Computer Modeling of Multi-Mass Electromechanical Systems

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Abstract. Industrial process plants and units are mostly multi-mass electromechanical systems with a number of features such as damping friction, elastic coupling, clearance and others. The article is devoted to computer modeling of multi-mass electromechanical systems taking into account elastic bonds of the first and second kind on the example of electromechanical systems of cold rolling mills. A comparison of the electromechanical processes obtained during the simulation with the monitoring data of real equipment confirmed their adequacy (the relative modeling error does not exceed 9%), that allows to use these models at modernization of existing and designing of new automatic control systems of electric drives of multi-mass electromechanical systems.

Keywords: modeling, multi-mass system, electromechanical system, electric drive, cold rolling mill, the first and second kind elastic bonds

1 Introduction

Currently, automation of technological and production processes using mathematical and computer models is the most popular and progressive approach to the modernization of existing and the development of new automatic control systems. The electric drive as an actuator of many units and complexes used in various industries, science and technology, largely determines their operational characteristics. In transient electromechanical processes, there is a continuous conversion of energy from one type to another due to the presence of various energy storage devices (electrical, electromagnetic, thermal, mechanical), as well as various energy converters interconnected by mechanical (elastic), electrical or magnetic bonds. The mechanical part of the electric drive may have a branched multi-mass system with gaps (backlashes) and visco-elastic mechanical elements (long shaft, cable, rolled metal strip), interconnected by a constant or variable gear ratio. During operation of an industrial unit, the magnitude of the moving mass and the moment of inertia (casting machines, winding and unwinding mechanisms of the rolled strip) can change, which affects the dynamics and statics of the entire system. All this leads to the complexity of the analysis and synthesis of automatic control systems, so the development of mathematical and computer models of multi-mass electromechanical systems is a relevant task.

2 Formal problem statement

The purpose of the work is the development and study of computer models of multi-mass electromechanical systems taking into account the elastic bonds of the first and second kind on the example of electromechanical systems of cold rolling mills (CRM).

3 Literature review

A fairly large number of works are known related to the study of the effect of elastic transmissions on the quality of transients of one-, two- [1-3], five- [4] and multi-mass systems [5]. Most of these systems are unbranched and take into account the influence of elastic bonds described by Hooke's law. Some of the researchers consider such systems taking into account dry friction [6, 7], as well as other nonlinearities [8, 9] to obtain properties that are closer to a real object. Some researchers use the procedure for identifying multi-mass systems, which is promising for obtaining mechanical parameters, such as inertia or shaft stiffness [10-12]. Multimass systems with elastic coupling are found in many industrial applications, for example, in wind power plants [13, 14], in public utilities, for example, when considering a passenger or freight elevator as a two- or three-mass system (engine, elevator car and counterweight) [15, 16], as well as in the automotive industry, for example, when considering the drive of electric vehicles taking into account the number of drive wheels, the distribution of torque between them [17, 18]. A number of works are devoted to the study of the dynamic properties of adaptive neuroregulators, optimal, relay, modal, and robust regulators based on a two-mass system with a complex mechanical structure [19-21] and a variable moment of inertia [20, 23], which confirms the interest of scientists in such objects. Models of two-mass and multi-mass systems are used in the educational process [24] and in developing educational and research laboratory stands based on them [25-27]. However, not enough attention is paid to the consideration of multi-mass systems with elastic gears of the first and second kind.

4 Mathematical description of multi-mass electromechanical systems

When creating automation systems using computer and microprocessor technology for predicting, designing and optimizing equipment parameters and cold rolling technology, the role of mathematical modeling increases [3]. The development of methods and universal mathematical models for studying the dynamic modes of operation of electromechanical systems is a very urgent task, which is caused by the desire of researchers to most fully reflect the features of the object in the model (complicate the model), on one hand, and present it as an element of the system (to simplify the model if possible), on the other [2]. One of the most common purposes of models is their application in the study and prediction of the behavior of complex processes and phenomena. Another, no less important, purpose of the models is to identify the most significant factors that form certain properties of the object, the consideration of which is necessary in the study of various processes or phenomena [4].

Since mathematical modeling is the most perfect and effective modeling method, which, when researching and optimizing, is based on modern methods of mathematical analysis, computational mathematics, and programming, it is advisable to study electromechanical complexes on mathematical models. However, the models of most EMSs are not always adequate to their originals because of the complexity of taking into account all the circumstances and features of real processes in the mathematical description.

