteristics become especially important.

On the other hand, improving and accelerating the process of construction production, raising it to a new level is possible only with high productivity and reliability of the relevant technological lines. With the growing international requirements for the quality of production processes, there is a need to increase and stabilize it.

To do this, currently used high-performance building complexes with the required level of quality of technological operations, which must be interconnected both in terms of productivity and reliability of the element base. Based on this, the presence of a weak mechanism (parts), more often than others fails and thus reducing the reliability of the entire line, is unacceptable in such a set of operations.

As a result, measures aimed at ensuring the reliability of the elements of mechanical equipment of technological lines for the production of building materials and products are crucial in this matter.

In addition, the issue of regulating the productivity of technological processes or their individual operations becomes important at this stage of development. Such regulation can reduce electricity consumption, improve system reliability and ensure efficient operation of the electric drive with the production mechanism.

The dynamic and static modes of operation of the electric drive of the gravitational concrete mixer were investigated, the system of the electric drive of the frequency converter - asynchronous, as a basic variant for the studied object was considered. Modeling of the calculated system is performed and dynamic characteristics are constructed. The stability and quality of the system by frequency criteria are evaluated.

Keywords: *electric drive, dynamic characteristics, gravitational concrete mixer, computer modeling, closed system.*

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1. Setting the Task

Operation of gravity concrete mixers' electric drive is normally determined by the properties of unregulated induction motor with a short-circuited rotor. The characteristics of the motor do not meet modern requirements to technological process, hence improvement of concrete mixers' performance through the use of up-to-date systems for electric drive control is a well-timed and urgent task.

In gravity mixers, mixing is carried out due to a free fall of material (Figure 1).

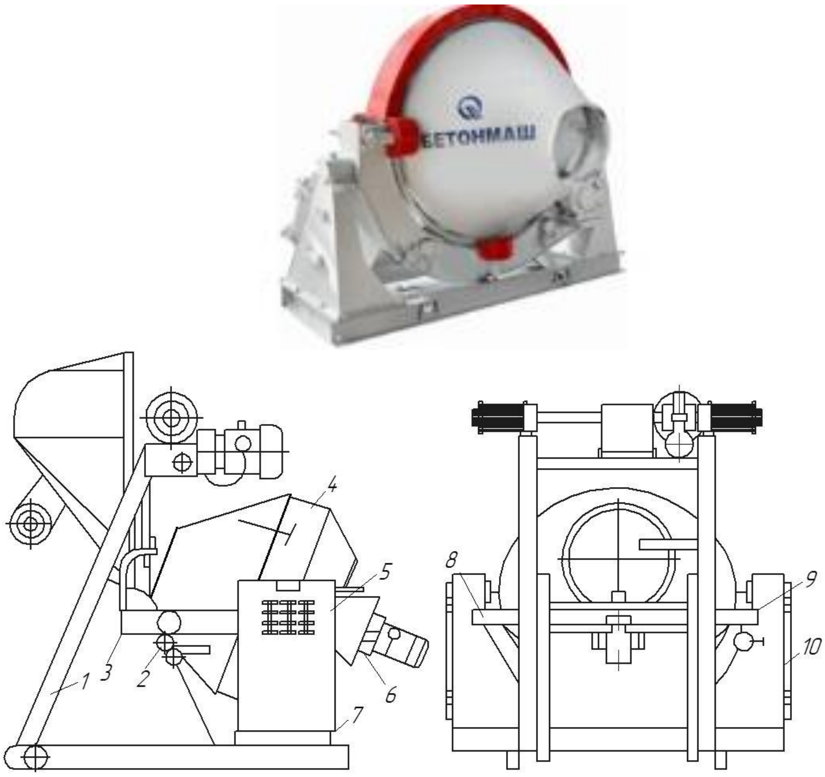

Fig. 1. Outer appearance of the gravity concrete mixer: 1 – guide; 2 – water dosing system; 3 – right channel assembly; 4 – mixer assembly; 5 – electrical cabinet doors; 6 – electrical equipment; 7 – mixer frame; 8 – left channel assembly; 9 - water supply system: 10 – key.

Forced mixers comprise mechanical mixing bodies interacting with mixture components.

Cyclic gravity concrete mixers are mainly of a pear shape, having an overturning unloading mechanism.

Blades are installed on the walls of the mixing tank, which blades, while the mixer bowl is rotating, capture the material and lift it up.

