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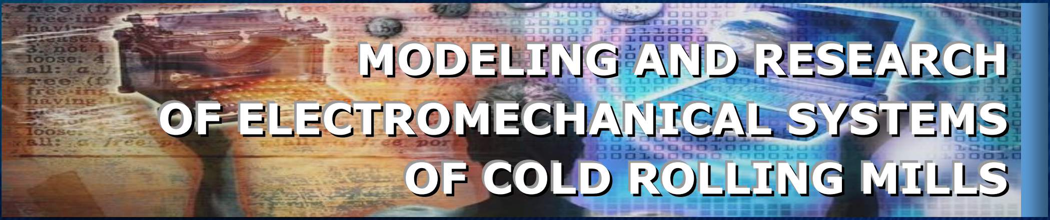

MODELING AND RESEARCH OF ELECTROMECHANICAL SYSTEMS OF COLD ROLLING MILLS

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Monograph

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The questions of mathematical description and a complex of computer interconnected models of electromechanical equipment for cold rolling mills taking into account elastic bonds of the first and second kind, the effect of termination, reversing and variability in the thicknesses of the rolled metal strip are considered. A multi-channel diagnostic complex of electric drives of the main mechanisms of cold rolling mills was developed and put into production, which allows real-time monitoring of electromechanical processes, recording in the archive, and also identifying the causes of emergencies. It is proposed the optimization of the control system for interconnected electric drives: the algorithm for controlling the speed of the working stand and the tension of the rolled strip is synthesized, models of these automatic control systems were created. The presented results of researching the synthesized and existing systems are obtained, analyzed and summarized.

For scientists, doctoral students, graduate students and undergraduates, as well as project managers and engineers-practitioners of the field of mathematical and computer modeling, automated electric drives and automatic control systems.

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CONTENTS

INTRODUCTION

This book is based on the results of scientific research on modeling of electromechanical systems of cold rolling mills. A mathematical description and a complex of computer-related interdependent models of electromechanical equipment for cold rolling mills were developed taking into account elastic bonds of the first and second kind, the effect of termination, reversing and variability in the thicknesses of the rolled metal strip. A diagnostic complex was created for monitoring the electromechanical processes of electric drives of rolling production units and identifying the causes of emergencies. An assessment of adequacy of the developed models to real equipment through the usage of results of diagnostic multichannel complex monitoring was carried out.

The main goal of the book is to show new possibilities for the development and research new development opportunities and studies of electromechanical systems of cold rolling mills using a complex of interrelated models of rolling production elements, which will improve the quality of cold rolling and reduce the number of emergencies caused by strip breakage during rolling.

To analyze and solve the problems posed, such methods as the theory of rolling, mechanics, electric drive and automatic control were used; numerical methods and computer modeling using applied programs were applied when developing a complex of rolling production elements models. For the synthesis of optimal control systems of rolling mill speed and strip tension, the methods of optimal control theory and the problems of analytical design of optimal regulators based on the concept of disturbed -undisturbed motion of A.M. Lyapunov were applied. Experimental verification of theoretical positions was carried out by conducting an experiment on real equipment using monitoring data with a diagnosing multichannel complex. A method for studying multi-mass interconnected electric drives of cold rolling mills is proposed taking into account changes in the moment of inertia, the static moment of resistance and thickness of the rolled metal by using the developed complex of mathematical models of rolling production elements. The theory of interconnected electric drives with elastic couplings was further developed by developing a mathematical model of a four-mass electromechanical system in which the motors of the rolling stand and the winding-unwinding mechanism are connected with their own working bodies by elastic couplings of the first kind, and the mechanisms between themselves - by elastic couplings of the second kind.

The monograph is written in separate sections united by one goal.

The first section gives a brief description of the electromechanical complex of cold rolling mills, formulates tasks and requirements for control systems, suggests methods for their optimization, justifies its relevance.

The second and third sections are devoted to the mathematical description of electromechanical processes, their interaction in the main mechanisms and units of cold rolling mills; creating on the basis of this description a complex of interconnected computer models of rolling production elements.

The fourth section introduces the creation of a diagnostic complex using the example of a training mill 1700-1 of cold rolling workshop No. 1 of Zaporizhstal JSC, describes the development of the hardware and software of the complex.

In the fifth section, the existing control system of this mill is modeled and the adequacy of the developed models to the real processes of rolling equipment is proved.

The sixth section proposes the optimization of the control system for interconnected electric drives: the algorithm for controlling the speed of the working stand and the tension of the rolled strip is synthesized, a model of this system is created, the results of comparing the synthesized and existing systems with external and parametric disturbances are presented.

The book is intended for engineers, scientists and specialists in the field of automated electric drives and automatic control systems, may be useful in the preparation of bachelors, masters and graduate students in the field of "Power engineering, electrical engineering, electromechanics" and "Automation and computer-integrated technologies."

Chapter 1.
ANALYSIS OF ELECTROMECHANICAL ROLLING SYSTEMS

1.1. Brief description of the cold rolling electromechanical complex

Metal rolling production is one of the most complex technological processes, since in this process the metal strip, mechanical elements, technological machines (winder, stand, unwinder, pressure devices, spindle, gear stand and others) of mills and electric drives of these mechanisms are closely interconnected.

It is known that electric drives (ED) of cold rolling mills (CRM) are complex electromechanical complexes (EMC) designed to control machines that convert electrical energy into mechanical energy, installed in close proximity to each other, performing joint work [1]. The CRMs are equipped with mechanisms for unwinding rolls and feeding the end of the roll into the work rolls of the stand, mechanisms for compressing the workpiece in one or several stands at the same time, as well as mechanisms for winding the rolls, packing them and transporting them to the warehouse.

With relatively small volumes of production of cold-rolled sheets and strips, for example, of special steels and many non-ferrous metals, single-cage reversible multi-roll mills equipped with powerful winding and tensioning barrels (coilers) are widely used. The maximum rolling speed on these mills is at the level of 10-15 m/s. New designs of single-strand mills, designed to work with increased compression forces at high speeds, are intensively developed.

The starting material for cold rolling is a hot-rolled strip, rolled on thin-sheet hot rolling mills and coiled into a roll, previously passed bell-type furnaces for annealing steel sheet rolls, a pickling unit for cleaning the surface of the strip from dross, cutting the front and rear edges of the strip, and oiling. The mechanical properties of cold rolled sheet steel are the most important characteristics of its quality, as it determines the ability to extract to obtain finished products. The quality of cold-rolled strips is characterized by rolling accuracy (including flatness), the level of mechanical properties, metal stampability, and surface quality. The inconsistency of the thickness of the cold-rolled strips (longitudinal thickness difference) is due to the longitudinal different thickness of the rolling (hot-rolled strip), the beating of the work roll system of the cold rolling mill, due to the eccentricity of the barrels and necks of the rolls. In turn, a change in mechanical properties affects the technological parameters of the cold rolling process itself. The complex of automation systems of a modern rolling mill is designed to implement such tasks: improving the quality of finished products as a result of automatic regulation of the main technological parameters; improving working conditions for production personnel; increasing mill productivity by reducing the duration of equipment overhauls and the number of emergencies caused by erroneous actions by maintenance personnel; improving the reliability of mill equipment due to more advanced technical diagnostics; reduction of energy consumption as a result of optimization of rolling modes.

1.2. Technological requirements for automatic control systems of cold rolling mills

To conduct the process of cold rolling and training, a number of technological operations are required to be carried out in the required sequence. This determines the on and off times of individual engines, as well as the ratio of their rotational speeds. The performance of these functions, as well as some other operations, is the subject of automation. In addition, the control and regulation systems of cold rolling mills should include elements that ensure reliable operation of automation devices and protect the system from abnormal and emergency conditions.

When rolling strips, the automatic control system (ACS) of the main line of the mill should provide the ability to perform a number of important operations and functions and meet the following requirements [2]:

- the ability to separately control the engines of the stand and winders, and for a multi-cage mill, the engines of each stand individually, the engines of the whole group of stands as a whole, or a specific combination of engines of individual stands and winders in a particular mill;
- the ability to quickly stop both the mill as a whole and its individual stands (for a multi-stand mill), which will not lead to an accident;
- turning off the engine of one stand, which resulted from the action of automatic protective devices or the operator’s influence on the relevant controls, causes the engines to turn off and stop all stands of the mill, which is also important to prevent metal scrap or roll breakage;
- the start of engines for inserting the strip should occur simultaneously or in the order they follow in the direction of movement of the metal, as well as the possibility of starting the engines of each subsequent stand when inserting metal independently of other stands (for a multi-stand mill) [3];
- the ability to quickly reduce the speed of the winder motor to a small value by the time the strip leaves the last stand, as well as when the strip breaks, in order to avoid injury to personnel by the end of the strip;
- if the work with metal in the rolls was interrupted, then to continue rolling after applying the start impulse, the engines should automatically acquire the speed preceding the abnormal operation of the mill;
- manual and automatic speed control of each of the engines should be possible without communication with the engines of other mechanisms;

- the possibility of reversing the rolls of the stand both with metal and when idle. This operation is also required for the winder's engine during the removal of the roll and when loading it into the barrel, when setting up the electromechanical equipment, and also after emergency situations [1];

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- the system should provide the ability to work with a push, i.e. must allow short-term rotation or a short-term change in the frequency of rotation of the motors of the stand and winders separately to tighten the loop formed during insertion, as well as to facilitate insertion itself. The mill as a whole should also allow the rolls to be turned by a push in any direction;
- the ability for each of the engines to report short-term more intense acceleration necessary to tighten the loop that arose during insertion or formed on the run of the mill, as well as to change the magnitude of the tension;
- winding barrel motors must be able to accelerate or decelerate regardless of the operation of other mill engines;
- ensuring the automatic maintenance of a constant tension between the stands of the mill (for a multi-stand mill) and between the stand and winders, as well as between the stand and unwinder, both at rest and in the steady state of rotation of the rolling rolls. In addition, during periods of acceleration and deceleration, such a change in tension should be implemented that would help maintain a constant thickness of the metal;
- continuous monitoring of the thickness of the strip entering the winder, as well as restoring the required size in case it deviates from the set value in excess of the prescribed tolerances. Other requirements are possible, due to the characteristics of each particular mill.

To determine the requirements for self-propelled guns for cold rolling mills, it is important to know the required value of engine accelerations in transient regulation processes. It is determined by the rate of change of the main technological adjustable parameters: the thickness of the rolled metal and its tension. Knowing the laws that acceleration of controlled motors should follow in various control and regulation modes, it is possible to determine the necessary laws of change in their magnetic field flux and voltage at their terminals, find the gear ratios of various parts of the control system, and other parameters [2].

1.3. Status and development trends of automation control systems of cold rolling mills

The problems of constructing and optimizing the ACS of interconnected electric drives of technological lines attract a wide attention of specialists. These issues were resolved by many scientists. In the works of N.N. Druzhinin [3], Y.M. Feinberg [2], Y.A. Bortsov, G.G. Sokolovsky [4], V.N. Egorov, A.B. Zelenov [5], A.V. Basharin, V.A. Novikov [6], V.I. Klyuchev, A.V. Sadovoy [7], L.G. Limonov [8], V. B. Klepikov, O.I. Tolochko [9], P.Kh. Kotsegub, O.P. Chorny, R.P. Gerasimyak and others questions of the theory of interconnected electromechanical systems with elastic bonds were developed, the main ways of their analysis and synthesis were identified.

In the works of N.N. Druzhinin, an in-depth analysis of the static and dynamic modes of a multi-motor electric drive of a continuous mill is given, taking into account the influence of the characteristics of the electric drive, the elasticity of the mechanical system and the parameters of the technological process, in particular, the dominant role of the elastic properties of the roll-stand system was shown [3]. In his works, the physical processes occurring during the winding and unwinding of the strip from the reel barrel are also widely covered. Using the coefficient of electromechanical coupling introduced by V.I. Klyuchev in assessing the effect of the elasticity of mechanical transmissions on the dynamics of electric drives [10] and in the synthesis of correction has simplified analytical studies and increased their visibility. Y.A. Bortsov and G.G. Sokolovsky considered the effect of elastic bonds on the dynamics of thyristor systems of electric drives built on the principles of subordinate regulation [4]. The need to implement the design and commissioning of electric rolling mills in a short amount of time caused the work of scientists O.V. Sledzhanovsky, N.P. Kunitsky in this direction. A.B. Zelenov outlined the principles of constructing electrical machine control and regulation systems [5]. O.I. Tolochko and P.Kh. Kotsegub paid attention to the study of systems of subordinate regulation with observers of the state of dynamic and static currents, systems of positional electric drives with combined control according to the driving and disturbing influences [9].

However, in most cases, the authors considered a two-mass system, which greatly simplifies the mutual influence of elastic bonds on electric drives.

Y.M. Feinberg gives a physical interpretation, a mathematical description of the laws that determine the relationship of electromechanical quantities with the parameters of the technological process, a mathematical description of the winding processes and correction of the roll solution [2]. I.P. Ronin paid great attention to the problem of complex automation of coilers [11], namely, the regulators of the tension of the strip between the cage and the winder, since the coiler’s ED is a particularly complex element in the overall mill or line system.

At the same time, adequate mathematical models of multi-mass EDs of CRMs that are simultaneously interconnected through the metal being machined and the “long shaft” have not been fully developed; the existing multi-mass models did not take into account the influence of the randomly varying thickness of the rolled strip.

Today, most of the existing rolling mills have the following general characteristics [12]:

- use of direct current drives with analog control systems;
- construction of an ED control system based on local controllers and relays;

- reliable operation of power rectifier sections and motors in the presence of a sufficient number of spare parts and quality service;
- high rigidity of the elements of the electromechanical system of the main drives of the rolling stands, which determines the dynamic capabilities of the drives;
- lack of information support system for the operation of electric drives, affecting the efficiency of rolling process control;
- the lack of a mathematical apparatus that allows the use of models of subsystems of CRM at the synthesis level.

