IMPROVING THE ENERGY EFFICIENCY OF OPERATION OF A MULTI-MOTOR PLATE CONVEYOR IN THE STEADY-STATE OPERATION MODE

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Resume
The established mode of operation of the conveyor with a nominal linear load is the most economically advantageous from the point of view of increasing the energy efficiency of mineral transportation, in which the cargo flow with minerals corresponds to the nominal productivity of the conveyor. An increase in the linear load of the working branch of the traction-bearing body to a nominal value reduces the share of unproductive consumption due to which energy savings are achieved for a certain period of time, characterized by its hourly average value.
The purpose of the work was to develop a technical solution to increase the energy efficiency of operation of multi-motor plate conveyors.

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1 Introduction

Modern belt conveyors are capable of processing the cargo flows of the largest mines and quarries in the next decade in terms of productivity [1-3]. However, this type of conveyor cannot operate on a curved track, as well as at high angles of inclination, which is typical for open-pit mining conditions. Ensuring the delivery process on curved routes, the possibility of increasing the angle of transportation, improves the technical and economic indicators of mineral extraction in quarries and sections, since at the same time it is possible to change the geometry of open mine workings, which leads to a reduction in unproductive costs by reducing the amount of work on stripping [4].

The practice of operating plate conveyors at mining enterprises in Kazakhstan and the experience of their operation abroad have shown that this type of conveyor, due to its design features, can be successfully applied in various industries in difficult mining, geological and production conditions for transporting a wide range of goods (coal, pellets, agglomerate, rocks and ores). In particular, in Kazakhstan, at the Molodezhny coal mine (Kazakhmys Coal LLP), a plate feeder of the KM PP 2-10-60 type is used to supply coal to the concentrator (Figure 1) with a frequency converter from Mitsubishi Electric E-700 (Figure 2), with which, depending on the volume of the coal flow, it is possible to adjust the frequency, increase or decrease the speed of the electric conveyor drive.

An analysis of the experience of operating plate conveyors at mining enterprises has shown that the use of modern frequency-controlled electric drives is a promising direction in improving the efficiency of operation of multi-motor plate conveyors, providing control of the speed of movement of the bearing web, control of load distribution between drives, elimination of equalizing forces in the conveyor traction circuit, automatic start of a multi-motor conveyor taking into account the elastic-viscous properties of traction-the load-bearing canvas and a number of other factors [5-8].

***Figure 1** Electric plate drive feeder type KM PP 2-10-60*

***Figure 2** Frequency converter of company „Mitsubishi Electric E-700“*

2 Substantiation of the relevance of the study

Technological schemes using the plate conveyors are preferable to conveyors with a belt traction and bearing body, for economic reasons, as well. This is due to the need to install additional crushing complexes in the case of belt conveyors, as well as the arrangement of transshipment points associated with the use of these conveyors on curved transport routes. When using the plate conveyors that bend in plan, the number of mechanisms and machines is significantly reduced, which significantly simplifies the technological scheme of transportation and increases the reliability of operation of the entire complex [9].

It is also possible to note an important design feature of the plate conveyors, characterized by the movement of the traction-bearing body of the conveyor on wheel pairs along a metal frame, which allows for significantly less resistance to movement during the conveyor operation compared, for example, with another type of chain conveyors - scraper conveyors. In these conveyors, the scrapers move along the surface of the metal grate, which leads to a significant increase in the energy consumed by the engines. At the same time, even full loading of the upper branch of the working web of the plate conveyor does not lead to a significant increase in the resistance to movement of the traction-bearing body of the conveyor when it is operating under rated load.

An important advantage of the plate conveyors, in terms of power indicators, is the possibility of transporting large-lump rock mass along a curved highway in one stop without transshipment points at low values of resistance to movement of the load-bearing body. When operating long-range main plate conveyors from 1000 to 6000 m, multi-motor designs are used. At the same time, ensuring a smooth start of a multi-motor chain conveyor is of a great practical importance, and is undoubtedly relevant for controlling and maintaining a workable static and dynamic state of the main plate conveyor structure operated in difficult mining and geological conditions [10-11]. With a non-unloading scheme for transporting the rock mass, due to the presence of a large number of intermediate drives in a plate conveyor, it is also necessary to solve the problem of automatic distribution of the total load between its drives [12-13].