At the upper point, while falling from the catching blades, the material causes movement of solution bulk.

In other words, mixing of the bulk proceeds from collision of mixture portions captured by the blades.

Stirring gets faster when the rotating tank tilts, and changing the tank's angle may improve the quality of mixing.

Influence on quality of obtained concretes and solutions is also produced by the form and quantity of blades, the angle of tank tilt and the speed of the mixer's tank rotation.

Advantages of gravity mixers include:

• possibility of preparing mobile mixtures with coarse aggregate,

• mixer's fast unloading, overturning tank – that's what cannot be implemented in forced mixers with bottom or sector gates,

• optimal ratio between the installation's weight and mixer tank's working volume,

• simplicity of design,

• high reliability.

Nevertheless, gravity mixers have serious disadvantages.

The major ones are their low versatility and impossibility of obtaining a homogeneous rigid mixture.

That is why gravity mixers are giving up their leading positions, being increasingly replaced by forced mixers designed for intensive operation as part of complexes for production of ready-mixed concrete and forming lines.

However, if almost all modern enterprises producing concrete products abandon gravity mixers, small construction sites with small volumes of operations, in case of mobile concrete preparation, undoubtedly require the use of gravity mixers.

To improve the operation of the electric drive system it is necessary to use computer simulations to investigate the dynamic characteristics of the electric drive system of a gravity concrete mixer and to model the calculation system and build dynamic characteristics of speed, engine torque, to investigate frequency stability. Construct the logarithmic amplitude of frequency and phase-frequency characteristics, according to which the stability reserves of the system are estimated.

2. Study Subject Analysis

To meet the requirements to the technological process of concrete production, it is proposed to use "frequency converter asynchronous motor" (AC-AD) control system instead of relay-contactor system to control gravity concrete mixer's electric drive.

The block diagram of the electric drive system is shown in Figure 2.

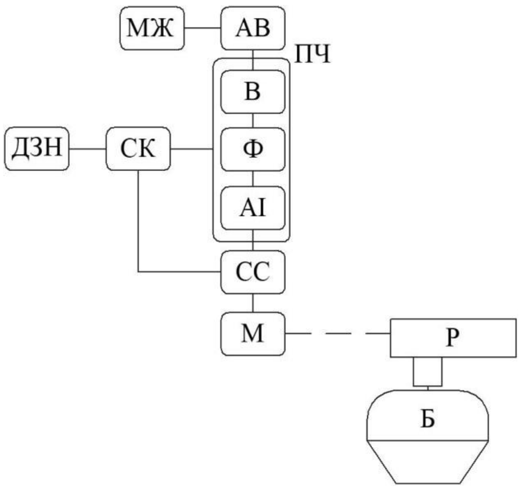

Fig. 2. Block diagram of concrete mixer's electric drive: МЖ – electric mains; АВ – circuit breaker; ПЧ – frequency converter; В – rectifier (adjustable or unregulated); Ф – inductive-capacitive (in the general case) filter; AI – stand-alone inverter (of current or voltage); ДЗН – source of set voltage; СК – control system; СС – current sensor; М – induction motor with short-circuited rotor; Р – concrete mixer reducer; Б – concrete mixer drum.

Today's frequency converters are designed either with the use of pulse-width modulation rectified in unregulated voltage rectifier or based on the principle of vector control. In this paper, we consider the first type of frequency converter. Such converter consists of unregulated rectifier, rectified voltage or current filter and current or voltage inverter.

At the first stage of conversion, the mains voltage is rectified by the input diode bridge, then smoothed and filtered.

At the second stage of conversion from constant rectified and filtered voltage, a set of pulses of certain frequency is generated. At the output of the frequency converter rectangular pulses are issued, which due to the inductance of motor stator windings are integrated and converted into the voltage close to sinusoidal one.

It should be noted that PWM inverter not only changes the output voltage frequency, but also regulates its average value, this allowing to abandon the controlled rectifier and to use a simpler diode rectifier.

Figure 3 shows the power section of circuit of frequency-regulated electric drive [12].