Based on the analysis of the literature, the following development trends for cold-rolling can be distinguished [12]:

- increased productivity of mills due to the integrated automation of the rolling process;
- improving the quality characteristics of cold-rolled steel (accuracy of geometric dimensions, surface condition, thickness, physical and mathematical properties and uniformity of the metal structure, etc.) by improving the quality of control of electromechanical systems of cold rolling mills;
- optimization of technological parameters of the rolling process;
- reduction of metal and energy intensity of equipment;
- re-equipment and modernization of control systems for EDs of CRMs.

Complex automation of the rolling process involves the construction of a multi-level automatic control system (ACS) of CRM EDs, which solves the following control problems [13]:

- development of control actions for the drives of the main and auxiliary mechanisms in accordance with the production program and current rolling parameters;
- direct or indirect assessment of technological parameters for regulating tension and loop formation, rolling control, starting commands for scissors, pushers, cooling nozzles, etc.
- presentation and image of installation and current values of parameters and coordinates, such as engine load, loop size, rolling tension, engine speed, rolling speed, strip end trim length and other production parameters;
- a dialogue between the maintenance personnel and the control system (CS), as well as display service and control of the rolling mill EA and the recording of the main process data;
- the use of monitoring results to confirm the adequacy of the created simulation models of CRM, which will be further used to create new and reconstruct existing rolling equipment.

In accordance with the ideology of block-modular design of complect electric drives, as a rule, it is possible to widely vary power modules and control modules that are part of power blocks and control blocks of a complect electric drive, with the aim of adapting them to the modes and conditions of operation of technological equipment [8].

Under these conditions, several steps for modernization of CRM ACSs [14] can be considered - the replacement of analog and relay-contact control systems with digital ones using industrial computers, technological controllers, logic controllers, intelligent peripheral modules and other things corresponding to the upper and middle level of automation. The next step is to supplement the above replacements for the analogue control units of the complect DC electronic drives with digital ones using drive controllers. This is advisable if the power rectifier equipment of the currently existing complect electric drives is in good, operable condition. At the same time, the direct current drive is presented as a new modern digital complect electric drive, preserving the old thyristor sections, which are the most expensive [14]. After modernization, favorable conditions are created for organizing a multi-level automatic process control system (APCS), since the main drives can easily be coupled with the level of control and organization of production [15]. The next step in modernization is the addition and replacement of power blocks of complect electric drives. Electric motors and power supply networks remain unchanged. The final step is the complete modernization of automated electric drives by replacing direct current electric drives with alternating current electric drives with replacement of drive motors. With new equipment, you should start immediately with the last points.

A modern approach in the field of modernization of rolling production is the replacement of DC motors with AC motors, however, it remains relevant and in demand to carry out modernization on existing equipment, namely, a reasonable combination of replacing worn, morally and physically obsolete electrical equipment with new, having high reliability indicators and quality, with reasonable maximum possible preservation of existing equipment, which in terms of its technical characteristics allows long-term further operation [8]. To confirm the correctness of the decision on this kind of modernization, the possibility of carrying out a mathematical experiment using simulation modeling is quite important [1, 4, 8, 16]. This method allows to increase the efficiency of reconstruction, reduce the time and cost of conducting a full-scale experiment, as well as the introduction of new equipment into commercial operation [17].

It is known that the normal functioning of new, high-performance cold rolling shops is impossible without the use of APCS. Their application gives positive results, but it is especially necessary on the main technological unit - a rolling mill, where the following operations are currently automated: inserting and removing rolls, setting the strip in the crate, setting the work rolls in working position, transshipment of work rolls and so on [1, 18]. The quality of the products to a large extent depends on the operation of automatic systems that control the rolling process itself. These include systems:

- automatic control of strip thickness (ACST).
- automatic tension control (ATC).
- automatic regulation of the profile and shape of the strip (ARPSS).
- automatic supply of cooling-lubricating liquid (ASCLL).

An analysis of publications on modeling and control of multi-mass electromechanical systems with elastic links, variable moments of load and inertia, a wide range of changes in operating speeds showed that it is promising to develop control systems that are stable with an unlimited increase in gain and guarantee an aperiodic transient with minimal overshoot and zero static mistake.

In this regard, the urgent task is to develop a control system using a set of interconnected multidimensional models of electromechanical equipment for cold rolling mills that meets the following requirements: the ability to separately control stand motors and winding-unwinding mechanisms; maintaining the required acceleration and deceleration rate by the technology; the ability to quickly stop the mill as a whole and individual units; ensuring the maintenance of the necessary stand speed, strip tension, minimizing overshoot in transient conditions.

1.4. Control tasks of cold rolling mills electric drives

When processing a steel strip in rolling mills, sections of units are connected by a single technological process. In this case, the shafts of the drive motors are connected to the mechanisms by a spindle, which can be represented in the form of elastic mechanical gears (elastic ties of the first kind), and the sections themselves are connected through the processed material, which forms elastic ties of the second kind in the first approximation [4].

When considering such a complex dynamic system, the following problems arise [19]:

- assessment of the effect of elastic bonds of the first and second kind on the dynamics of electric drive systems (BOT);
- the choice of ways to optimize the dynamics of interconnected BOT.

The control system for technological units connected through the processed material is a multidimensional multiply connected system, in the general case with variable parameters, in which the electrical, mechanical and technological factors are interconnected in a certain way. In this case, each unit has its own control system, but since the units are connected by a single technological process, the control signal must be formed taking into account the need to coordinate individual units.

One of the main requirements that are imposed on a multi-motor drive system of a rolling mill is to ensure strip transportation at a given speed and maintaining a given tension in all operating modes in all sections of the unit or any of its parts [8]. This is a prerequisite for ensuring the quality of the rolling process, maintaining the quality and thickness of the transported material, the quality of the roll’s winding, reducing the number of strip breaks. To fulfill this requirement, one of the mechanisms of the unit or its individual part is defined as the leading one. Its speed determines the speed of the strip, and, consequently, the performance of the unit. The ED of this mechanism is performed with an ACS of the speed of the electric motor. The remaining mechanisms, respectively, become driven, determining the magnitude of the tension of the strip in the corresponding sections of the unit. The ED of these mechanisms are performed with ACS of tension. In this case, direct and indirect tension control systems can be applied to control the electric drives of the corresponding mechanisms.

A sufficiently important condition for the normal rolling process is to maintain a predetermined constant or variable ratio of rotational speeds of rolling engines and winder motors both in the steady state mode of metal speed and during periods of acceleration and deceleration of the mill [20]. The very choice of the power supply method for rolling engines is made taking into account considerations about the possibility of obtaining flexible control of the rotational speed of rolling engines and winding-unwinding device motors. For modern powerful continuous and reversing mills, the power of the rolling engines of each of the stands, as well as the engines of the unwinders and winders, is carried out from separate thyristor converters [2].

Control systems for DC motors of CRM EDs, built on the principle of subordinate regulation and tuned to modular or symmetric optimums, make it easy to synthesize control systems with the required transient quality indicators. In order to make the system of subordinate speed control astatic with respect to load, the proportional speed controller is usually replaced by a proportional-integral one. A higher quality of transients in single-band direct current drive systems during the development of both controlling and disturbing influences can be achieved by introducing additional positive feedback on static current or replacing feedback on the full current of the armature circuit with feedback on its dynamic component while maintaining the speed regulator’s P- structure. To improve the dynamics of astatic systems of subordinate speed control, it is also possible to close the current circuit by the dynamic current identified by the state observer or supplement the system with a channel for compensating the influence of the load on the static properties of the drive using the identified moment of static resistance [9].

1.5. Control means for the electromechanical complex of cold rolling

Modern means of automation of the technological process of rolling include various types of computing devices (CD), which include industrial computers, specialized controllers, single-chip microcircuits, built-in single-board computers, control computing systems. As a rule, in the automation systems of technological objects, CDs carry out organizational and applicational functions.

Organizational functions provide control in the CD itself and serve to maintain the structure of the system in the required state and to manage device configurations.

Applied functions are determined by the specific tasks of monitoring and managing a technological object. These include: collection and primary processing of data; process control; process management, its stabilization and optimization; auxiliary functions [21].

Collection, primary data processing and control of the rolling process correspond to the group of information functions of the CD. In more detail, these functions can be represented in the following form: collection and storage of information about the state of the technological process and control system devices; continuous monitoring of compliance of rolling parameters and control system with acceptable values; issuing information to the operator about the mismatch of the parameters with the permissible values; continuous or periodic recording of values of controlled parameters; alarm in the event of an emergency; operational communication with CD of other levels and a number of other functions. Management, stabilization and optimization correspond to the group of aircraft control functions. These functions are as follows: starting and stopping the rolling complex or its sections; the formation of control actions providing the maintenance of a given rolling mode; performing calculations to determine a number of technological parameters (solving parametric identification problems); automatic process optimization in accordance with the accepted quality criterion.

In this regard, requirements are put forward, firstly, to the choice of computing device and software, and secondly, to numerical methods and algorithms that implement a particular task. Not always, but most of the time these requirements are interconnected.

Programmable controllers and information management systems with a wide range of intelligent modules are widely used in modern automated control systems for the technological process of rolling [22]. The named CDs are built on the basis of microprocessor technology. Modern microprocessors (MP) are characterized by: developed register structure; the conveyor principle of executing a prefetched command that increases channel throughput ability; distributed hardware-firmware control device that provides increased performance of MP; multiplexed generalized address / data channel with the possibility of expanding the address space; developed means of building multiprocessor systems; multifunctionality of the use of outputs of a large integrated circuit, which allows you to adapt the MP to the level of complexity of the developed system [21, 23]. It is these structural solutions that determine the main technical parameters and functionality of modern MP.

The programmable controller has a large set of functional modules, network tools, means for displaying data on the process, programming tools and remote control (portable remote controls). The input / output modules of analog and discrete information contain nodes for galvanic separation of signals, a node for multiplexing analog input signals, as well as converters: analog-to-digital (ADC); digital-to-analog (DAC), discrete-to-digital (DDC) and digital-to-discrete (DDC).

The configuration of the controller determines the communication system of the channels with the inputs and outputs of the controller, as well as options for the interaction of channels. In the general case, the channel inputs are connected not only to the controller inputs, but also to the outputs of other channels. Such an opportunity allows one to implement a multiply connected (interconnected) structure in which correction signals are generated, cascade circuits are organized, logical switching is performed, and program control is carried out.

Industrial computers currently have the same architecture as personal computers (PCs). In addition, industrial computers have a large range of digital and analog input / output modules, communication boards, expansion cards and accessories [22]. High PC performance, a large range of modules and efficient software tools allow one to solve a wide range of automation tasks.

1.6. Optimization methods of control systems for electric drives of cold rolling mills

The main disturbing influences at the mill are destabilizing signals from the rolled metal (temperature, front and rear tension, chemical composition, rolled thickness, width, rolling speed, etc.) and from the stands (heated work rolls, work roll wear, change in the elastic modulus of the work roll system, a change in the friction in the bearings when the rolling speed changes, the eccentricity and ovality of the rolls). The technological processes of rolling workshops are characterized by frequent changes in parameters, the appearance of random factors, various kinds of nonlinearities, noise and interference, many feedbacks and other factors that impede the implementation of control strategies based on the idea of linearization and stationarity of systems.

In this regard, it is urgent to develop a set of interconnected mathematical and computer models of electromechanical equipment for cold rolling mills that take into account the elastic bonds between the engine and the actuator, the elastic coupling of the mechanisms through the rolled metal strip, the possibility of changing the thickness, as well as the effect of breaking and reversing the rolled strip. Using this mathematical description of the rolling process in the synthesis of speed and strip tension control systems allows maintaining the necessary stand speed, strip tension, minimizing the overregulation in transient conditions with zero static error.

The development of control algorithms for electric drives of technological facilities for various industrial purposes is usually carried out taking into account two most important quality assessments - speed (taking into account restrictions on power consumption) and related performance and integral quadratic estimation of control errors and the associated quality of the process. Achieving positive results in the second assessment determines (taking into account energy resources) a positive result in the first assessment.

In theory and practice of controlling interconnected electromechanical systems, one strives to obtain normalized dynamic processes based on standard control algorithms for small and large changes in variables, taking into account the totality of the physical features of the technical means on the basis of which the electromechanical system is implemented.

For autonomous systems with small changes in variables, these are settings of control loops that are “optimum modulo” (OM) and “symmetric optimum” (CO), widely known in the methods of cascade (slave) control, and in modal control methods — standard root distributions of characteristic polynomials [16].

From a single point of view, control algorithms for local and interconnected objects in the modes of small and large deviations of variables are synthesized. Based on the aggregation procedures (obtaining from the original model an equivalent model with fewer variables) and attraction (organizing attracting sets in the phase space), control algorithms are synthesized and provide optimality in speed and accuracy.

In modern synthesis technologies, computer programs that implement all of the above methods are widely used. These programs support the high speed of computational procedures, which is ensured by the use of effective numerical algorithms for solving systems of equations, searching for the roots of polynomials and eigenvalues of matrices, conditional extrema of functions, etc. [24]. The most important requirement for software and methodological support is to free the designer from auxiliary actions that distract from solving the main problems. The most important requirement for software and methodological support is to save the designer from auxiliary actions that distract from solving the main problems. In the synthesis, the main task is to select the elements and structure of the system to meet the requirements for its behavior. Computer synthesis methods are supported by software tools that are most convenient for the designer. In the course of the technological process, adjustments to individual parameters are possible (according to actual process data), aimed at improving the rolling performance. One of these indicators is the separation of specific energy in the stand, the group of stands and in the rolling mill as a whole. In particular, when changing the assortment or deviating the temperature and physicomechanical properties of the workpiece from the values provided by the technological instructions, it is possible to adjust the rolling speed in order to minimize specific energy. This correction can be performed by an automatic optimization system implemented on technological controllers and is a secondary system with respect to speed control systems, the ratio of stands speeds, tension, loop and deflection of the rolled material. Automatic optimization systems can also correct variable control algorithms in order to minimize dynamic errors. In particular, when managing rolled tension close to zero (approaching free rolling), the dynamic deviations of the front and rear tension in the inter-cage spaces should be minimized [23]. This can be done automatically, by evaluating the tension regulators, leading to minimization of these estimates.

