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Electric drive excitation control for improved performance of hot rolling mill finishing groups

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The study presented in the paper investigates rigorously the methods for enhancing the performance of interconnected electric drives within the finishing group of a hot rolling mill. In particular, it examines the impact of supply voltage fluctuations on drive precision and the interactions mediated by the rolled metal strip. A detailed analysis of the existing power supply system identifies the primary causes of dynamic deviations in drive operation.

A combined angular velocity control system is proposed to regulate the excitation of DC electric motors. The adaptive control strategy modulates magnetic flux during grid voltage drops, thereby reducing speed fluctuations and minimising tension inconsistencies in the inter-stand gaps. Unlike conventional systems that disregard supply voltage variations, the adaptive approach significantly improves the stability of the rolling process.

A mathematical model of the system, incorporating second- and third-order elastic couplings arising from both mechanical and electromagnetic interactions among the drives, is developed. Numerical simulations conducted in MATLAB/Simulink validate the efficiency of the proposed method. Optimal values for the relative reduction in the magnetic flux are determined to minimise discrepancies in drive currents and strip elongation. The results confirm that implementing adaptive control enhances system stability, improves rolling quality, and reduces the load on the power supply, thereby supporting its adoption in rolling mills operating under unstable grid voltage conditions.

Keywords: hot rolling, dynamic modes, elastic connections, voltage fluctuations, two-zone regulation

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INTRODUCTION

Metal rolling production is a sophisticated technological process that seamlessly integrates the physical and chemical principles of metal deformation with the operation of advanced mill machinery and the precision of cutting-edge electrical drive systems.

The introduction of automated control systems and optimisation of operating modes of rolling mills not only improves the quality of products but also allows enterprises to meet modern requirements for sustainable development and environmental safety.

Modern industrial standards require stability of thickness, mechanical properties, and the structure of rolled metal, which is possible only with high-precision control of technological processes. Temperature variations, structural changes in the metal, and instability of strip tension between stands adversely impact the quality of the final product. This necessitates enhancing control systems to boost the competitiveness of rolling production [1.

LITERATURE REVIEW

The precision of interconnected multi-motor electric drives in the finishing group of a rolling mill is crucial for maintaining the quality of hot-rolled products. Consequently, research in this field focuses on advancing automatic control systems for these electric drives [2–4].

Research [5, 6] has demonstrated that power supply stability and quality significantly influence the performance of electric drives in the finishing group of the rolling mill. This, in turn, affects the consistency of the rolled material, the quality of the final product, and the overall efficiency of the rolling process. Periodic voltage drops, resulting from shock loads in synchronous electric drives of the roughing group, can lead to unfavourable dynamic operating conditions thus reducing control accuracy and increasing energy losses.

A hierarchical control system consisting of two automation levels interacting is proposed in [7]. Each level performs calculations and adjustments in the corresponding control loop.

Metal deformation processes during rolling and models of the behaviour of elastic stresses at the contact point between the rolling tool and the workpiece under repeated cyclic loads is examined in [8].

Study [9] focuses on developing indirect tension and loop size control systems (TLSCS) by implementing a high-speed automated thickness regulation system utilising hydraulic gap control (HGC).

A real-time machine vision system that employs a fuzzy logic-based algorithm for process analysis and control is introduced in [10].

A more detailed analysis of how shock loads in synchronous electric drives impact the operation of finishing group electric drives through an electromagnetic communication loop is provided in [11]. However, it does not account for the influence of metal strip tension in inter-stand gaps, which can significantly affect the dynamic characteristics of the system.

The focus in [12] is on analysing the performance of the finishing group in a hot rolling mill while considering the rigidity of the metal strip in inter-stand gaps. However, it does not explore the potential for influencing the finishing group operation of the mill through the control capabilities of DC electric drives.

Thus, one relatively little-studied method of improving the performance indicators of the finishing group of a rolling mill under conditions of periodic supply voltage drops is the use of adaptive control of the angular velocity when controlling the excitation of DC electric drives.

Therefore, it is important and topical to study the possibilities of improving the accuracy of the operation of interconnected electric drives of the finishing group under conditions of low grid voltage quality.

RESEARCH MATERIALS

The rolling process represents the final stage of the production cycle in ferrous metallurgy, playing a crucial role in shaping the ultimate characteristics of the finished products.

The main volume of hot-rolled sheet steel is produced on continuous wide-strip hot-rolling mills, which ensure high productivity and compliance with modern requirements for metal quality. The rolling process on such mills is a complex technological operation, the accuracy and stability of which determines not only the quality of the products, but also the overall economic efficiency of metallurgical production.

A hot rolling mill is a highly interconnected electromechanical system comprising diverse electrical and electromechanical equipment with significant installed capacity. Coordination of the operation of all its units requires high-precision control and automation systems that ensure process stability, reduce energy costs, and minimise process deviations.

Figure 1 shows the layout of the technological equipment of sheet rolling shop N1 of Qarmet Joint Stock Company (JSC).

The facility operates a continuous wide-strip hot-rolling mill 1700, consisting of five roughing stands, seven finishing stands, multiple cutting units, and a spar strip unit. Rolling takes place on the mill 1700 process line, which is divided into five functional zones: the loading section, heating furnace section, roughing and finishing stand groups, and a cleaning line [12].

The roughing group of the mill features a sequence of process units, including a vertical stand, a horizontal scale breaker 'duo', the first working stand 'quarto', and four universal working stands (2 to 5) equipped with vertical rolls (edgers). This equipment configuration enables efficient preliminary workpiece processing before it advances to the finishing stand group.