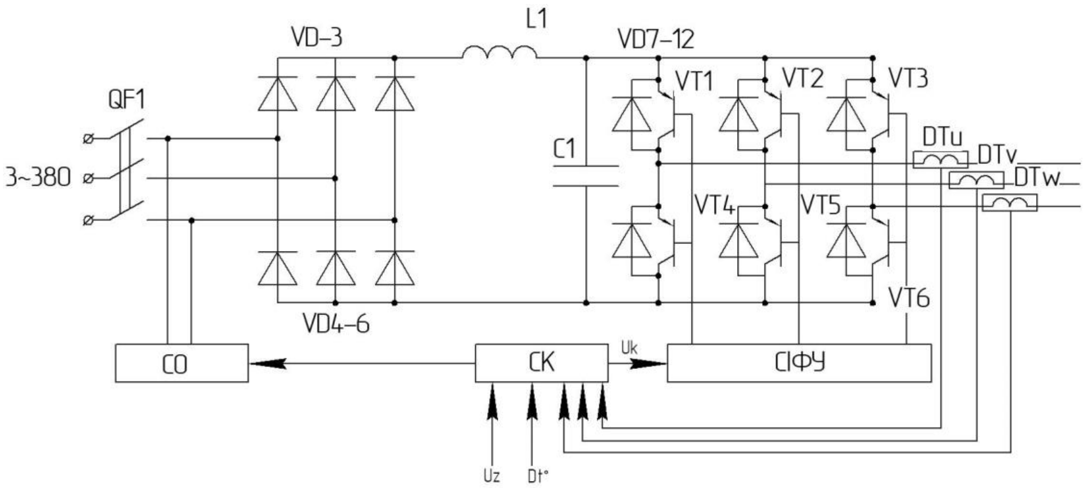

Fig. 3. Power section of the frequency converter

The power section of the electric drive consists of uncontrolled rectifier (VD1 − VD6), capacitive filter (C1), transistor-type autonomous voltage inverter (VT1 − VT6), current sensors (DTu, DTv, DTw), speed sensor and motor [10]. Frequency converter's power circuit also shows CO – cooling system; CK – control system of the converter; Dt - temperature sensor of the converter; Uz – reference voltage; Uk – control voltage.

Frequency converters are assembled according to the diagram shown in fig. 3, designed for general industrial performance and ensure rotation speed control in induction motors of series 4A, AIR or other induction motors with a capacity up to 315 kW in the frequency range from 1 to 100 Hz.

Electric drives can operate in the mode of rotation speed stabilization under variable load or under load stabilization by means of rotation speed reduction.

Converter's rectification function is performed by unregulated rectifier, which is usually assembled according to three-phase bridge circuit [1-2]. Rectified voltage is smoothed by capacitive filter. Filter capacity additionally performs the function of power storage, which is returned by the electric motor in a brake mode, and the function of reactive conductivity in the reverse current circuit.

Implementation of FC-IM system will improve both static and dynamic characteristics of the electric drive, and as a result – concrete mixer's overall performance.

3. Setting out the Basic Material

Today's frequency converters are designed either with the use of pulse-width modulation rectified in unregulated voltage rectifier or based on the principle of vector control. In this paper, we consider the first type of frequency converter. Such converter consists of unregulated rectifier, rectified voltage or current filter and current or voltage inverter.

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Implementation of FC-IM system will improve both static and dynamic characteristics of the electric drive, and as a result – concrete mixer's overall performance.

Computer simulation and study of closed electric drive system's dynamic characteristics require generation of electric drive system's model.

Generating the electric drive system's mathematical model.

Figure 2 shows the electric drive's block diagram built on the basis of induction motor's linearized model. The block diagram shows: Uzs – reference current voltage, PC – current regulator, Rc(p) – transmission function of current regulator, ЛО – signal limitation link at the current regulator's output, ПЧ – frequency converter, Wf(p) – transmission function of ПЧ, pi - 3,14, zp - number of the motor's pole pairs, АД – induction motor, We(p) – transfer function of АД's electrical section,

Wm(p) – transfer function of АД's mechanical section, Mc – load moment, ks (kzzs) –current feedback factor.

PC current regulator with transfer function Rs(p) supplies voltage to frequency converter ПЧ through limitation link ЛО; k_h – rotation speed feedback factor; АД – block diagram of the induction motor, which is represented by linearization of its mechanical characteristics in the operational section; Mc – static load [11].