Due to the high level of modern programming, it is possible to take into account a set of EMS identification factors when choosing a software product, such as the type of mathematical description of the EMS under study; features of data presentation; type of presentation of calculation results; the possibility of flexible changes or editing of the mathematical model, algorithms, accuracy, selection and automation of the use of numerical methods in the calculation of systems of differential equations, the ability to automate the calculation process [5]. To solve the problems of researching automated EP systems, the following software tools are used: MATLAB, MATHCAD, LABVIEW, MATHEMATICA and others.

It is convenient enough to consider EMS as a set of structural schemes, especially when it is necessary to synthesize the structure and parameters of control systems. Conventionally, it is possible to single out CRM aggregates that are universal for most mills: winding and unwinding devices, rolling stand, leveling machine, scissors cutting rolled metal. In addition, all these units are interconnected: the unwinding device feeds the rolled strip to the work rolls of the rolling stand, from the stand the strip enters either the subsequent stands (if it is the multi-train mill), or to the leveling machine, from which the strip comes out, which is fed to the winder, or scissors for transverse or longitudinal cutting for the subsequent formation of sheets of the required format. Each of these units is driven by an electric motor, which is elastically connected to the actuator through a long shaft. Therefore, in the above set of basic elements of CRM, it is necessary to add such structural units as the “long shaft” and the “rolled strip”, which are elastic bonds of the first and second genera. The selection of the most suitable method for solving practical rolling problems is often a rather difficult task, the solution of which when creating a model of a specific production equipment, namely, CRM, will require significant time costs.

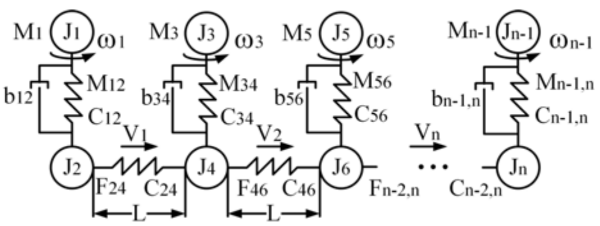

Fig. 1. Kinematic diagram of a multi-mass interconnected system taking into account elastic bonds of the first and second kind

Therefore, the idea of creating a library of blocks for constructing the necessary CRM is relevant.

As a multi-mass interconnected system, a mechanical system with rotating masses connected in series by elastic elements taking into account viscous friction is considered. In addition, in the general case, it is possible to take into account dry friction, changes in the moments of inertia of rotating masses and gear ratio in gears.

Figure 1 shows the system in question, where $J_1, J_2, J_3 ... J_n$ - rotating mass of system, N·m·sec, $\omega_1, \omega_2, \omega_3 ... \omega_n$ - angular velocities of specified masses, sec^{-1}, $M_1, M_2, M_3 ... M_n$ - moving mass moments, N·m, $M_{12}, M_{34}, M_{56} ... M_{n-1,n}$ - moments created in the elastic coupling of the first kind of "long shaft", N·m, $C_{12}, C_{34}, C_{56} ... C_{n-1,n}$ - elasticity of the long shaft connection, N·m /rad, $b_{12}, b_{34}, b_{56} ... b_{n-1,n}$ - intrinsic viscosity coefficient in gears between J_{n-1} and J_n, N·m·sec, $F_{24}, F_{46} ... F_{n-2,n}$ - tensile forces occurring in a second kind of elastic coupling (e.g. a metal strip being rolled), N, L - the distance between adjacent masses connected by a second kind of elastic coupling, m.

As is known, the total moment acting on n rotating mass is equal to the algebraic sum of moments which are attached to this mass. In general, these are: motor torque, load resistance torque, deformation torque of the elastic element (elastic torque), dry and viscous (internal and external) friction moments, as well as variable elastic torque due to non-uniform machine running [28].

Mass with inertia moment J_n is an electric motor that drives a rotary actuator J_{n-1}. They are connected by the elastic coupling of the first kind of "long shaft", the deformation of which is linear and subject to Hook's law.