1.7. The relevance of applying mathematical modeling to the improvement and optimization of electric drive control 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].

One of the important stages of mathematical modeling is the transition from technical and conceptual formulations of the problem to mathematical, that is, a description of the object under study in the language of mathematical formulas and equations. Therefore, often there is a need to “break down” the task into several simpler subtasks, which have either known solutions, or which can be solved using proven methods. For this purpose, it is convenient to use structural modeling methods, which allow simplifying the problem at the stage of formulation by studying the internal structure of the object in question, studying the properties of individual elements of the object and the relationships between them. At the same time, structural diagrams, relationships of subsystems and their elements are easier to depict graphically, which simplifies the analysis of objects of study [4].

Positive experience has been accumulated in the world on the creation of mathematical models of the cold rolling process or its individual coordinates, however, many of these models have a limited scope, issues of modeling these systems are insufficiently addressed taking into account variable multi-mass parameters simultaneously interconnected through the rolled metal and the “long shaft” of electromechanical systems (EMS) of cold rolling mills (CRM). It is difficult to change the structure of the studied EMC both in the electrical and in the mechanical parts, which does not allow creating constructionally different models of rolling production units for preliminary experiments at the design stage of new control systems.

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 block diagram of the CRM is shown in Figure 1.1.

Currently, in engineering practice, various software products are used to solve research and optimization problems: specialized packages; program libraries; mathematical programming systems. There are techniques and algorithms that are well developed which allow you to explore the modes of operation of complex electromechanical complexes; analyze their quality, calculate frequency characteristics and pulse transition functions; to study the dynamics of complex systems containing elements with nonlinear characteristics; calculate optimal processes in the presence of limitations.

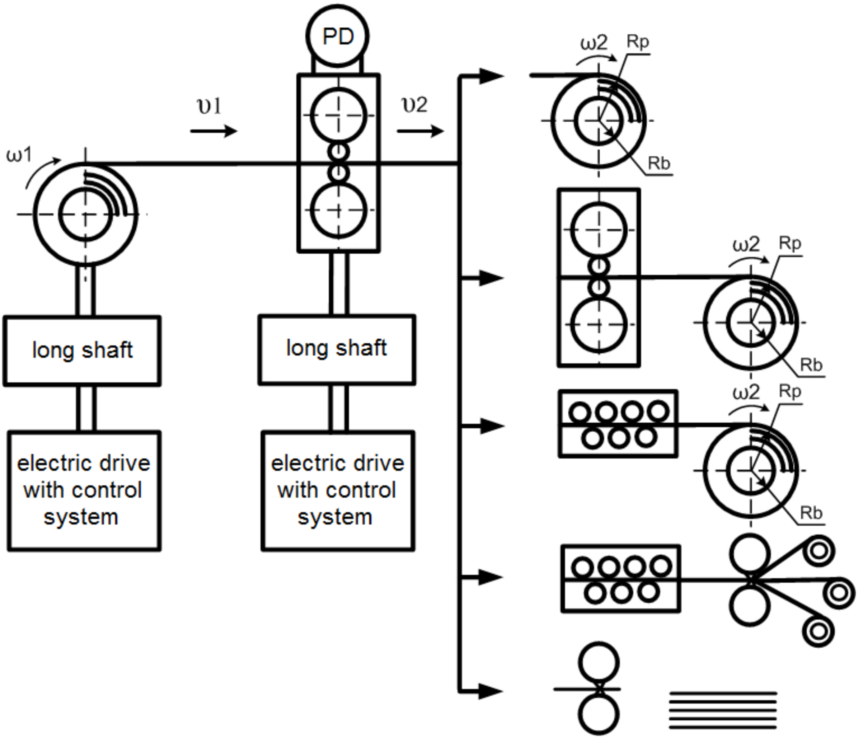


Figure 1.1 - Structural diagram of a cold rolling mill

Therefore, when choosing one or another software product, it is necessary to take into account the type of mathematical description of the electromechanical system under study, the features of the representation of the model data, by what order of differential equations or by what order and type of matrix (symmetric, degenerate, etc.), or how many structural elements of the graph an electromechanical system is described, the type of presentation of the calculation results, the number and type of non-linear characteristics that describe the control and disturbing influences, the flexibility of changing the mathematical model.

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

Chapter 2.

MATHEMATICAL DESCRIPTION OF ELECTROMECHANICAL PROCESSES AND THEIR INTERACTION IN THE BASIC MECHANISMS OF COLD ROLLING MILLS

There are a fairly large number of different types of designs of cold rolling mills, depending on the requirements for the products. On skin-rolling and continuous mills rolling in one direction is produced, in accordance with the technological features of production, therefore such mills can be equipped with one or more rolling stands. The reversible mills produce rolling in both directions, therefore they are equipped with two winders, one of which is installed in front of the working stand, and the second behind the stand. Single-stand reversing mills are used for rolling sheets of small batches with a wide assortment of sizes, as well as for rolling alloy sheet steel. They require an individual approach to the choice of speeds, reductions and other rolling parameters [13].

Changing the rolling parameters and the settings of the ED control loops on a running mill without stopping it is almost impossible. Therefore, mathematical modeling with experimental verification of the results is accepted as the most economical research method.

The advantages of mathematical modeling include the possibility of highlighting the most important properties of an object for research, abstracting from its non-essential characteristics. Modeling allows us to formulate new hypotheses and gain new knowledge about the object, which were not available during its study. The construction of the model and the formalization of the relations between its elements allows us to eliminate gaps in knowledge about the object and identify new qualitative problems that could not initially be foreseen. Modeling complex interconnected objects, such as cold rolling mills, makes it possible to avoid too high costs necessary for their direct research.

2.1. Winding-unwinding device

Automated electric drive of winders and unwinders of cold rolling mills is among the most complex industrial electric drives. The complexity and characteristic differences are due to the main function of these drives - to regulate with high accuracy the tension of the wound strip with a variable roll diameter, load, moment of inertia during rolling and maintaining the various linear speed of the strip required by the technology.

The main objective of the development of the theory and practice of the use of electric devices for winding and unwinding mechanisms is to increase the accuracy of tension control and minimize dynamic and static errors.

Peculiarities of ED of winders and unwinders of CRM associated with the need to take into account the variable parameters of the rolling process, with the presence of various kinds of elastic bonds, introduce certain complications both in the mathematical description, calculations, and in the structure of the drive, its control system [25]. According to technological requirements, the winder's ED must carry out such a winding of the strip, in which the rolls have the correct cylindrical shape with a flat side surface. For rolling mills, a necessary requirement is also to maintain a constant strip thickness in a single pass. In addition to a number of technological factors, compliance with these requirements is significantly affected by the magnitude and nature of the strip tension. Therefore, the main technology requirement for such systems is to ensure constant tension, both at steady-state speed and in transient conditions.

When winding, the strip is in an elastic-stressed state. The specified tension must be maintained in all operating modes of the mill: at zero speed (rest mode), during acceleration and deceleration, when rolling at a steady speed. The required accuracy of the tension control is determined by its influence on the quality of the products and, first of all, on the longitudinal thickness difference of the strip [11, 25]. Maintaining a given tension is also required to obtain the necessary flatness of the strip (lack of waves, wariness, corrugation) and ensuring the density of the roll's winding.

The tension of the strip is created with the help of electric winding devices: winders and unwinders. On reversible single-stand cold rolling mills, the winder and unwinder are installed on opposite sides of the working stand, and after reversing the direction of metal rolling, the winder and unwinder are interchanged [5, 13]. The winder electric drive operates in a motor mode, providing the output tension of the strip. The unwinder engine is in generator mode. The driving engine in this case is the rolling stand motor.

During the rolling process, the strip is unwound from one winder and wound onto another, while the diameters of the rolls are continuously changing (Figure 2.1). To maintain a constant linear rolling speed, it is necessary to reduce or increase the speed of the engine of the unwinding mechanism depending on the operating mode of the mill. The change in the diameters of the rolls during the entire rolling cycle should be taken into account to maintain the constant tension of the strip of rolled metal [2, 3, 26].

The angular speed of the engine is determined taking into account the linear speed of the strip υ and the current value of the radius of the roll R_p from the ratio:

$$\omega = \upsilon \cdot i / R_p \, , \qquad (2.1)$$

where υ – linear speed of the strip movement($\upsilon = Const$),
i – gear ratio.

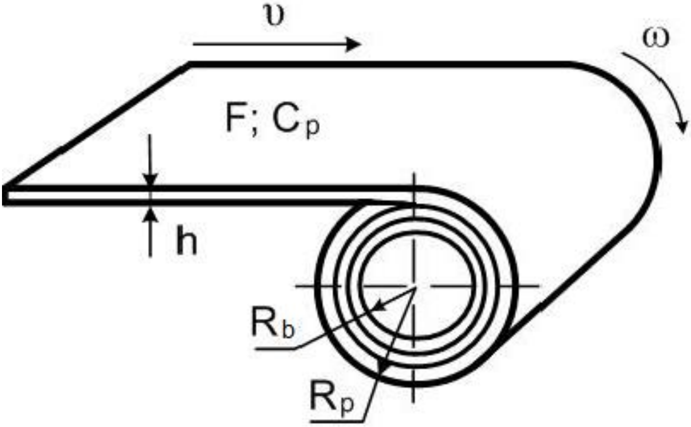


Figure 2.1 - Scheme of winding a strip into a roll

The moment of resistance on the shaft of the winding-unwinding device is found through its components [13]:

$$M = M_1 + M_2 + M_3 + M_4, \tag{2.2}$$

where M_1 – useful moment needed to create a given tension F;
M_2 – the moment necessary to overcome mechanical losses in the "engine - mechanism" system;
M_3 – the moment spent on the deformation of the bending of the strip when winding the roll;
M_4 – dynamic moment, providing acceleration of the winding device during acceleration and braking, as well as when changing the radius of the roll.

Depending on the operating mode of the mill (rolling in the forward or reverse direction), the ratio between the mentioned components of the moments can be different. The useful moment is determined by the value of the force F and in some cases significantly exceeds the value of the loss moment, which allows us to neglect the influence of the latter on the operation of the mill [26]. The thinner the rewound strip of metal, the less is the moment value.

In the process of winding with constant tension, the useful moment is directly proportional to the radius of the roll:

$$M_1 = FR_p. \tag{2.3}$$

With constant strip tension (regardless of radius), the net power is proportional to the strip speed and is found from the ratio:

$$P_1 = F\upsilon. \tag{2.4}$$

Expressions (2.3) and (2.4) can serve to construct an automatic control system with an indirect measurement of tension. If we neglect the difference between the moment on the motor shaft and the useful moment (assuming that the influence of the last three terms in expression (2.2) is small or will be compensated), and also neglect the mechanical losses of the electric motor, then we can assume that the electromagnetic moment of the engine should be changed according to the law [23]:

$$M_{\text{EM}} = FR_p / i. \tag{2.5}$$

On the other hand, the moment of the DC motor of independent excitation is equal to:

$$M_{\text{EM}} = C_d \Phi I_A, \tag{2.6}$$

where Φ and I_A – magnetic flux and motor armature current, respectively;
C_d – motor constructive constant.

As a result of comparing the last two expressions, the most common law of indirect control of the strip tension can be formulated: for a given constant tension F, it is necessary to keep the armature current constant, changing the excitation flux Φ of the motor in proportion to the radius of the roll.

From the generalized Lagrange equation, the dynamic moment is determined by this equation:

$$M_4 = J_\Sigma(t)\frac{d\omega(t)}{dt} + \frac{\omega(t)}{2}\cdot\frac{dJ_\Sigma(t)}{dt} = J_\Sigma(\alpha)\frac{d\omega(t)}{dt} + \frac{\omega^2(t)}{2}\cdot\frac{dJ_\Sigma(\alpha)}{d\alpha},$$

however, one of the components of the dynamic moment can be neglected with a slow change in the moment of inertia, then the dynamic moment on the motor shaft is:

$$M_4 = J_\Sigma \frac{d\omega}{dt}, \tag{2.7}$$

where J_Σ – the total moment of inertia of the rotating parts of the winder together with the roll, reduced to the motor shaft.

Based on (2.1), let us determine the derivative of the angular velocity:

$$\frac{d\omega}{dt} = \frac{i}{R_p}\frac{d\upsilon}{dt} - \frac{\upsilon i}{R_p^2}\frac{dR_p}{dt}. \tag{2.8}$$

In this case, the dynamic moment M_4 of the engine can be represented in the form of two components [5]:

$$M_4 = M_{41} + M_{42}. \tag{2.9}$$

The component M_{41} is required to create acceleration $d\upsilon/dt$ for a given radius of the roll R_p and is equal to:

$$M_{41} = \frac{J_\Sigma i}{R_\text{p}}\frac{d\upsilon}{dt}. \tag{2.10}$$

The component M_{42} accounts for the change in the radius of the roll R_p and is calculated in the form of:

$$M_{42} = -\frac{J_\Sigma \upsilon i}{R_\text{p}^2}\frac{dR_\text{p}}{dt}. \tag{2.11}$$

The moment of inertia J of the roll consists of two parts: a constant moment of inertia J' (rotating parts of the mechanism and the engine's own moment) and a moment of inertia of the wound (unwound) metal roll [13] changing with the roll's radius:

$$J'' = m(R_p - R_б)^2 / i^2. \tag{2.12}$$

In the last expression, the parameter m is calculated as:

$$m = \rho \cdot 10^3 \pi \left(R_p^2 - R_б^2 \right) b \tag{2.13}$$

and represents the mass of material in a roll with specific density ρ [$кг/м^3$], with current radius R_p, radius of the barrel (on which the material is wound, R_b) and material thickness b.

