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Rolling stand electric drive model regarding influence of power supply network parameters

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ABSTRACT

Operation mode of hot rolling mill finishing group stands of ArcelorMittal Temirtau JSC electric drives along with thyristor converter units, intended for the drives supply effect significantly the power network parameters. While being carried out the experimental research on operating modes of power network supplying the rolling mill, some oscillograms were constructed that indicate voltage during the rolling process. Analyzing the oscillograms it appears that there are unacceptable voltage drops throughout the network (more than 10%), that, in its turn, effects negatively the main and auxiliary electric drives functioning. Electric drive simulation model have been constructed with the aim accomplishment to learn more about operating modes features of finishing group stands electric drives as well as power network supplying the hot rolling mill, where the main objective is getting the decreased parameters of their mutual influence. The scientific project purpose is verification of the mathematical model choice correctness, construction of a simulation model of the electric drive control system for the main drives of the hot rolling mill stands, taking into consideration the parameters of the power supply network and checking its adequacy.

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1. INTRODUCTION

One kind of the metallurgical main products variety is hot-rolled sheet [1]. In 2021 the World Steel Association published the ranking of the biggest metallurgical companies in the world in accordance with their manufacturing achievements in 2020. Thus, 107 manufacturers representing 21 countries were included in the ranking. The first place in the global ranking was taking by China Baowu (a Chinese group), ArcelorMittal finished the second, and HBIS Group Chinese company, with the result of 43.76 mln tons of steel melted during 2020, closes the top three. The dominant position in this ranking is taken by such companies as Shagang Group (China), Nippon Steel (Japan), POSCO (South Korea); Indian and Luxembourgian companies, manufacturers from the USA and Iran form the list of leading metallurgical companies in the world [2], [3].

At present there has been a significant increase in the production of hot-rolled metal in China, Iran, India, Italy, Vietnam. However, the main globally recognized hot-rolled steel manufacturers having retained their own production are ArcelorMittal JSC (Kazakhstan), China Baowu Group, HBIS Group (China), ThyssenKrupp (Germany), Nippon Steel (Japan), POSCO (South Korea); Nizhnetagilsk metallurgical plant, Novolipetsk metallurgical plant, Magnitogorsk metallurgical plant (Russia), Mariupol metallurgical plant named after Ilich, Zaporozhstal PJSC (Ukraine) until February, 2022 [4]. In order to meet the ever-increasing demands of consumers on the volume of production as well as on quality of hot-rolled metal, manufacturers are faced with the need of modernize their production. Production modernization requires thorough initial study of both the production technology and the operating modes of main and auxiliary equipment.

The issues of technological process reconstruction as well as rolling production are covered in scientific works [5]–[12]. In their works the authors reveal the issues of the state of the billets during rolling process, the influence of vibration characteristics on the quality of the rolled products, the temperature distribution throughout the strip thickness and rolling stands work rolls during hot rolling, the hot rolling mills productiveness, control of the produced rolled products parameters. However, in their works the authors do not take into account the power supply network influence on the operation mode and the quality of products, which is typical for hot rolling mills.

At the same time, the technological process reconstruction is impossible without the automation systems modernization of rolling mill main and auxiliary electric drives. These are the people having made a significant contribution to the study of automation systems and rolling mill electric drive modernization [13]–[17]. In their writings, in addition to the modernizing control systems problems, the reseachers [18]–[24] consider the issues of modeling control systems for electric drives, present their proposed technical solutions to ensure optimal operating modes of electric drives in order to improve the rolled products quality. However, the problem of mutual influence reducing of power supply network and the hot rolling mill main drives still remains unresolved. In their scientific papers the authors [25]–[27] have covered the study of power supply network issues as well as load buses voltage stabilization in order to ensure energy stability and its efficiency increase in the industrial sector. However, some specific features of metallurgical production operating modes have power supply system differing significantly from systems of any other industrial brunches. The scientific project main objective is verification of the mathematical model choice correctness, construction of a simulation model of the electric drive control system for the main drives of the hot rolling mill stands, taking into consideration the parameters of the power supply network and checking its adequacy.