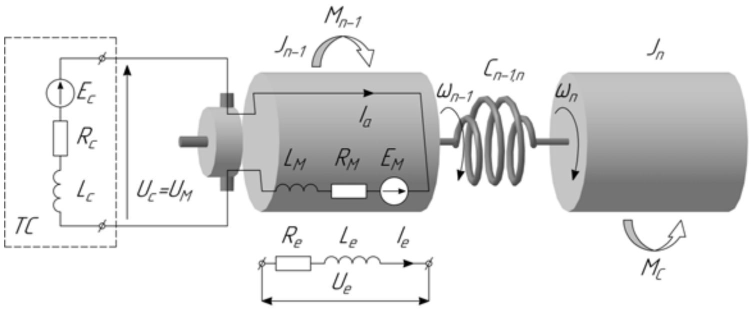

Fig. 2. Two-mass DC motor electric drive model with independent excitation

At the Figure 2 TC - thyristor converter equivalent circuit; E_c, R_c, L_c - EMF, internal impedance and inductance of the thyristor converter that feeds the motor anchor; U_c, U_M, U_e - voltage of converter, motor and excitation winding; I_a, I_e - anchor circuit current and excitation winding; R_e, L_e - internal impedance and inductance of the excitation winding; M_C - resistance torque.

$$
\begin{cases}
E_c = E_M + I_a R_\Sigma + L_\Sigma \dfrac{dI_a}{dt}, \\
R_\Sigma = R_c + R_M, \\
L_\Sigma = L_c + L_M, \\
E_M = C_c \cdot \omega_{n-1}, \\
M_{n-1} = C_m \cdot I_a,
\end{cases} \tag{1}
$$

where $C_c = \dfrac{U_{nom} - I_{nom} \cdot R_M}{\omega_{nom}}$ - – constructive engine coefficient, V·sec; $C_m = \dfrac{M_{nom}}{I_{nom}}$ - mechanical engine steel, N·m/A, $U_{nom}, I_{nom}, \omega_{nom}, M_{nom}$ - nominal voltage, current, angular speed and torque, which are calculated according to the passport data of the engine.

The elastic torque is proportional to the angle of rotation of the shaft or the difference in rotation angles of the individual masses. $M_{n-1,n}$, viscous friction torque M_{vf} in the elastic element is proportional to the difference in velocity and very small, the torque of external viscous friction. M_{evf} (damping torque) is proportional to speed and affects the dynamic torque, but its value is negligibly small and often not taken into account in the calculations. The elastic coupling of the first kind is described by the system (2), where p – Laplace operator, β_n - mass damping coefficient J_n N·m·sec.

$$
\begin{cases}
M_{n-1,n}(p) = C_{n-1,n}(\varphi_{n-1}(p) - \varphi_n(p)) = \dfrac{C_{n-1,n}}{p}(\omega_{n-1}(p) - \omega_n(p)), \\
M_{vf}(p) = b_{n-1,n}(\omega_{n-1}(p) - \omega_n(p)), \\
M_{evf}(p) = \beta_n \omega_n(p), \\
M_{n-1,n}(p) - M_C = J_n p \omega_n(p), \\
M_{n-1}(p) - M_{n-1,n}(p) = J_{n-1} p \omega_{n-1}(p).
\end{cases} \tag{2}
$$

Positioned actuators one after the other J_n, J_{n-2} (for cold rolling mills, it is a unwinding mechanism, stand or stands, a winding mechanism) are connected by elastic bonds of a second kind, such as the transported material or the rolled metal strip, which are described by the system (3).

$$
\begin{cases}
F_{n-2,n}(p) = \dfrac{C_{n-2,n}}{p}\{V_{n-1}(p) - [1 + \varepsilon_{n-2,n}(p)]V_n(p)\}; \\
\varepsilon_{n-2,n}(p) = \dfrac{1}{C_{n-2,n} L} F_{n-2,n}(p);
\end{cases} \tag{3}
$$

where $\varepsilon_{n-2,n}$ - percentage elongation.

The mathematical description of the state of the metal between the cage and the winding-unwinding mechanism was supplemented by the ability of reversing

$$F'_{n-2,n}(p)=\begin{cases}\dfrac{C_{n-2,n}}{p}\left\{V_{n-1}(p)-\left[1+\varepsilon_{n-2,n}(p)\right]V_n(p)\right\},\ if\ V_{n-1}-V_n>0-winding;\\ \dfrac{C_{n-2,n}}{p}\left\{V_n(p)-\left[1+\varepsilon_{n-2,n}(p)\right]V_{n-1}(p)\right\},\ if\ V_{n-1}-V_n<0-unwinding;\\ 0,\ if\ \ V_{n-1}-V_n=0-lack\ of\ tension\ \ during\ \ a\ technological\ pause.\end{cases} \quad (4)$$

During the rolling process, the strip along the entire length has a different thickness, which, however, falls within the tolerance limits for deviation. Changing the value of *h* affects the tension of the strip F_C, as well as its elastic properties. The thickness variation should also be taken into account when calculating the current value of the radius of the roll, mass, and the moment of inertia of the roll.

