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SIMULATION OF METALLURGICAL PROCESSES

Increasing the Energy Efficiency of the Cyclic Action Mechanisms in Rolling for a Roller Bed Used as an Example

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Abstract—The possibility of increasing the energy efficiency of the production cycle in a roller bed is briefly reviewed and justified. The sequence diagram of operation of the electrical drive in a roller bed is analyzed, and the possible increase in the energy efficiency is calculated. A method for energy saving is described for the application of a frequency-controlled asynchronous electrical drive of drive rollers in a roller bed with an increased capacitor capacity in a dc link. A fine mathematical model is developed to describe the behavior of the electrical drive during the deceleration of a roller bed. An experimental setup is created and computer simulation and physical modeling are performed. The basic information flows of the general hierarchical automatic control system of an enterprise are described and determined with allowance for the proposed method of increasing the energy efficiency.

Keywords: energy saving, roller bed, asynchronous electrical drive, energy efficiency, energy recuperation, estimation of energy consumption, automation, control system

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INTRODUCTION

To increase the efficiency and to decrease the costs of rolling are challenging problems for scientists, designers, and operators. To maintain and to increase the product quality are impossible without modern approaches to automation, control, and technical diagnostics systems with allowance for the optimization of resource consumption and the application of resource-saving technologies. These problems can be solved on various production scales using various approaches [1, 2]. Using the electrical drives and the control systems of a grade 650 roller bed as an example, we consider a possible and technically feasible version for decreasing the energy consumed for cyclically operating systems. The application of a frequency-controlled asynchronous drive for rolling, where it was rarely used, leads to an increase in the service characteristics of equipment due to meeting the requirements of a technological process, improvement of control and observation indices, and increasing the reliability and safety of operation. In comparison with uncontrolled ac and dc electrical drives, the use of frequency-controlled asynchronous drives saves electric power when rational technological process control algorithms are used.

The energy efficiency of such drives can be additionally increased using an internal energy recuperation system and integration of additional control blocks into a technological process control system. Such a system is especially efficient for mechanisms with significant momenta of inertia applied to an motor shaft; mechanisms with an active momentum and operating conditions with a large number of acceleration and deceleration, such as lifting-and-shifting machines for horizontal and vertical load motion; and press-forging equipment. As an example, we consider the technological system of a grade 650 roller bed and focus on the lower levels of automation, including electrical drives and primary data processing and communication channels, and their integration into a global automatic control system of rolling.

EXPERIMENTAL

The loading diagram of the electrical drive of the drive rollers of a grade 650 roller bed is shown in Fig. 1 [3]. The total operating cycle time is 56.2 s: the starting (acceleration of slab) time is 6.5 s, the deceleration (stop of slab) time is 5.1 s, operation at a steady speed is 31.2 s, and the pause is 13.4 s. As follows from the diagram and an analysis of the operation times of the electrical drive in a production cycle, the deceleration of the electrical drive (stop of slab) accounts for 9% of the cycle time.

During deceleration, the kinetic energy (Eq. (1)) accumulated in the moving and rotating masses can be converted into electric energy, stored, and "reused" when an electric machine passes into a generator mode. The generator mode of the electric machine during the deceleration of the roller bed is caused by the fact that the sufficiently high momentum of inertia of the mechanism does not allow the rate of shaft rotation to change instantly, unlike the rate of magnetic