2. STATEMENT OF THE PROBLEM

A technological process distinctive feature of modern hot-rolled metal production is its characteristic of being energy-intensive production which is accompanied by voltage dips resulting from powerful shock loads when the strip enters the stand. The issues of power quality indicators as well as voltage dips in the power supply network of metallurgical enterprises were being worked at by such scientific researches as [28]–[37]. The authors named above take up the factors that affecting the electricity quality both in a modern industrial enterprise conditions and within metallurgical production. The authors reveal the possibility of electrical energy quality improving in metallurgical production due to the reduction of voltage dips influence appearing while being operated the arc steel-smelting furnaces. However, arc steel furnaces operation modes are different from those in which rolling production does. Thereat, the authors do not take into consideration the voltage dips magnitude being created by rolling production as well as the impact they have on the quality of products having been produced.

For several years one of the ArcelorMittal Temirtau structural subdivisions (The Republic of Kazakhstan) had been carrying out the work on power supply system technical examination applying experimental determination of the electric energy quality indicators. These surveys results showed that the main relatively powerful specific receivers are concentrated in the certain areas of ArcelorMittal Temirtau, it appeared that they affected negatively the electrical energy quality indicators. In terms of power quality indicators, one such unfavorable area is the power supply system from which the 1,700 continuous broad strip hot-rolling mill of ArcelorMittal Temirtau JSC SRS-1 is powered. At present the 1,700 hot-rolling mill power supply is carried out according to the scheme shown in Figure 1. 1,700 hot-rolling mill is located at ArcelorMittal Temirtau JSC SRS-1 which is provided with energy supply by №6 10 kV voltage substation. Figure 2 shows the voltage recorder on the busbars of the №6 substation [38].

The analysis of the register diagram shown in Figure 2 indicates the voltage dips presence caused by shock impacts of current during the periods of metal capture and ejection by the stands rolls. As a result, there is a significant influence on the stands operating modes and electric drives of the 1,700 continuous broad strip hot-rolling mill of ArcelorMittal Temirtau JSC SRS-1. The use of high-power thyristor converters as power sources for the main electric drives leads to the generation of higher harmonic currents in the network, a significant distortion of the voltage curve shape, and ultimately reduces the electrical network technical and economic indicators. With the aim of negative impact elimination, there have been the power supply network modernization which supposes the commissioning of a reactive power thyristor compensator (RPTC) at the main step-down substation 1. Thus it has become possible to ensure dynamic compensation of the reactive power taken by the mill energy consumers; mains voltage stabilization along with voltage fluctuations neutralization; filtering of higher harmonic currents; electric network power factor increasing and reducing the effect of the network voltage distortion on the rolling mill electric wires operation. However, the RPTC installation did not allow to obtain the desired result totally-to neutralize the voltage dips. In addition, a significant shortage of energy capacities in the power supply system of the 1,700 hot-rolling mill of ArcelorMittal Temirtau JSC SRS-1 leads to a decrease in the mains voltage frequency up to 48 Hz and below. Thus, such an operation mode of the mill is not considered to be acceptable, and the impact of power consumers of sharply variable load on the electricity quality is the threat to the stable operation of ArcelorMittal Temirtau power supply system.