Let us supplement the well-known mathematical description of elasticities of the second kind [28] by taking into account the variable thickness of the strip, as well as the following condition under which the effect of breaking the strip is simulated, that is, when the current value of the tension force in the strip $F_{n-2,n}$ achieves the critical $F'_{(n-2,n)max}$, the metal strip breaks, and in the mathematical description the output value of the tension force $F'_{n-2,n}$ is nullified:

$$F'_{n-2,n}=\begin{cases}F_{n-2,n},\ if\ F_{n-2,n}<F'_{(n-2,n)max},\\ 0,\ if\ F_{n-2,n}\geq F'_{(n-2,n)max},\end{cases} \quad (5)$$

$$F'_{(n-2,n)max}=K_r\cdot F_{(n-2,n)rab}, \quad (6)$$

where K_r – coefficient of tensile strength of the material (in the model it is accepted as K_r=1,5); $F_{(n-2,n)rab}$ – metal tension force during operating modes of rolling.

Quantities K_r, $F_{(n-2,n)rab}$ are determined taking into account the physical and mechanical properties of the material and the geometric dimensions of the rolled strip.

When describing the elastic coupling of the second kind, the following assumption is accepted [28]: the material is homogeneous and has the same thickness and length along the whole length; the influence of the mass of the material on its deformation can be neglected; the deformation has a purely elastic character and is uniformly distributed along the cross-section; wave processes related to the distribution of deformation along the length can be neglected.

$$\begin{cases}J'_{n-1}(p)=m_{n-1}(p)(R_{n-1}(p)-R_0)^2/i^2;\\ m_{n-1}(p)=\rho\cdot\pi(R^2_{n-1}(p)-R^2_0);\\ R_{n-1}(p)=\sqrt{R^2_0+\dfrac{h}{\pi}V_{n-1}(p)};\\ V_{n-1}=R_{n-1}\omega_{n-1}(p);\\ V_n=R_n\omega_n(p).\end{cases} \quad (7)$$

The mathematical description of the winding (unwinding) device takes into account J'_{n-1} - variable component of the inertia moment of the winding (unwinding) device of CRM, m_{n-1} - metal coil mass; i - gear ratio; ρ - specific gravity of rolling material; R_0 - winder drum radius, h - the thickness of the metal strip rolled, as shown in the system (7).

5 Computer models of multi-mass electromechanical systems

When modeling using the Simulink libraries of the MATLAB, the principle of visual programming according to structural schemes is implemented, according to which the user draws a model of the object on the screen from the library of standard blocks and performs calculations in automatic mode, with the ability to control the calculation time and establish initial conditions. Also, user has the opportunity to choose a method for solving differential equations (Runge-Kutt, Rosenbrock, Dormand-Prince, Adams, etc.), choose the type of solution (with variable or constant step), upgrade library blocks, create their own, as well as creating new block libraries, which is especially important when conducting research in a fairly narrow industry, for example, the production of cold rolled sheets.

Based on the mathematical description of the multi-mass electromechanical systems, computer models have been created that simulate the operation of winding-unwinding mechanisms, a working stand, as well as a model of a rolled strip of metal, taking into account changes in strip thickness and an emergency caused by strip breakage. These models were controlled using models of DC motors of independent excitation and automatic control systems. Each model is an independent subsystem with ports of input and output coordinates. For convenience, a separate logo was created, which is depicted on the model above, an interface for introducing and changing the parameters of each of the subsystems. This approach has advantages, since any unit has the ability to connect to another through mechanical, electrical and information communication channels. It is possible to observe any electromechanical coordinates and set various rolling modes depending on the process. One of the main units of the cold rolling mill is a winding (unwinding) mechanism *Motalka*. Based on system (7), a of the winding mechanism of the mill, shown in Figure 3, and the similar models structure shown in Figure 4, created in Matlab / Simulink.