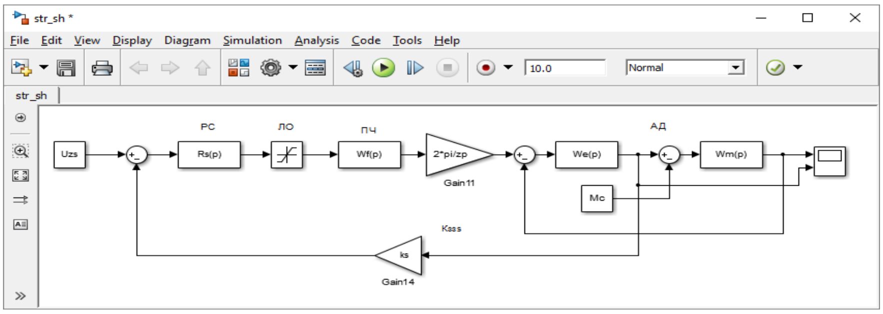

Fig. 4. Block diagram

For simulation, let us use linearized model of the induction motor.

Electric drive's control system will be calculated using a ten-volt scale. That is reference voltage $U_{zh.max} = 10$ (V). The limitation link will limit the signal at $\pm U_{zh.max}$ level.

The frequency converter is represented by the first-order aperiodic link

$$f = \frac{k_f}{T_f p + 1} U_k, \qquad (1)$$

where f – frequency at the converter's output, Hz; k_f – frequency converter's efficiency; T_f – frequency converter's time constant (assumed equal to 0.001 s); U_k – control voltage, V.

Frequency converter's efficiency may be calculated using the formula

$$k_f = \frac{f_n}{U_{z.max}} = \frac{50}{10} = 5.$$

Transfer function of the IM's electrical section is as follows:

$$W_e(p) = \frac{\beta}{T_e p + 1}, \quad (2)$$

where β – stiffness coefficient of IM's mechanical characteristics; T_e – electromagnetic time constant AD, p.

The stiffness coefficient is calculated Using the formula:

$$\beta = \frac{2M_{kn}}{s_{kn} \cdot \omega_0}, \quad (3)$$

where ω_0 – rotation speed of ideal idling, rad/s to be calculated using the formula:

$$\omega_0 = 0{,}1047 \cdot n_0, \quad (4)$$

$$\omega_0 = 0{,}1047 \cdot 1000 = 104{,}72 \text{ (rad / s)};$$

$$\beta = \frac{2 \cdot 70{,}374}{0{,}453 \cdot 104{,}72} = 2{,}97 \text{ (H} \cdot \text{s / m} \cdot \text{rad)};$$

The electromagnetic time constant is calculated using the formula:

$$T_e = \frac{1}{\omega_0 \cdot s_{kn}}, \quad (5)$$

$$T_e = \frac{1}{0{,}453 \cdot 104{,}72} = 0{,}021 \text{(with)},$$

$$W_e(p) = \frac{2{,}972}{0{,}021p + 1}.$$

The factor of conversion of supply voltage frequency into angular velocity of ideal idling is calculated using the formula:

$$\frac{2 \cdot \pi}{z_p} = \frac{2 \cdot 3{,}14}{3} = 2{,}094 \text{(rad / s} \cdot \text{Hz)}.$$

Motor current feedback ratio:

$$k_s = \frac{U_{z.max}}{M_{kn}}, \quad (6)$$

$$k_s = \frac{10}{70{,}374} = 0{,}142 \text{ (B} \cdot \text{s / rad)}.$$

Computer simulation of the electric drive system.

Using Matlab application package (APP), let us generate computer model of IM during load start-up that will be generated by the concrete mixer. This load is cyclic in nature with cycle duration of 3.24 s. Let us present the computer model of linearized induction motor in Figure 5.

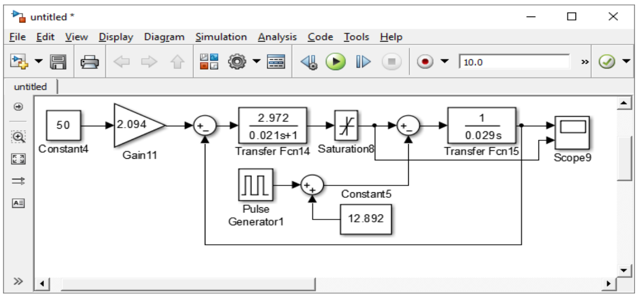

Fig. 5. Computer model of IM at direct start-up of cyclic loading, which is generated by the concrete mixer

The input of IM's computer model is supplied with the nominal supply voltage frequency of 50 Hz. The load in the software is generated by rectangular pulse generator. Saturation element Saturation 8 performs within computer model the function of limiting the IM's electromagnetic moment BP at the critical level.