The finishing stand group consists of an intermediate roller table with a pocket, a rack-type strip ejector, drum shears, a finishing scale breaker 'duo', and seven 'quarto' stands, numbered 6 to 12.

The working rolls of the roughing group stands are driven by a synchronous electric motor with a power of 4200 kW, which ensures the stability of the preliminary rolling process.

Seven consecutive finishing stands, 'quarto' Nos 6–12, are designed to bring the rolled products to a specified strip thickness. The electric drive of the working rolls in this group is carried out from DC motors with separate excitation: a motor with a power of 3150 kW is used for stand 6, and electric machines with a power of 3600 kW for stands 7 to 12. This drive configuration guarantees high precision and stability in the rolling process. For the continuous broad strip hot rolling mill 1700 at Qarmet JSC, power for hot rolling production is supplied from the electrical grid at a voltage of 110 kV, following the scheme in Fig. 2.

The power supply for the 1700 mill is provided via substation No. 6 (10 kV) from the two-transformer main step-down substation MSDS-1A (110/10 kV).

The 10 kV secondary windings of TRDNM-63000/110/10 dynamically stable transformers create a two-section switchgear that feeds four sections of substation 6, supplying power to the 1700 hot rolling mill equipment.

Additionally, substations powering auxiliary mill mechanisms and other process sections are linked to 10 kV buses of the main step-down substation.

As indicated in [6], the synchronous electric drives in the roughing group of the rolling mill experience substantial shock loads when the slab enters the rolls. With specific parameters of the power supply system, these shock loads can cause significant voltage drops on the buses of one of the transformers of the two transformer substations.

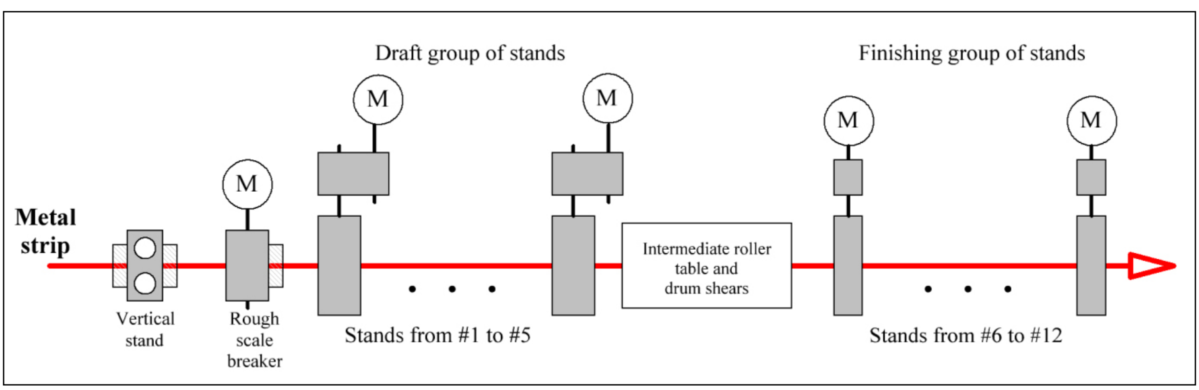

Fig. 1. Schematic layout of the technological equipment of sheet rolling shop No. 1 of Qarmet JSC, Temirtau

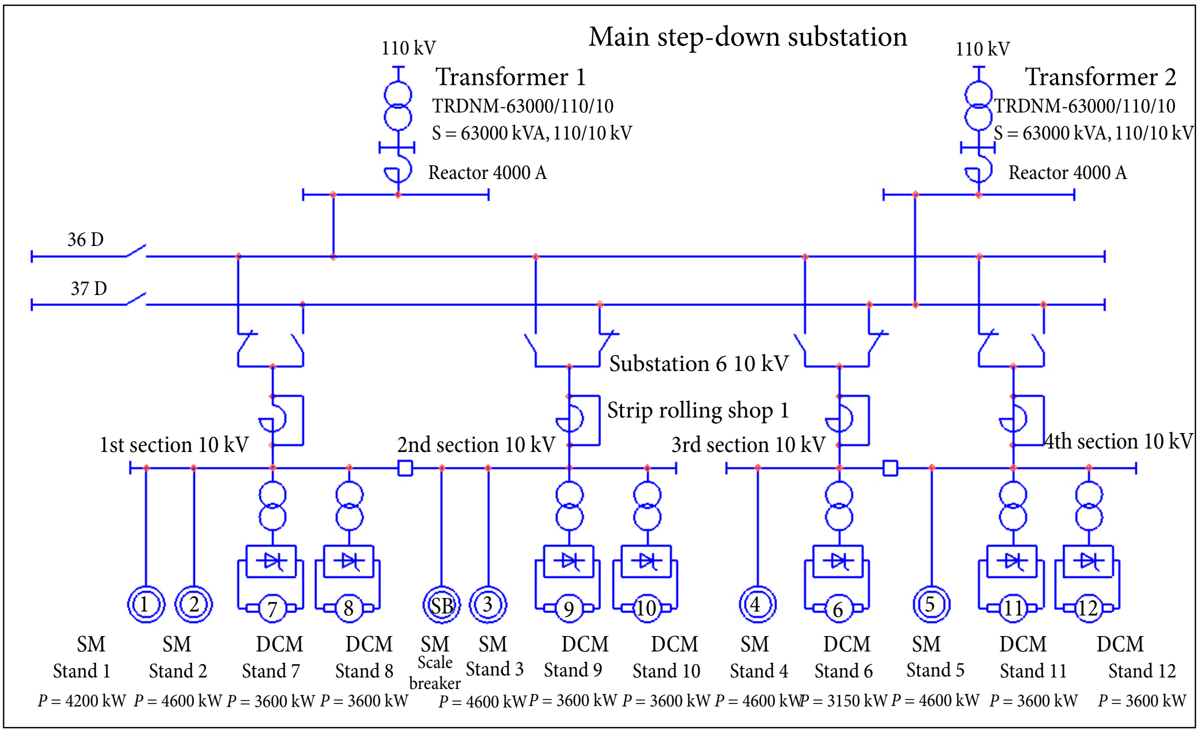

Fig. 2. The schematic of the power supply system for the 1700 mill

Figure 3 shows a voltage drop log during metal rolling on the buses of substation 6 (10 kV), supplying the continuous broad strip hot rolling mill 1700 plant [11].

