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PREVENTING THE DEVELOPMENT OF EMERGENCY MODES OF INTERLOCKED ELECTRIC DRIVES OF A ROLLING MILL UNDER THE IMPACT LOADS

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Abstract

In recent years, due to the tightening of competition in the global market of steel producers, the requirements for the quality of hot-rolled steel have increased. The finishing group of the rolling mill is characterized by a complex structure of mechanical and electrical parts. The operation of electric drive systems of such units is characterized by the interrelation of electromagnetic processes, mechanical phenomena and technological factors. As experimental studies have shown, the quality of the supply voltage is inextricably linked with the impact nature of the loads in the rolling stands of the roughing and finishing groups of the hot rolling mill. A decrease in the supply voltage may be accompanied by the development of emergency modes of synchronous electric drives, leading to a decrease in the quality of the finished product.The paper developed a mathematical model of the power supply system of the rolling mill JSC "ArcelorMittal Temirtau". It is shown that this can lead to loss of synchronism of the synchronous motor. Such a voltage drop has a significant impact on the operation of DC electric drives of the finishing group. Various strategies are proposed to counter the development of emergency situations.

Keywords: power supply network, voltage drops, electric drive, hot rolling mill, mathematical and simulation modeling

1. INTRODUCTION

Metallurgy is one of the industries in which the issues of production automation and control are traditionally of key importance in solving problems of increasing production efficiency and ensuring product quality. For most metallurgical machines and units, the following features are characteristic: a significant length of equipment involved in a single technological process; a wide range of technological characteristics of equipment - speeds up to several tens of m/s, unit capacities of individual units up to several thousand kW, technological power loads up to several tens of MN; high requirements for the accuracy of maintaining technological parameters; difficult and very difficult working conditions (shock loads, high vibration, high gas and dust content of the environment, operation of equipment with duty cycle close to 100%, in many cases continuous operation of equipment); strict requirements for the reliability and non-failure operation of the equipment [1]. In the complex of the metallurgical industry, rolling production is of particular interest, which, in the face of growing requirements for the quality of products, requires the development, development and implementation of modern technologies and techniques that allow increasing not only the volume of products, but also its quality.

In their papers, the authors [2-5] reveal the main problems of power supply for metallurgical enterprises, the possibility of improving the stability and efficiency of the electrical equipment of metallurgical units, the issues of reactive power compensation and the need to ensure the electromagnetic compatibility of powerful nonlinear loads, including electric arc furnaces and rolling mills.

An analysis of the causes of impact loads, the degree of their influence and possible technical solutions to reduce dynamic moments in the mode of sharply variable loads are most detailed in the papers of the authors [6-14]. However, the technical solutions they offer do not sufficiently solve the existing problems, and for many enterprises they are generally unacceptable, since they require large material investments [15-18].

The work of metallurgical enterprises in the mode of a sharp dependence of a significant impact on the quality of electricity [19-21]. Investigation of possible ways to maintain power quality indicators within a possible path for modeling power supply systems of metallurgical enterprises using MATLAB/Simulink modeling software packages [22-25].

2. FORMULATION OF THE PROBLEM

A feature of the powerful interconnected electric drives of the rolling mill is the connection through the power supply system. Known scientific papers devoted to solving this problem mainly consider only the operating modes and the mutual influence of interconnected electric drives through a rolled metal strip.

The purpose of this paper is to study electromagnetically connected by means of a power supply network of powerful electric drives of a rolling mill, to establish the nature and numerical values of such mutual influence. To achieve this goal, it is necessary to solve the following tasks:

1) To develop a mathematical model of a system of interconnected electric drives of a hot rolling mill;
2) To develop methods for compensating the influence of synchronous electric drives of the roughing group on the stability of the operation of the electric drive of the finishing group and justify the most appropriate of them;
3) To obtain numerical estimates of the results of using the proposed method for improving the stability of the electric drive of the finishing group.

3. MATERIALS AND RESEARCH METHODS

The rolling production of JSC "ArcelorMittal Temirtau" includes a hot-rolling shop, two cold-rolling shops, a hot-dip galvanizing and aluminizing shop, and a polymer coating line.

In the metallurgical cycle of JSC "ArcelorMittal Temirtau", sheet rolling shop # 1 is intended for the production of hot rolled products. The workshop operates a 1700 continuous wide strip hot rolling mill with five roughing and seven finishing stands, several cutting units and a spar strip unit. Rolling takes place on the production line of the 1700 mill, that, in turn, is divided into five zones: the loading section, the heating furnace section, the roughing, finishing groups of stands, and the harvesting line of the mill [26, 27]. The roughing group of the mill consists of a series of vertical stands, a horizontal duo descaler, the first working stand "quatro" and four working universal stands #2-#5 with vertical rolls (edgers).

The layout of the rolling stands in the section of the roughing group is shown in Fig. 1. The finishing group of stands consists of an intermediate roller table with a pocket and a slatted roll ejector, flying shears, a “duo” finishing descaler and seven “quatro” stands #6-#12.

The harvesting line of the mill consists of a discharge roller table with showering devices, pulling rollers, three hot strip coilers with puller trolleys, tilters, bale receivers and bale conveyors with turntables. Furnaces are designed for heating slabs before rolling. The electric drive of the work rolls of the roughing group stands is carried out from a synchronous AC motor with a power of 4200 kW.