Graphs of transient processes of motor speed and its torque when starting-up the motor load generated by the concrete mixer are shown in Figure 6.

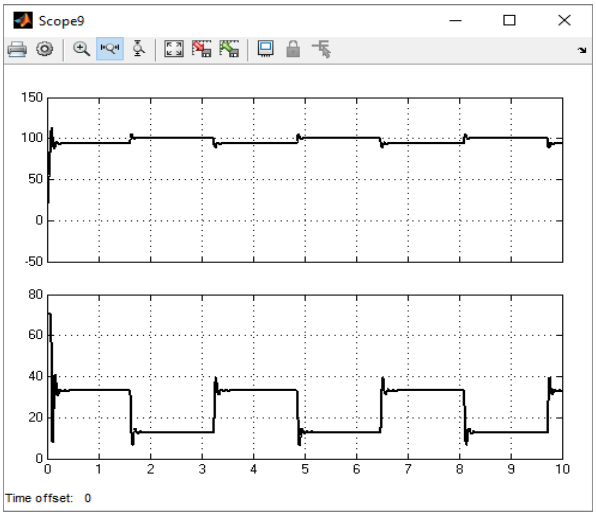

Fig. 6. Graphs of transient processes of motor speed (top) and its torque (bottom) when starting-up the motor load generated by the concrete mixer

To generate a computer model of FC-IM system, one should calculate the parameters of speed controller. For this purpose, let us adjust the speed circuit to the modular criterion of optimality, since starting the concrete mixer in household conditions is not the task of accelerated (quick) start. Calculation of the system has been performed in Mathcad mathematical package.

According to the results of calculation of the system adjusted to the modular criterion of optimality, we obtain the following current regulator:

$$R_s(p) = 0{,}09041 \cdot p + \frac{43{,}56}{p} - 0{,}00001132 \cdot p + 2{,}256 \cdot 10^{-8} \cdot p^2 - 4{,}53 \cdot 10^{-11} \cdot p^3 + 9{,}06 \cdot 10^{-14} \cdot p^4 \cdot$$

Since, starting from the third term of the current regulator's transfer function, the order of numbers is 10-5, continuing to increase, these terms may be neglected. In this way we obtain the current regulator's transfer function:

$$R_s(p) = 0{,}09041 \cdot p + \frac{43{,}56}{p} \cdot$$

Hence, the current regulator is proportionally integrated.

In Matlab APP, let us generate the computer model of FC-IM system during load start-up that will be generated by the concrete mixer. Let us present the system's computer model in Figure 7.

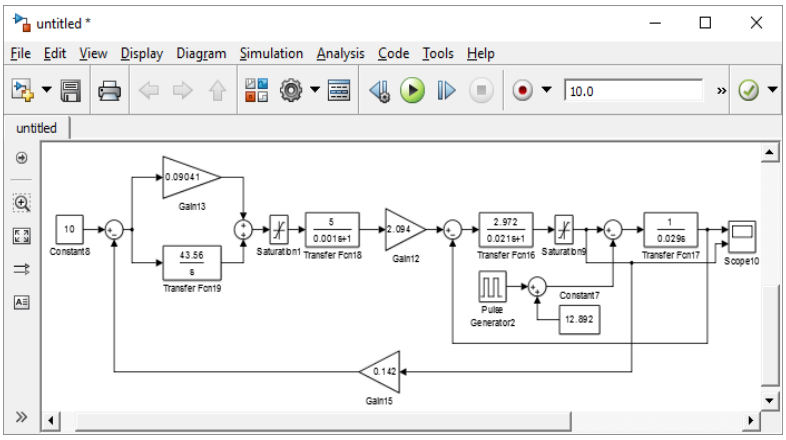

Fig. 7. Computer model of FC-IM system during load start-up that will be generated by the concrete mixer

The system's input is supplied with a linearly increasing signal limited to the value of $U_{z.max}$. Signal limitation link is set at the controller's output at ± 10 levels V.

Graphs of transient processes of motor speed and its torque when starting-up the load of FC-IM system generated by the concrete mixer are shown in Figure 8.