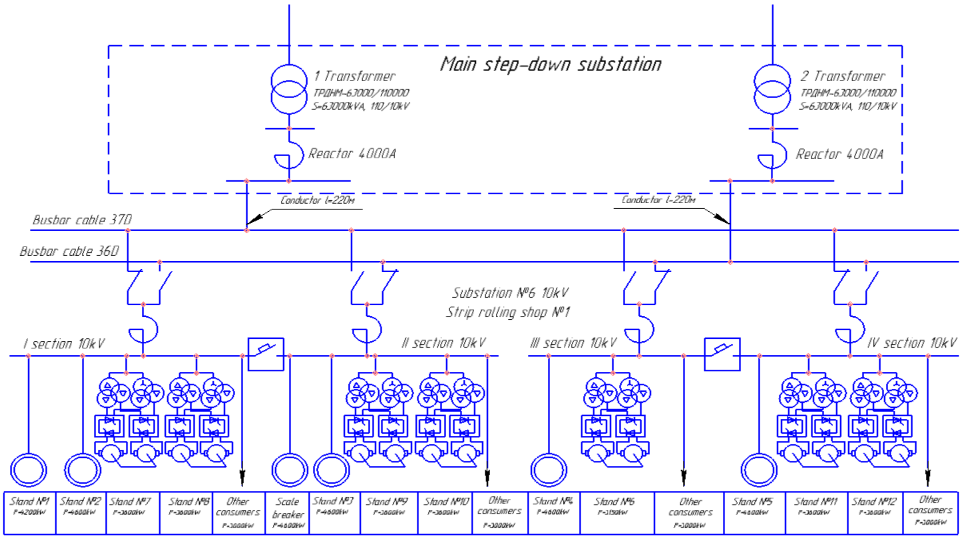

Figure 1. ArcelorMittal Temirtau JSC SRS-1 power supply scheme

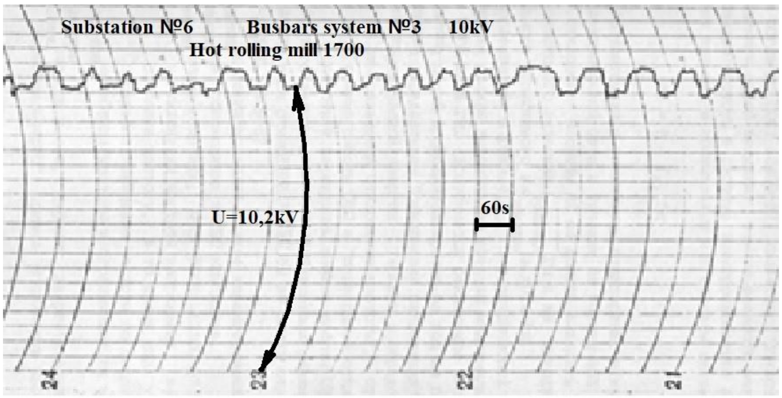

Figure 2. №6 substation busbars voltage register diagram

3. RESEARCH METHODS

When performing the study there have been used such methods as the experiment planning and conducting techniques, mathematical modeling and synthesis, as well as automatic control systems parametric optimization with IT technology application. To assess the power supply system state of ArcelorMittal Temirtau JSC SRS-1 1,700 hot-rolling mill some experiments were carried out to study the substation 6 power supply network which provides energy consumption for the mill main drives. The electricity quality main indicators were determined and while being rolled voltage dips register diagram was made in accordance with the experimental studies results of power supply system data of ArcelorMittal Temirtau JSC SRS-1 1,700 hot-rolling mill that were obtained due to application of “Resurs-UF2M” [39] energy quality indicators device certified on the territory of the Republic of Kazakhstan [40]. Figure 3 shows a voltage dips register diagram on the №6 10 kV substation busbars during metal rolling.

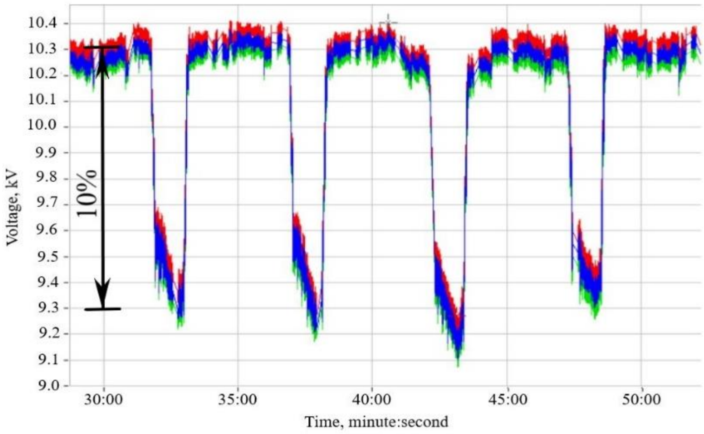

Figure 3. Register diagram of №6 10 kV substation busbars voltage during metal rolling

The register analysis indicates that the voltage dips can be observed during the entire rolling process and their average values exceed the maximum allowable values regulated by the 32,144-2,013 adopted state standards (Figure 3) [41]. Entering the rolls, the metal causes a shock load and a voltage drop as a result, while register diagram clearly shows the shock load surge and then load drop. According to the nature of interference generated by the hot rolling mill electrical receivers, the most significant influence on the mains voltage is manifested in a change in its level and distortion of the sinusoidal shape of the curve shown in Figure 4 [42].

Arising in the network 10 kV voltage fluctuations exceed the 32,144-2,013 adopted state standards of normalized flicker dose value - subjective human perception of appearing in artificial light sources luminous flux fluctuations such as flickering caused by voltage fluctuations in the supplying electrical network. These factors all affect negatively the operation of both the main drives of the ArcelorMittal Temirtau JSC SRS-1 1,700 hot-rolling mill and auxiliaries. Thus, there appears the necessity of simulation model creation and its adequacy checking up in order to carry out more careful analysis of the power supply network parameters influence on the main electric drives operation modes of the broad strip hot rolling mill finishing group stands.