The experience of operating multi-motor plate conveyors at mining enterprises in Kazakhstan shows that the operating modes and technological parameters of industrial conveyors at most coal mines are extremely inefficient in terms of actual electricity consumption.

The actual energy consumption of the leading electric drive of the plate conveyor, as is known, can be determined by the following formula:

$$E = Nt = \frac{W_{ub}\vartheta\, t}{10^3 \eta_p}, \text{ kWh,} \qquad (1)$$

where: W_{ub} - is the resistance to movement of the upper branch of the traction-bearing body of the conveyor, N; η_p - is the efficiency of the electric drive gearbox; ϑ - is the linear speed of movement of the conveyor working web, m/s.

The resistance to movement of the upper branch of the traction-bearing body of the conveyor is determined by the following formula:

$$W_{ub} = L_c g[(q_{wb} + q_l)w' \cos\beta + q_{wb} \sin\beta], \text{ N,} \qquad (2)$$

where: L_c - conveyor length, m; q_l - linear weight of the load per running meter of the working web of the traction-bearing body, N/m; q_{wb} - linear mass of 1 m of the working branch of the traction-bearing body, N/m; w' - the coefficient of resistance to movement; β - conveyor installation angle, °; g - gravitational acceleration.

Figure 3 shows exponential dependencies reflecting the potential dynamics of changes in energy consumption by the leading electric drive of the P-80K multi-motor plate conveyor in steady-state operation.

The analysis of dependencies presented in Figure 3 shows that with an increase in the linear load on