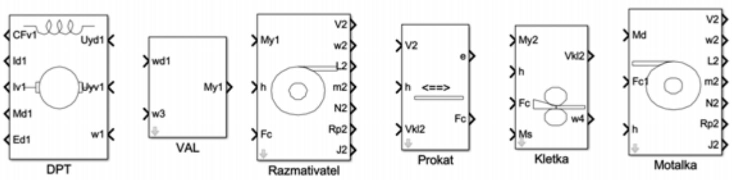

Fig. 3. Computer models of multi-mass electromechanical systems

The difference between the computer model of the unwinder from the one of the winder is that in the model of unwinder at the initial instant of time, the moment of inertia, diameter, and mass of the roll are maximum, and in the model of the winder are minimum, they take into account the direction of movement of the strip and the tasks of initial conditions.

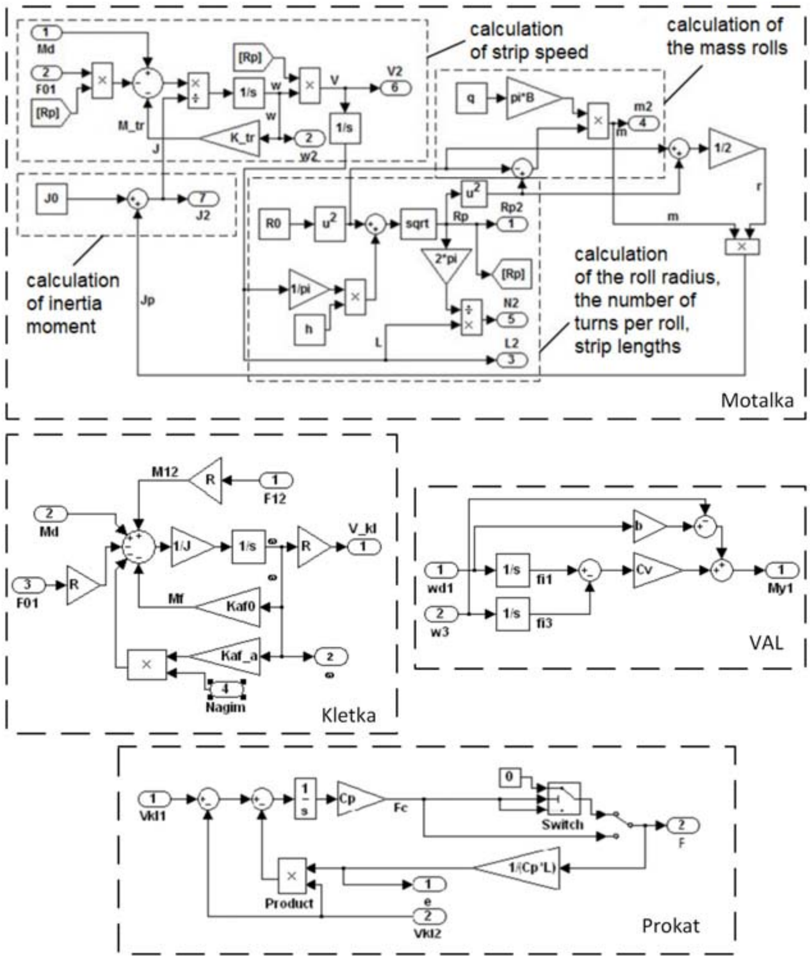

Fig. 4. - Model structures of the winding mechanism *(Motalka)*, working stand (*Kletka*), “long shaft” (*VAL*) and rolled metal (*Prokat*)

The model of the working stand (*Kletka*) takes into account not only the rotating masses and the balance of moments, but also provides the possibility of loading the stand from the pressure channel (pressure screws) through the *Nagim* input port. The coefficients of friction and rolling designated in the model as *Kaf0*, *Kaf_a*, the pressure force F_N from the side of the pressure screws is indicated by *Nagim*, since there is no possibility to use indexes in the application package in which the simulation was performed. Therefore, the linear speed of the strip at the exit of the stand is indicated by V_kl, the forces forming the front and rear tension in the stand are indicated by *F12* and *F01*, respectively.

According to (1), a model *VAL* was created that simulates the elastic "long shaft" connection between the engine and the drive (Figure 4). In the VAL model, the internal damping coefficient is denoted by *b*, the angle of rotation of the motor shaft is *fi1*, the angle of rotation of the shaft of the drive mechanism (of winder, unwinder, stand and others) is *fi3*, ω_{d1}, ω_3 – are the angular speeds of rotation of the shaft ends. This model does not take into account gaps in the mechanical part and, if necessary, can be supplemented by dead zones or non-linear blocks. But this will complicate the whole model, which is not always advisable.