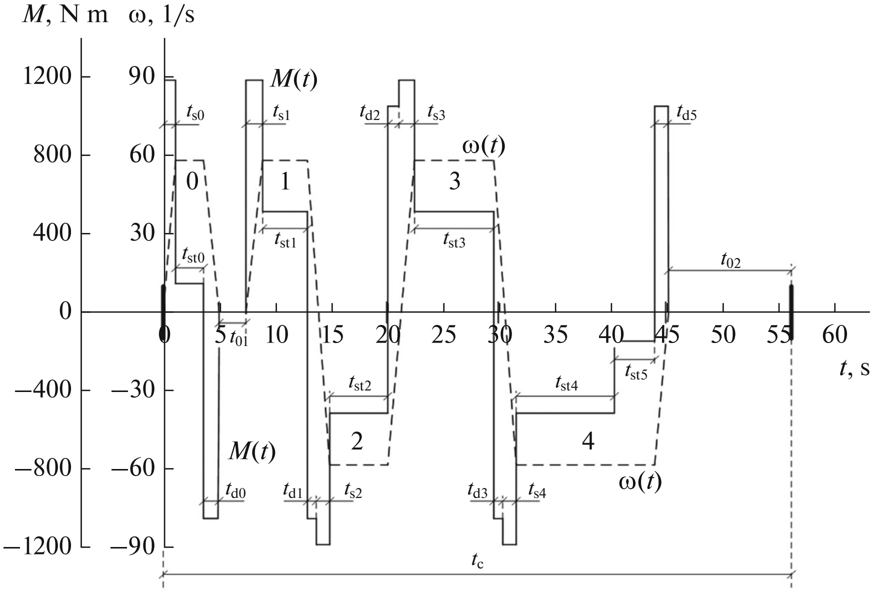

Fig. 1. Sequence diagram of operation the electrical drive in a grade 650 roller bed. The times are given for the following sequence diagram sections: 0 stands for transportation before the first pass; 1, for the first pass; 2, the second pass; 3, the third pass; and 4, the fourth pass and transportation. t_{s0}, t_{s1}, t_{s2}, t_{s3}, and t_{s4} are start times; t_{st0}, t_{st1}, t_{st2}, t_{st3}, t_{st4}, and t_{st5} are the operation times at a steady speed; t_{d0}, t_{d1}, t_{d2}, t_{d3}, t_{d4}, and t_{d5} are the deceleration times; and t_{01} and t_{02} are the pause times.

field rotation. The magnetic field in the converter–motor system changes much faster,

$$Jd\frac{\omega}{dt} = M_{\mathrm{m}} - M_{\mathrm{r}}, \tag{1}$$

where J is the moment of inertia of the mechanism applied to the shaft, ω is the angular rate of rotation of the electric motor, t is the time, M_{m} is the moment developed by the electric motor, and M_{r} is the moment of resistance applied to the electric motor shaft.

According to the equation of the mechanical characteristics of a frequency-controlled asynchronous drive [4, 5] and the operating conditions of an asynchronous generator [6, 7], an electric machine passes into the generator mode when the motor shaft speed is higher than the rate of rotation of the magnetic field specified by the current converter frequency.

The generator mode appears during the deceleration of the mechanism or a change in the rate of rotation down from the previous value, which corresponds to the deceleration of the electrical drive of the drive rollers in the roller bed (see Fig. 1). In this case, the energy flux direction changes; that is, energy “comes back” to the converter. A brake resistor, in which the recuperated energy of the electrical drive is converted into heat, is placed in most commercial converters to release the recuperated energy. Energy is most rarely returned to the supply main (converters with an active rectifier) when the structure of power circuits and the control system of a frequency converter changes [4]. This method needs active–passive current and voltage filters at the input of a converter, which are necessary to improve the harmonic composition and the quality of the energy returned to the supply main, which increases the cost of such a system by many times. An alternative to energy recuperation to the supply main is internal recuperation [6–9]. The energy to be recuperated is stored in internal energy storage in a converter. The storage capacity is increased with respect to the base value. Such energy storage can be a battery of capacitors or storage cells, which do not change their basic characteristics at the switching frequencies of power keys and operate in the calculation voltage range of a direct current link.

For energy to be recuperated the asynchronous machine should be maintained in the generator mode; that is, the asynchronous motor needs a reactive energy influx during deceleration. Otherwise, the electric machine loses excitation and passes into the self-running-out mode. Control of the transistor keys of the converter during a decrease in the frequency is the lower level of controlling the deceleration mode of the entire roller bed.

The deceleration time and intensity should be determined by a production cycle and, hence the current position of a slab, technological operations, and other technological factors.

The well-known subsystems of the optimum acceleration and deceleration of electrical drives with limited acceleration and jerks that operate in rolling mills remain unchanged in the proposed structure. To provide energy saving, we transform the resident part of the algorithms of controlling energy fluxes in the internal recuperation mode.

Therefore, the generalized system of increasing the energy efficiency of a grade 650 roller bed, which is shown in Fig. 2, is technically executed on the lower level in the electrical drive system with additional energy storage systems and includes the systems of controlling the electrical drives of drive rollers, the roller bed, and enterprise resource planning.