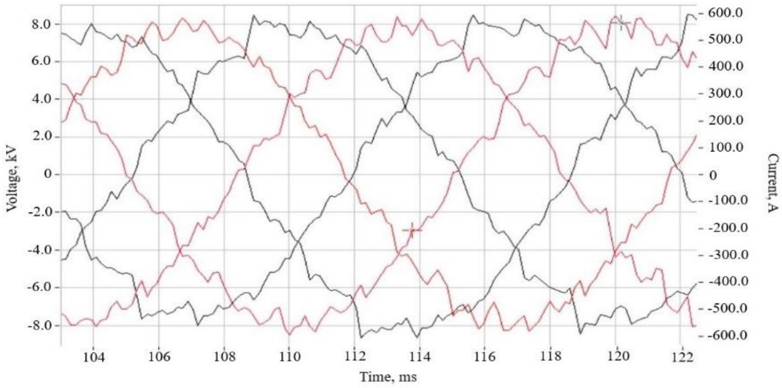

Figure 4. Current and 10 kV voltage curve shape during rolling

4. RESULTS AND DISCUSSION

The production process continuity does not allow any experiments to be carried out within real time production conditions on a mill, therefore there have been developed the mathematical and simulation models of the electric drive of the ArcelorMittal Temirtau JSC SRS-11,700 hot-rolling broad strip mill finishing group stands. The rolling mill finishing stand electric drive is described by the following equations system (1). Unlike the standard motor voltage equation worked out in accordance with Kirchhoff law for the armature circuit, a part $i_a R_T + L_T \frac{di_a}{dt}$ in the first equation of the (1) equation system takes into account the voltage drop across the supply transformer, and consequently, the power supply network parameters influence. The mathematical description of the operation of independent excitation DC motor in the field winding circuit looks like (2).

$$\begin{cases} U = i_a R_a + L_a \frac{di_a}{dt} + c\Phi\omega + i_a R_T + L_T \frac{di_a}{dt} \\ U - i_a R_T - L_T \frac{di_a}{dt} = i_a R_a + L_a \frac{di_a}{dt} + c\Phi\omega \\ M - M_c = J_\Sigma \frac{d\omega}{dt} \\ M = c\Phi i_a \end{cases} \quad (1)$$

where U - mains voltage, V;
R_T - power transformer active resistance, Ω;
Ra - motor armature circuit active resistance, Ω;
L_T - power transformer inductive resistance, H;
La - motor armature circuit inductive resistance, H;
ω - motor angular velocity, rad/s;
cΦ - EMF coefficient, where Φ = const;
cΦω - EMF motor, V;
ia - armature circuit current, A;
M - electromagnetic torque developed by motor, N*m;
Mc - electric drive torque load, N*m;
J_Σ - mechanism inertia moment, kg*m^2.

$$\begin{cases} U = i_в R_в + L_в \frac{di_в}{dt} \\ U_в = i_в R_в + 2p_П \xi W_в p\Phi \\ 0 = i_{вT} R_{вT} + 2p_П \xi W_{вT} p\Phi \\ F = i_в W_в + i_{вT} W_{вT} \\ \Phi = f(F) \end{cases} \quad (2)$$

where Uв - excitation winding voltage, V;
iв - current in electric motor excitation winding, A;
Rв - excitation winding impedance, Ω;
$p_П$ - poles pair number;
ξ - coefficient taking into account that leakage flux part is not linked to all turns of the excitation winding;
Wв - excitation winding turns number;
$W_{вT}$ - turns number of a fictitious eddy current short circuited winding per pole;
Φ - useful magnetic flux of a pole, Wb;
$i_{вT}$ - current in a fictitious short circuited winding, A;
$R_{вT}$ - impedance of a fictitious eddy current short circuited winding per pole, Ω;
F - magnetizing force, Ampere-turn [43].

An electric drive simulation model has been developed in accordance with (1), (2) control systems using MATLAB applied programs kit for technical calculations problems solving within Simulink software simulation complex [44]–[46]. The model was made out in accordance with real parameters of the №6 stand of the ArcelorMittal Temirtau JSC SRS-1 1,700 hot-rolling broad strip mill finishing group stands. The simulation model of hot rolling mill stand electric drive is shown in Figure 5.