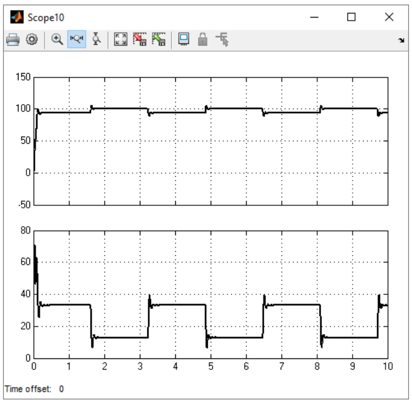

Fig. 8. Graphs of transient processes of FC-IM system speed (top) and motor torque (bottom) when starting-up the motor load generated by the concrete mixer

It follows from transition process graphs that the system responds to load variations as follows: when the load is gained during materials' lifting in the concrete mixer's drum, the speed of the electric drive decreases, and when the load is dropped – on the contrary, it increases. Speed decrease and increase is insignificant in view of the fact that the load grows more than twice [7-8].

Let us compare the results of computer simulation of the motor and FC-IM system. To do this, let us generate the computer model shown in Figure 9.

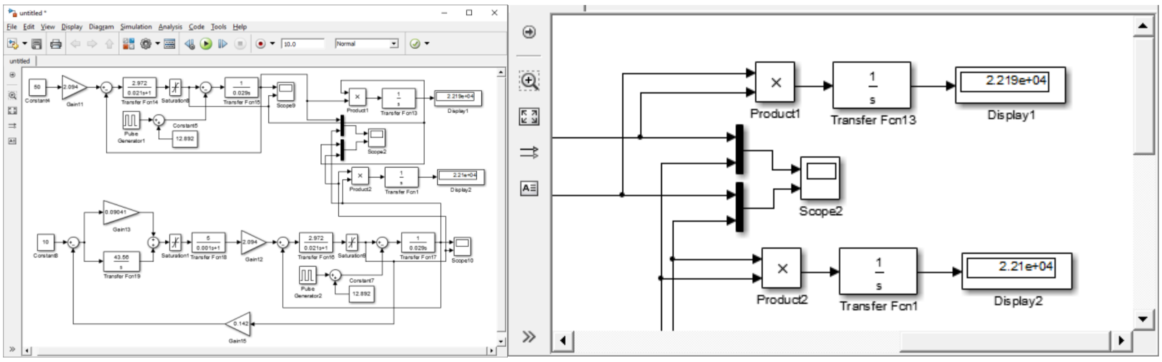

Fig. 9. Computer model of the motor and FC-IM system

The comparison of graphs of transient processes of motor speed and its torque during load start-up generated by the concrete mixer is shown in Figure 10.

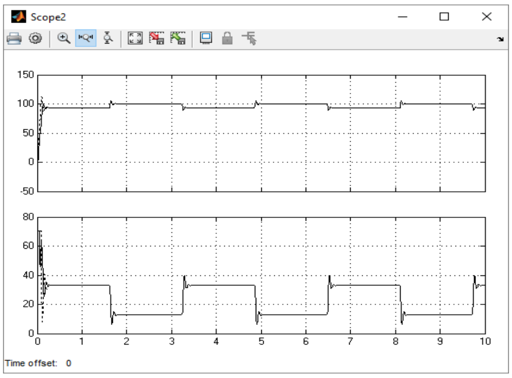

Fig. 10. Comparison of graphs of transient processes of motor speed (top) and torque (bottom) at load start-up in the motor and FC-IM system generated by the concrete mixer

In Figure 11, let us consider the process of electric drive acceleration in detail.

Comparison of the graphs confirms that, with calculated speed controller and feedback on motor current, FC-IM system operates with better control quality parameters than without any feedback.

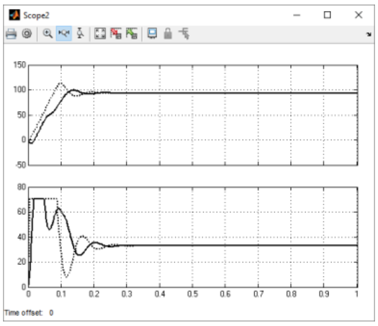

Fig. 11. Comparison of graphs of transient processes of motor speed (top) and torque (bottom) during load start-up in the motor and FC-IM system generated by the concrete mixer

The amount of electricity consumed by the motor and FC-IM system can be calculated using the formula:

$$E = \int M \cdot \omega \cdot dt\,, \tag{7}$$

where M is IM moment, Nm;

ω - motor speed, rad/s.