Given the latter the obtained result is:

$$J = J' + J'' = \frac{\rho \cdot 10^3 \pi b}{2 \cdot i^2} R_p^4 + J_0, \tag{2.14}$$

where

$$J_0 = J' - \rho \cdot 10^3 \pi b R_\mathrm{b} / 2i^2. \tag{2.15}$$

Substituting them in (2.10) and (2.11) we obtain:

$$\left.\begin{aligned} M_{41} &= \left(\frac{\rho \cdot 10^3 \pi b}{2i} R_\mathrm{p}^3 + \frac{J_0 i}{R_\mathrm{p}} \right) \frac{d\upsilon}{dt}, \\ M_{42} &= \left(\frac{\rho \cdot 10^3 \pi b}{2i} R_\mathrm{p}^2 \upsilon + \frac{J_0 \upsilon i}{R_\mathrm{p}^2} \right) \frac{dR_\mathrm{p}}{dt}. \end{aligned}\right\} \tag{2.16}$$

The relationship between the radius of the roll and the speed of rewinding can be established by writing expressions for changing the volume of the roll ΔV_p within the time *t*, during which the radius of the roll varies from R_b to R_p:

$$\Delta V_p = \pi \left(R_p^2 - R_b^2 \right) b. \tag{2.17}$$

On the other hand, the volume of the roll ΔV_p can be calculated through the length l_p of the rewound strip during the time *t* (with its known thickness *h* and width *b*) from the following dependencies [3]:

$$\left.\begin{aligned} l_p &= \int_0^t \upsilon dt, \\ \Delta V_p &= b h_{var} \int_0^t \upsilon dt. \end{aligned}\right\}, \tag{2.18}$$

where $h_{var} = h_{const} \pm \sigma$ – varying thickness of the strip, σ – thickness deviation.

From the expressions (2.17) and (2.18), the current value of the radius of the roll is determined from the relation:

$$R_{\text{p}} = \sqrt{R_{\text{b}}^2 + \frac{h_{\text{var}}}{\pi}\int_0^t \upsilon dt}\ , \tag{2.19}$$

and its derivative is found in the form:

$$\frac{dR_{\text{p}}}{dt} = \frac{h_{\text{var}}\upsilon}{2\pi\sqrt{R_{\text{b}}^2 + \frac{h_{\text{var}}}{\pi}\int_0^t \upsilon dt}} = \frac{h_{\text{var}}\upsilon}{2\pi R_{\text{p}}}. \tag{2.20}$$

After substituting (2.19), (2.20) into expression (2.16) for M_{42}, the obtained result is:

$$M_{42} = -\left(\frac{\rho \cdot 10^3 \pi b}{2i} R_{\text{p}} + \frac{J_0 i}{R_{\text{p}}^3}\right)\frac{h_{\text{var}}}{2\pi}\upsilon^2. \tag{2.21}$$

During unwinding, when the sign of dR_p/dt is negative, the sign of M_{42} will change to the opposite one. Expressions (2.14) - (2.21) make it possible to calculate the time dependence of the roll radius, moment of inertia, and dynamic time moments for known parameters R_b, h_{var}, J_0, ρ, b and a given nature of the change in speed over time.

The following requirements are imposed on drive control systems for winding-unwinding and tensioning mechanisms: they must provide two operating modes - regulation of the engine speed and regulation of the strip tension [1]. The first mode is auxiliary and does not have strict requirements for the quality of regulation. This mode is used to insert a strip, transport it without tension, and limit the engine speed when the strip breaks.

In the frequency control mode, it is necessary to provide: push mode in both directions with a given rate of change and level of speed; accuracy of maintaining speed of about 5-10%; time of the increase in speed during the push without reaching the current limitation of 0.1 ... 0.2 s.

In tension control mode: synchronization of the speed of the drive of the winding-unwinding mechanisms and the drive of the rolls of the mill stand; the range of speed regulation in the mode of maintaining tension is not more than 1:50 (determined by the product of the multiplicity of the rolling speed of 10...20 by the multiplicity of the change in the diameter of the roll of 1.5...4.0); tension control range for different mills is 1:5...1:20, in some cases 1:50; the accuracy of maintaining a constant tension in the steady state is 3...12%; the accuracy of maintaining a constant tension in the dynamic mode is 3...8%; time for working out a step-by-step task of tension is not more than 2 s, overshoot is not more than 10%; limitation of exceeding the speed of the barrel when the strip is broken at a maximum speed of 5%, at insertion speed - 15%, followed by a stop of the drive.

The control systems for winders and unwinders are built on the same principle, since these mechanisms are characterized by a close kinematic scheme; winding processes are determined by the same ratios of the basic quantities, and qualitatively identical requirements are imposed on them.

Depending on the measurement of the controlled variable, two methods of regulating the tension are known: direct and indirect. The first assumes the presence of an ACS of tension, closed by deviation, with a feedback signal from the tension meter. For such tension control systems, a signal proportional to tension is used as feedback, which is calculated by the signal from the output of the load sensors (conductors, torsion bars) taking into account the correction of the gravity of the strip, gravity of the loop holder and inertia forces. If the installation of the sensors is difficult, then the second method is used - indirect regulation - by current, EMF of the winder motor, moment developed by the loopholder motor [27]. When using this method, most of the parameters included in it are determined by calculation, which leads to significant errors in determining the tension. However, using microprocessor technology, the error is significantly reduced.

Currently, dual-zone ACS is quite often used in the production of ACS tension, in which the flow corresponds to the speed of rotation of the winder’s barrel. Acceleration to the main speed occurs with the full flow of the engine, therefore, the EMF changes in proportion to the speed of rotation; above the main speed, the flow decreases as the rotation speed increases at the nominal value of the EMF. Thus, in the start-brake modes, a more complete use of the motor power of the winder is provided.

The use of ACS dependent flow control provides an improvement in the technical and economic indicators of the winder's ED: it significantly reduces the armature current at the beginning of the roll’s winding; allows one to select the engine at the actually required maximum rotation speed, taking into account winding a part of the roll during acceleration; allows to reduce the rated power of the engine and power source, if the maximum strip tension is required to be provided at a rolling speed below the maximum; reduces the consumption of reactive energy.

2.2. Rolling stand

It is known that the stand is the main technological equipment of the rolling mill, which deforms the metal due to the rotation of the rolls of the working stands. Rolling can take place in one of the modes: non-reversible (the passage of metal is made only in one direction) or reversible (rolled metal passes between the rolls several times).

The stands are classified according to the number and location of the work rolls, according to the mode of operation. According to the number of work rolls, stands of rolling mills are divided into two-roll, three-roll, four-roll and multi-roll [8]. As a rule, work rolls in which metal compression occurs are driven. Two-roll and three-roll stands are used in cases where the ratio of the diameter of the work roll to its length $D_B/l_B > 0,4$, which provides sufficient bending stiffness of the roll. Such stands are installed on crimping, preparing, sorting and pipe mills. The three-roll stand has one engine, the two-roll stand can have one or two engines with individual or group drive of the work rolls. Four-roll stands, in addition to two workers, performing roll metal compression, have two backup rolls, which makes it possible to increase the rigidity of the work rolls. Work rolls individually powered through gear stands are driven. Depending on the power of the drive, one or two motors, mechanically connected on one shaft are used.

The group electric drive of the stand consists of engine 1, couplings 2, gear stand 3, spindles 4, pressure device, two work rolls 5 (figure 2.2).

The pressure device (pressure screws) are designed to move the upper work roll in the vertical direction to provide the necessary amount of metal compression. The gear stand is designed to transmit from one rotation engine to two or three rolls. It is a gear transmission, which consists of two or three gears of the same diameter, placed in a closed box. Spindles are used to transmit rotation to the rolls from the gear stand. Each such spindle has hinges at its ends. Couplings are made to connect the engine and gear stand.

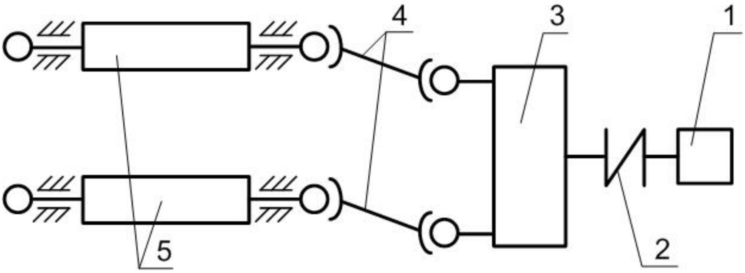


Figure 2.2 - Kinematic scheme of the rolling mill stand electric drive

Let us consider a simple rolling process [1], which is shown on the figure 2.3, where b_1, b_2; h_1, h_2; l_1, l_2, υ_1, υ_2, F_1, F_2 – width, thickness, strip length, linear speed, tension before and after rolling in the stand; ω_d – the angular velocity of the work rolls of the stand.

Simple rolling has the following assumptions:

- metal is homogeneous;
- the work rolls have the same diameter and the same peripheral speed;
- metal is deformed by each roll equally.

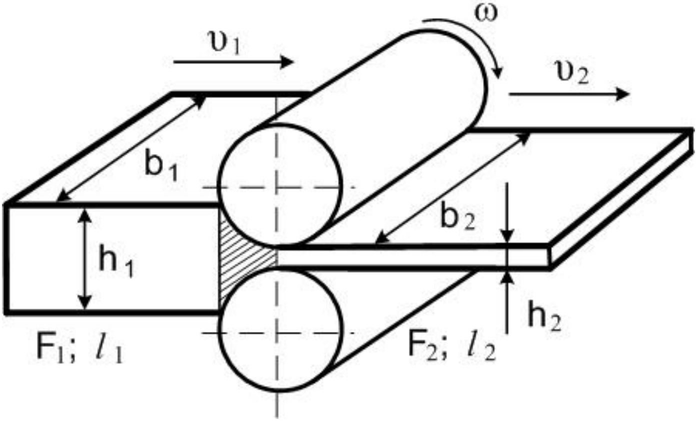


Figure 2.3 - Simple rolling of metal in a stand

Metal rolling can be performed in several passes, that is, several single passes of metal through the work rolls during their rotation. In the process of rolling, the workpiece is elongated by compressing the metal with rolls and correspondingly reducing its cross section due to the fact that the width of the metal as a result of rolling increases slightly. Absolute elongation value:

$$\Delta l = l_2 - l_1, \tag{2.22}$$

as well as the extraction ratio, which is the ratio of the length of the metal after rolling to the length of the metal before rolling.

The expansion of metal during cold rolling is insignificant; therefore, it can be neglected [13]. Then we will have such an expression:

$$\lambda = l_2 / l_1 = F_1 / F_2 = h_1 / h_2 . \tag{2.23}$$

To determine the load of the rolling engine, it is necessary to know the energy that goes into changing the shape of the workpiece, i.e., to determine the pressure forces or the rolling moment created during the processing of metal. There are two ways to determine the rolling moment: analytical according to empirical formulas and using specific energy consumption curves per ton of rolled metal [23].

Let us use the analytical method according to which the moment on the stand motor shaft is equal to:

$$M = M_r + M_f + M_i + M_d \, , \tag{2.24}$$

where M_r – the rolling moment, which is necessary to perform the work of deformation of the metal and to overcome the friction forces between the metal and the work rolls in the deformation zone;

M_f – the moment of additional friction forces in the work roll bearings and gears (gearbox, gear stand, spindles) when rolling metal without taking into account the friction forces that act when the stand is in idle mode;

M_i – moment of the idle mode, that is, of the friction forces that occur in the work roll bearings and gears (gearbox, gear stand, spindles) in the absence of rolling in the stand - free rolling;

M_d – dynamic moment necessary to overcome the inertia forces in transient electromechanical processes with a change in speed.

Let us consider separately the stands of the rolling mill. Remaining within the framework of linear theory, let us assume that the moment of resistance consists of at least two components: the moment of friction M_f and moment of rolling M_r, which are proportional to the speed of rotation of the rolls of the stand, and the latter also depends on the proportionality coefficient of the pressure force F_N from the side of the pressure screws.

Under the assumptions made for these moments, the following equations can be written [26]:

$$\left. \begin{aligned} M_f &= K_{Mf} \, K_h \omega; \\ M_r &= K_{Mr} \, \omega F_N . \end{aligned} \right\} , \tag{2.25}$$

where K_{Mf}, K_{Mr} - proportionality coefficients of friction and rolling, respectively;

K_h – coefficient of variable strip thickness, $K_h = h_{var} / h$.

As already mentioned, one of the main operations of the cold rolling mill is performed using rotating work rolls located in the working stand. Therefore, when designing and modernizing the main electric drives of mill stands, it is important to take into account the requirements for them [1]. Namely:

- smooth start and braking in the minimum time;
- stepless speed adjustment from insertion 0.5 ... 1 m/s to a maximum working 30 m / s in the range 30:1 ... 50:1;
- regenerative braking using a reversible group of valves (50% power);
- coordination of rolling speeds between stands and winding devices with an accuracy of 1%;
- ensuring the necessary values of the strip tension in all operating modes of the mill with an accuracy of 3...5%;
- the possibility of joint and separate control of the motors of stands and winders;
- the ability to change the speeds of the engines of each stand while maintaining the specified acceleration and deceleration rates;
- creating a tension of rest;
- the possibility of pushing work;
- the ability to change the degree of rigidity of the mechanical characteristics of the engines of the main drive;
- automatic deceleration of the mill when approaching welds at the end of rolling;
- emergency braking when the strip breaks.

The mathematical model of the rolling stand as an object of multiconnected regulation should describe the relationship of the main control and disturbing influences with adjustable and measured parameters [17]. There are many models that describe the set of parameters that affect the rolling stand, however, when presenting the stand model as a multidimensional and interconnected object, it is necessary to take into account parameters such as the tension of the rolling strip and the rolling speed. Through these parameters, the crate is connected with both subsequent and previous mechanisms: stands and coilers. Interconnections through forward tension and strip thickness are influenced by variables in all subsequent interstand spaces, and the strip entry speed, which determines the back tension together with the speed of the previous stand, transfers the influence of the control actions of this stand to previous interstand spaces. In addition, controlled and uncontrolled disturbances can be applied to each stand — the first of them includes fluctuations in the input thickness and back tension of the strip, the second includes changes in the coefficient of friction in the work roll gap, the mechanical properties of the strip, and others [28]. Based on the models, automatic tension control systems are being developed that can stabilize the rolling process and improve product quality. On existing CRMs, local ACSs are made primarily in the form of feedback systems acting on control variables of one or more stands as a function of the deviation of the controlled variable. The presence of direct and feedback between separate stands negatively affects the operation of such systems due to the mutual influence of individual control loops. The elimination of these relationships requires the introduction of complex cross-links between individual regulators.