The simulation model is a two-zone speed control system and includes the following interconnected systems [47]: i) acting on the voltage of the thyristor converter of automatic speed control system with a slave current control loop in the armature winding; and ii) electromotive force control system with a slave current control loop in the excitation winding. Both systems were developed on subordinate regulation principle and they are: i) automatic speed control system which includes an internal (slave) circuit-a current circuit and an external circuit-speed; and ii) system of electromotive force automatic regulation which includes an internal (slave) circuit-the circuit of excitation current and an external current-the electromotive force (EMF).

The simulation model (Figure 5) contains the following blocks: i) U_{ZS}-motor speed voltage setting block; ii) Regulator of speed (W_{RS}(p))-speed regulator block; iii) Regulator of current (W_{RC}(p))-current regulator block; iv) Thyristor converter-thyristor converter block; v) DC machine electrical part-DC machine block (electrical part); vi) DC machine mechanical part-DC machine block (mechanical part); vii) Ms-static torque setting block; viii) Un- supply transformer output voltage; ix) $U_{Z\ EMF}$-block setting the voltage of the motor electromotive force; x) Regulator of EMF-electromotive force regulating block; xi) Regulator of magnetic flux - excitation current regulator block; xii) Thyristor field winding converter-thyristor exciter block; xiii) DC machine field winding (If)-DC machine block (field winding); xiv) DC machine field winding (Φ)-DC machine block (with a transfer function between the field winding current and magnetic flux); xv) DC Machine design coefficient-block for setting the design coefficient of the DC machine; xvi) Scope-block for fixing changes in the signals applied to its input in time and plotting diagram (oscillograms) [48]; xvii) Powergui-block used to set the modeling method (continuous or discrete) [49]; xviii) K_f-excitation current feedback block; xix) K_{Tfwc}-thyristor converter transfer coefficient in the motor excitation winding circuit; xx) Kcff – armature circuit current loop feedback block; xxi) Ksff-armature circuit velocity loop feedback block; xxii) $K_{EMF\ ff}$-motor electromotive force loop feedback block; xxiii) R_T-block accounting the active resistance of the supply transformer; xxiv) L_T-block accounting the inductive resistance of the supply transformer.