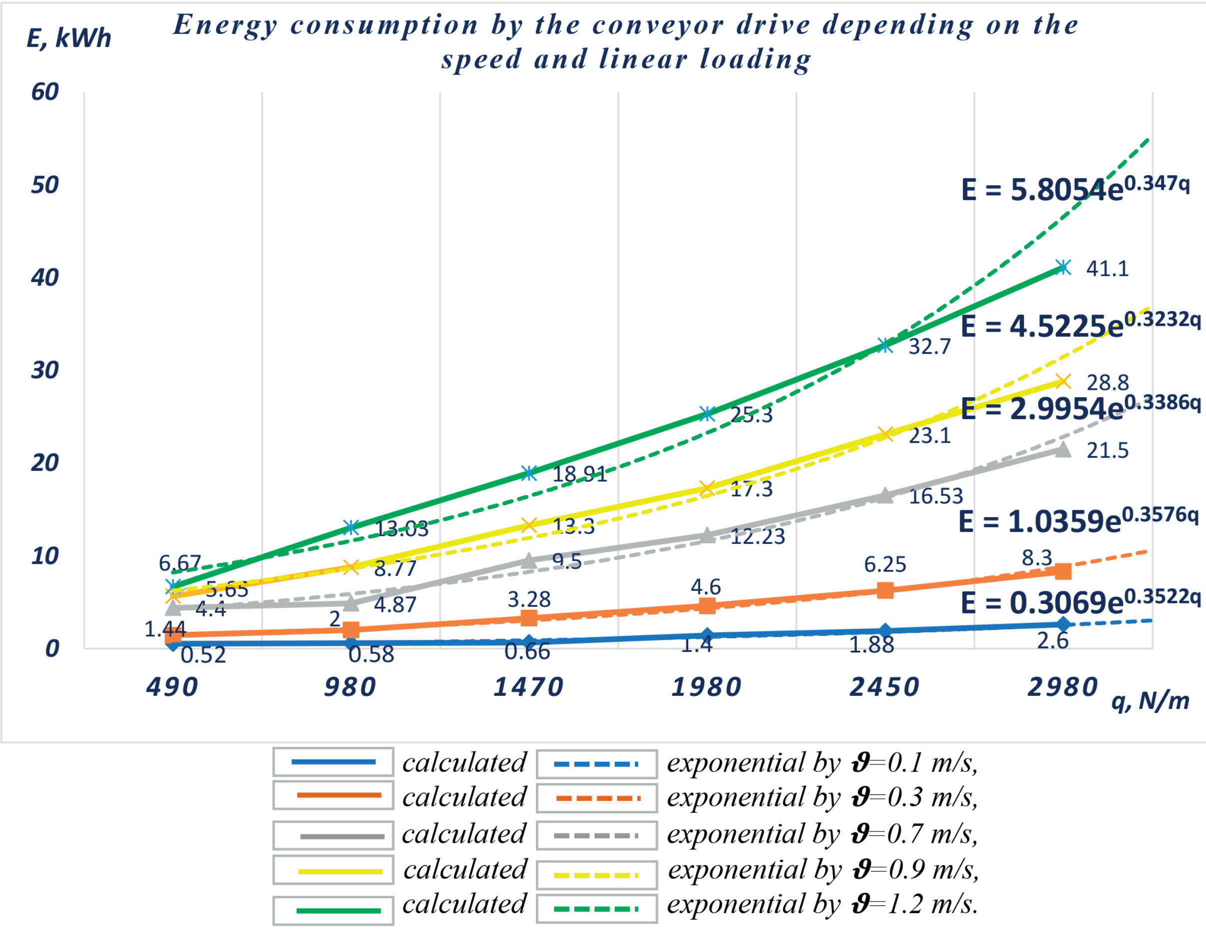


Figure 3 *Dependences of the energy consumed by the electric drive of the P-80K multi-motor plate conveyor on the linear speed of the traction body and the linear load of the working web*

the conveyor working web from 490 to 2980 N/m, at different speeds of the traction body (0.1 - 1.2 m/s), the actual energy consumption of the leading electric drive of the P-80K conveyor increases by 5-6 times. Thus, the problem of unreasonable power consumption in steady-state operation of a multi-motor plate conveyor is an urgent scientific task.

In connection with the above, this work has set the goal of developing a technical solution that would allow for the implementation of measures to increase the energy efficiency of operation of multi-motor plate conveyors.

3 The above diagram and mathematical description of a multi-motor plate conveyor in steady-state operation

After reaching the nominal speed of the traction-bearing body 1, the conveyor begins to load ore from the hopper 2 (Figure 4). When the traction-bearing body is fully loaded with cargo 3, the head drive 4 of the conveyor and the tail driven electric drive 5 of the lower branch 7, respectively, begin to work on moving the loaded upper branch 6 of the traction-bearing body.

The elements of the traction-bearing body of a multi-motor plate conveyor have elasticity, rigidity, inertia - the values of which must be taken into account when developing a mathematical model describing the dynamic processes occurring in various nodes of the conveyor during its operation. To solve the problems of dynamics, the studied conveyor nodes can be represented as separate inertial elements connected by elastic bonds. In addition, for unsteady processes (start-up, braking, speed changes), it is necessary to take into account the influence of rotating and linearly moving parts of the traction body, the electric drive and the weight of the load. To do that, the method of bringing all the moving masses to the shafts of the corresponding engines was used. Calculation formulas are compiled to fully bring the moments of inertia of rotating parts of gearboxes, a moving traction-bearing body, and the weight of the load to the engine shafts. The above diagram of a multi-motor plate conveyor with asynchronous frequency-controlled electric drives is shown in Figure 5.