An analysis of the dynamics of the control systems relative to the speed of the electric motor [19], when applying the P-speed controller, showed that the ARS behaves stably only at low values of the gain of the controller, at which the stand's work roll ED does not provide the required static accuracy of maintaining the work roll speed necessary for normal operation of CRM [7].

Requirements for the CRM stand's ED ACS [3]:

- exact mismatch of the rolling speeds between the stands and winding devices in full accordance with the value of the actual extraction for all operating conditions of the mill;
- providing technologically necessary values of the tension of the strip between the stands and the winder both in the steady rolling mode, and during accelerations and decelerations of the mill, as well as during a stop.
- speed control from insertion to maximum working speed with dual-zone control should be smooth and vary widely;
- the ability to implement separate and simultaneous regulation of the speed of rotation of the motors of the mill stands in the presence and absence of metal in the mill stands.

2.3. Straightening machine

Straightening machines are designed to give the rolled material a flat and smooth surface (for sheets) or the correct geometric shape in length (for long sections). In accordance with this, the correct machines are divided into two groups: sheet-correcting and sort-correcting.

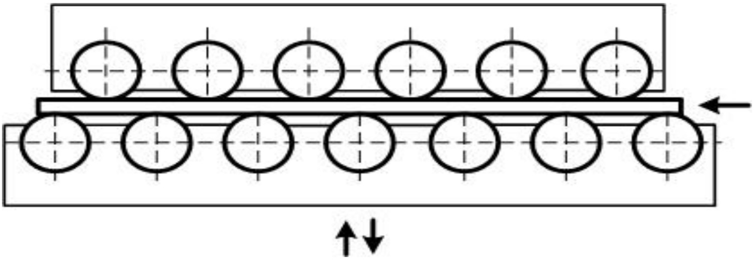


Figure 2.4 - Sheet-straightening machine with parallel arrangement of rollers

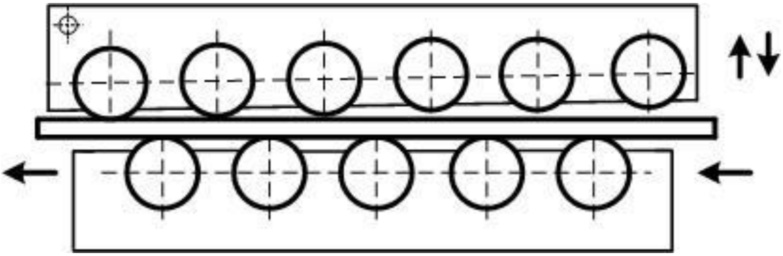


Figure 2.5 - Sheet-straightening machine with an inclined arrangement of rollers

The multi-roller straightening machines with parallel (Figure 2.4) or inclined (Figure 2.5) arrangement of rollers are the most widely used for straightening sheets in CRW. The first ones straighten thick (over 12 mm) sheets, and the second ones straighten thin ones.

If the rollers are arranged in parallel, then the sheet bends equally along the entire path of its movement; if it is inclined, then the greatest bend takes place under the first rollers; as the sheet advances, its deflection decreases, and in the last rollers, the curvature is completely eliminated, which is an advantage of machines with an inclined arrangement of rollers.

The main parameters of multi-roll sheet straightening machines: roller pitch, diameter, roller barrel length and thickness of the sheets to be straightened on this machine. The pitch of the rollers determines the quality of the straightening and the amount of pressure on the rollers of the straightening machine. Editing accuracy increases with decreasing the pitch of the rollers. However, this simultaneously increases the pressure on the rollers, which makes it difficult to design the machine. The speed of straightening is selected depending on the required performance of the machines and the line as a whole.

The electric drive of the rollers of the straightening machines operates in continuous operation with a constant load. The metal feed rate to the straightening machine is usually very high, and the pauses in the main drive are negligible. The operating mode of the straightening machines is irreversible, however, in the control schemes of the electric drive of the rollers, the possibility of reverse is provided, which is necessary during revisions of machines or in the elimination of accidents.

Most roller straightening machines require adjusting the speed of straightening in order to obtain the optimal mode for various grades and sections of rolled metal. The control range is determined in each case by the specific operating conditions of the straightening machine.

For the main electronic drive of the straightening machines, as a rule, DC motors of independent excitation with a speed control range of up to 3:1 due to the weakening of the magnetic flux are used.

If it is assumed that the leveling machine is a mechanism similar to the cage with upper and lower rolls without pressure screws, then the mathematical description of the leveling machine will take the form [5]:

$$M = M_r + M_f + M_i + M_d \,, \tag{2.26}$$

where M_r – the straightening moment, which is necessary to perform the work of deformation of the metal and to overcome the friction forces between the metal and the work rolls of the straightening machine in the deformation zone;

M_f – the moment of additional friction forces in the work roll bearings and gears (gearbox, gear stand, spindles) when straightening the metal without taking into account the friction forces that occur when the machine is idle;

M_i – idle mode moment, i.e. the friction forces that occur in the work roll bearings and gears (gearbox, gear stand, spindles) in the absence of straightening in the straightening machine;

M_d – dynamic moment necessary to overcome inertia forces in transient electromechanical processes.

2.4. Direct current drive motors for rolling machinery

Technological requirements for the depth and smoothness of speed control, as well as for the quality of tension control, determine the widespread use of DC motors in the rolling production for electric drives of stands, winders and unwinders of CRM.

The operating mode of the winding motor is cyclic (acceleration, operation at reduced speed, operation during rolling at a steady speed, braking, pause), however, the duration of pauses and transient modes is relatively short, therefore, the calculation of the engine must be performed for a long steady state. The main parameters of this steady state are strip tension and rolling speed. The armature current of the winding motor generally changes during winding as a function of the radius and rolling speed, depending on the applied tension control system. Reducing the time of acceleration and braking of the rolling mill contributes to the growth of its productivity and, which is especially significant, increases the yield of metal. If it is impossible or impractical to increase the acceleration rate of the mill for other reasons, then with a less dynamic winder drive, the error in adjusting the strip tension in transient conditions decreases [25].

The most complex requirements for electric DC machines are presented in electric drives of large rolling mills, where machines with the highest power are used.

When calculating and designing the main drives of reversing mills, one should know the overload capacity of the rolling engine at different speeds of rotation, i.e., have at their disposal the so-called operational characteristics of the engine. The latter determine the dependence of the maximum allowable values of power, current and engine torque on the rotation speed.

For driving the work rolls of CRM, DC motors with a low rated rotation speed are used (40 ÷ 70 rpm).

The small value of the rotational speed of the old-fashioned CRM rolling engines (50 rpm) led to a limitation in the productivity of the mills. This is explained by the fact that due to the presence of a low angular velocity, there is a need to weaken the motor flow already in the first passes, which leads to an increase in its current at specified load torque values, i.e., to overheating of the motor.

There is a point of view [13], which is based on the fact that the intensification of the operating mode of a crimping mill should not be obtained by increasing the rolling speed, but by using increased reductions and thereby reducing the number of passes. The increase in crimping causes the use of engines with a higher rated torque, which can be done by increasing the power of the engines or while maintaining the same power by reducing the nominal speed.

In the last passes, when the metal length is already becoming significant, in order to reduce the rolling time, it is necessary to increase the rolling speed, which is done by weakening the engine field. Rolling metal with a weakened field is carried out at reduced moment values, since the overload capacity of the engine decreases with increasing speed and is inversely proportional to the weakening of the field. The required degree of attenuation of the motor field usually does not exceed 0.5 of the nominal.

An independent excitation motor is the most common type of DC motor. When considering its mathematical description, let us assume that the demagnetizing effect of the armature reaction is compensated, and the inductance of the armature circuit is constant.

The normal circuit for switching on the DCM of independent excitation (IE) is presented in Figure 2.6, where the following designations are adopted: I_A, I_E - currents in the armature and excitation winding circuits (A); E_A - EMF of the anchor (V); and M - angular velocity (rad/s) and torque (N•m) of the engine.

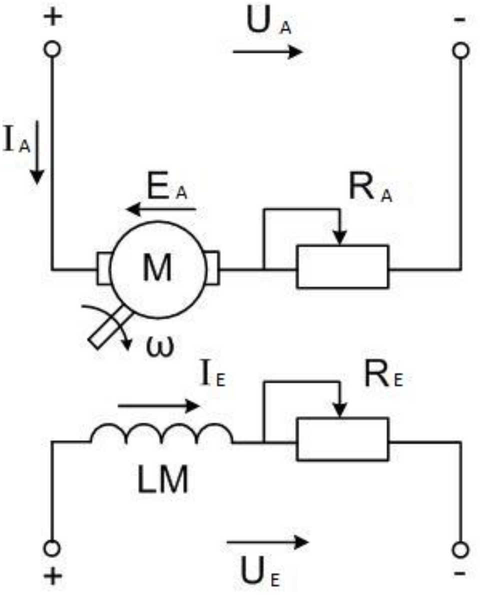


Figure 2.6 - Normal connection circuit of DCM of IE

When steady motion is applied, the mains voltage applied to the motor is balanced by the voltage drop of the armature circuit and the EMF induced in the armature, the voltage balance equation written for the anchor circuit will look like:

$$U_{м} = I_A \cdot R_A + E_A, \tag{2.27}$$

where $R_A = R_{A1} + R_{A2}$ - total resistance of the armature circuit, which consists of the internal resistance of the armature R_{A1} and the resistance of the auxiliary resistor R_{A2} for control of the armature current. I_A.

The structure of R_{A1} includes the resistance of the armature winding, the resistance of the auxiliary pole winding and the resistance of the compensation winding (if the DCM has these windings).

The EMF induced in the engine armature, as is known, is determined by the formula:

$$E_A = C_{м} \cdot \Phi \cdot \omega, \tag{2.28}$$

where $C_м = \dfrac{p \cdot N}{2 \cdot \pi \cdot a}$ - constructive electromechanic constant of the motor (p - the number of pole pairs, N - the number of active conductors of the armature winding, a - the number of pairs of parallel branches (of armature winding) filed in the SI unit system, and in the practical system, the electromechanic constant of the motor $C_e = \dfrac{p \cdot N}{60 \cdot a}$; the connection is the same between $C_м$ and C_e as between ω and n - angular velocity and frequency of rotation, namely:

$$\omega = \frac{2 \cdot \pi}{60} n , \tag{2.29}$$

where $\varPhi$ - magnetic flux of the motor, if the motor is compensated and the armature reaction does not appear, then this is the main flux, the flux created by the excitation current is the MMF of the excitation winding.

Since for the DCM with independent excitation $\varPhi = const$, then from the expression $M = C_м \cdot \varPhi \cdot I_A$ it is obvious that $M = \kappa \cdot I_A$, i.e. $M \equiv I_A$.

Methods of controlling speed by influencing the electric motor can be divided into two main groups:

- methods that provide speed control of the electric motor by changing or adjusting the parameters of the power supply network of the engine, namely, the voltage of the network and the frequency of the network;
- methods that provide speed control of the electric motor by changing the parameters of the electric motor itself (active or inductive resistance of the motor windings, the number of turns of the windings, the number of pairs of poles and so on);

For the considered electric motors in accordance with their electromechanical characteristic

$$\omega = \frac{U_м - I_A R_A}{C_м \varPhi} . \tag{2.30}$$

There are three ways to control the speed:

- by changing the magnitude of the voltage of the supply network ($U_м$);
- by changing the resistance of the armature chain (R_A);
- by changing the magnitude of the main magnetic flux of the engine ($\varPhi$).

Changing the magnetic flux is mainly used to control the speed. This method is widely used in electronic drives due to the simplicity of its implementation and cost-effectiveness, since regulation is carried out in a relatively low-power motor excitation circuit and is not accompanied by large power losses.

The regulation of magnetic flux using this method is carried out only in the direction of its decrease (attenuation) compared to the nominal. An increase in the magnetic flux should be caused by an increase in the excitation current, but since the nominal magnetic flux is created by the nominal excitation current, an increase in the excitation current above the nominal one causes additional unacceptable heating of the motor. The engine is designed and constructed in such a way that its magnetic system is close to saturation even when the engine is in idle mode. That is, the operating point of the motor is located on the magnetization curve within the saturation, therefore, a subsequent increase in the excitation current cannot cause an increase in the magnetic flux.

Magnetic flux can be measured using Hall sensors, but in most cases it is set by the magnetization curve of the motor.

2.5. Interconnection between the actuator and the motor through the long shaft

As a rule, when considering dynamic loads, the mechanical bonds between the moving masses of the system were assumed to be absolutely rigid. It is known that the representation of the mechanical part of the electric drive by the given link reflects the actual nature of the mass movement in the system only on average, since it does not take into account the effect of elasticity of real mechanical bonds. Due to the finite rigidity of these bonds, the mechanical part of the electric drive is an elastic system, the application to which controlling (engine torque) or disturbing (load) influences causes vibrations of the coupled masses that increase the maximum load of bonds and complicate the accuracy of working out the required trajectories of the machine’s working body movement [4, 19].

The possibility of neglecting the phenomenon of elasticity is often associated with the fact that the natural frequency of elastic oscillations of the engine – actuator mechanism (E - AM) system is much higher than the frequencies of existing automatic drive control systems. However, the increased speed of the automatic system, due to the use of thyristor converters and high-quality control system elements, often cannot be realized due to the influence of elastic mechanical bonds.