Analysis of the register diagram shows that throughout the rolling process, voltage drops reach 10% of the rated value and last up to 2.5 seconds [6]. When the metal enters the rolls,

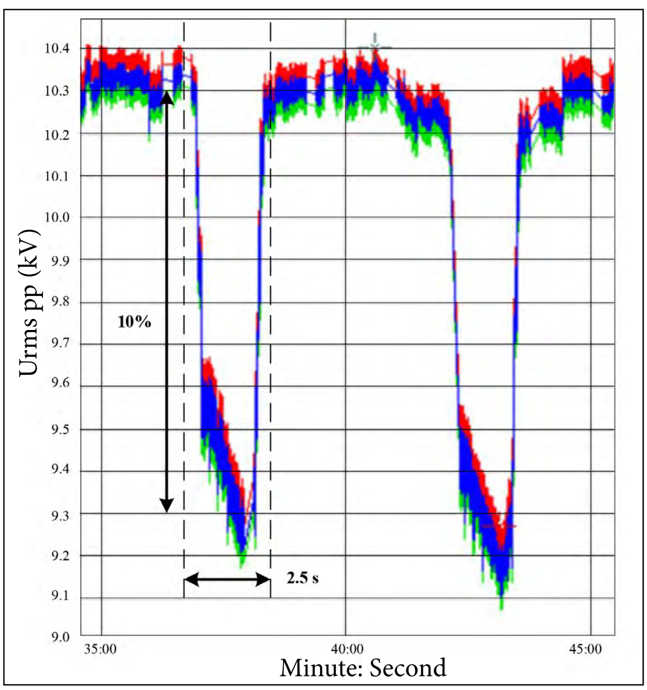

Fig. 3. Voltage register diagram on the buses of substation 6 10 kV during the rolling period

a sudden load application occurs, leading to a voltage drop. The register diagram distinctly displays the impact load surge followed by a subsequent decrease in load.

The existence of various types of elastic connections is a key characteristic of the electromechanical system of the hot rolling mill.

The roll drive of the roughing and finishing stands operates as a two-mass electromechanical system powered by an electric motor through a gearbox and a long shaft. In this setup, the kinematic transmission functions as an elastic link. These systems are classified as possessing first-kind elasticity.

The following assumptions are made in analysing such systems:

1. The elements of the system to which forces and moments are applied are considered absolutely rigid and are not subject to deformation.

2. The mass of the elastic links is either ignored or considered in the composition of the reduced masses.

3. The relationship between the moment (force) and deformation remains unchanged, that is, the elastic link has constant rigidity.

4. The deformation of elastic elements is linear and subject to Hooke's law.

5. Wave processes that occur during deformation can be neglected.

The performance of the electric drives of the multi-motor interconnected finishing group is also influenced by second-kind elasticity, which arises due to the limited rigidity of connections between individual drives. In this scenario, the rolled metal strip within the inter-stand gap acts as the elastic element.

A key aspect of the topology of the hot rolling mill power supply system is the requirement for an even distribution of electrical loads between the transformers in the two-transformer main step-down substation. Consequently, the DC electric drives operating in the finishing group of the rolling mill are linked to different transformers. This design characteristic of the power supply grid of the mill results in electromagnetic interaction between the electric drives of the roughing and finishing groups. It is shown in [12] that shock loads of the synchronous electric drive of the roughing group cause an uneven distribution of supply voltages in the finishing group of the mill, and this kind of interaction through the elements of the power supply system is proposed to be classified as elasticity of the third kind. Combinatorial analysis indicates that in the configuration of the power supply system depicted in Fig. 2, there is always at least one pair of consecutive finishing stands whose electric drives receive power from different transformers within the two transformer substations.

As follows from the diagrams in Fig. 1 and Fig. 2, there are two pairs of sequentially located finishing stands whose drive motors are connected to different power transformers, namely, stands 6 and 7, as well as stands 10 and 11.

MATHEMATICAL MODEL OF A METAL STRIP IN THE INTER-STAND GAP

Let us consider the gap of metal between adjacent units (Fig. 4). In the figure, R_1 and R_2 are the radii of the barrels of the working rolls of the first and second stands; υ_{kl1}, υ_{kl2} are the linear velocities of the material movement through the rolls of the first and second stands; l is the distance between the axes of adjacent stands; C_p is the rigidity

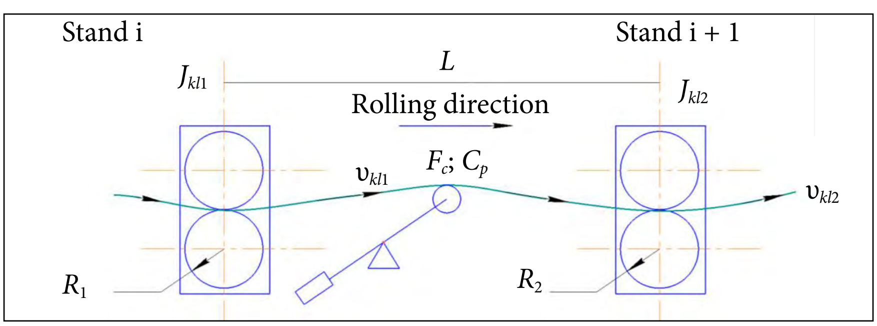

Fig. 4. Electromechanical system of an interconnected rolling mechanism with second-order elasticity

of the elastic connection; F_C is the strip tension force.