The masses of the upper branch of the traction body, the sprocket and the rotating parts of the first gearbox are driven to the rotor of the drive motor; the masses

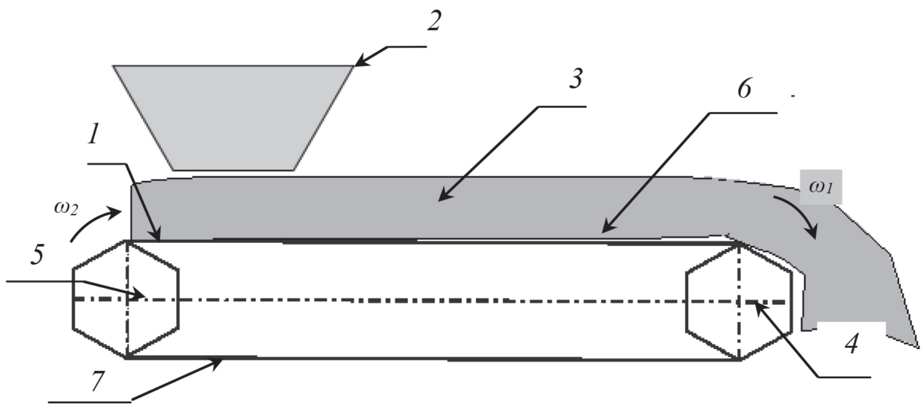


Figure 4 *Diagram of loading a multi-motor plate conveyor with ore*

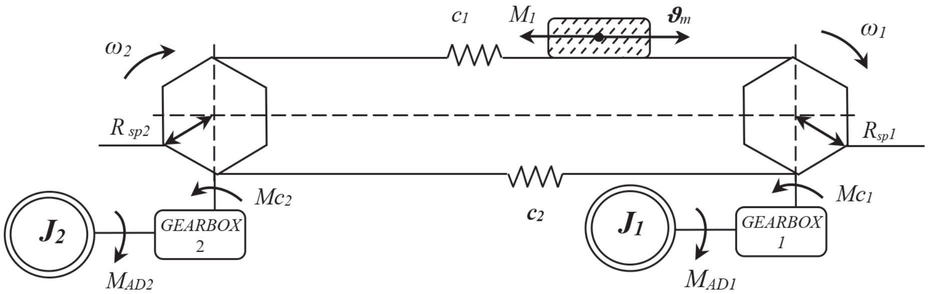


Figure 5 *The above diagram of a multi-motor plate conveyor with asynchronous frequency-controlled electric drives*

of the lower branch of the traction-bearing body, the sprocket and the rotating parts of the second gearbox are driven to the rotor of the driven motor. Thus, the conveyor is replaced by a two-mass system connected by elastic bonds of the lower and upper branches.

The conditions under which the necessary load distribution between the electric drives is ensured (taking into account the limitation of unreasonable dynamic overloads in the traction-bearing body of the plate conveyor) are described by the following system of equations [14]:

$$J_{\Sigma 1}\frac{d\omega_1}{dt} = M_{AD1} - M_{c1} - M_{lm} - \\ - c_1\int(\omega_1 - \omega_2)dt + c_2\int(\omega_2 - \omega_1)dt, \quad (3)$$

$$J_{\Sigma 2}\frac{d\omega_2}{dt} = M_{AD2} - M_{c2} - c_2\int(\omega_2 - \omega_1)dt + \\ + c_1\int(\omega_1 - \omega_2)dt, \quad (4)$$

where: M_{AD1} - is the electromagnetic moment developed by the first master electric motor; M_{c1} - is the static moment reduced to the shaft of the first electric motor; M_{AD2} - is the electromagnetic moment developed by the second slave electric motor; M_{c2} - is the static moment reduced to the shaft of the second motor; M_{lt} - is the moment of resistance forces from the mass of the load transported; ω_1, ω_2 - are the angle speeds of rotation of the first and second electric motors, respectively; $J_{\Sigma 1}$ - is the inertia moment of the upper branch of the traction body taking into account the mass of the load transported reduced to the master electric motor; $J_{\Sigma 2}$ - is the inertia moment of the lower branch of the traction body taking into account the mass of the load transported reduced to the slave electric motor; c_1, c_2 - are the coefficients of rigidity of the upper and lower branches, respectively.