Consider the E - AM system, in which the concentrated rotating masses of the engine and mechanism are interconnected through a gearbox and a long shaft. Two-mass electromechanical systems in which the kinematic transmission connecting the engine with the actuator body is the elastic link are called systems with elasticities of the first kind. When analyzing such systems, the following assumptions are used [4]:

- the elements of the mass, to which the forces and moments acting in the system are applied, remain undeformed;
- the mass of the elastic links can be neglected or attributed to the given masses;
- the proportionality coefficient between the moment (force) and the deformation remains constant, i.e. the elastic link has constant rigidity;
- the deformation of the elastic links occurs in accordance with Hooke's law and is linear;
- wave processes during deformation can be neglected.

In view of the foregoing, in assessing the dynamic properties of a rolling mill as an object of control, let us apply the mathematical apparatus of the theory of automatic control with corresponding transfer functions and frequency characteristics.

When considering a two-mass stand electric drive system (figures 2.7 and 2.8), the engine *M1* causes the rotation of the work rolls of the stand; ω_{d1} – angular velocity of the engine *M1*; J_{d1} – moment of inertia of the engine and the gearbox, J_{kl} – reduced moment of inertia of the work rolls of the rolling stand; M_{f1}, M_{f3} – external friction moments; C_1 – elastic joint stiffness - long shaft; b_1 – internal damping coefficient proportional to the mismatch of the angular velocities of two adjacent masses; M_{13} – elastic moment; ω_{d1}, ω_{13} – spindle ends' angular speeds; φ_1 и φ_3 – angles of rotation of the long shaft.

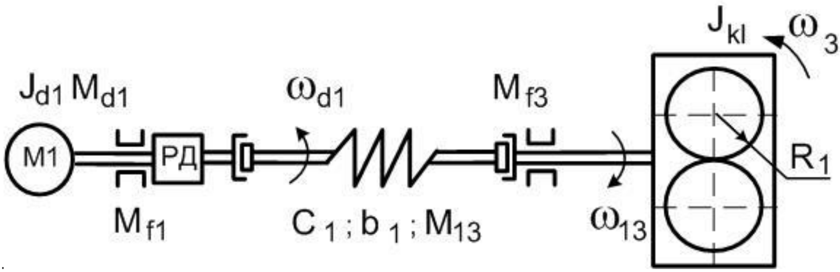


Figure 2.7 - Two-mass electromechanical system of a rolling mechanism with elasticities of the first kind

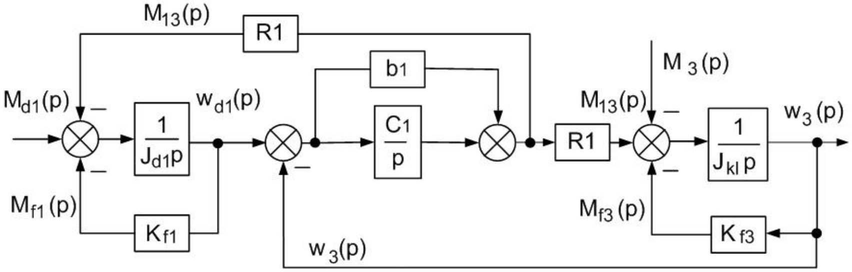


Figure 2.8 - Structural diagram of the mechanical part of one stand in the form of a two-mass electromechanical system with elasticities of the first kind

In this case, the stiffness of the shaft is equal to [26]:

$$C_1 = \frac{c'_s \cdot c'_g}{c'_s + c'_g}, \tag{2.31}$$

where c'_s – shaft stiffness; c'_g – gearbox and couplings' stiffness.

Moments of external viscous friction of the engine and stand:

$$\begin{cases} M_{f1}(p) = k_{f1} \cdot \omega_1(p); \\ M_{f3}(p) = k_{f3} \cdot \omega_3(p), \end{cases} \tag{2.32}$$

where k_{f1}, k_{f3} – coefficients of viscous friction.

Let us write down the equations in operator form (quantities not reduced to the motor shaft are denoted by dashes). The reduction should be made in accordance with the expressions:

$$M(p) = \frac{M'(p)}{i}; \ \omega_3 = i \cdot \omega'_3(p); \ J_{kl} = \frac{J'_{kl}}{i^2};$$

$$k_{f3} = \frac{k'_{f3}}{i^2}; \ C_1 = \frac{C'_1}{i^2}; \ b_1 = \frac{b'_1}{i^2}.$$

Then the system of differential equations is converted to the form of

$$\left.\begin{aligned}
&M_{d1}(p)-\frac{1}{i}\left\{M'_{13}(p)-b'_1\left[\omega_{d1}(p)-\omega'_3(p)\right]\right\}-\\
&-k_{f1}\omega_{d1}(p)=J_{d1}p\omega_{d1}(p);\\
&M'_{13}(p)+M'_3(p)-b'_1\left[\omega_{d1}(p)-\omega'_3(p)\right]-k'_{f3}\omega'_3(p)=J'_{kl}p\omega'_3(p);\\
&M'_{13}(p)=\frac{C_1}{p}\left[\omega_{d1}(p)-\omega'_3(p)\right];\\
&\varphi_1(p)=\frac{\omega_{d1}(p)}{p};\\
&\varphi_3(p)=\frac{\omega'_3(p)}{p}.
\end{aligned}\right\} \qquad (2.33)$$

After reducing these values to the motor shaft, taking into account the gear ratio of the gearbox, we obtain:

$$\left.\begin{aligned}
&J_{d1}p\omega_1(p)=M_{d1}(p)-M_{13}(p)-\\
&-b_1\left[\omega_{d1}(p)-\omega_3(p)\right]-k_{f1}\omega_{d1}(p);\\
&J_{kl}p\omega_3(p)=M_3(p)+M_{13}(p)+\\
&+b_1\left[\omega_{d1}(p)-\omega_3(p)\right]-k_{f3}\omega_3(p);\\
&M_{13}(p)=\frac{C_1}{p}\left[\omega_{d1}(p)-\omega_3(p)\right];\\
&\varphi_1(p)=\frac{\omega_{d1}(p)}{p};\ \varphi_3(p)=\frac{\omega_3(p)}{p}.
\end{aligned}\right\} \qquad (2.34)$$

2.6. Mathematical description of the conditions of the metal strip in the inter-stand gap

Let us consider the metal gap between adjacent units (figure 2.9), where υ_{kl2} – linear velocities of the material movement through the work rolls of the first and second stands; l – distance between axes of adjacent stands; C_p – stiffness of the elastic joint (transported material); F_C - strip tension force.

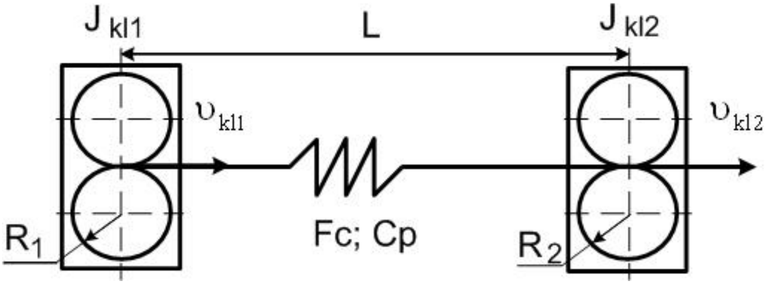


Figure 2.9 - Two-mass electromechanical system of a rolling mechanism with elasticities of the second kind

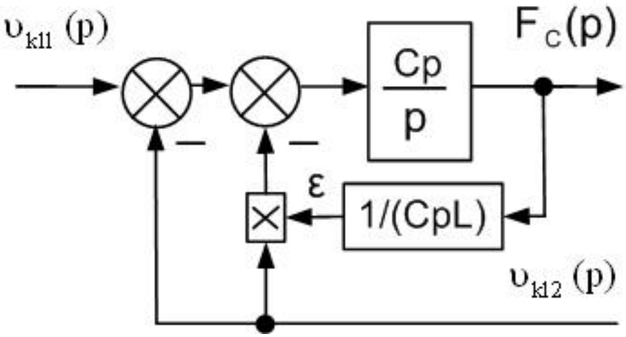


Figure 2.10 - Structural diagram of an elastic joint of the second kind represented by a rolled strip of metal

According to figures 2.3, 2.9 and 2.10, as well as formulas (2.22), (2.23), the deformation of the material in the stretch section with the length of *l* is described by the differential equation [3]:

$$\frac{d\varepsilon}{dt} = \frac{\upsilon_{kl1}}{l} - (1+\varepsilon)\frac{\upsilon_{kl2}}{l}\,, \tag{2.35}$$

where ε – relative extension; υ_1 и υ_2 – linear speeds of the material at the exit of the first and second unit during rolling.

$$\varepsilon = \frac{\Delta l}{l} \tag{2.36}$$

The tension arising in the material is related to the absolute value of the tension Δl through the ratio:

$$F_C = C_p \Delta l = C_p l \varepsilon \, . \tag{2.37}$$

Substituting the value ε from (2.30) in (2.32), we obtain in operator form the equations characterizing the system under consideration [13, 19]:

$$\left.\begin{aligned} F_C(p) = \frac{C_p}{p}\{\upsilon_{kl1}(p) - [1+\varepsilon(p)]\upsilon_{kl2}(p)\}; \\ \varepsilon(p) = \frac{1}{C_p l} F_C(p); \\ \upsilon_{kl1}(p) = R_1\omega_1(p); \;\; \upsilon_{kl2}(p) = R_2\omega_2(p), \end{aligned}\right\} \tag{2.38}$$

where R_1, R_2 и ω_1, ω_2 – respectively, the radii and angular velocities of the first and second stands.

Using (2.30), the mathematical description of the state of the metal between the cage and the winding-unwinding mechanism was supplemented by the ability of reversing

$$F'_C = \begin{cases} \dfrac{C_p}{p}\{\upsilon_{kl1}(p) - (1+\varepsilon(p)\upsilon_{kl2}(p)\}, \; if \; \upsilon_{kl1} - \upsilon_{kl2} > 0 - winding; \\ \dfrac{C_p}{p}\{\upsilon_{kl2}(p) - (1+\varepsilon(p)\upsilon_{kl1}(p)\}, \; if \; \upsilon_{kl1} - \upsilon_{kl2} < 0 - unwinding; \\ 0, \; if \;\; \upsilon_{kl1} - \upsilon_{kl2} = 0 - \text{lack of tension during a} \\ \text{technological pause.} \end{cases} \tag{2.39}$$

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 (2.19), mass (2.13), and the moment of inertia of the roll (2.12).

Let us supplement the well-known mathematical description of elasticities of the second kind [4] 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_C achieves the critical $F'_{C\,max}$, the metal strip breaks, and in the mathematical description the output value of the tension force F'_C is nullified:

$$F'_C = \begin{cases} F_C,\ if\ F_C < F'_{C\max}; \\ 0,\ if\ F_C \geq F'_{C\max}, \end{cases} \tag{2.40}$$

$$F'_{C\,max} = K_r \cdot F_{C\,rab}, \tag{2.41}$$

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

Quantities K_r, $F_{C\,rab}$ are determined taking into account the physical and mechanical properties of the material and the geometric dimensions of the rolled strip.

Under the terms of the technology, cold metal processing refers to the rolling of a thin sheet (less than 1 mm thick). Such a thin sheet cannot be obtained during hot rolling due to the formation of scale on the metal surface, the thickness of which is commensurate with the small thickness of the sheet. Practice shows that during cold rolling, the metal becomes hard and its deformation resistance increases. At the same time, it becomes fragile, i.e. metal in the process of cold rolling loses its plastic properties.

The curve in the tensile diagram [3, 29] (Figure 2.11) can conditionally be divided into the following four zones.

The OA zone bears the name of the zone of elasticity (the limit of proportionality). Here the material obeys Hooke's law. The magnitude of the force for which Hooke's law remains valid depends on the geometric dimensions and physical properties of the material.

The magnitude of the proportionality limit depends on the degree of accuracy with which the initial portion of the diagram can be regarded as a straight line.

The degree of deviation of the curve $F = f(\varepsilon)$ from the line $F = E\varepsilon$ is determined by the magnitude of the angle that the tangent to the diagram with the axis F comprises, where E – Young's modulus. Within Hooke's law, this angle is determined by the value $\frac{1}{E}$. It is generally believed that if the value $\frac{d\varepsilon}{dF}$ ended up being *50%* more than $\frac{1}{E}$, then the limit of proportionality is reached.

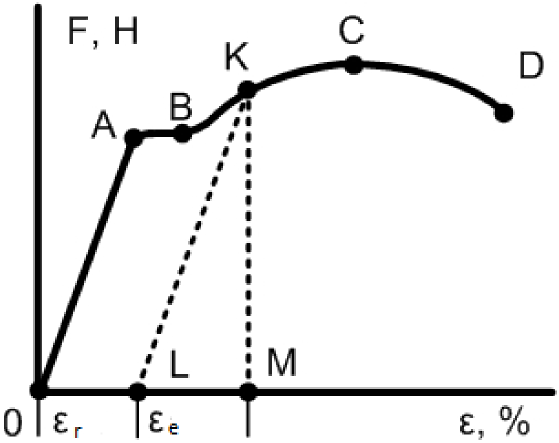


Figure 2.11 – Rolling strip stretching diagram

In order to find the proportionality limit [29] (point A, Figure 2.11), it is necessary, after each additional load, to unload the test sample of the strip and observe to see if permanent deformation has formed. Since plastic deformations in individual crystals appear already at the very early stage of loading, it is clear that the value of the elastic limit, as well as the proportional limit, depends on the accuracy requirements that are imposed on the measurements taken. Typically, the residual strain corresponding to the elastic limit is taken within $\varepsilon_r = (1-5)\cdot 10^{-5}$, i.e. $0{,}001-0{,}005\ \%$. According to this tolerance, the elastic limit is denoted by $\sigma_{0{,}001}$, or $\sigma_{0{,}005}$.

It must be said that the elastic limit and the proportional limit are difficult to determine and sharply change their value depending on the conditionally accepted norm on the angle of inclination of the tangent and on the residual deformation.