Also, Figure 4 shows a metal model connecting two neighboring units. Note that by its structure it is universal, suitable for all sections of the stand. This model is a second kind elastic link, since the force (moment) between adjacent drives is transmitted through the transported material. To illustrate the consideration of material's properties, namely the residual elongation when the strip is broken, the dependence F = f(ε) is simulated, which displays the tensile strength of the material (Figure 5). Comparing the obtained dependence with the stretching diagram of the rolled strip, it can be seen that it corresponds to theoretical [29]

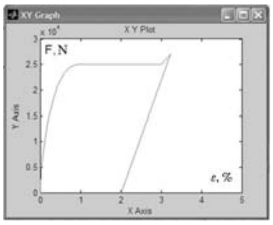

Fig. 5. Dependence F=f(ε) representing the tension of the material

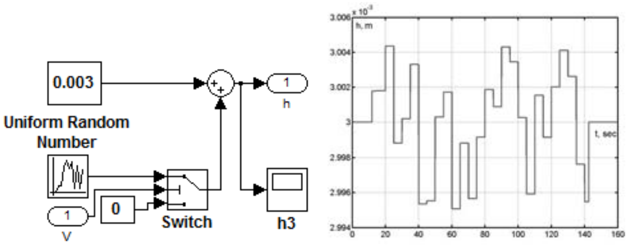

Fig. 6. Model of the strip thickness former and signal shaper thickness of a random nature

To simulate random influences from the rolled metal's side, *Motalka, Prokat, Kletka* blocks can be supplemented with input ports *h*, which allows us to study the operation of these mechanisms with a random change in the thickness of the rolled material. The inconsistency of the value of h leads to a change in the stiffness of the strip *Cp* and affects its elastic properties. Also, the influence of the thickness of the strip is taken into account in the model of the winder (when calculating the current value of the radius, mass, moment of inertia and mass of the roll) and the stand, where the resistance moment changes with *h* due to an increase in the rolling force.

For example, Figure 6 shows a model of a shaper of the thickness of a strip of random nature and the generated signal. To simulate changes in the strip thickness, a source of a random signal with a uniform distribution (uniform random number) was used. The signal level is limited by the values of Maximum and Minimum above and below, the frequency of signal changes is set by the Sample time parameter, the range of variation of the value of *h* is 0,4%.

6 Experiments and results

To check the adequacy of the developed computer models, the multi-mass electromechanical system of the single-stand cold rolling mill of cold rolling shop No. 1 of Zaporizhstal JSC was simulated (Figure 7) and the simulation results under normal rolling conditions and in case of a strip break were compared with the results of monitoring of this mill [30] in an industrial environment (Figure 8, Figure 9). The data for modeling coincide with the data of real equipment with existing automatic control systems (*SAU*), rolling of one roll is considered.

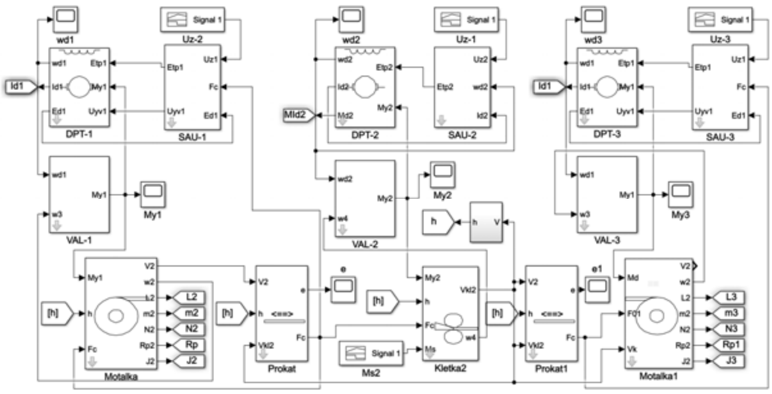

Fig. 7. Multi-mass electromechanical system of the single-stand cold rolling mill model

Comparison of the model obtained and experimental values shows that the relative error does not exceed 8.12%. The average statistical relative error of the entire model was calculated $\overline{a}_m$ =3,79 %.