Seven continuously located finishing stands "quarto" #6 - #12 are designed for rolling rolls into strips of a given thickness. The electric drive of the work rolls is carried out from a DC motor of independent excitation with a power of 3150 kW for stand #6 and 3600 kW for the rest of the stands. Winders are designed for winding the strip into rolls. As a result of rolling through the finishing group of mill 1700, we obtain a finished strip with a thickness of 1.5 mm to 14 mm and a width of 650 mm to 1600 mm [26].

In the rolling mode in the stands, when the rolls grip the rolled metal strip, shock loads occur. The resulting dynamic shocks have a negative impact on the operation of electromechanical equipment, which leads to increased wear of the work and backup rolls of rolling stands, failure of electrical and hydraulic equipment, accidents of various typologies, and an increase in the end trim of the metal. All this leads to an increase in the defectiveness of hot rolled products, a decrease in the productivity of the rolling mill, an increase in the cost of products, etc. [27]. The fundamental factors that determine the level of impact loads during the gripping of the metal by the rolls are the rolling speed, the temperature and shape of the front end of the strip, the beating of the elastic forces and the angular gaps in the joints. Studies of dynamic loads during rolling of thick strips on single-stand hot rolling mills have shown that under shock loads, the dynamic torque developed by the main electric drive can exceed the steady rolling torque by 1.5…2 times [28, 29].

The solution to this problem is complicated by the fact that the software for the process of the mill is not available, which makes it difficult to explain the causes of such emergencies. Thus, this reduces the productivity of the mill, and consequently, the profit of the enterprise as a whole. Significant energy intensity of rolling production imposes increased requirements for the organization of reliable, rational modes of operation of the power supply system (PSS).

In the context of a shortage of energy resources, the dynamics of the outstripping growth of electricity tariffs, the economic efficiency of

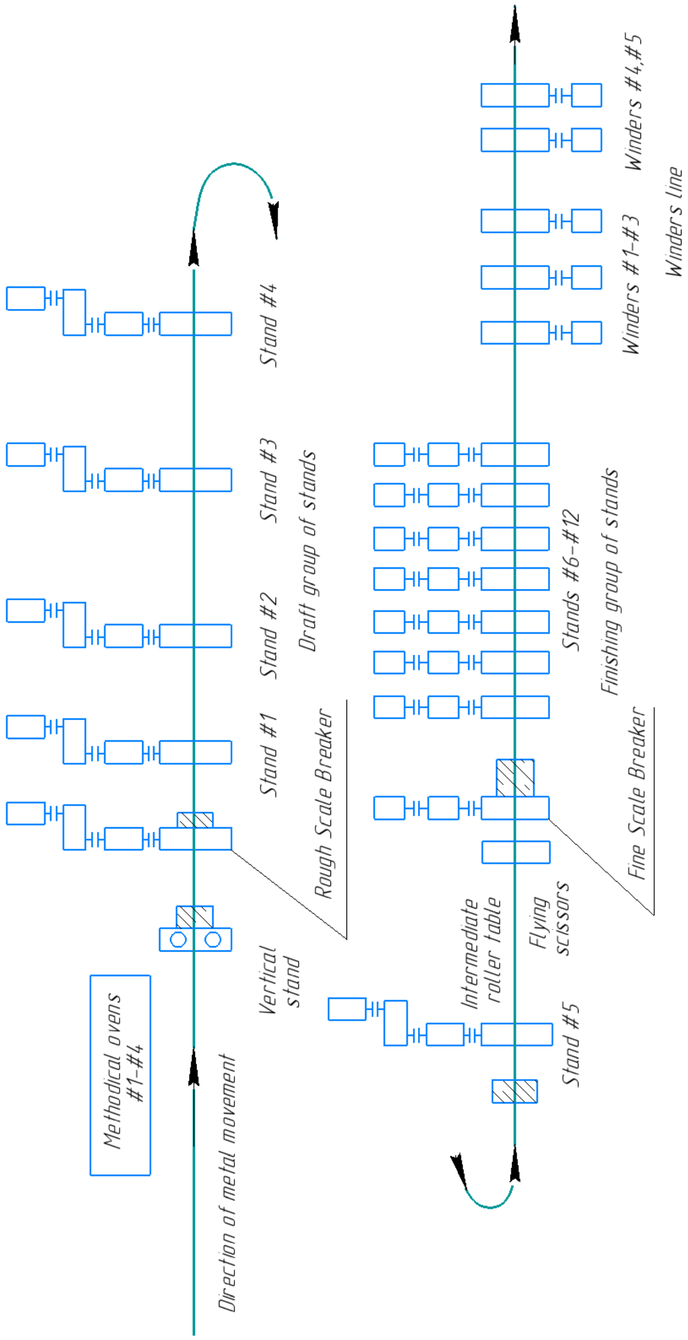


Fig. 1. Layout of the rolling stands in the rolling line

introducing energy-saving measures that ensure the optimization of the energy-intensive technological process of metal rolling and power consumption modes, increasing the profitability of production, and the competitiveness of products [30-32] is indisputable.

The work of rolling production is characterized by shock loads. For the effective functioning of the power supply system, it is necessary to have a certain power reserve. This will ensure a minimum level of fluctuations in the mains voltage.

The hot-rolled production is supplied with power from the power system at a voltage of 110 kV according to the scheme shown in Fig. 2.