When operating an electric drive of a multi-motor plate conveyor, in the case of placing motors at the ends of the conveyor, the ratio of traction forces of the drives is not equal to the ratio of their installed capacities - this is explained by uneven chain drawing, the difference in loading of empty and loaded branches, which leads to high dynamic loads [15]. To reduce the dynamic forces in the chain, it is advisable to distribute the loads between the drives so that each engine is loaded on its own branch. In the load distribution system, the leading drive is the first head drive loaded on the working branch [16]. The end driven electric drive, accordingly, works to move the lower empty branch of the traction-bearing body.

Figures 6 and 7 show a block diagram and a block diagram of an algorithm for controlling and distributing loads between frequency-controlled electric drives of a multi-motor plate conveyor [17].

The essence of the method of controlling and distributing loads between frequency-controlled asynchronous electric drives of a multi-motor plate

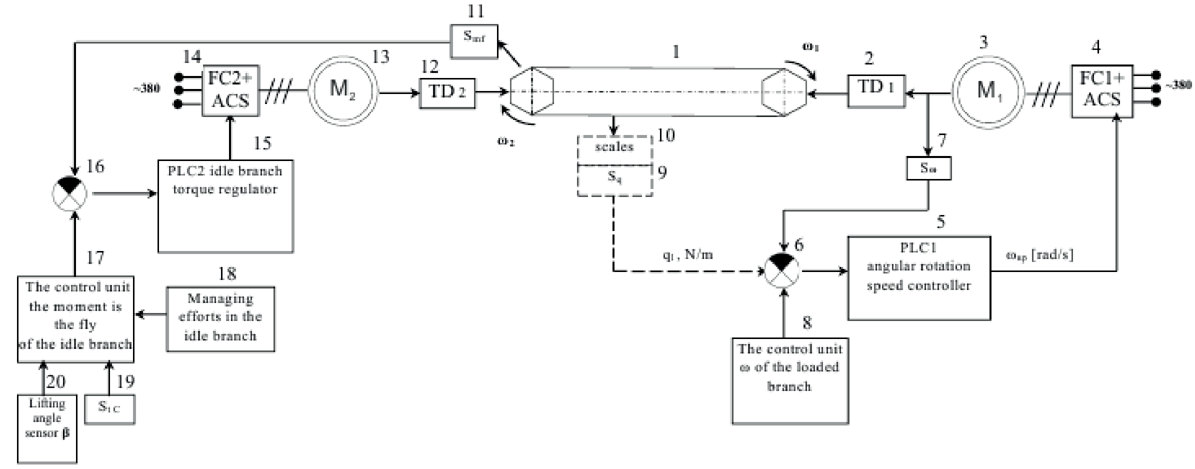


Figure 6 *Structural block diagram of a frequency-controlled electric drive for controlling and distributing loads between drives of a multi-motor plate conveyor*

conveyor, based on measuring the loads of the leading and driven electric drives of the conveyor, correcting the control signal of the driven electric drive in the function of the measured loads and controlling the speed of the leading electric drive, is as follows. The linear loading of the working branch and the forces in the idle branch of the traction-bearing body, the ambient temperature and the lifting angle of the conveyor are measured. In the established modes of operation of the conveyor, in accordance with the changing linear loading, the speed of movement of the working branch is regulated by the driving electric drive, the torque setpoint of the driven electric drive of the idle branch is changed, taking into account the ambient temperature and the angle of lifting of the conveyor, and when the forces in the idle branch change, the traction torque of the driven electric drive is adjusted relative to the torque setpoint of the electric drive of the idle branch [17].

The proposed method can be implemented based on the known technical solutions as follows.

4 Execution of control system units and load distribution between electric drives of a multi-motor plate conveyor

All the blocks can be made based on the known technical solutions [17]. Conveyor 1 includes a steel and a traction-bearing body of the conveyor (a load-bearing cloth made of steel plates attached to a chain traction body), while the first transmission device of the drive electric drive (TD 1) 2 and the second transmission device of the driven electric drive (TD2) 12 are made in the form of standard cylindrical gearboxes. The first asynchronous electric motor of the drive 3, and the second asynchronous electric motor of the driven drive 13, are asynchronous motors with a short-circuited rotor.