Figure 11 allows implementing the dependence in a structural form. It was found based on the results of simulating the electric drive's operation for 10 s that when the motor is running without feedback, the cost of power consumed for 10 s is 22,190 Watts, and when operating in FC-IM system – 22,100 watts. The difference in power consumption is 90 Watts in favor of FC-IM system.

Hence, the system has been calculated correctly. It optimizes the control action with good quality indicators and since transient characteristics reach an established value, it can be argued that the system is stable.

System research for stability and manageability [11] presents calculation of FC-IM system's speed controller. Having the transfer function of the speed controller, one can find the system's overall transfer function and test it for stability and manageability.

$$W(p) = \frac{879670}{p^2 + 500p + 125000}.$$

Let us enter the system's transfer function in Matlab command line and perform its "margin" conversion, as shown in Figure 11. As a result of performing the "margin" function with respect to the general transfer function of the electric drive system we obtain the logarithmic amplitude and phase-frequency characteristics. Let us present them in Figure 12.

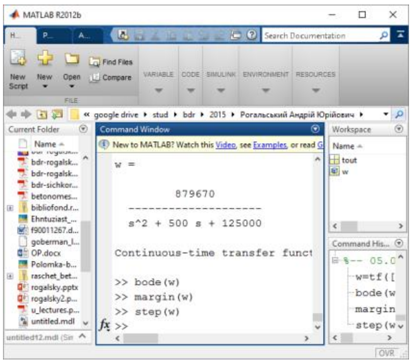

Fig. 12. Matlab command line during construction of the system's frequency characteristics described by transfer function "W"

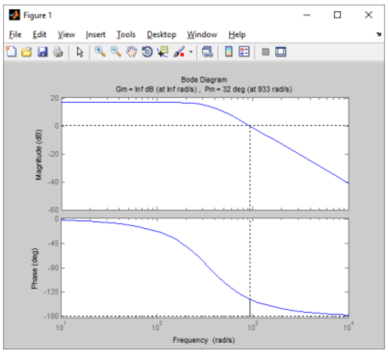

Fig. 13. Logarithmic amplitude-frequency (top) and phase-frequency (bottom) characteristics of the system

Because the cutoff frequency is less than the critical frequency, the system will be stable. Frequency characteristics constructed by Matlab APP immediately show the amplitude and phase stability reserves. Thus, the margin of stability is unlimited by amplitude (inf), and 32 degrees by phase.

To build the system's transient characteristics, let us use "Step" function in Matlab APP. The transition characteristic is presented in Figure 14. Let us plot coordinates of important points thereon.

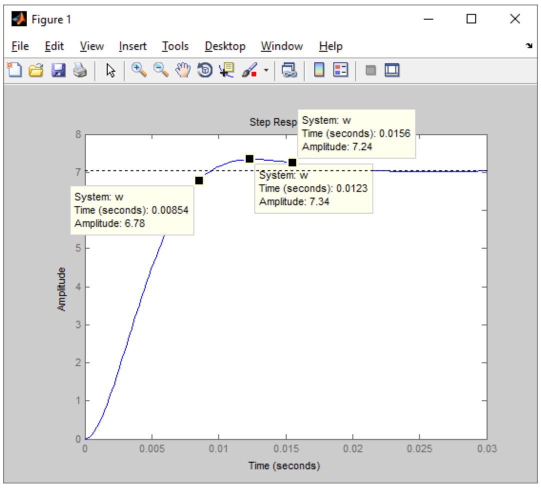

Fig. 14. Transient characteristics of the system

From the transient characteristic we can find the value of overregulation.

$$\Delta X = \frac{7{,}34 - 7{,}04}{7{,}04} \cdot 100\% = 4{,}26\%.$$

Installation time is 0.0085 s with adjustment time being 0.0156 s. Thus, the transition process duration is insignificant, and the system quickly reaches the established value.

Based on quality indicators, we can conclude that the system will be a high quality one.

Drawing up the electric drive's basic circuit diagram

The basic circuit diagram is shown in Figure 15.