Mill 1700 is supplied with power from a two-transformer main step-down substation MSDS-1A 110/10kV through substation #6 with a voltage of 10kV. The main load of the main step-down substation is the rolling stands of the mill.

The secondary windings of 10 kV of these dynamically stable transformers type *TRDNM* - 63000/110/10 form a two-section switchgear, from which four sections of 10 kV of substation #6 of the hot rolling mill 1700 are powered.

The substations of the auxiliary machinery of the mill, as well as a number of other technological areas, are also connected to the 10 kV MSDS busbar sections.

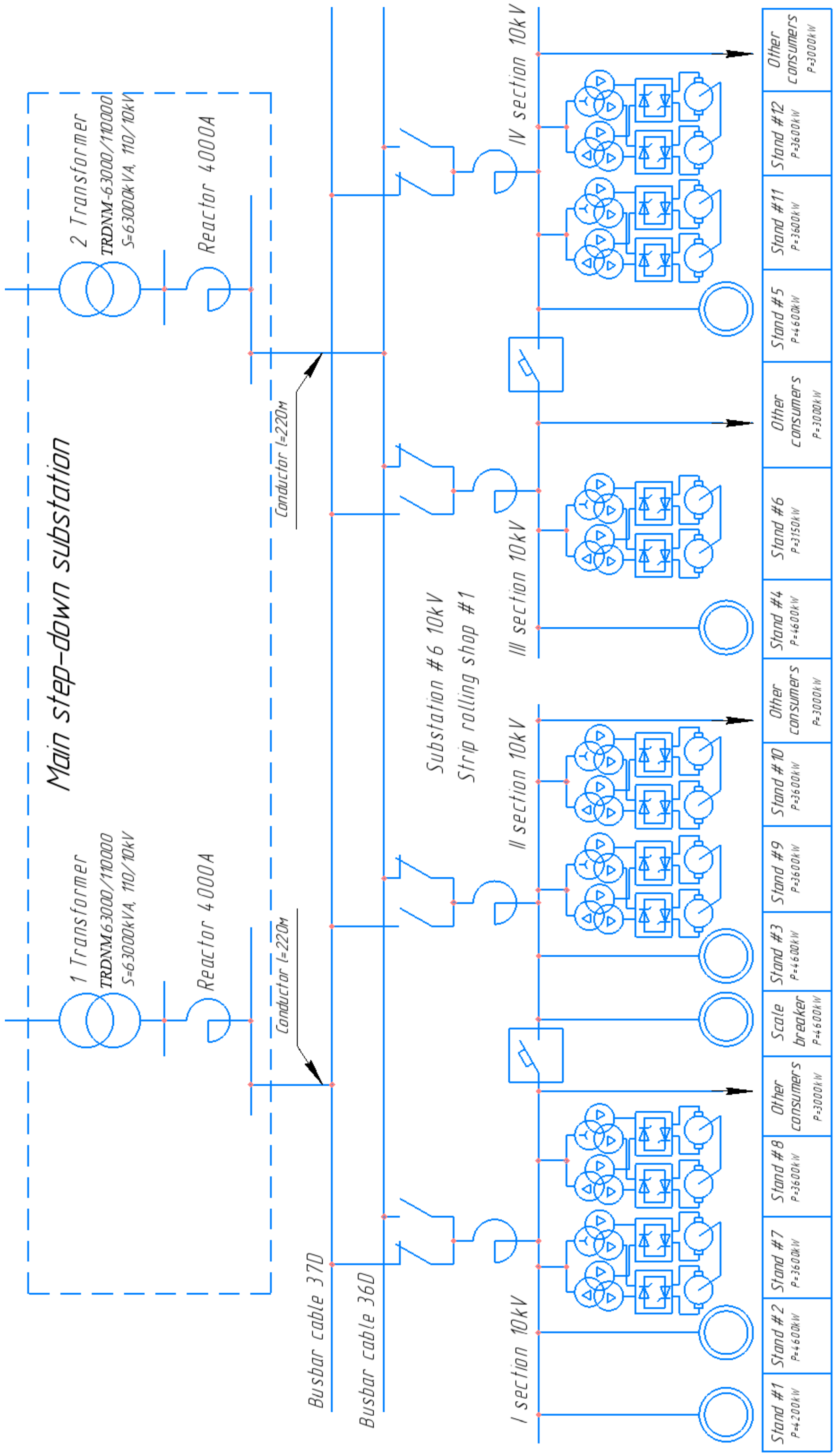


Fig. 2. Scheme of power supply of the mill 1700

A feature of the power supply system of the hot rolling mill 1700 in terms of reactive power compensation is:

1) To the buses of each 10 kV section, together with thyristor DC electric drives of the finishing group, at least one synchronous electric drive of roughing stands is connected.
2) The range of rolled strips determines the load on the stands, the range of their change is predictable.
3) The peak power of the operating main drives (variable component) and the power of auxiliary units (conditional-constant component) determine the loads in 10 kV sections.
4) Schemes for connecting thyristor converters (TC) and synchronous motors of the stands basically allow for reactive power compensation by stepwise switching on of capacitor banks and smooth control of the excitation current of the synchronous motor.