According to Fig. 4, the linear deformation of the material in the metal strip section with length L is described by the following equation:

$$\Delta L = \int_0^t \left(\upsilon_{kl1} - \upsilon_{kl2}\right) dt, \qquad (1)$$

where ΔL – the absolute value of the elongation of the metal strip in the inter-stand gap, m; υ_{kl1} and υ_{kl2} – linear velocities of the metal strip at the exit from the first and second stands during rolling, m/s, which can be calculated using the angular velocity of the corresponding electric drive and the radius of the roll R.

The tension in the metal strip is proportional to the absolute extension, ΔL, as expressed by the following ratio:

$$F_c = \frac{E \cdot S \cdot \Delta L}{L}, \qquad (2)$$

where F_C – metal strip tension force; E – Young's coefficient of the band material in the inter-stand gap; L – the distance between the stands, *m*.

The torque created by this force is defined in terms of the radius of the roll R. ε – relative elongation, %;

$$\varepsilon = \frac{\Delta L}{L}, \qquad (3)$$

where ΔL – absolute value of tension, m; L – the distance between the axes of adjacent stands, *m*.

The torque produced by the elastic deformation of the metal strip is added to the load torque of the electric drive of each stand. This factor is incorporated into the mathematical model for the interconnected electric drive of the finishing group, accounting for the interaction among the drives of individual stands through the rolled metal strip – an elastic bond of the second kind.

We employ the simplified calculation scheme shown in Fig. 5 to model the interconnected multi-motor electric drive of the finishing group in a hot rolling mill.

The scheme proposed in Fig. 5 considers the interaction of electric drives of individual stands connected by a strip of rolled metal (elasticity of the second kind). It is also possible to consider voltage changes in the supply grid of electric drives of individual stands resulting from shock loads of synchronous electric drives of the roughing group (Fig. 2, the elasticity of the third kind). The advantage of this scheme is

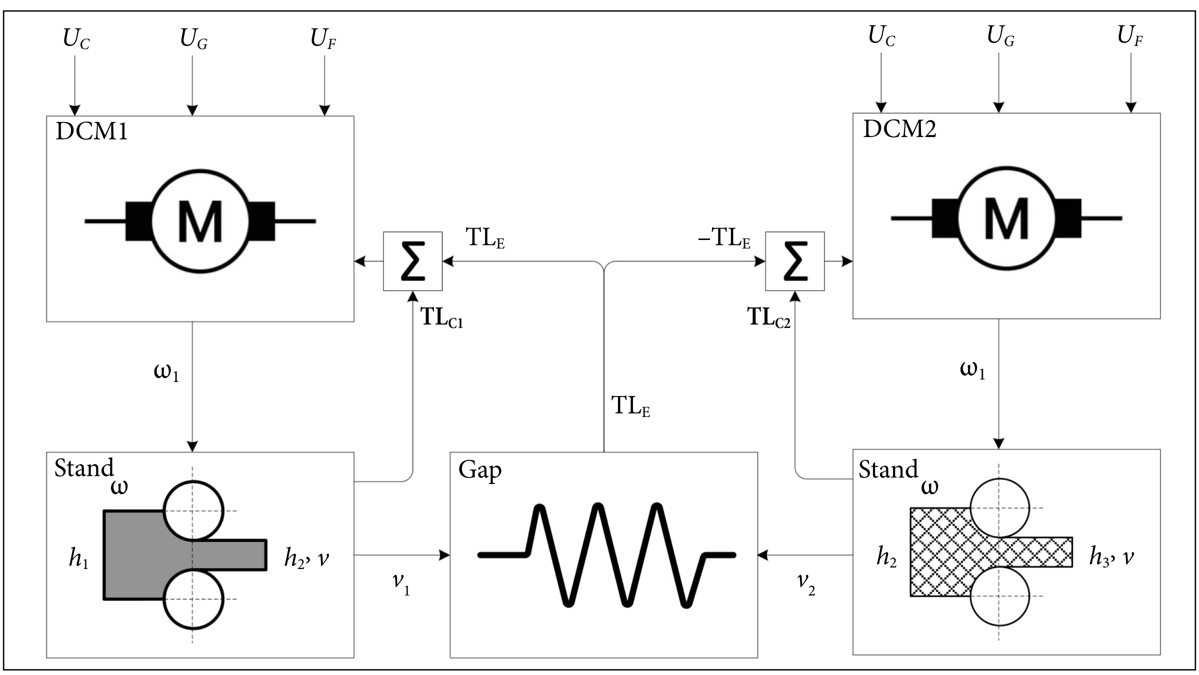

Fig. 5. Simplified calculation scheme of the interconnected multi-motor electric drive of the finishing group of the hot rolling mill

the possibility of studying rolling modes, considering the possible parametric asymmetry of individual drive motors.

MATHEMATICAL MODELLING OF A DC MOTOR

When modelling a separately excited DC motor, several common assumptions are made:

1. The excitation current is assumed to remain constant.
2. Magnetic saturation is ignored in both the main and leakage flux paths.
3. The effects of the eddy current circuit are neglected.
4. The machine is fully compensated, i.e., the armature reaction is not considered.