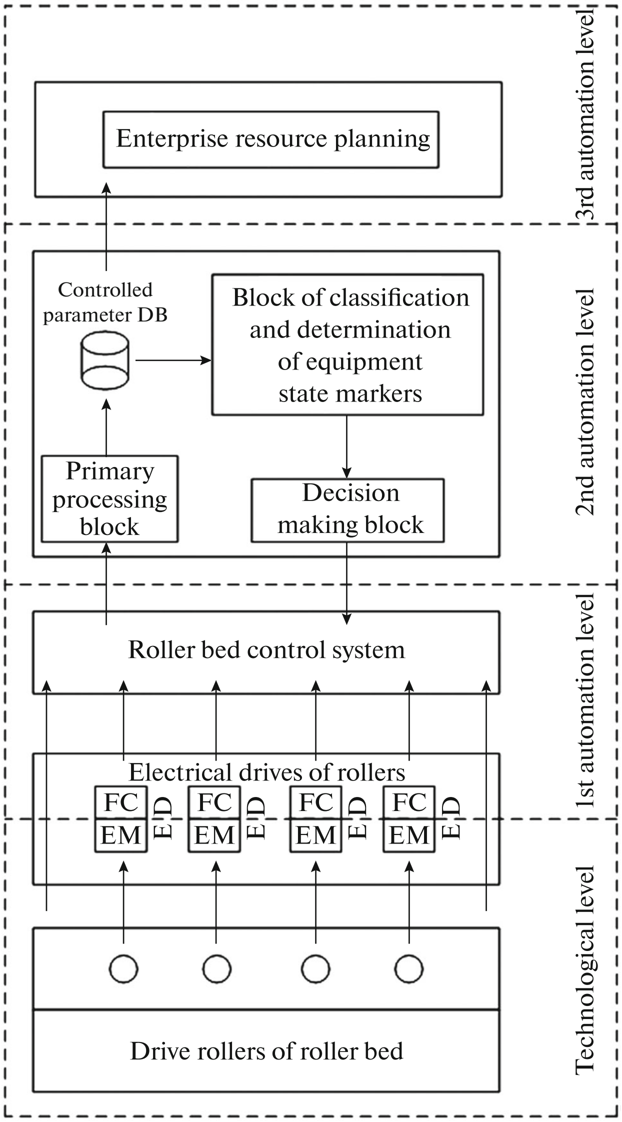

Fig. 2. Automation system of a grade 650 roller bed: EM is an electric motor; FC, frequency converter; ED, electrical drive; and DB, database.

Information on the current speed, the current, the voltage, and the moment of resistance on the motor shaft from a technological level is supplied to the system of controlling the electrical drives of the drive rollers in the roller bed. Information on the position of a slab and other technological data from sensors and actuators, which are necessary for accurate positioning, execution of technological operations, and fulfillment of safety requirements, is available for the control system of the roller bed. The data that are analogous to the information supplied from motors with allowance for filtration and estimation and transition from instantaneous to effective values are the parameters that are supplied from the control system of electrical drives to the control system of the roller bed [10].

Information on the state of drivers and slab position is transmitted to the next automation level, where it is processed and stored (see Fig. 2). Moreover, a decision about the possibility of energy saving is made using the “markers” of transition of electrical drives into the generator mode.

The current slab position is taken into account to predict the possibility of maintaining the generator mode and to estimate its characteristics, which is achieved with a decision making block.

The final analysis and prediction of the electric power cost are performed using information in a second-level automation database, which is transferred an enterprise resource planning system.

We used the methods of mathematical, computer, and physical simulation, including the development of an experimental setup for data acquisition and analysis, in order to support the possibility of energy saving using internal energy recuperation in a frequency-controlled asynchronous drive, as applied to a roller bed.

For computer simulation, we used the refined system of differential equations for an asynchronous electric motor that was developed in [6] and is presented below. A computer model of an electrical drive with an increased storage capacity in a dc link was developed in the Matlab Simulink system for the energy recuperation mode during slab deceleration (Figs. 3, 4). The simulation