The negative impact of high-power thyristor converter units of the mill stands on the supply network, manifested in network voltage dips and generation of current harmonics, affects the stability of the modes of all other power consumers connected to the MSDS electrical network area. There are failures in the operation of the aluminizing units and the pipe shop. The impact on the supply network, exerted by the mill through shock load surges, the generation of harmonic current by the converter units of the finishing stands of the mill, negatively affects the quality of electricity, causing deep voltage dips in the network, a significant distortion of the voltage curve. Voltage dips in the 10 kV network during rolling are shown in Fig. 3 [33, 34, 35].

Due to the significant level of reactive power consumed and, as a result, the current, at present, due to the rolling of energy-intensive profiles, it is not possible to implement the power supply modes provided for by the design scheme simultaneously for two bus sections (switching on a 10 kV sectional switch) by one input.

When performing the work, the analysis and systematization of literature data made it possible to identify the existing problem of the influence of power supply voltage dips both on the quality of finished products and on the operation of the entire technocenosis of hot rolling mills.

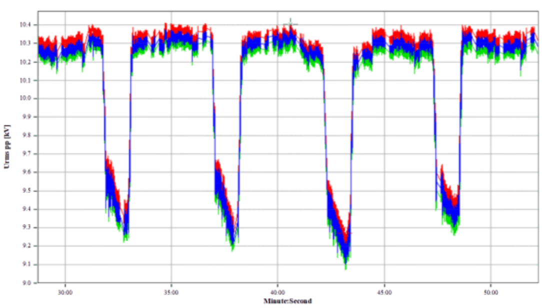


Fig. 3. Voltage dips in the network 10 kV during rolling

The methods of observation and measurement used for the power supply system of the 1700 mill, on the basis of which an analysis of its work was carried out and conclusions were drawn about the mutual influence of the electric drives of the mill and the power supply system, made it possible to construct a hypothesis about a voltage decrease of about 10% when metal enters the roughing and finishing stands of the mill. Further, using the methods of generalization and synthesis, mathematical and simulation models of the power supply system of the mill were built and computer simulation was carried out. The used static methods of analysis and interpretation of empirical data, comparison of the results of simulation modeling and experimentally obtained diagrams of the power supply system confirmed the hypothesis put forward and made it possible to propose a solution to the existing problem.

4. MODELING

To develop a mathematical model of the electromechanical system of the 1700 hot rolling mill, Fig. 2, the MATLAB/Simulink program with the SimPower Systems library was used. This library contains elements of the main devices that form the system under study, allows you to configure the parameters of individual elements and their connection schemes.

When modeling a synchronous machine, the following assumptions were made:

- the magnetic field in the gap is considered as plane-parallel;
- the magnetic axis of the excitation winding coincides with the longitudinal axis of the machine;
- magnetic axes of phase windings are shifted by $2\pi/3$; neglect the fields of higher harmonics and the moments from these fields;
- the influence of eddy currents and hysteresis is not taken into account;
- influence of saturation is not taken into account;
- stator phase windings are symmetrical.

When modeling a DC motor, the following assumptions were made:

- we neglect the saturation value both along the contour of the main magnetic flux and along the scattering contour;
- we do not take into account the influence of the eddy current circuit;
- the machine is fully compensated, that is, there is no influence of the armature reaction.

4.1. Mathematical modeling of the synchronous motor of the draft group

As a drive synchronous motor, an SDSZ-17-64-6UHL4 type motor with the following technical characteristics was adopted: rated power 4000 kW, voltage 10000 V, rotation speed 1000 rpm, efficiency 95.1%. The synchronous motor model implemented in MATLAB is shown in Fig. 4.

To confirm the reliability of the proposed model, we present the results of calculating the process of asynchronous start-up, synchronization and load surge on the shaft of a synchronous motor, shown in Fig. 5.

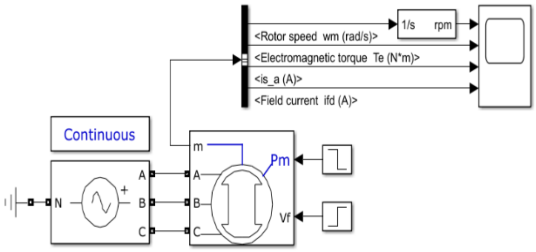


Fig. 4. Implementation of the synchronous motor model in MATLAB

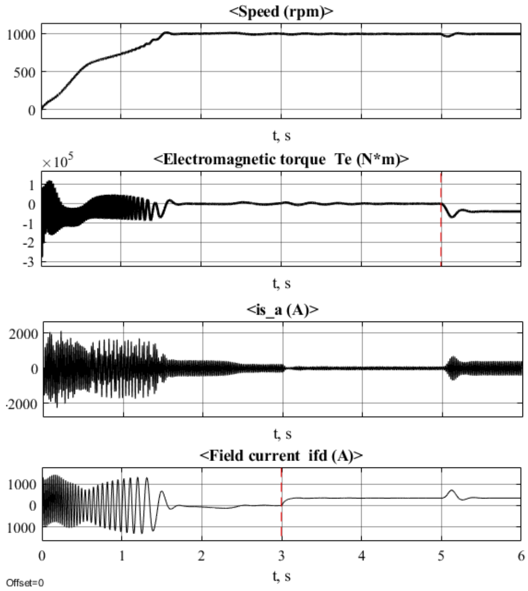


Fig. 5. Dynamic processes of asynchronous start, synchronization (t = 3s) and load surge (t=5s) on the shaft of a synchronous motor

The given graphs coincide with theoretical ideas about dynamic processes in synchronous motors. The numerical values of the rotational speed and stator current coincide with the passport values. All this confirms the adequacy of the proposed model of a synchronous motor.