The first frequency converter with an automatic control system (FC1+ACS) 4, and a second frequency converter with an automatic control system (FC1+ACS) 14 - standard converters that convert AC mains voltage into variable power supply frequencies of asynchronous electric motors 3 and 13.

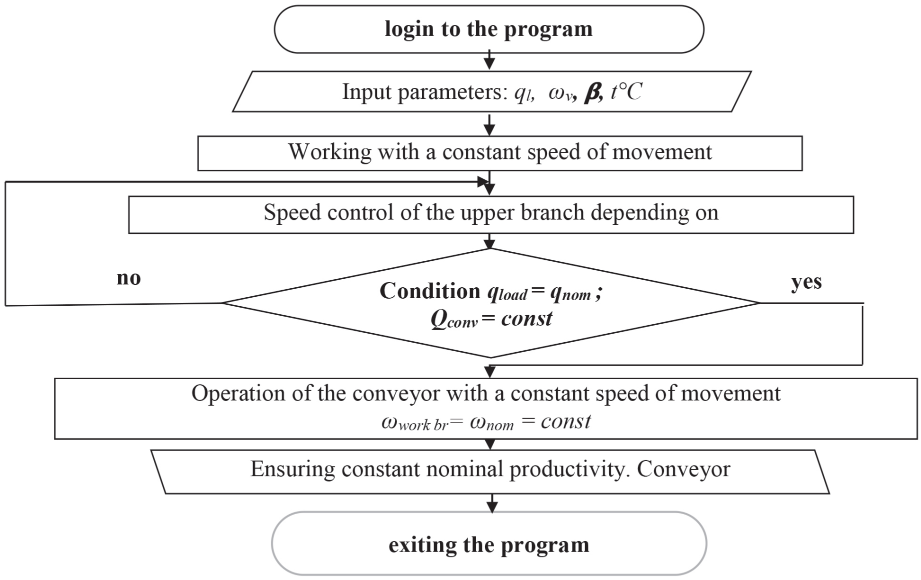
The first PLC1 (Programmable Logic Controller), the angular velocity controller 5 of the first electric motor 3 is a programmable logic controller with an adaptive law for regulating the angular velocity of rotation of the rotor of the first electric motor from the actual linear load of the traction-bearing body of the conveyor 1, direct dependence.

The second PLC2, controller 15 is a programmable logic controller with an adaptive law for regulating the traction torque (TT) of the driven second electric drive of the conveyor, taking into account the actual forces in the idle branch of the traction-bearing body.

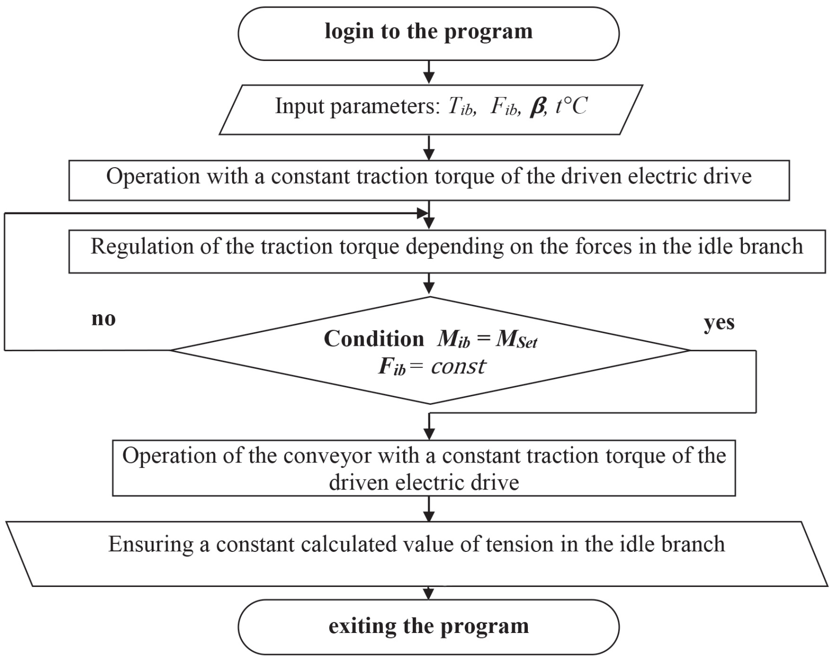
The first adder of the drive 6 is a standard device that converts information signals (analog or digital) into a signal equivalent to the sum of these signals and, in this case, determines, depending on the linear load of the working branch of the traction-bearing body of the conveyor 1, the difference between the calculated set and the actual measured values of the rotation speed of the first electric motor 3.