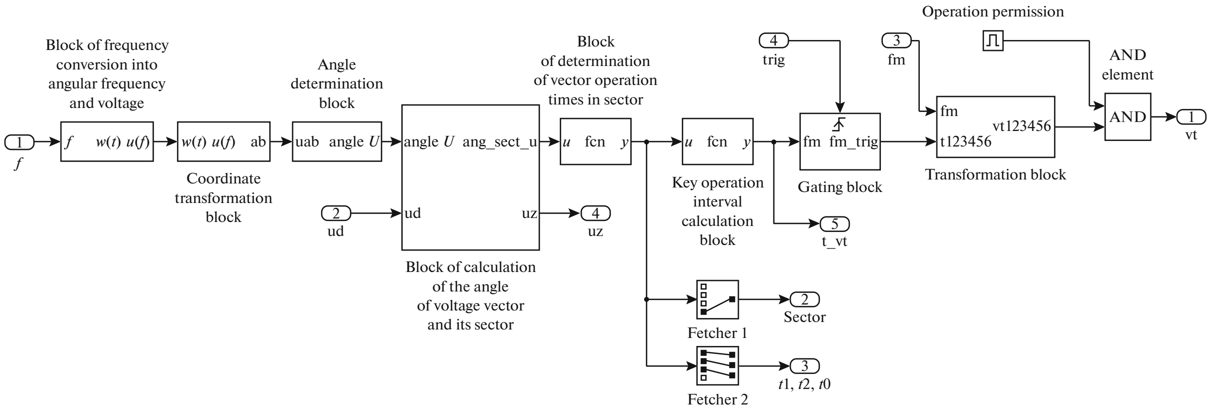

Fig. 3. General control system executing roller bed control algorithms.

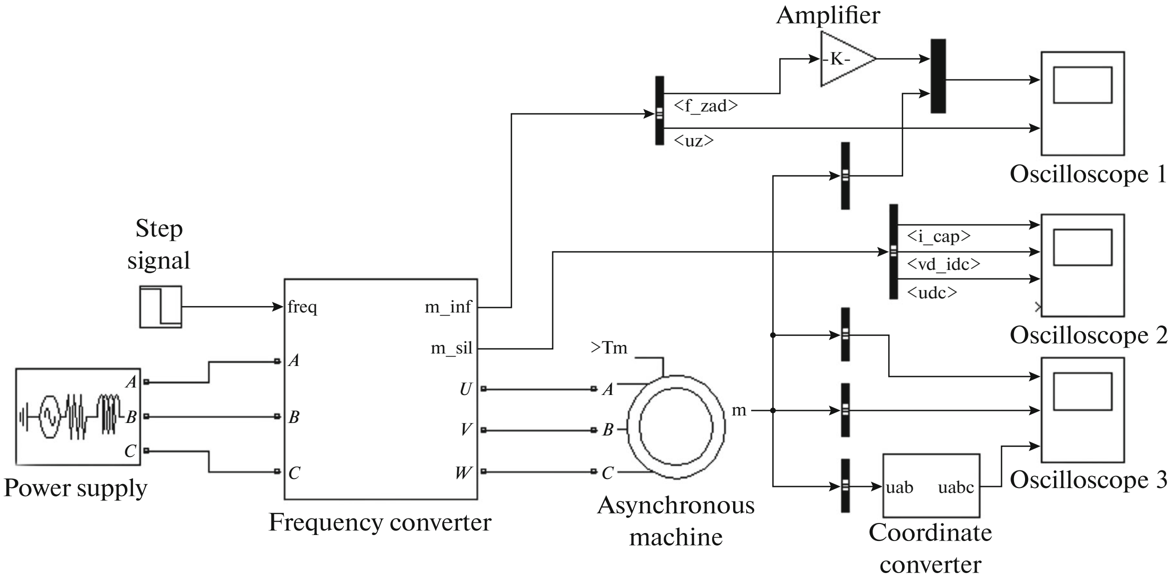

Fig. 4. General view of the model of the asynchronous electrical drive.

results are shown in Fig. 5. When a slab decelerates, the dc link voltage increases, which indicates the conversion of kinetic energy into electric energy and its accumulation. To estimate the energy conversion efficiency in the internal recuperation mode, we introduce a recuperation coefficient, which reflects the efficiency of conversion of one type of energy into another and simultaneously characterizes the energy losses during this conversion. The coefficient can be found as the ratio of the change in the electric energy to the change in the mechanical energy (see Eq. (3)),