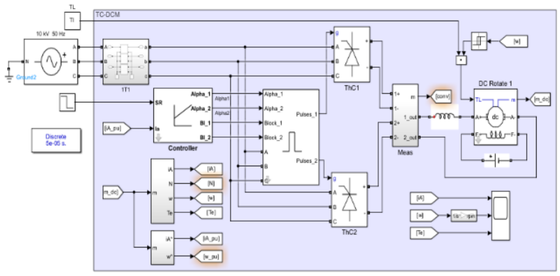
4.2. Mathematical modeling of the DC electric drive of the finishing group

A reversible thyristor direct current electric drive is currently used as an electric drive for the finishing group stands. As a DC drive motor, a P2-630-215-8S type motor with the following technical characteristics was adopted: rated power 3150 kW; armature voltage 750 V; rotation speed 150 rpm; efficiency 92.5%

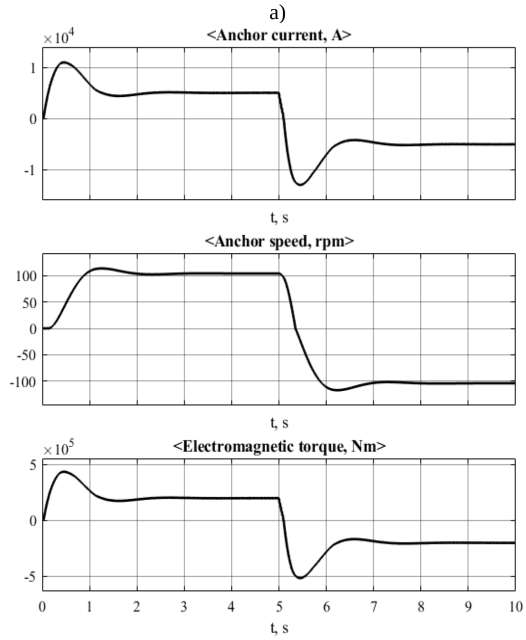
The proposed implementation of the mathematical model of a reversible thyristor DC electric drive is shown in Figure 6,a, the results of modeling the process of starting and reversing the electric drive are shown in Fig. 6, b.

4.3. Mathematical modeling of shop power supply system of hot rolling mill 1700

Based on the models of electric drives proposed above, a model of the 1700 mill power supply system was developed, shown in Fig. 7.



a)



b)

Fig. 6. Mathematical modeling of a reversible thyristor direct current electric drive: a) - implementation of the model; b) - diagrams of the process of starting and reversing the electric drive

The structure of this model corresponds to the power supply scheme of the 1700 mill, Fig. 2. The model is supplemented with elements that take into account the presence of power transformers and current-limiting reactors.

However, the practical use of this model is limited not only by its complexity. To obtain adequate research results, this model should be supplemented with equations that determine the mechanical relationships that arise between the electric drives of the finishing group during sheet rolling. It is also quite a difficult task to model the probabilistic nature of the loads in the workshop power supply system. In accordance with the purpose of this study, it is permissible to neglect the influence of the mechanical interconnection of the electric drives of the finishing group. This allows you to significantly simplify the model of the studied power supply unit. We will assume that only one synchronous motor and one direct current electric drive operate in the investigated node of the power

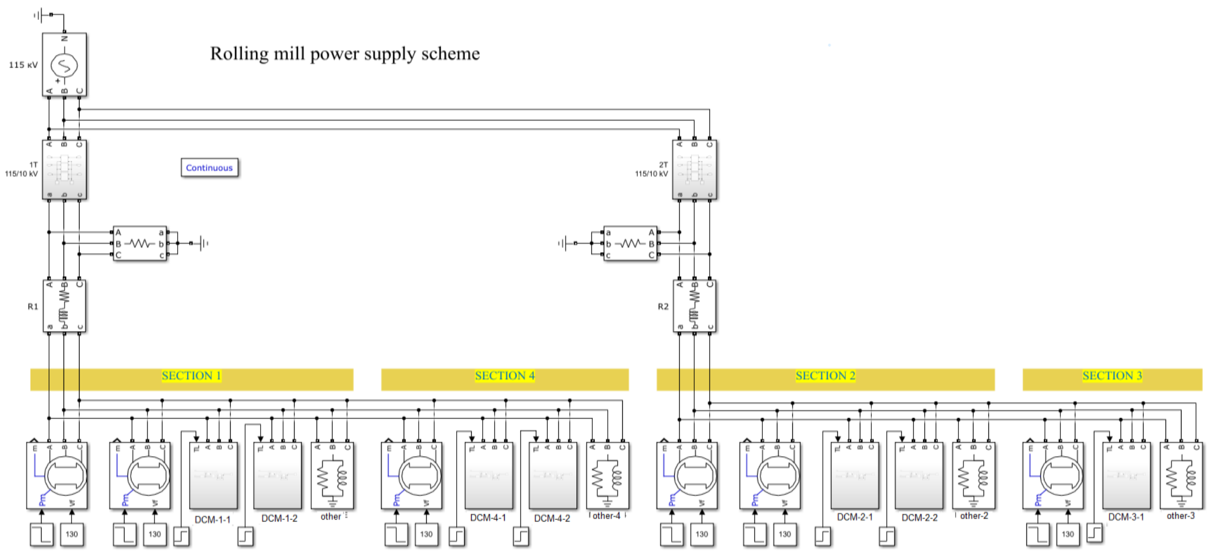


Fig. 7. Model of the 1700 mill power supply system

supply system. Other power equipment (power transformers, current-limiting reactors) are not changed.