The DC motor equations in canonical form have a well-known form:

$$\begin{cases} L_\Sigma \dfrac{dI_A}{dt} = U_A - k\phi \cdot \omega - I_A R_\Sigma \\ J\dfrac{d\omega}{dt} = k\phi \cdot I_A - T_L \end{cases}, \tag{4}$$

where L_Σ – inductance of the armature circuit, *H*; R_Σ – active resistance of the armature circuit, Ohms; U_A – armature voltage, *V*; I_A – armature current, *A*; ω – angular velocity of the armature, 1/*c*; *J* – the moment of inertia of the armature, kg·m^2; *k*Φ – motor voltage coefficient, *V*·*c*; T_L – the moment of resistance of the electric drive, *N*·*m*.

Also, this paper will neglect the discreteness of the controlled thyristor converter using average value modelling.

Currently, a reversible thyristor DC electric drive with separate excitation is used as an electric drive for the finishing stands at the continuous broad strip hot rolling mill 1700. A dual-armature DC electric motor of the P2-630-215-8S type with separate excitation is used. Dual-armature motors are often used in electric drives of rolling stands due to their lower moment of inertia than single-armature motors of the same power. The electric motor of the P2-630-215-8S type has the following technical characteristics: rated power 3150 kW; armature voltage 750 V; rotation frequency 150 rpm; rated efficiency 92.5%.

A two-zone regulation system is the standard approach for controlling the speed of the electric drive of the working rolls in the finishing group of a rolling mill. This automatic control mechanism enables a wide range of speed adjustments while ensuring optimal energy efficiency, weight, size, and overall economic performance of the drive.

We use the well-known structural diagram shown in Fig. 6 to mathematically model a separately excited DC motor with adjustable excitation.

For the study, it is necessary to complicate the known linearised model of the thyristor converter in order to take into account the fluctuations in the supply grid voltage. The proposed linearised mathematical model of the thyristor converter is presented in Fig. 7.

In this mathematical model, the UC input corresponds to the control action, range (–1, 1); the grid input describes the state of the power grid, and range (0, 1) shows how much the supply voltage has decreased about the rated value.

Figure 8 shows the implementation of the mathematical model of a dual-loop subordinate control system of the angular velocity of a DC motor. This model implements PID controller current and speed controllers.

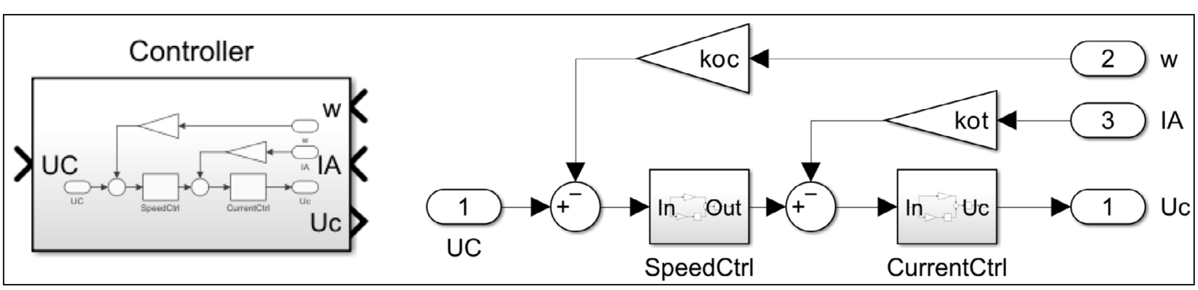

Fig. 6. Structural diagram of a separately excited DC motor: a – subsystem icon; b – subsystem implementation

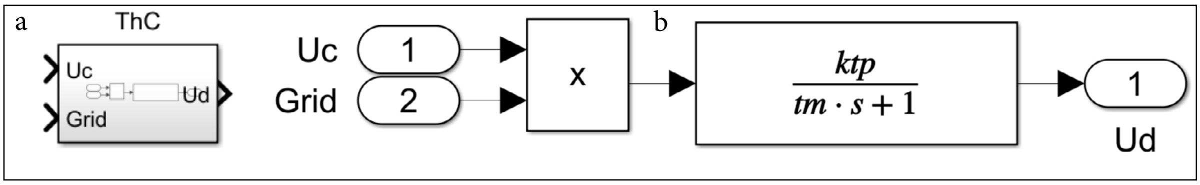

Fig. 7. Structural diagram of a thyristor converter: a – subsystem icon; b – subsystem implementation

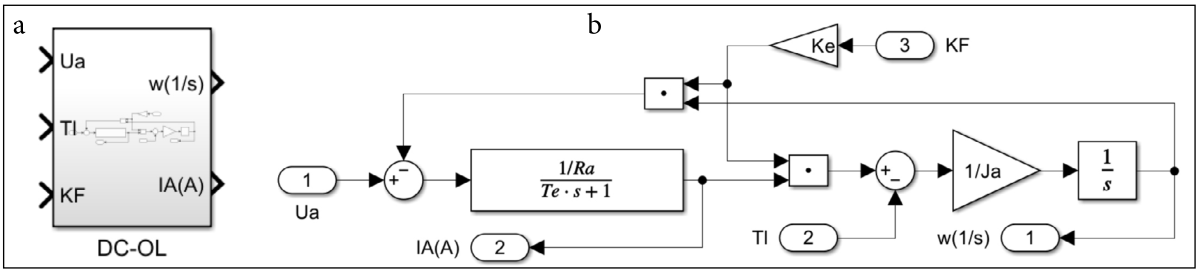

Fig. 8. Structural diagram of a dual-loop subordinate control system: a – subsystem icon; b – subsystem implementation

Figure 9 shows the implementation of a mathematical model of a pair of finishing stands of a hot rolling mill with electric drives connected through a metal strip in the inter-stand gap using MATLAB/Simulink.