$$\begin{gathered}
\begin{cases}
u_1 = R_1 i_1 + \sigma(\psi_\mu) L_1(\psi_\mu)\dfrac{d}{dt} i_1 \\
+ R_2 \dfrac{(L_\mu(\psi_\mu))^2}{L_2(\psi_\mu)^2} i_1 - R_2 \dfrac{L_\mu(\psi_\mu)}{L_2(\psi_\mu)^2}\psi_2 \\
+ \dfrac{L_\mu(\psi_\mu)}{L_2(\psi_\mu)} j\omega\psi_2; \\
0 = \dfrac{R_2}{L_2(\psi_\mu)}\psi_2 - \dfrac{R_2 L_\mu(\psi_\mu)}{L_2(\psi_\mu)} i_1 \\
+ \dfrac{d}{dt}\psi_2 - j\omega\psi_2; \\
M_{\text{em}} - M_{\text{r}} = J\dfrac{d}{dt}\omega,
\end{cases} \\
\psi_\mu = \frac{L_{\sigma 2} i_1 + \psi_2}{1 + \dfrac{L_{\sigma 2}}{L_\mu(\psi_\mu)}}; \\
\psi_1 = L_{\sigma 1} i_1 + \psi_\mu; \\
\sigma(\psi_\mu) = 1 - \frac{L_\mu(\psi_\mu)^2}{L_1(\psi_\mu) L_2(\psi_\mu)}; \\
M_{\text{em}} = \frac{3}{2} p_\tau \frac{L_\mu(\psi_\mu)}{L_2(\psi_\mu)} \operatorname{Im}(\bar{\Psi}_2^* \bar{I}_1).
\end{gathered} \tag{2}$$

Here, u_1 is the voltage applied to the stator winding; i_1 is the current in the stator winding; R_1 and R_2 are the stator and rotor winding resistances, respectively; L_1 and L_2 are the stator and rotor winding inductances, respectively; $L_{\sigma 1}$ and $L_{\sigma 2}$ are the leakage inductances of the stator and rotor winding, respectively; L_μ is the mutual inductance; ψ_μ is the flux linkage of the mutual inductance; ψ_1 and ψ_2 are the flux linkages of the stator and rotor winding, respectively; σ is the scattering coefficient; and p_τ is the number of pairs of asynchronous machine poles. We have

$$k_{\text{rec}} = \frac{\Delta W_{\text{el}}}{\Delta W_{\text{mec}}} = \frac{\dfrac{C}{2}\left|U_2^2 - U_1^2\right|}{\dfrac{J}{2}\left|\omega_2^2 - \omega_1^2\right|}, \tag{3}$$

where k_{rec} is the energy recuperation coefficient, ΔW_{el} is the change in the electric energy at the capacitor, ΔW_{mec} is the change in the mechanical energy at the electric motor shaft, C is the capacitor capacity, U_1 is the initial capacitor voltage, U_2 is the final capacitor voltage, ω_1 is the initial angular velocity of the electric motor, and ω_2 is the final angular velocity of the electric motor.

The authors of [8, 9] presented the results of the experimental investigations performed to determine the maximum possible recuperation coefficient for various voltages, control algorithms, and other conditions and recorded dependences to support the adequacy of the mathematical model. Figure 6 shows the storage voltage for the generator mode of an electrical drive. The discrepancy between the experimental and calculated data is at most 10%, which points to accuracy of the mathematical model. The recuperation coefficient calculated by Eq. (3) reaches 50%.

To estimate the decrease in the energy consumed by the system under study, we performed experimental

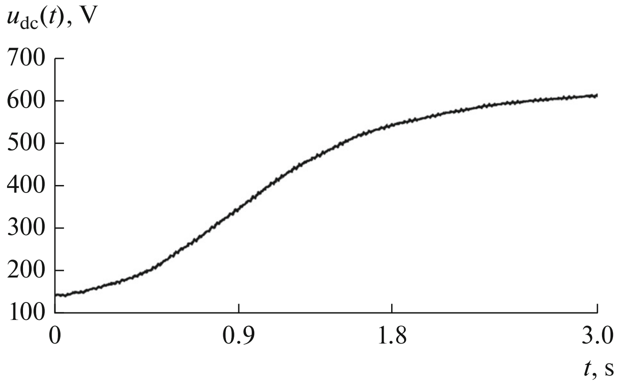

Fig. 5. Root-mean-square dc link voltage of the frequency converter obtained by computer simulation when the frequency changes from 50 to 30 Hz.