The resulting simplified model of the power supply unit is shown in Fig. 8. This model allows you to study both the operation of a synchronous motor with a shock load on the shaft, and the impact of shock loads on the operation of a DC electric drive.

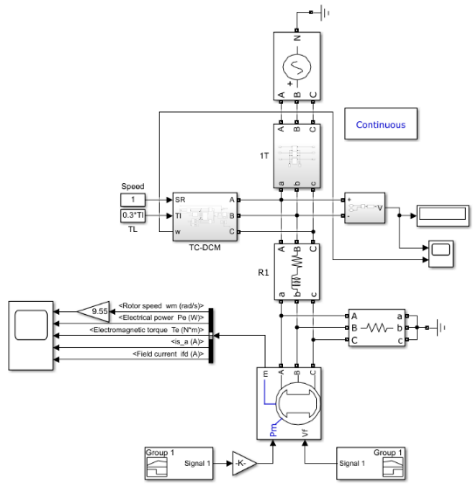


Fig. 8. Mathematical model of the simplified power supply unit of the rolling mill 1700

In accordance with the results of experimental studies presented in Figure 3, the duration of the shock load that is applied to the shaft of a synchronous motor is approximately 2 s. However, slight deviations in the magnitude of the load on the shaft can lead to dramatic changes in the operating modes of a synchronous motor.

Fig. 9 (a) shows graphs of the dynamic modes of operation of a synchronous motor with a rated shock load applied at the time t=8 s.

Fig. 9,b shows similar graphs for the operation of a synchronous motor with an increase in load of only 2.5% of the nominal. Fig. 9,b shows a synchronous

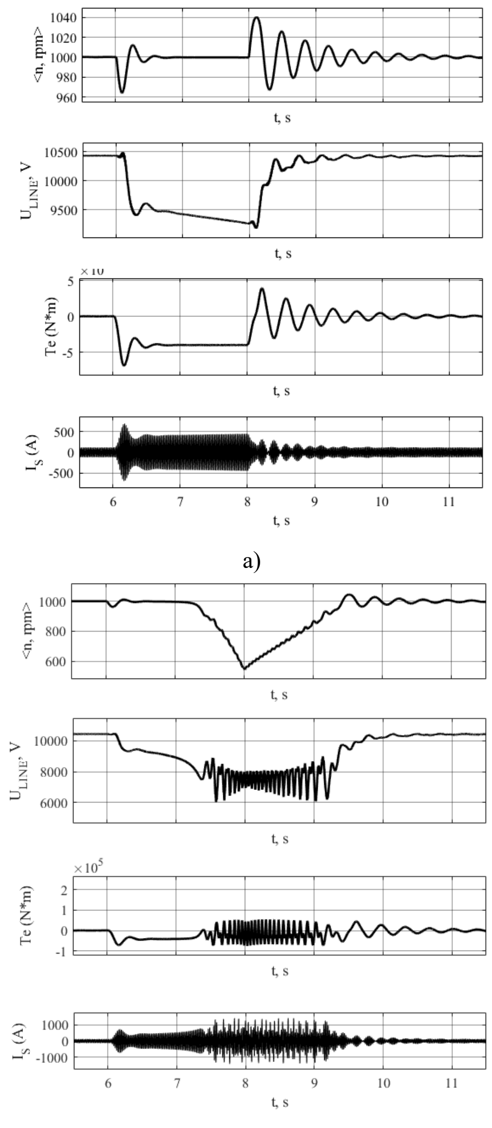


Fig. 9. Dynamic modes of operation of a synchronous motor with a shock load: a – $T_L = T_{Lrated}$; b - $T_L = 1.025 \cdot T_{Lrated}$

motor falling out of synchronism. However, in fig. 9, a we observe the development of this emergency process. This is manifested in an increase in the armature current and a slow decrease in the mains voltage. A synchronous motor does not fall out of synchronism just because of a load shedding. The graph of the change in the supply voltage in Fig. 9,a coincides quite accurately with the results of experimental studies presented in Fig. 3.

Let us consider the effect of shock loads of a synchronous motor on the operation of DC electric drives of the finishing group. Fig.10 shows graphs of changes in the supply voltage and the angular velocity of the DC electric drive of the finishing group under the impact load of a synchronous motor.