Scales 10 is a standard weighing device with a linear load sensor 9 of the upper branch of the traction body. The angular velocity sensor 7 is a standard sensor for measuring the rotational speed of the rotor of the first electric motor 3.

The rotation speed control unit 8 is a standard unit that sets the calculated value of the rotor speed of the first electric motor, made in the form of an analog or digital setpoint. The force sensor on the shaft of the end sprocket 11 is a standard force measurement sensor (tensile moment) applied to the shaft of the end sprocket of the driven drive from the tension of the upper branch



a) ensuring constant conveyor performance



b) ensuring a constant calculated value of tension in the idle branch of the conveyor

Figure 7 *Block diagram of an algorithm for controlling and distributing loads between frequency-controlled electric drives of a multi-motor plate conveyor*

of the traction body. The second adder of the driven electric drive 16 is a standard device that converts information signals (analog or digital) into a signal equivalent to the sum of these signals.

The control unit of the calculated force value in the idle branch of the traction-bearing body 18 is a block that sets the calculated value of the traction torque of the driven electric drive. Temperature sensor 19 is a standard sensor for measuring ambient temperature. The lifting angle sensor 20 is a standard analog or digital sensor that determines the lifting angle (tilt) of a multi-motor plate conveyor.

5 Verification of the proposed technical solution

The developed algorithm for controlling and distributing loads between the frequency-controlled electric drives of a multi-motor plate conveyor was implemented in laboratory conditions in the computer environment of the FR CONFIGURATOR2 program at the stands of Mitsubishi Electric with a frequency converter of the FR-A800 series. The obtained simulation results were positively evaluated by production specialists, who recommended the proposed technical solution for practical use in the operation of plate conveyors in open-pit mining [15].

Thus, the developed method of controlling and distributing loads between frequency-controlled electric drives of a multi-motor plate conveyor, in authors' opinion, will ensure the necessary operational mode of operation of the conveyor with a nominal linear load, by regulating the speed of movement of the working body of the conveyor. The maximum load of the traction-bearing body of the conveyor in steady-state operation is the most economically advantageous, from the point of view of increasing the energy efficiency of the operation of the plate conveyor. In this regard, the proposed automated control system for a multi-motor electric drive, implemented based on the PLC, is configured in such a way that it measures the linear load of the working web in the real time and regulates the speed of its movement, which ensures the maximum loading of the upper branches and eliminates unreasonable power consumption of the electric drive.

6 Conclusions

The developed method for controlling and distributing loads between frequency-controlled asynchronous electric drives during operation of a multi-motor plate conveyor is based on regulating the linear speed of movement of the traction-bearing body depending on the actual linear load of the working branch.

This ensures the nominal capacity of the conveyor, and, at the same time, the calculated value of the tension of the idle branch is achieved by controlling the traction torque of the driven electric drive of the conveyor in the steady-state operating modes. The results of the proposed technical solution are:

- ensuring the necessary performance of a multi-motor plate conveyor;
- increasing the service life of the elements of the traction-bearing body of the conveyor by reducing dynamic overloads in established operating modes;
- the expected reduction (up to 10-15%) of unjustified electricity consumption for the empty run of the conveyor, as a result of regulating the speed of movement of the working body.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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