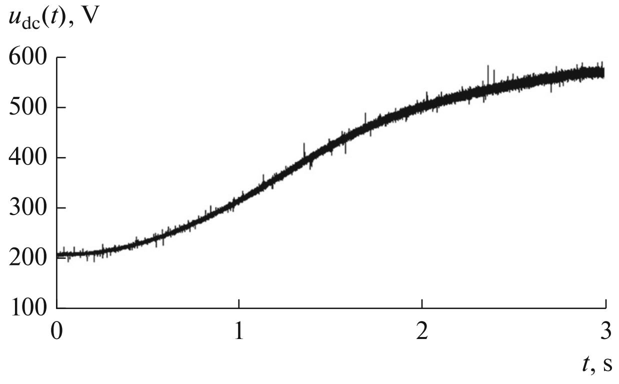

Fig. 6. Root-mean-square dc link voltage of the frequency converter obtained by physical modeling when the frequency changes from 50 to 30 Hz.

studies using an industrial computer-assisted frequency converter and calculation for the work sequence diagram shown in Fig. 2. To estimate the possible decrease in the energy consumed in a grade 650 roller bed, we calculated the energy consumption using the sequence diagram and the following formulas, which are valid under various conditions [8].

For steady conditions, we have

$$W_{\mathrm{el{\wedge}st}} = \sum_{j=0}^{N} \frac{M_{ri}\Omega}{\eta} t_i = 890\ \mathrm{kJ}, \qquad (4)$$

where M_{ri} is the moment of resistance at the electric motor shaft, Ω is the rate of electric motor rotation with allowance for sliding, η is the electric motor efficiency, and t_1 is the interval time.

For starts, we have

$$W_{\mathrm{el{\wedge}s}} = \frac{1}{\eta}\sum_{j=0}^{N} \frac{M_{\mathrm{sm}}}{M_{\mathrm{sm}} - M_{\mathrm{r}i}} J_i \frac{\Omega^2}{2} = 233\ \mathrm{kJ}, \qquad (5)$$

where M_{sm} is the start moment of the electric motor taken with allowance for limitations, M_{ri} is the moment of resistance at the electric motor shaft, Ω is the rate of electric motor rotation with allowance for sliding, η is the electric motor efficiency, and J_i is the moment of inertia applied to the motor shaft.

For deceleration (recuperation coefficient determined experimentally is used), we have

$$W_{\mathrm{el{\wedge}d}} = k_{\mathrm{rec}}\sum_{j=0}^{N} \frac{M_{\mathrm{dm}}}{M_{\mathrm{dm}} + M_{\mathrm{r}i}} J \frac{\Omega^2}{2} = 165\ \mathrm{kJ}, \qquad (6)$$

where M_{dm} is the deceleration moment of the electric motor taken with allowance for limitations.

Provided the deceleration energy accumulates and can be “repeatedly” used in the production cycle, the efficiency of the system under study is

$$ef = \frac{W_{\mathrm{el{\wedge}d}}}{W_{\mathrm{el{\wedge}st}} + W_{\mathrm{el{\wedge}s}}} \times 100\% = \frac{165}{233 + 890} \times 100\% = 15\%. \qquad (7)$$

To support the reliability of the calculation data, we simulated the following cycle during a physical experiment: drive acceleration, deceleration and operation under steady conditions for two different rates of rotation (analog of roller bed operation). The experiment was carried out at an increased equivalent moment of inertia to imitate the real mechanism. Readings were recorded for a connected brake resistor and in the absence of a brake resistor with in increased dc link capacitance. To estimate the consumed energy, we used the classical energy approach [5]. The energy was calculated by the formula

$$W_{\mathrm{el}} = \sum_{j=0}^{N} u_j i_j \Delta t, \qquad (8)$$

where Δt is the time interval between two recorded points.

An experimental bed was created to perform experiments in the laboratory of the Department of Control and Calculation Systems of Vologda State University. This bed implies the possibility of connection of either an external capacitance to the dc link or a brake resistor. The functional scheme of the experimental bed is shown in Fig. 7. To measure the electric circuit and the voltage, we used Hall sensors (Lem), which made it possible to broaden the frequency range of measurements and to increase the accuracy. An Lcard system was applied for data acquisition and transfer to a computer. The parameters of the measuring devices and their metrological characteristics with brief comments are given in Table 1.

When analyzing the metrological characteristics of the data acquisition system in current and voltage channels, we can state that the relative measurement error of the current channel is ±1.9% and that of the voltage channel is ±2.3%, which ensures the reliability of the obtained experimental data.