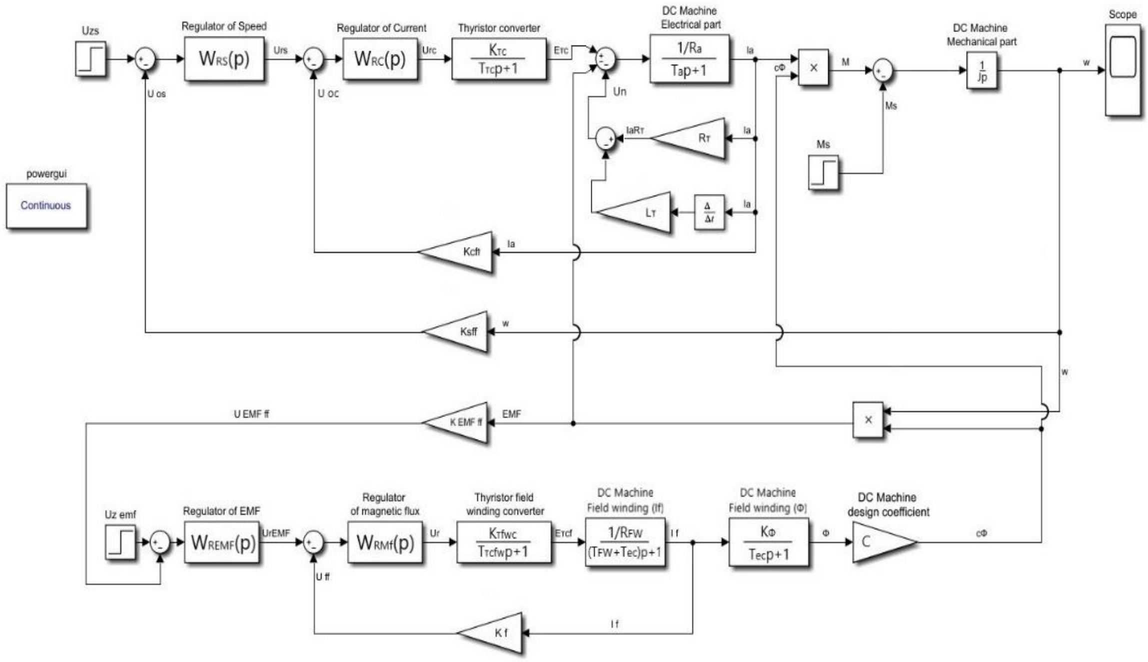

Figure 5. Structural scheme of stand drive simulation model

Basic excitation acting in the simulation model is static moment application. An additional excitation acting in the simulation model is the whole complex of blocks that function in the power supply network parameters condition. The blocks create the information about the voltage dips in the power supply network in the period of rolling. R_T, L_T are such blocks accounting the voltage dips on a supply transformer active and inductive resistance consequently. Transitional process graphs turned out as a result of modeling are shown on Figure 6. On the graph Figure 6(a) shown transitional process in velocity loop w=f(t) with nominal load. On the graph Figure 6(b) shown transitional process in armature circuit current loop Ia=f(t) with nominal load. On the graph Figure 6(c) shown transitional process in electromotive force loop EMF=f(t) with nominal load. On the graph Figure 6(d) shown transitional process in excitation current loop If=f(t) with nominal load.

On the graphs shown in the Figure 6, at the time point t=10 s, the shock application of the load is simulated at the moment the metal enters the rolls of the stand during rolling. Impact load leads to the failure of the stand electric drive speed. A change in the rolling speed that is significant in time leads to metal tension violation in the inter-stand gaps, to non-compliance with the temperature regime of rolling having resulted low-quality items production. The results comparative data of simulation modeling and relative deviations from the electric motor parameters required by the production technology are shown in Table 1.

Table 1. Simulation modeling results and 2П25/105-3,15 electric motor nominal data

Parameter	Motor angular velocity (rad/s)	Armature circuit current (A)	Electromotive force (V)	Electromagnetic torque developed by motor (N*m)	Current in electric motor excitation winding (A)
Nominal parameters	3.926	4,580	696	802,500	155
Simulation modeling results	3.925	4,576	688.4	802,500	153.8
Δ, %	0.03	0.09	1.09	0	0.77

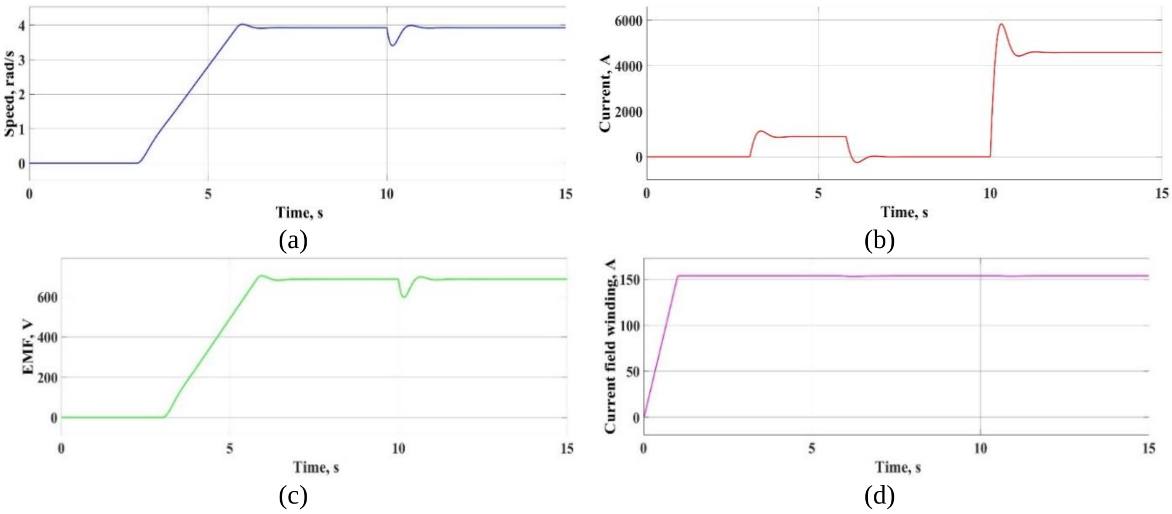

Figure 6. Graphs of transitional process in velocity loop w=f(t), rad/s (a) armature circuit current loop Ia=f(t), A (b) electromotive force loop EMF=f(t), V (c) excitation current loop If=f(t), A (d) with nominal load

The experimental results analysis given in Table 1 allows the following conclusions to be made: the simulation results practically coincide with the electric motor nominal parameters. A significant number of experiments (more than 100) were carried out with the aim of compliance degree assessment of the simulation model with the real electric drive of the main drives of the continuous hot rolling mill finishing group stands as well as to study the transient processes quality on simulation models during rolling. The simulation experiments comparative analysis results and the electric motor nominal data indicated that there were discrepancies between the model main coordinates and real electric drive parameters that did not exceed 5%. This fact testifies to the adequacy of the developed model and the possibility of its application for the operating mode analysis of the continuous hot rolling mill main electric drives. Besides the excitation effect caused by shock load application at the moment the metal enters the stand, the hot rolling mill stands electric drive operation is effected by voltage decrease in the power supply network. An additional perturbing action, simulating the power supply network voltage decrease, was applied at the moment of time t =12s in order to consider the possible influence in the simulation model of the hot rolling mill power supply network.