Using the developed computer models, the work of a four-stand CRM was simulated (Figure 10). The *ZADANIE* subsystem is created on the basis of the "speed wedge" principle, that is, the angular speed of the engines of each next stand has a steeper section of acceleration to the operating speed compared to the previous one and, accordingly, a higher working speed. This is due to the increase in the length of the strip after processing it with each stand. For each subsequent stand, the corresponding value of the pressing force is set, that is, the force with which the pressing screws act on the rolled strip is regulated. In the SAU units, a linear change in the voltage across the windings of the armature of the motors was set, and the voltage in the field winding was varied based on maintaining a constant linear velocity and tension of the rolled metal during winding and unwinding (taking into account the variation of the current radial size of the roll).

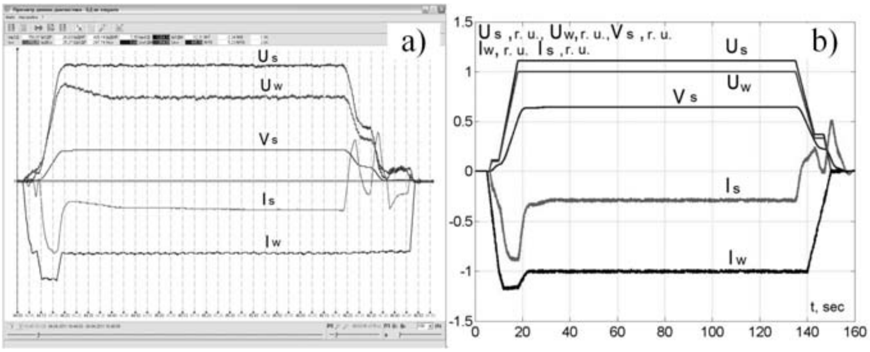

Fig. 8. Average CRM electromechanical processes (a), simulation results (b) under normal rolling conditions

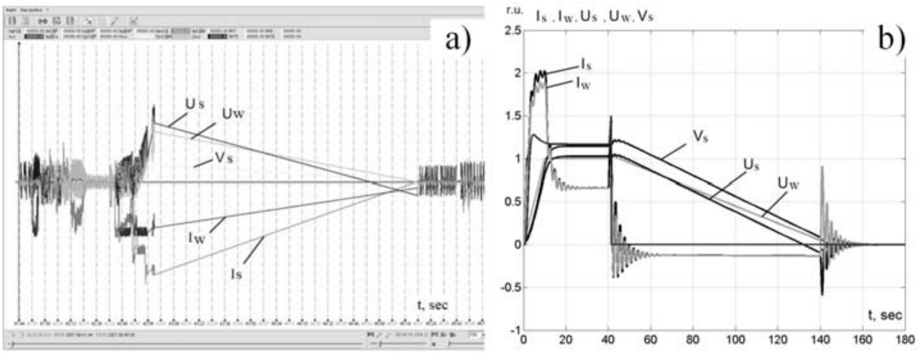

Fig. 9. Average CRM electromechanical processes (a), simulation results (b) in case of a strip break

At the Figure 11: currents of armature windings of engines (a); angular velocities of the motors of the stands (b); linear speeds of the strip movement (c); changing the radius of the roll on the winder (d); a change in the mass and moment of inertia of each of the stands (e), (f). The numbers 1, 2, 3, 4 indicate the working stands of the mill: the first, second, third and fourth, respectively. The speed task for these stands is set based on the principle of “speed wedge”, that is, the speed of metal passage through the stands increases from the first stand to the fourth, as it is necessary to maintain a constant volume of the metal. Each subsequent stand increases the length of the rolled strip and reduces the thickness, so the linear speed of the strip increases. When winding a coil, the mass, moment of inertia and radius of the roll increase, as shown in Figure 11 (d), (e,) (f).

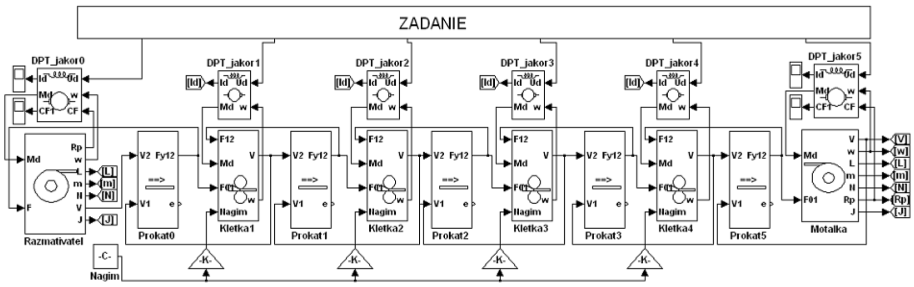

Fig. 10. Multi-mass electromechanical system of the four-stand cold rolling mill model