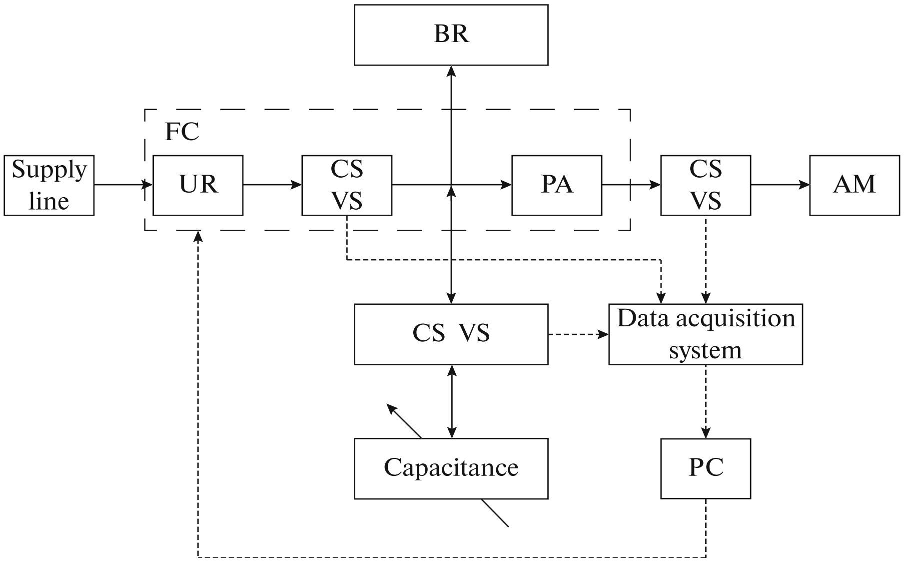

Fig. 7. Functional scheme of the experimental setup: FC stands for frequency converter; UR, for uncontrolled rectifier; PA, power assembly of transistors; CS, current sensor; VS, voltage sensor; AM, asynchronous machine; PC, personal computer; Capacitance, assembly of capacitors with a controlled capacity; and BR, brake resistor.

The parameters of the WD100LR asynchronous machine used in experiments are as follows:

Number of pairs of poles, p	2
Nominal voltage U_{nv}, V	220
Nominal current I_n, A	6.6
Nominal rate of shaft rotation n_n, rpm	1450
Moment of inertia J, kg m^2	0.011

The dependences recorded during experiments are shown in Fig. 8. Cyclic acceleration, deceleration, and rotation at a given rate were performed when frequencies were changed stepwise from 30 to 50 Hz during acceleration and from 50 to 30 Hz during deceleration. The voltage increases rather smoothly at the beginning of deceleration (from the 6th and 18th seconds) when the brake resistor is disconnected and a capacitor battery is connected (Fig. 8a). The voltage does not exceed a critical value for capacitors, since the capacitor capacity is chosen according to the energy to be taken by the capacitance, which was described in [6, 7]. After the end of deceleration (from 7.3 and 19.3 seconds), the voltage decreases, since the stored energy begins to be consumed for drive operation. An energy influx from the power main is absent, since the dc link voltage is higher than the voltage formed upon the rectification of the supply-line voltage, which is indicated by the absence of electric circuit in the supply main (see Fig. 8a).

As follows from the data presented in Fig. 8b, the dc link voltage begins to increase during deceleration (from the 6th and 18th seconds); and the input diode bridge is cut off, which is indicated by the absence of an electric circuit in the input circuit; and energy consumption from the supply main is ceased. When the voltage reaches about 800 V, “protection” is turned on: it connects the brake resistor and dissipates the deceleration energy in the resistance. The protection operate voltage is determined by the maximum voltage of the dc link capacitors. Even a qualitative estimation

Table 1. Metrological characteristics of measurement devices

Type	Description	Basic parameters	Metrological characteristics
LEM LA-100	Current sensor	$I = \pm 100$ A	Conversion accuracy ±0.45%
		$f \leq 100$ kHz	Nonlinearity <0.15%
LEM LV-25p	Voltage sensor	$U = \pm 1000$ V	Conversion accuracy ±0.8%
		$f \leq 20$ kHz	Nonlinearity <0.2%
Lcard L783M	Data acquisition system	$f_{discr} = 3$ MHz	Main reduced error 1%