At the moment of time $t = 10$ s, due to the start of metal rolling by the synchronous electric drive of the roughing group, following the experimental data of Fig. 3, the supply voltage decreases by 10%, the duration of the voltage drop is 2 s.

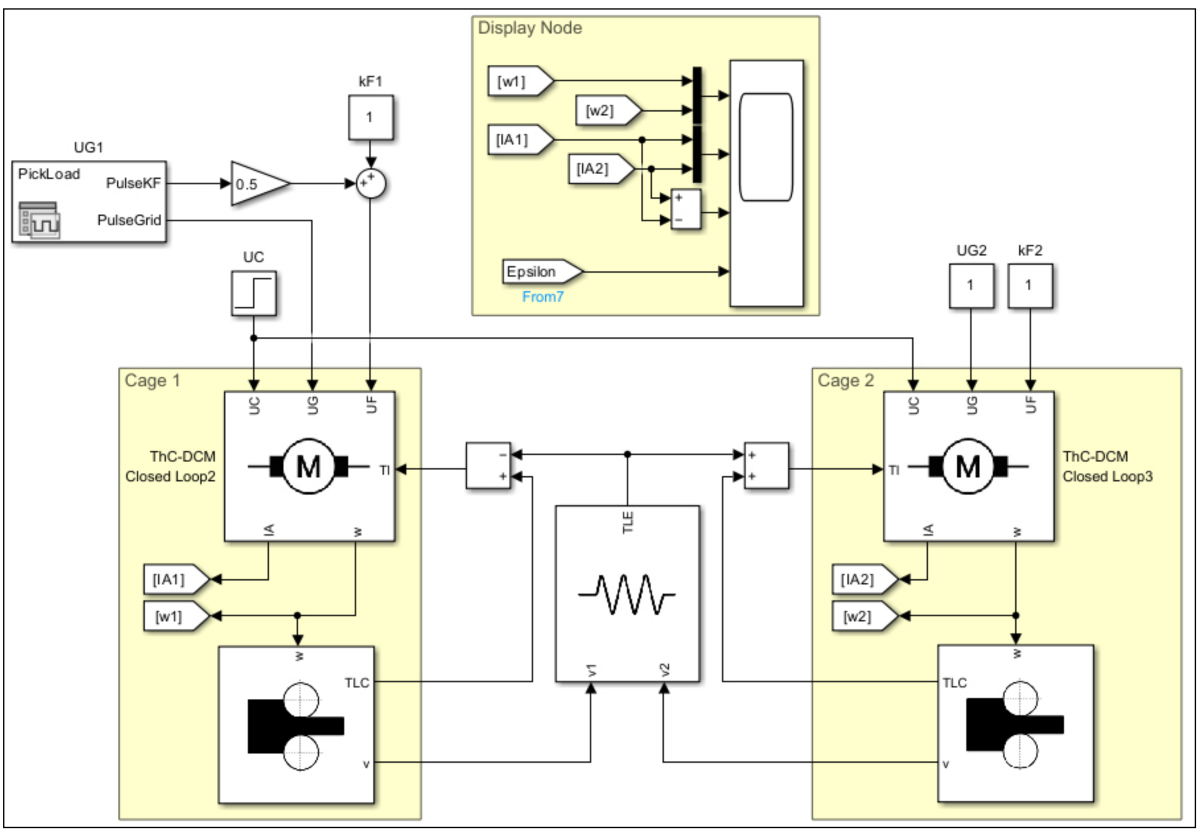

Fig. 9. Structural diagram of two consecutively arranged finishing stands of a hot rolling mill connected by a metal strip

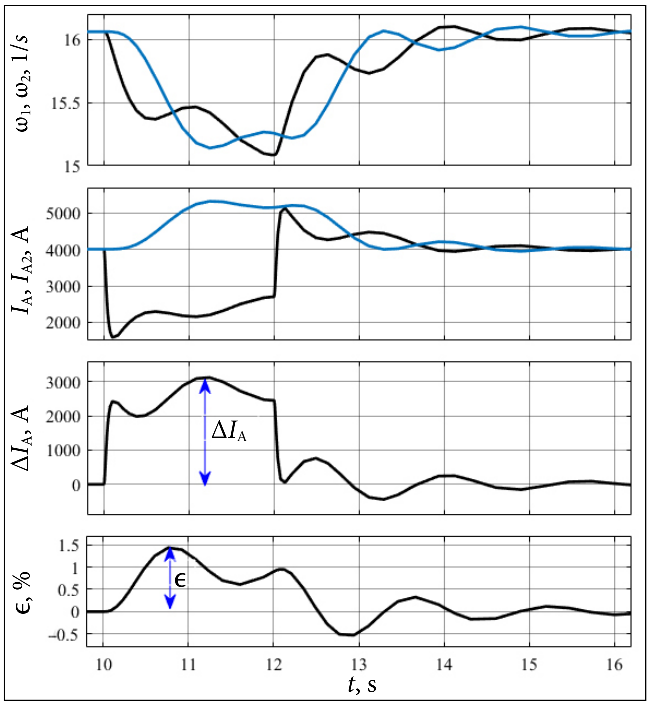

Fig. 10. Dynamic mode of operation of the finishing group stands in the case of a failure of the supply voltage on the drive motor of one of the stands

Figure 10 shows the results of calculations of the dynamic operating modes of the stands of the finishing group under the specified conditions.

Even though the electric drives of individual stands are equipped with a closed system of subordinate speed control when the supply voltage of one of the interconnected electric drives decreases, a drop in the angular velocity of two electric drives, which is caused by the elastic properties of the strip of rolled metal, is observed.