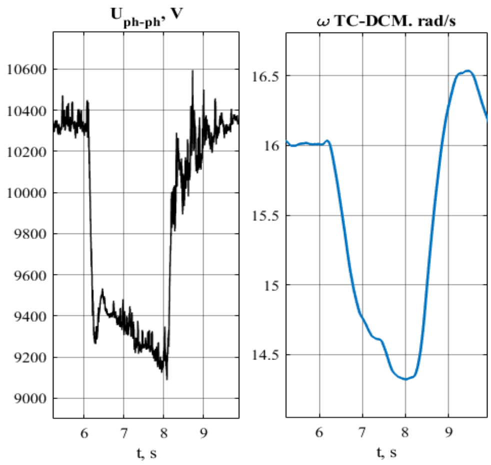


Fig. 10. Results of mathematical modeling of the operation of a DC electric drive under shock loads of a synchronous motor

The result obtained quite accurately coincides with the results of an experimental study of the quality of the supply voltage, shown in Figure 3. The deviation of the results of mathematical modeling is no more than 5%. The drop in the angular velocity of the DC electric drive in this case was 1.6 rad/s, which was 10% of the steady-state speed. Such a significant drop in the angular velocity can significantly affect the quality of processing of hot-rolled sheet steel.

Mathematical modeling of the dynamic modes of a synchronous motor is performed without taking into account the saturation of steel. An additional study found that the effect of this phenomenon on the magnitude of the change in the angular velocity of the DC electric drive of the finishing group is within 0.5%. Therefore, such an assumption is admissible.

Based on the well-known theoretical concepts of the operation of a DC electric drive, several different strategies can be proposed to improve the stability of the angular velocity of an DC electric drive:

1. The use of a closed system for stabilizing the angular velocity. This most obvious method cannot be applied under the conditions of a hot rolling mill, since electric drives in the rolling mode form a multi-motors electromechanical system with a rather complex structure of the control object.
2. Impact on the speed by weakening the magnetic flux of the DC motor. The application of this approach is hampered not only by the circumstances mentioned above, but also by the significant inertia of the excitation winding.
3. Impact on the speed by overexciting the synchronous motor for the period of billet rolling. Overexcitation of a synchronous motor leads to an increase in voltage in the load node and directly affects the main reason for the drop in the angular velocity of the finishing group electric drives. It is this method that seems to be the best, since this effect simultaneously affects all DC electric drives connected to the load node. In addition, this improves the working conditions of other mechanisms and processes of the rolling mill technocenosis. An additional advantage of this solution is the low installed power of the synchronous motor exciter. The signal to control the excitation of the DC motor can be obtained using a photo sensor mounted on the receiving roller tables directly in front of the stand. A certain difficulty is created by the inertia of the excitation winding of a synchronous motor.

To establish the nature of the influence of overexcitation of a synchronous motor on the performance of the power supply unit and the electric drive of the finishing group, an experiment planning method was applied. The following values were chosen as factors influencing the outcome of the experiment: the voltage value of the excitation winding of the synchronous motor for the period of billet rolling in the roughing group U_f and the duration of the mismatch between the supply of increased voltage to the excitation winding and the start of billet rolling Δt, Fig. 11.

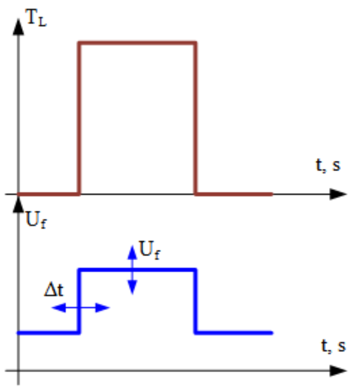


Fig. 11. Determination of the factors of a two-factor experiment to study the effect of overexcitation of a synchronous motor

As experimental responses, we register the minimum voltage at the power supply terminals ΔU and the drop in the angular velocity of the electric drive of the finishing group Δω.

The table of the performed two-factor experiment is shown in Table 1.

The results of the two-factor experiment were processed using the STATGRAHICS program.

As a result of processing the experimental data obtained on the mathematical model, a regression model was obtained for the dependence of the voltage drop of the supply network ΔU on the excitation voltage of the synchronous motor Uf and the mismatch value Δt in the form of a second-order equation:

$$\Delta U\left(Uf,dt\right)=\begin{pmatrix}88.943-1.0155\cdot Uf-6,994\cdot dt+\\+0.00293\cdot Uf^{2}+0,0438\cdot Uf\cdot dt+\\+5.116093\cdot dt^{2}\end{pmatrix},(1)$$

Table 1. Two-factor experiment to study the effect of overexcitation of a synchronous motor

	Factors				Responses	
#	X1	X2	Uf, V	dt, c	dU, %	dw, %
1	0.707	0.707	174.14	0.707	5.99	6.19
2	-0.707	0.707	145.86	0.707	4.50	7.94
3	0.707	-0.707	174.14	-0.707	4.93	6.19
4	-0.707	-0.707	145.86	-0.707	5.19	7.69
5	-1	0	140	0	5.57	7.62
6	1	0	180	0	-1.60	-2.19
7	0	1	160	1	5.86	8.06
8	0	-1	160	-1	6.09	7.24
9	0	0	160	0	1.40	3.40

The response surface calculated by this equation is shown in Fig. 12.