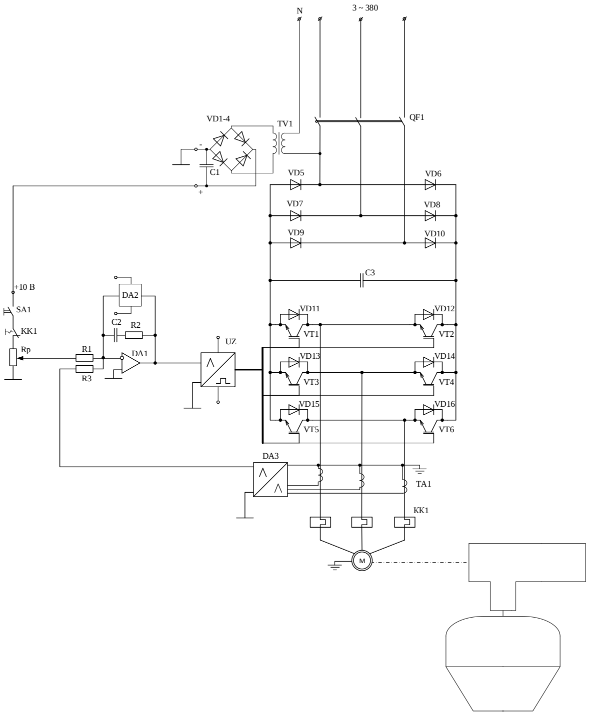

Fig.15. Basic circuit diagram of the electric drive's operating system.

The basic circuit diagram shows: N – power supply neutral, 3 ~ 380 three-phase voltage 0.4 kV, VD1-4 – diodes of unregulated power supply rectifier, TV1 – control circuit supply voltage transformer, QF1 – three-pole circuit breaker, C1 – capacitance for pulsation smoothing at the output of the control system's rectifier, VD5 – 10 – diodes of the frequency converter's unregulated rectifier, C3 – smoothing capacitance at the output of the FC rectifier, SA1 – control voltage supplying switch, KK1 – thermal relay, Rp – control voltage regulating potentiometer, R1 - R3 – current regulator resistors, DA2 – voltage limiting unit at the current regulator's output, DA1 – analog microcircuit, based on which the current regulator (operational amplifier) is implemented, C2 – current regulator's capacitance that sets the intensity of the current regulator's integrating component, UZ – analog-digital microcircuit, based on which the system of pulse-phase control of the voltage inverter (inverter driver) is designed, VD11 – 16 – diodes of reverse current overflow through the transistor at the time of its closure, VT1 – 6 voltage inverter transistors, DA3 - current sensor (normalizing converter), TA1 – current transformer, M - induction motor with short-circuited rotor.

To start up the system, one should supply voltage with circuit breaker QF1 and supply control voltage 10 V by closing SA1. When supplied control voltage is 10 V, the motor will rotate at its rated speed. Should the voltage drop below 10 V, the motor speed will decrease in proportion to this change.

A circuit with two operational amplifiers, one of which performs the function of inversion, is used as analog microcircuit DA1. Based on the other one, a proportional-integral regulator is designed. Analog microcircuit DA2 serves as the signal limiter. Digital circuit UZ performs the function of IPCS.

Diodes VD5 - VD10 perform the function of single-phase AC voltage rectification. On their basis, bridge-type single-phase rectifier is designed.

Capacitance C3 is used to smoothen (stabilize) the voltage at the unregulated rectifier's output.

Bipolar transistors VT1 – VT6 perform the function of DC voltage inversion to three-phase variable. Opposite to each transistor's direct channel, a shunt diode is connected, which performs the function of protecting the transistors at closure during operation under active-inductive load. Transistors and shunt diodes make up the voltage inverter.

Elements (coils) of thermal relay KK1 perform the function of protecting the motor against overheating. During overheating, the thermal relay breaks control voltage to 10 V.

Analog microcircuit DA3 performs the function of converting the current signal in three phases into an analog signal suitable for the current regulator's operation.

4. Conclusions

The dynamic and static modes of operation of the electric drive of the gravitational concrete mixer were investigated in the work.

The system of electric drive frequency converter - asynchronous motor with short-circuited rotor is considered.

Modeling of the calculated system is performed and dynamic characteristics of speed, engine torque are constructed.

According to the simulation results, the system works well, works out the setting signal. This confirms the accuracy of the calculations.

The electric drive system is investigated for stability by frequency criterion. The logarithmic amplitude of frequency and phase-frequency characteristics are constructed, according to which the stability reserves of the system are estimated. The margin of stability in amplitude is unlimited.

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