The AB zone is called the general yield zone, and the section of the AB diagram is called the yield point. Here, a significant change in the length of the sample occurs without a noticeable increase in load. The next, more specific characteristic is yield strength. The term “yield strength” means the stress at which strain increases without a noticeable increase in load. In cases where the diagram does not have a clearly defined yield point, the stress value at which the permanent deformation $\varepsilon_r = 0{,}002$ or *0,2%* (figure 2.11) is conventionally taken as the yield strength. In some cases, the set limit is $\varepsilon_r = 0{,}5\ \%$. The conditional yield strength is denoted by $\sigma_{0{,}2}$, and $\sigma_{0{,}5}$ depending on the accepted tolerance for permanent deformation. The BC zone is called the hardening zone. Here, the elongation of the sample is accompanied by an increase in the load, but immeasurably slower than in the elastic section. Point C is the ratio of the maximum force that the sample can withstand to its initial cross-sectional area and is called the ultimate strength, or temporary resistance. The portion of the CD curve is called the local yield zone. Point D corresponds to the destruction of the sample. If the test specimen, without leading to failure, is unloaded (point K, Figure 2.11), then during the unloading the relationship between the force F and the elongation ε will be depicted as a straight line KL. Experience shows that this line is parallel to the line OA. When unloading, the elongation does not completely disappear. It decreases by the value of the elastic part of the elongation ε_e (segment LM). The OL segment is the residual elongation ε_r. It is also called plastic elongation, and the corresponding deformation is plastic deformation. Thus:

$$\varepsilon = \varepsilon_e + \varepsilon_r \tag{2.42}$$

If the strip was loaded within the OA section and then unloaded, then the elongation will be purely elastic, and $\varepsilon_r = 0$. When the strip is reloaded, the tensile diagram takes the form of a straight line LK and then - the KCD curve (Figure 2.11) as if there was no intermediate unloading. The MK segment corresponds to the preload force [23]. Thus, the form of the diagram for the same material depends on the degree of initial loading (drawing), and loading itself now plays the role of some preliminary technological operation. It is very significant that the segment LK turns out to be larger than the segment OA. Consequently, as a result of preliminary drawing, the material acquires the ability to withstand large loads without permanent deformations. The ratio of the maximum force that the sample can withstand to its initial cross-sectional area is called the tensile strength, or temporary resistance, and is denoted by $\sigma_{вр}$ (for compression – $\sigma_{вс}$). The phenomenon of increase of the elastic properties of the material as a result of preliminary plastic deformation is called cold hardening. In a tensile test, another material characteristic is determined. This is the so-called elongation at break. *δ %.*

2.7. Mathematical description of the rolling process with looping

The designs of the loop pits are diverse [23], in the particular case it can conditionally be presented as a loop that is formed under the influence of gravity depending on the ratio of the velocities υ1 and υ2 of two neighboring units (Figure 2.12), change in the length and mass of the loop itself, as shown in expressions (2.43 - 2.46). However, in practice there are other designs of loop pits, more complex in terms of the relationship of the forces transmitted through the metal, with additional tensioning mechanisms. This mathematical description can be supplemented in case of a design change [30]. Moreover, in spite of the simplicity of the loop pit case under consideration, control systems of all mechanisms in a given electromechanical system feel a significant effect of the gravity component of the loop due to the inconstancy of mass.

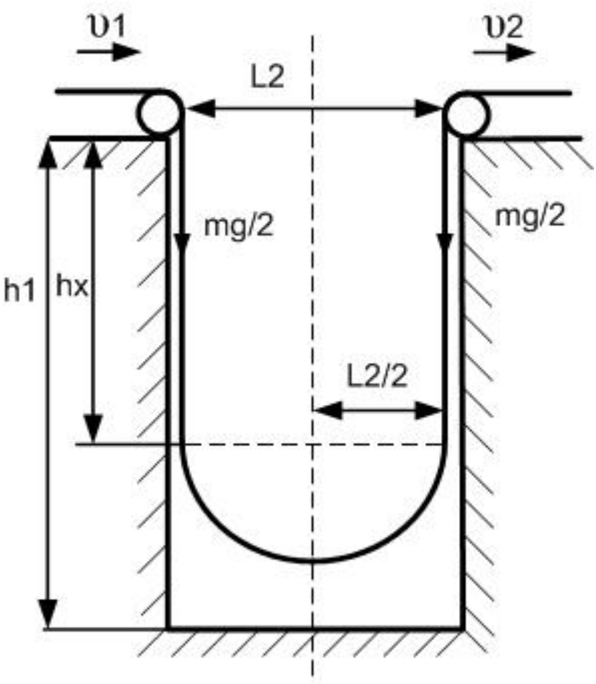


Figure 2.12 - Kinematic scheme of the loop hole

In our case, when choosing the representation of the loop in the loop pit, it is accepted that it consists of an arc and two straight lines. Then the loop and arc lengths are calculated according to the expressions:

$$l_{loop} = l_{arc} + 2h_x\,, \tag{2.43}$$

$$l_{arc} = \pi \frac{l_2}{2} \tag{2.44}$$

To determine the magnitude of the disturbing effect created by varying the magnitude of the loop, the gravity and mass of the loop are determined:

$$F_{loop} = m_{loop} g \; ; \tag{2.45}$$

$$m_{loop} = \rho V_{loop} , \tag{2.46}$$

where b – width of rolled strip, h – strip thickness, V_{loop} – loop volume, $V_{loop} = l_{loop} bh$.

We neglect the forces of friction in the support rollers or take them into account as proportional to the linear velocities and the forces acting on them from the side of the metal mass. Given the weight of the metal, the forces of the front and rear tension in the subsequent and previous mechanisms are proportional to the loop size.

2.8. Mathematical description of four-mass models of interconnected rolling mill mechanisms

In an interconnected electric drive of two neighboring stands (kinematic and structural diagrams in Figures 2.13 and 2.14, respectively), motors *M1* and *M2* actuate the rotation of the rolls of the first and second stands, respectively; ω_{d1} and ω_{d2} – angular speeds of engines *M1* and *M2*; J_{M1}, J_{M2} – moment of inertia of the engines *M1* and *M2* with gearboxes, J_{kl1}, J_{kl2} – reduced moments of inertia of work rolls of rolling stands; M_{f1}, M_{f2}, M_{f3}, M_{f4} – external friction moments; C_1, C_2 – elastic joint stiffness - long shaft; b_1, b_2 – internal damping coefficient proportional to the mismatch of the angular velocities of two adjacent masses; M_{13}, M_{24} – engine torques in elastic gears; $\upsilon_{kl1}, \upsilon_{kl2}$ – linear velocities of the material through the work rolls of the first and second stands; *l* – the distance between the axes of adjacent stands; C_p – stiffness of the elastic joint (transported material); ω_3, ω_4 – spindle ends' angular speeds.

To maintain a constant tension of the rolled strip, it is necessary to provide a constant value of the elastic force acting in the metal. Elastic force F_C acts only on the section of the strip between the two stands and equal in magnitude to *l* – the distance between the axes of the stands. In this case, a part of the strip equal to *le* is not influenced by the elasticity force F_C, since it is outside the inter-stand distance *l*.

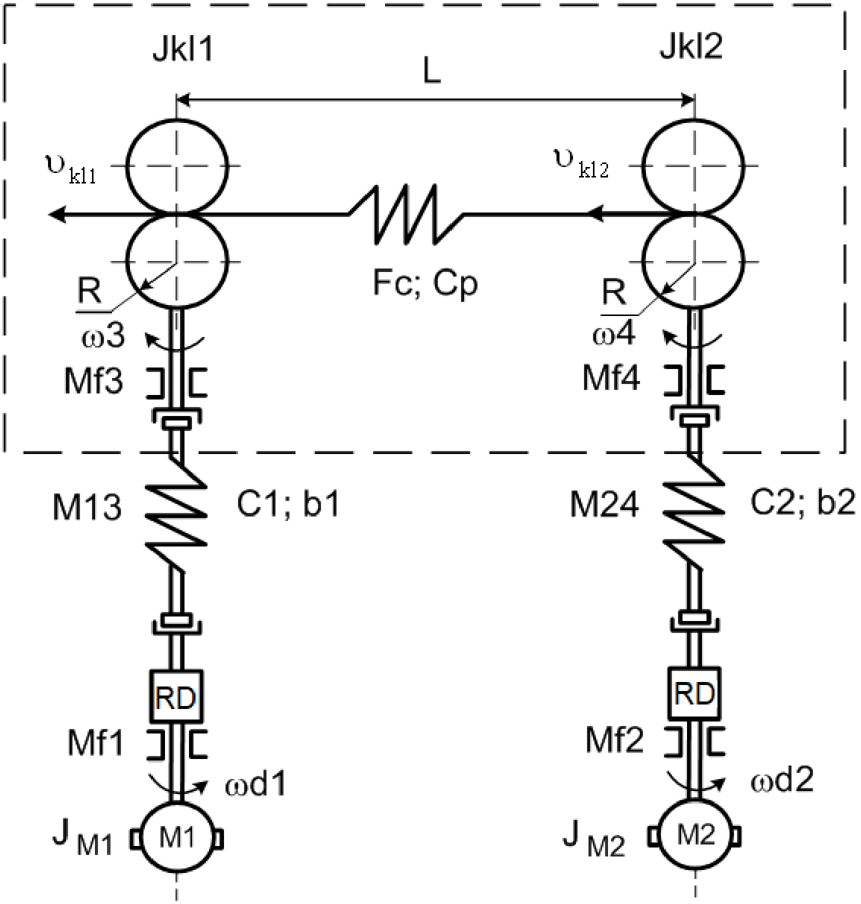


Figure 2.13 - Four-mass electromechanical system of a rolling mechanism with elasticities of the first and second kind

The presence of elastic coupling of mechanisms through the strip, as one of the factors influencing the dynamic characteristics of the electric drive, must be taken into account when developing control systems [4.19]. This is especially true in connection with an increase in the speeds of metal processing units and an increase in the requirements for the quality of the processed strip [8].

Let us consider a two-mass system, which consists of work rolls of the first stand, a rolled strip and work rolls of the second stand (Figure 2.14), which is indicated by a dashed line in Figure 2.13.

The moment created by the “long shaft” elastic coupling, which was considered earlier, is the input to the structural scheme under consideration. The output coordinate of this circuit is the angular velocity of the second stand. The first and second stands are described by similar equations, taking into account the differences in the indices.

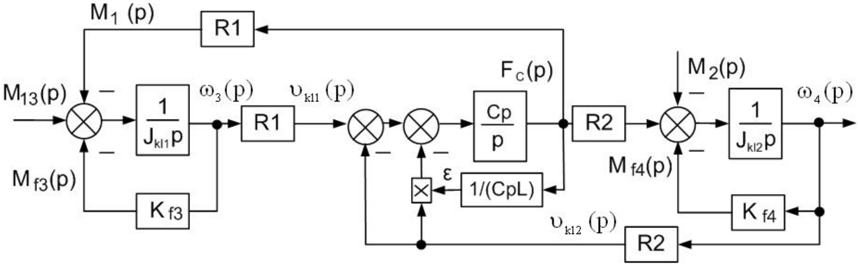


Figure 2.14 - Structural diagram of a two-mass electromechanical system with elasticities of the second kind

The system of equations of the interconnected electric drive of two adjacent stands taking into account (2.22) - (2.28) in operator form is equal to:

$$\left.\begin{aligned}
&J_{kl1}p\omega_3(p)=M_{d1}(p)-F_C(p)R_1-k_{f3}\omega_3(p);\\
&J_{kl2}p\omega_4(p)=M_{d2}(p)+F_C(p)R_2-k_{f4}\omega_4(p);\\
&F_C(p)=\frac{C_p}{p}\{\upsilon_{kl1}(p)-[1+\varepsilon(p)]\upsilon_{kl2}(p)\};\\
&\varepsilon(p)=\frac{1}{C_pL}F_C(p);\\
&M_{d1}(p)=i_{d1}(p)C\Phi_1;\\
&M_{d2}(p)=i_{d2}(p)C\Phi_2;\\
&i_{d1}(p)=\frac{1}{R_{d1}(T_{d1}p+1)}(U_{d1}(p)-C\Phi_1\omega_3(p));\\
&i_{d2}(p)=\frac{1}{R_{d2}(T_{d2}p+1)}(U_{d2}(p)-C\Phi_2\omega_4(p)),
\end{aligned}\right\}\tag{2.47}$$

where T_{d2} – electromagnetic time constant of the electric drive;
R_{d2} – resistance of the armature circuit;
C – design coefficient of the electric drive;
U_{d1}, U_{d2} – thyristor converter output voltage.

If we assume that R_1 and R_2 do not change during the work, for linearization, the equations must be considered in increments:

$$F_C(p) = \frac{C_p}{p}\left\{\left(\Delta\upsilon_{kl1}(p) - (1+\varepsilon_0)\Delta\upsilon_{kl2}(p)\right) - \frac{\upsilon_{20}}{C_p L}\right\}, \tag{2.48}$$

where υ_{20} and ε_0 – initial values of the linear speed of the canvas at the end of the plot and relative elongation.

After obtaining the equations in operator form, we can describe the system in matrix form.

$$\dot{x} = Ax + Bu\ . \tag{2.49}$$

If, when compiling the state vector, all variables describing systems with elasticities of the first and second kind are taken into account, we obtain a bulky system that is very difficult to carry out the task.

Therefore, joint tuning is preceded by tuning individual systems with elasticities of the first and second kind, and after that their work is compatible.