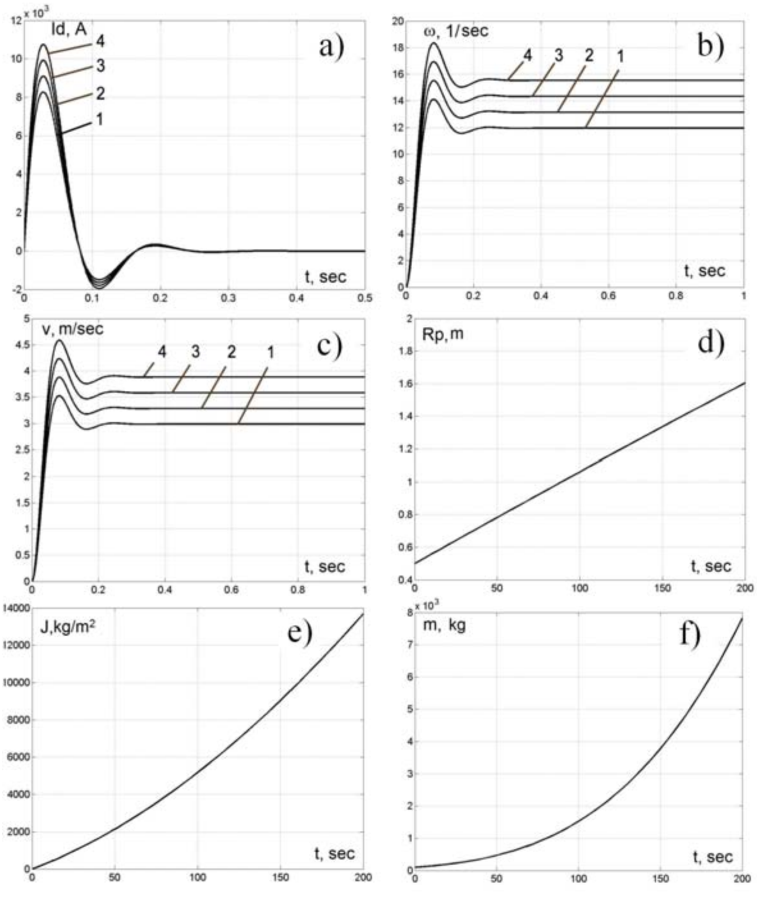

Fig. 11. Graphs of transients on four-stands cold rolling mill

Comparison of the transient graphs obtained during the simulation with the data of the operating equipment of Zaporizhsal JSC confirmed the adequacy of the developed model of the four-stand mill. Thus, we can conclude that the developed mathematical and computer models of the main drives, automatic control systems, actuators and transients are adequate for the real equipment and transient schedules of the mills cold rolling shop No. 1 of Zaporizhstal JSC.

7 Conclusion

Complex of interconnected computer models of the basic elements of rolling production has been developed, which allows you to take into account the elastic bonds of the first and second kinds between the electric drives of the rolling stand and the winding-unwinding mechanism.

Method for studying multi-mass electromechanical systems on example of the main mechanisms of cold rolling mills with variable moments of inertia, static resistance, and metal strip thickness by using the developed complex of computer models of the basic elements of rolling production is proposed.

The mathematical description of the rolling processes of the strip has been improved by taking into account its variable thickness, the effect of breakage and the dependence of the tension force on the relative elongation, which is the basis for the development of mathematical models that allow you to simulate the work and study the quality of control processes for the interconnected electric drives of the main mechanisms of cold rolling mills. A parameter is introduced that takes into account the variable thickness of the metal strip and allows to increase the adequacy and accuracy of mathematical models of the winding-unwinding mechanism and rolling stand.

A comparison of the electromechanical processes obtained during the simulation with the monitoring data of real equipment confirmed their adequacy (the relative modeling error does not exceed 9%) and the possibility of using the developed set of computer models for the synthesis and study of cold rolling mills control systems.

Thus, the consistent use of well-known packages in solving problems of a particular industry allows us to obtain the desired result in the study and modernization of existing control systems, as well as in the development of new control systems for multi-mass electromechanical systems.

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