In this case, an elongation of the strip in the inter-stand gap ε occurs. Also noteworthy is the occurrence of a significant violation of the uniformity of current loads of the electric drives of individual stands, which can introduce additional complications into the operation of the power supply system of the rolling mill.

At $t = 10$ s, when the synchronous electric drive of the roughing group initiates metal rolling, experimental data (see Fig. 3) show that the supply voltage drops by 10% for a duration of 2 s.

Figure 10 presents the calculated dynamic operating modes of the finishing group stands under these conditions.

Although the electric drive of each stand is equipped with a closed-loop subordinate speed control system, a voltage drop in one of the interconnected drives causes a decrease in the angular velocity of the two drives. This effect is attributed to the elastic properties of the rolled metal strip. Consequently, an elongation occurs in the inter-stand gap (ε), negatively impacting the quality of the rolled sheet.

Moreover, there is a significant imbalance in the current loads among the individual drives, potentially introducing additional complications to the power supply system of the rolling mill.

As indicators of the quality of the dynamic mode of the finishing group stands with a decrease in the supply voltage, we will consider the maximum value of the difference in the currents of the drive motors ΔIA and the maximum value of the elongation of the rolled strip ε (Fig. 10).

To reduce the impact of the identified negative phenomena, it is possible to use additional control properties of the electric drives of the rolling stands of the finishing group by influencing the magnetic flux of the drive motors. If the supply voltage of DCM is reduced, the magnetic flux of the motor must be reduced to stabilise its speed, as shown in Fig. 11. Although the excitation winding of a DC motor has significant inertia, a sufficient number

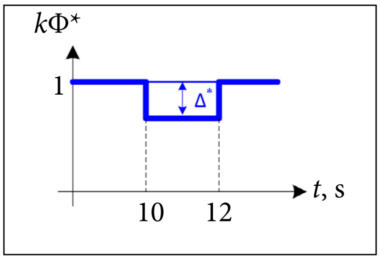

Fig. 11. An approximate diagram of the regulation of the magnetic flux of the drive motor of the finishing rack of a rolling mill when the supply voltage drops

of technical solutions are known for forcing excitation and ensuring the required speed of electromagnetic processes in the excitation winding.

Practically important is the question of the influence of an additional control channel for the excitation of the drive motor on the dynamic modes of the interconnected electric drive and the determination of the optimal value of the depth of regulation of the magnetic flux in a certain sense.

To solve this problem, the mathematical model shown in Fig. 9 was used to study the dynamic performance of the interconnected electric drives in the finishing group.

The relative decrease in the magnetic flux of the drive motor varied from 0 to 0.2 in increments of 0.025.

Based on the results of processing the results of mathematical modelling, regression models of the dependences of the current difference of the drive motors ΔIA and the lengthening of the rolled strip ε on the relative decrease in the magnetic flux *F** were constructed in the form of linear regression equations:

$$\Delta(\Phi^*) = 2.568 \cdot 10^4 \cdot \Phi^* + 3.1233 \cdot 10^3$$

$$E(\Phi^*) = -9.6678 \cdot \Phi^* + 1.4377. \quad (5)$$

The regression coefficient of these models exceeds 95%, which indicates a sufficient level of compliance with experimental data.

The results of (5) show that the minimum value of the current difference of the drive motors ΔI_A is achieved with a relative decrease in the magnetic flux $\Phi^* = 0.1216$. The minimum lengthening value of the rolled strip ε is achieved with a relative decrease in the magnetic flux $\Phi^* = 0.1487$.

In Fig. 12, the diagrams illustrate the performance of the excitation control system for