On the graphs shown on Figure 7, at t=10s time moment there is an imitation of the load shock application when the metal enters the stand rolls while being occurred the rolling process. On the graph Figure 7(a) shown transitional process in velocity loop w=f(t) in accordance with the effect of power supply network voltage dips. On the graph Figure 7(b) shown transitional process in armature circuit current loop Ia=f(t) in accordance with the effect of power supply network voltage dips. On the graph Figure 7(c) shown transitional process in electromotive force loop EMF=f(t) in accordance with the effect of power supply network voltage dips. On the graph Figure 7(d) shown transitional process in excitation current loop If=f(t) in accordance with the effect of power supply network voltage dips. But at t=12s time moment there is an additional perturbing action applied to the electric drive control system of the hot rolling mill stand, which creates (simulates) voltage dips in the power supply network during rolling. In accordance with the simulation modeling results analysis, shown by graphs in Figures 6 and 7, there apperes a rolling velocity decrease caused by both perturbing action simulating the metal entrance the finishing group rolling stand and by excitation resulted by power supply network voltage dips during the rolling process.

On the model these perturbations are spaced in time. However, real rolling conditions do not exclude possible coincidences of these perturbations that lead to more significant rolling parameters deviations from the figures required by the production technology. On Figure 8 there are graphs of transient processes at the time moment when voltage dips in the power supply network coincide in time with shock loads. On the graph Figure 8(a) shown transitional process in velocity loop w=f(t) at the moment when the supply network voltage dips coincide in time with shock loads. On the graph Figure 8(b) shown transitional process in armature circuit current loop Ia=f(t) at the moment when the supply network voltage dips coincide in time with shock loads. On the graph Figure 8(c) shown transitional process in electromotive force loop EMF=f(t) at the moment when the supply network voltage dips coincide in time with shock loads. On the graph Figure 8(d) shown transitional process in excitation current loop If=f(t) at the moment when the supply network voltage dips coincide in time with shock loads.

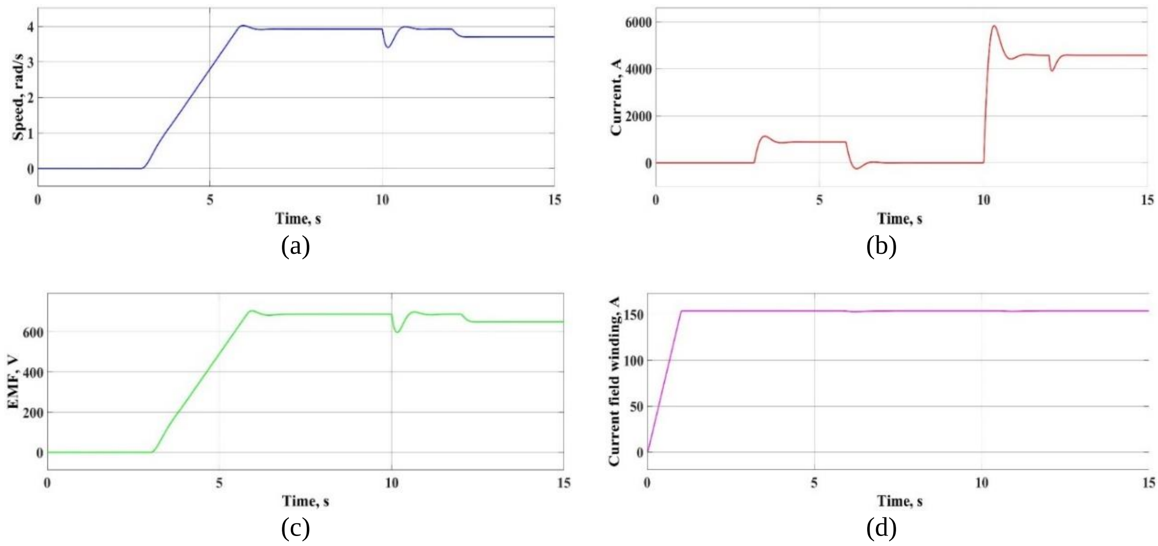

Figure 7. Transient processes graphs in the speed circuit w=f(t), rad/s (a) armature circuit current loop Ia=f(t), A (b) EMF loop EMF=f(t), V (c) excitation current loop If=f(t), A (d) in accordance with the effect of power supply network voltage dips