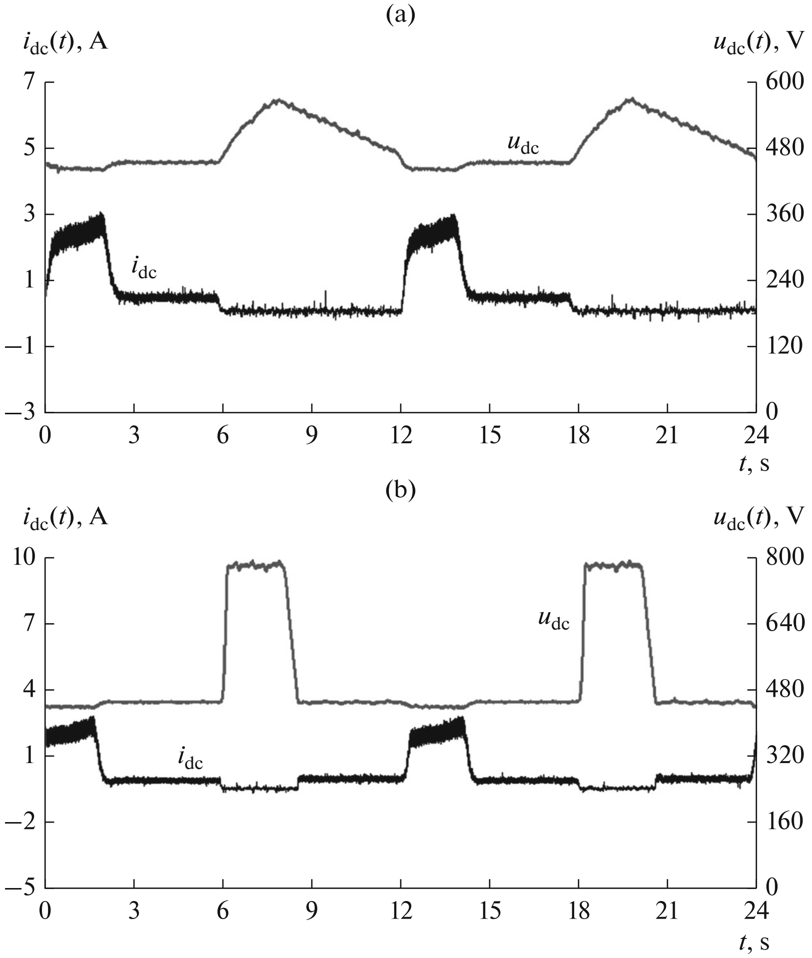

Fig. 8. Instantaneous dc link voltage and current in the frequency converter: (a) without a brake resistor with an increased capacitance and (b) with a brake resistor.

of the experimental curves demonstrates that the energy consumption is lower than in the case of using the brake resistor.

When the brake resistor is used, the quantitative energy consumption indices per mechanism operation cycle are calculated by an integral method using the expression

$$W_1 = \sum_{j=0}^{N} u_j i_j \Delta t = 5393 \text{ J} \tag{9}$$

(see Fig. 8a).

The quantitative energy consumption indices per mechanism operation cycle in the absence of the brake resistor with a connected increased capacitance are

$$W_2 = \sum_{j=0}^{N} u_j i_j \Delta t = 4497 \text{ J} \tag{10}$$

(see Fig. 8a).

The decrease in the energy consumption when external energy storage (capacitor) is used in comparison with the traditional energy drop across the brake resistor is

$$ef = \frac{W_1 - W_2}{W_1} \times 100\% \\ = \frac{5393 - 4497}{5393} \times 100\% = 16.7\%. \tag{11}$$

CONCLUSIONS

The proposed version of increasing the rolling efficiency is based on the use of a frequency-controlled asynchronous drive with an increased capacitor capacity in a dc link and ensures a significant decrease in the energy consumption for cyclic mechanisms with substantial equivalent momenta of inertia. The reliability of the obtained results was supported by the calculation data obtained using a mathematical model and the results of physical modeling on a developed experimental setup, which provided the investigation of energy circulation conditions on a technological level, including the conditions of internal energy recuperation in a frequency converter in the deceleration mode.

The decrease in the energy consumption for the electrical drives in a roller bed is about 17%. The decrease in the energy consumption of the entire rolling mill is about 1% if we do not take into account all other cyclic mechanisms and assume that they are not affected by the proposed energy-saving mechanism and the roller bed drive power accounts for 6% of the power of all rolling mill drives.

The integration of the elements of the proposed system into a general hierarchical automatic control system in an enterprise makes it possible to decrease the electric energy consumption in rolling and to provide potential possibility of predicting and planning the enterprise resources.

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