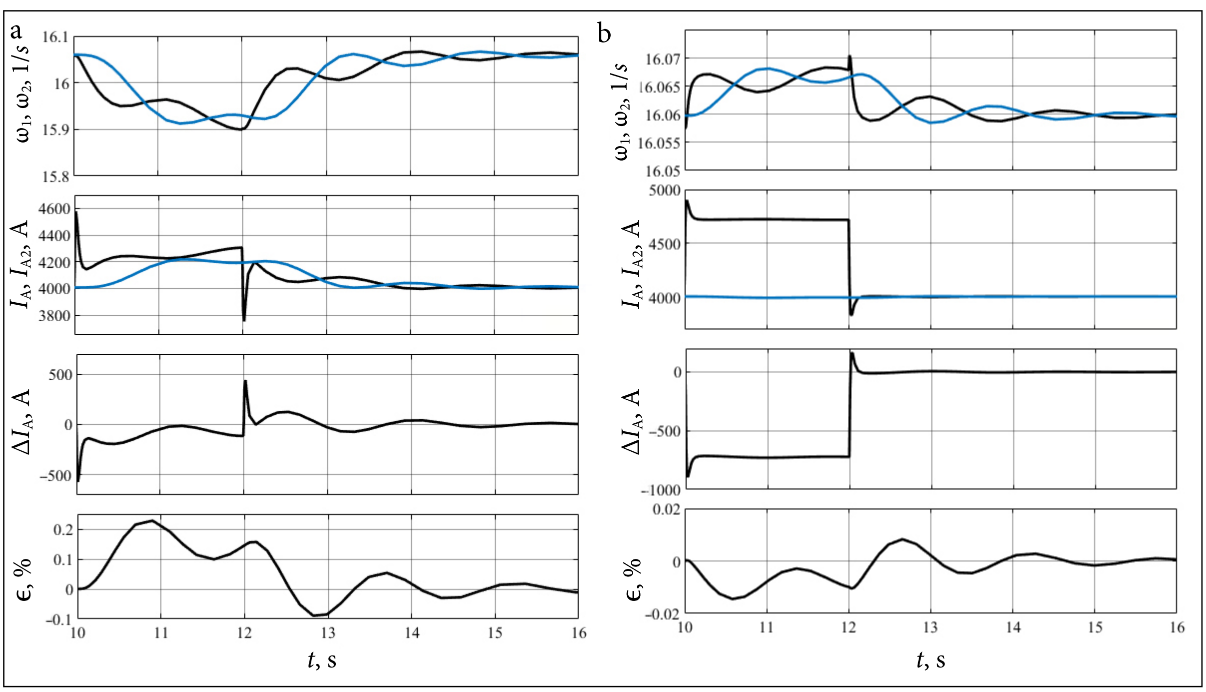

Fig. 12. Dynamic modes of operation of the finishing group stands when the supply voltage drops on the drive motor of one of the stands at different values of the relative decrease in the magnetic flux Φ^*: a – for the minimum value of the current difference of the drive motors ΔI_A; b – for the minimum elongation value of the rolled strip ε

the electric drive of the finishing stand. At time $t = 10$ s, a voltage dip in the power supply occurs. This event persists for 2 s, after which the supply voltage returns to its nominal level at $t = 12$ s.

Figure 12a presents the results of modelling the dynamic operating modes of the finishing group when the electric drive excitation control system is configured to minimise armature current deviation according to the first of equations (5). Under these settings, the deviation of the armature currents remains at approximately 100 A. The relative elongation of the metal strip is 0.2%.

If the electric drive excitation control system is configured in accordance with the second of equations (5) to minimise the relative elongation (Fig. 12b), the relative elongation of the metal strip is reduced tenfold to 0.02%. However, in this scenario, the armature current deviation in the two-motor electric drive reaches about 800 A, which adversely affects the mechanical components of the finishing stand.

The final decision regarding the choice of the excitation control law in the interconnected electric drive of the finishing stand should be made by the rolling mill process engineering department.

CONCLUSIONS

This paper examines the feasibility of using an excitation control system for interconnected electric drives in the finishing group of a hot rolling mill. The goal is to enhance the quality of the final product. The operation of these interconnected electric drives is influenced by second-order elastic couplings through the rolled metal strip and by third-order elastic couplings through the power supply system.

To improve the precision of the finishing group in the hot rolling mill, we propose controlling the DC electric drive excitation under supply voltage dips.

This paper presents a mathematical model of interconnected, regulated DC electric drives in the hot rolling mill finishing group. The model accounts for the influence of the rolled metal strip on the motion of individual electric drives. Moreover, it incorporates the ability to adjust the excitation of each electric drive.

Mathematical modelling of the system – including the effects of second- and third-order elastic couplings – demonstrated that a reduction in magnetic flux during a voltage drop helps equalise the current loads among interconnected electric drives and maintain consistent metal strip tension during voltage fluctuations, ultimately improving the quality of rolled products.

Adaptive angular velocity control of the electric drives of the finishing group minimises the adverse effects of supply voltage fluctuations on the rolling process dynamics, thereby enhancing control accuracy and stabilising the technological regime.

This control method is recommended for implementation on rolling mills equipped with DC electric drives operating under unstable power supply conditions, as it will enhance production efficiency and product quality.

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ELEKTRINĖS PAVAROS SUŽADINIMO VALDYMAS KARŠTOJO VALCAVIMO STAKLIŲ GALUTINIO APDIRBIMO GRUPIŲ NAŠUMUI PAGERINTI

Santrauka

Straipsnyje pateiktame tyrime analizuojami tarpusavyje sujungtų elektrinių pavarų, naudojamų karštojo valcavimo staklių galutinio apdirbimo grupėje, našumo didinimo metodai. Visų pirma nagrinėjamas maitinimo įtampos svyravimų poveikis pavaros tikslumui ir sąveikai, kuriai daro įtaką valcuojama metalo juosta. Atlikus išsamią esamos maitinimo sistemos analizę, nustatytos pagrindinės dinaminių pavaros veikimo nuokrypių priežastys.

Siūloma kombinuota kampinio greičio valdymo sistema, skirta nuolatinės srovės elektros variklių sužadinimui reguliuoti. Prisitaikanti valdymo strategija moduliuoja magnetinį srautą tinklo įtampos kritimo metu, taip sumažindama greičio svyravimus ir įtampos neatitikimus tarp stovų tarpeliuose. Skirtingai nuo įprastinių sistemų, kuriose neatsižvelgiama į maitinimo įtampos svyravimus, adaptyvusis metodas gerokai pagerina valcavimo proceso stabilumą.

Sukurtas sistemos matematinis modelis, į kurį įtrauktos antros ir trečios eilės tampriosios jungtys, atsirandančios dėl mechaninės ir elektromagnetinės pavaros sąveikos. Skaitmeninis modeliavimas, atliktas MATLAB / „Simulink“ programa, patvirtina siūlomo metodo veiksmingumą. Nustatytos optimalios santykinio magnetinio srauto sumažinimo vertės, kad būtų sumažinti pavaros srovių ir juostos pailgėjimo neatitikimai. Rezultatai patvirtina, kad pritaikomojo valdymo įgyvendinimas padidina sistemos stabilumą, pagerina valcavimo kokybę ir sumažina elektros energijos tiekimo apkrovą, todėl jį galima pritaikyti valcavimo staklėse, veikiančiose esant nestabiliai tinklo įtampai.

Raktažodžiai: karštasis valcavimas, dinaminiai režimai, tampriosios jungtys, įtampos svyravimai, dviejų zonų reguliavimas