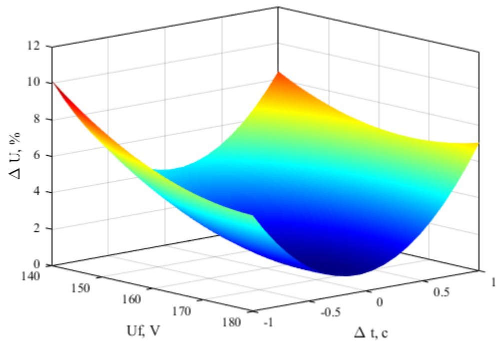


Fig. 12. Response surface for the dependence of the supply voltage drop $\Delta U\left(Uf,dt\right)$

As a result of processing the experimental data obtained on the mathematical model, a regression model was obtained for the dependence of the angular velocity drop of the finishing group electric drive Δω on the excitation voltage of the synchronous motor Uf and the mismatch value Δt in the form of a second-order equation:

$$\Delta\omega\left(Uf,dt\right)=\begin{pmatrix}41.967-0.3307\cdot Uf+1.2495\cdot dt+\\+0.00056\cdot Uf^{2}-0.00625\cdot Uf\cdot dt+\\+5.1592\cdot dt^{2}\end{pmatrix},(2)$$

The response surface calculated by this equation is shown in Fig. 13.

As the analysis of the results of experimental studies shows, an increase in the level of excitation of a synchronous motor leads to a decrease in the voltage drop in the power supply unit and an increase in the stability of the angular velocity of the DC electric drive. The best results can be obtained at zero mismatch Δt, that is, when the signal for forcing excitation of the synchronous motor is applied directly at the moment the billet enters the rolls of the rolling stand. This result is explained by the fact that the increase in the stator current and the resulting decrease in the supply voltage does not occur instantly. And the inertia of the process of changing the stator current of a synchronous motor is commensurate with the inertia of the excitation winding.

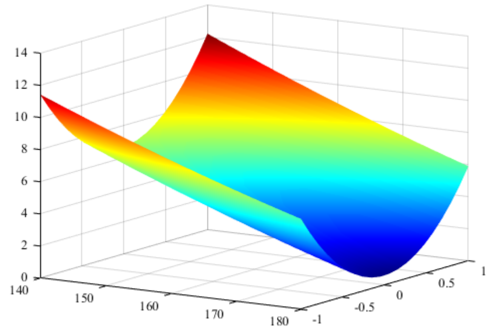


Fig. 13. Response surface for the dependence of the angular velocity drop of the electric drive $\Delta\omega\left(Uf,dt\right)$

5. RESULTS

To study the effect of sharply variable loads of electric drives of the roughing group on the quality of the supply voltage and the operation of the electric drives of the finishing group of the rolling mill, a complete, Fig. 7, and simplified, Fig. 8, a, model of the power supply unit of the rolling mill has been developed. The adequacy of this model is confirmed by the coincidence of the simulation results, Fig. 9, b, with experimental studies of the quality of the supply voltage, Fig. 3. It is shown that the voltage drop of the supply network caused by the impact load of a synchronous motor can reach 8–10% of the nominal value. The resulting decrease in the angular velocity of the electric drives of the finishing group can reach up to 10% of the steady-state speed. To improve the stability of the angular velocity of the electric drives of the finishing group, three different strategies for controlling the electromechanical equipment of a rolling mill are proposed. The expediency of using the forcing of the synchronous motor of the roughing group for the duration of the billet crimping is substantiated.

Using the methods of planning the experiment, it was found that the best results can be obtained with a zero mismatch Δt, that is, when the signal for forcing the excitation of the synchronous motor is applied directly at the moment the billet enters the rolls of the rolling stand. The magnitude of the excitation forcing should be the maximum possible.

6. DISCUSSION

The limitation of this study is that the complex of studies was carried out on a simplified model of the electromechanical system of a rolling mill. The effect of a possible deviation of the angular velocity of the electric drive of the finishing group on the quality of the finished product of the rolling mill is not shown.

The disadvantage of this study is that the upper allowable limit for forcing the excitation of a synchronous motor has not been established. Determining the maximum allowable level of forcing a synchronous motor is possible with a more detailed analysis of the thermal conditions of a synchronous motor during forcing. The advantage of the proposed solution in comparison with the closed excitation control system of a synchronous motor is not substantiated. The use of such a control system can potentially significantly reduce the inertia of electromagnetic processes in the excitation winding and provide higher stability indicators for the operation of electric drives of the finishing group.

The development of this research may consist in the development of a mathematical model of the finishing group of a rolling mill as a multi-motor and multi-coupled electromechanical system and an assessment of the impact loads on the quality of rolled products. Another area of research is an in-depth study of the thermal regimes of a synchronous motor during excitation forcing.

7. CONCLUSION

1. The developed mathematical model of the system of electrically interconnected electric drives of the roughing and finishing group of the rolling mill made it possible to establish the numerical characteristics of the impact loads of a synchronous motor on the quality indicators of the supply voltage and the stability of the angular velocity of the electric drives of the finishing group.
2. A method is proposed for preventing the development of emergency situations in electric drives of a hot rolling mill by forcing the excitation of the synchronous motor for the rolling period. This allows not only to increase the stability of the electric drive of the finishing group, but also to improve the working conditions of the entire technocenosis of the rolling mill.
3. The studies of the influence of the process of forcing a synchronous motor, carried out using the methods of planning an experiment, made it possible to obtain regression equations for the dependences of the voltage drop of the supply network and the stability of the angular velocity on the influencing factors. The best performance can be obtained by forcing the excitation of the synchronous motor directly at the moment the billet enters the rolls of the rolling stand.
4. The development of this research may consist in the development of a mathematical model of the finishing group of a rolling mill as a multi-motor and multi-coupled electromechanical system and an assessment of the impact loads on the quality of rolled products.

Another area of research is an in-depth study of the thermal regimes of a synchronous motor during excitation forcing.

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