Analysis of simulation modeling results has made out that these simulation experiment data reflect the real processes occurring in the electric drive of the hot rolling mill stands in the condition of shock loading, as well as operation under decreased voltage in the power supply network. These processes are important are important for hot rolling mills operating at high speeds and taking place within small distances between the stands [50]. Thus, the simulation model structure makes out the interconnection between the real electric drive parameters and power supply network.

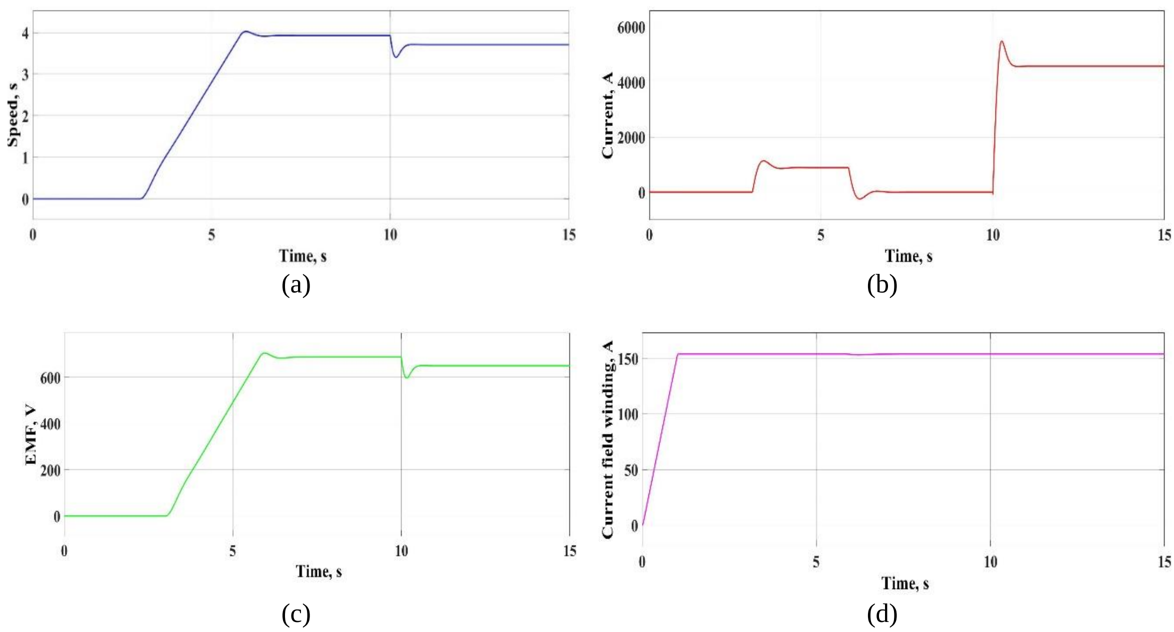

Figure 8. Graphs of transient processes at the velocity loop w= f(t), rad/s (a), armature circuit current loop Ia=f(t), A (b), EMF loop EMF=f(t), V(c), excitation current loop If=f(t), A (d) at the moment when the supply network voltage dips coincide in time with shock loads

5. CONCLUSION

Analysis of transient graphs obtained in the real study course of power supply network, operating modes of hot rolling mill electric drives indicates an increase in the time of rolling speed dynamic dip under shock load application. All this can cause a deviations from the required parameters and lead to a decrease of rolled items quality within the continuous production which characterized by high technological requirements for speed and temperature conditions. Thus, in accordance with the analysis of the research results having been obtained, the following conclusions can be made: i) The experiment obtained results correspond qualitatively to the process situation and theoretical ideas about it; the model structure with accuracy sufficient degree for engineering calculations carrying out corresponds to the real process. ii) The resulting mathematical model can be used to research and develop methods for the stand electric drive controlling of the hot rolling mill finishing group stands, as well as to reduce the negative impact of the power supply network parameters to power consumers operation. iii) The resulting simulation model can be applied to study the stand electric drive operation modes of the hot rolling mill finishing group stands.

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