In accordance with the model obtained, the state vector of the object

$$x = col[i_{d1}, \omega_3, F_c, \omega_4, \varepsilon, i_{d2}]\ . \tag{2.50}$$

Input influences vector

$$u = col[U_{d1}, U_{d2}]\ . \tag{2.51}$$

The system of normalized equations

$$\begin{cases}
\omega_3 = \dfrac{1}{T_{kl1} p}\left[M_{d1} - F_C \cdot R_1 - k_{f3} \cdot \omega_3\right]; \\
\omega_4 = \dfrac{1}{T_{kl2} p}\left[M_{d2} + F_C \cdot R_2 - k_{f4} \cdot \omega_4\right]; \\
F_C = \dfrac{1}{T_{c_p} p}\left[(R_1\omega_3(p) - (1+\varepsilon_0)R_2\omega_4(p)) - \dfrac{\upsilon_{20}}{C_p L}\right]; \\
\varepsilon = \dfrac{1}{C_p L} F_C; \\
i_{d1} = \dfrac{1}{R_{d1}(T_{d1}p+1)}\left(U_{d1} - C\Phi_1\omega_3\right); \\
i_{d2} = \dfrac{1}{R_{d2}(T_{d2}p+1)}\left(U_{d2} - C\Phi_2\omega_4\right).
\end{cases} \tag{2.52}$$

Let us transform the system of normalized equations to the form:

$$\left.\begin{aligned}
\omega_3 &= \frac{1}{T_{kl1} p} i_{d1} - \frac{R_1}{T_{kl1} p} F_C - \frac{k_{f3}}{T_{kl1} p}\omega_3; \\
\omega_4 &= \frac{1}{T_{kl2} p} i_{d2} + \frac{R_2}{T_{kl2} p} F_C - \frac{k_{f4}}{T_{kl2} p}\omega_4; \\
F_C &= \frac{R_1}{T_{c_p} p}\omega_3 - \frac{R_2(1+\varepsilon_0)}{T_{c_p} p}\omega_4 - \frac{\upsilon_{20}}{C_p L} e; \\
\varepsilon &= \frac{1}{C_p L} F_C; \\
i_{d1} &= -\frac{1}{T_{d1} p} i_{d1} + \frac{1}{R_{d1} T_{d1} p} U_{d1} - \frac{1}{R_{d1} T_{d1} p}\omega_3; \\
i_{d2} &= -\frac{1}{T_{d2} p} i_{d2} + \frac{1}{R_{d2} T_{d2} p} U_{d2} - \frac{1}{R_{d2} T_{d2} p}\omega_4.
\end{aligned}\right\} \tag{2.53}$$

The system matrix and control matrix have the form:

$$A=\begin{bmatrix} \frac{-k_{f3}}{T_{kl1}} & 0 & -\frac{R_1}{T_{kl1}} & 0 & \frac{1}{T_{kl1}} & 0 \\ 0 & -\frac{k_{f4}}{T_{kl2}} & \frac{R_2}{T_{kl2}} & 0 & 0 & \frac{1}{T_{kl2}} \\ \frac{R_1}{T_{c_p}} & -\frac{R_2(1+\varepsilon_0)}{T_{c_p}} & 0 & -\frac{\upsilon_{20}}{C_p l} & 0 & 0 \\ 0 & 0 & \frac{1}{c_p l} & 0 & 0 & 0 \\ -\frac{1}{R_{d1}T_{d1}} & 0 & 0 & 0 & -\frac{1}{T_{d1}} & 0 \\ 0 & -\frac{1}{R_{d2}T_{d2}} & 0 & 0 & 0 & -\frac{1}{T_{d2}} \end{bmatrix} B=\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{R_{d1}T_{d1}} & 0 \\ 0 & \frac{1}{R_{d2}T_{d2}} \end{bmatrix}$$

The equation of state in expanded form:

$$\frac{d}{dt}\begin{bmatrix} \omega_3(t) \\ \omega_4(t) \\ F_C(t) \\ \varepsilon(t) \\ i_{d1}(t) \\ i_{d2}(t) \end{bmatrix}=\begin{bmatrix} \frac{-k_{f3}}{T_{kl1}} & 0 & -\frac{R_1}{T_{kl1}} & 0 & \frac{1}{T_{kl1}} & 0 \\ 0 & -\frac{k_{f4}}{T_{kl2}} & \frac{R_2}{T_{kl2}} & 0 & 0 & \frac{1}{T_{kl2}} \\ \frac{R_1}{T_{c_p}} & -\frac{R_2(1+\varepsilon_0)}{T_{c_p}} & 0 & -\frac{\upsilon_{20}}{C_p l} & 0 & 0 \\ 0 & 0 & \frac{1}{C_p L} & 0 & 0 & 0 \\ -\frac{1}{R_{d1}T_{d1}} & 0 & 0 & 0 & -\frac{1}{T_{d1}} & 0 \\ 0 & -\frac{1}{R_{d2}T_{d2}} & 0 & 0 & 0 & -\frac{1}{T_{d2}} \end{bmatrix}\cdot\begin{bmatrix} \omega_3(t) \\ \omega_4(t) \\ F_C(t) \\ \varepsilon(t) \\ i_{d1}(t) \\ i_{d2}(t) \end{bmatrix}+\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \frac{1}{R_{d1}T_{d1}} & 0 \\ 0 & \frac{1}{R_{d2}T_{d2}} \end{bmatrix}\cdot\begin{bmatrix} U_{d1}(t) \\ U_{d2}(t) \end{bmatrix}$$

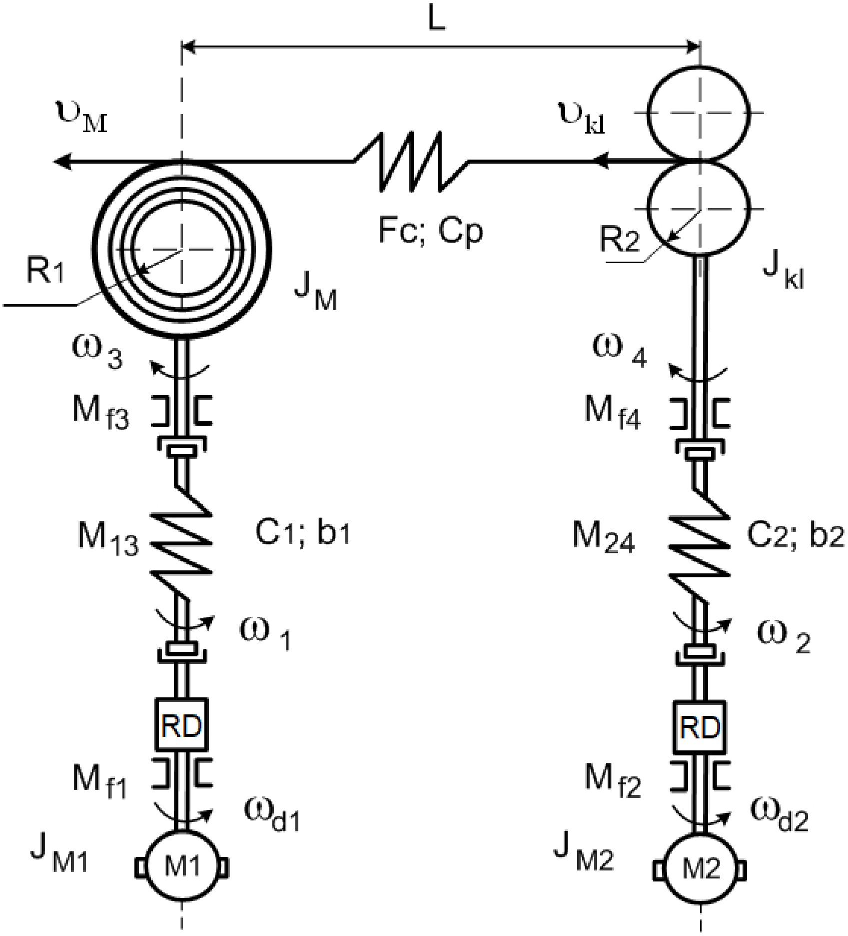


Figure 2.15 - Four-mass electromechanical system of a rolling mechanism with elasticities of the first and second kind

The interconnected electric drive of the winding mechanism and the cage adjacent to it (kinematic diagram, Figure 2.15) is described by similar expressions (2.47), however, it is necessary to take into account the variable radius of the roll. The change in the angular rotational speeds of the unwinder and winder does not occur in time according to a linear law, since these changes depend on the variation of the current radius of the roll. The larger the radius of the roll, the lower the angular velocity of rotation of the barrel and vice versa.

With this in mind, system (2.47) takes the form:

$$\left.\begin{aligned}
&J_M p\omega_3(p) = M_{d1}(p) - F_C(p)R_1(p) - k_{f3}\omega_3(p);\\
&J_{kl} p\omega_4(p) = M_{d2}(p) + F_C(p)R_2 - k_{f4}\omega_4(p);\\
&F_C(p) = \frac{C_p}{p}\left\{\upsilon_{kl}(p) - \left[1+\varepsilon(p)\right]\upsilon_M(p)\right\};\\
&\varepsilon(p) = \frac{1}{C_p L}F_C(p);\\
&R_1(p) = \sqrt{R_0^2 + \frac{h}{\pi}\upsilon_M(p)};\\
&M_{d1}(p) = i_{d1}(p)C\Phi_1;\\
&M_{d2}(p) = i_{d2}(p)C\Phi_2;\\
&i_{d1}(p) = \frac{1}{R_{d1}(T_{d1}p+1)}(U_{d1}(p) - C\Phi_1\omega_3(p));\\
&i_{d2}(p) = \frac{1}{R_{d2}(T_{d2}p+1)}(U_{d2}(p) - C\Phi_2\omega_4(p)),
\end{aligned}\right\} \tag{2.54}$$

where ω_1, ω_3 – spindle ends' angular speeds; ω_4 – angular speed of rolls of the stand; J_{d1} – moment of inertia of the rotor of the engine M1 and gearbox, J_M –moment of inertia of winder; M_{f1}, M_{f3} – external friction moments; M_{13} – elastic moment; C_1 – stiffness of the elastic element; C_p – rigidity of the transported material; b_1 – coefficient of internal damping; F_C – tension force of rolled strip; L - the distance between the axes of the rotating mechanisms; R_1 – roll radius; R_2 – stand's work roll radius; k_{f3}, k_{f4} – viscous friction coefficients; T_{d2} – electromagnetic time constant of the electric drive; R_{d2} – resistance of the armature circuit; $C\Phi$ – design coefficient of the electric drive; U_{d1}, U_{d2} – thyristor converter output voltage.

Thus, the mathematical models of the winding-unwinding mechanism and stand were further developed taking into account a variable parameter that takes into account the thickness of the metal strip, which made it possible to increase the degree of model adequacy. Based on theoretical dependencies obtained as a result of theoretical studies, which, in turn, depends on the geometric dimensions of the strip, steel grade, and therefore on the yield strength of the material, on the elongation of the strip, a mathematical model of the rolled strip during its breaking is developed, which made it possible to formulate requirements for the control system of the main electric drives in the conditions of the specified emergency.

Based on the analysis of existing designs of cold rolling mills, the mathematical model of the electromechanical system is supplemented by the effect of reversal and rolling with loop formation.

The addition of the mathematical description of the rolled strip with its variable thickness, the influence of the strip break effect, taking into account the dependence of the metal tension force on the relative elongation, makes it possible to increase the adequacy and accuracy of the mathematical model when constructing an optimal control system for the interconnected electric drives of the rolling mill.

Chapter 3.
COMPUTER MODELS COMPLEX OF ROLLING PRODUCTION ELEMENTS

3.1. Analysis of computer simulation tools for interconnected electric drives of cold rolling mills

Currently, in engineering practice, various software products are used to solve research and optimization problems: specialized packages; program libraries; mathematical programming systems. Well-developed techniques and algorithms that allow one to explore the modes of operation of complex electromechanical complexes; analyze their quality, calculate frequency characteristics and pulse transition functions; to study the dynamics of complex systems containing elements with nonlinear characteristics; calculate optimal processes in the presence of limitations; to study the dynamics of stochastic systems [4, 7, 8, 31].

When choosing a software product, the following must be considered:

- type of mathematical description of the studied electromechanical system;
- features of the presentation of model data;
- by what order of differential equations, or by what order and type of matrix (symmetric, degenerate, etc.), or by how many structural elements of a graph an electromechanical system is described;
- type of presentation of the calculation results;
- the number and type of non-linear characteristics that describe the parameters of the object, controlling and disturbing influences;
- the possibility of flexible changes in the mathematical model.

At the design stage of an electromechanical system, possible solutions are usually evaluated based on intuition and previous experience. However, at present, as a rule, tools are required to standardize the decision-making process.

During the setup of electromechanical complexes, as well as in the automated selection of the best design solutions, computer-aided research and synthesis methods are widely used. These methods allow to increase the efficiency of decision-making and reduce the time and cost of putting equipment into commercial operation [14].

Mathematical modeling is the most advanced and efficient modeling method, which in research and optimization is based on modern methods of mathematical analysis, computational mathematics and programming. As a rule, computer studies of electromechanical complexes are carried out 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 the majority 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 ability to flexibly modify or edit 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 [15]. To solve the problems of researching automated EP systems, the following software tools are used: MATLAB, MATHCAD, MAPLE, MATHEMATICA, STATISTICA and others.

It is convenient enough to consider EMS in the form of structural schemes, especially when it is necessary to synthesize the structure and parameters of control systems. Therefore, the application package for modeling dynamic Simulink systems of the MATLAB environment has significant advantages over others.

When modeling using the Simulink libraries of the MATLAB environment, 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.

When working with Simulink models, the 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.

The optimality of the parameters of the rolling process control system is assessed by the quality of transients under disturbing and controlling influences [7].

In the rolling mode with tension, it is possible to form a control action by abruptly changing the task for speed (5% of the initial speed) and obtain curves characterizing changes in technological parameters, such as the angular speeds of rotation of the rolls of adjacent stands, rolling force, and tension in transition mode. The rolled strip is in both stands simultaneously. The input of metal into the rolls is accompanied by a surge in the magnitude of the tension, which is worked out by the control system of the subsequent stand by correcting the speed of rotation of the work rolls.

At the moment of entry into the subsequent stand, the metal experiences the greatest longitudinal force. This circumstance is explained by the initial mismatch of the speeds of adjacent stands and depends on the settings made by the operator at the stage of preparing the mill for work. The tuning parameters should be adjusted during the process based on the current performance of the mill.

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 units of cold rolling mills.

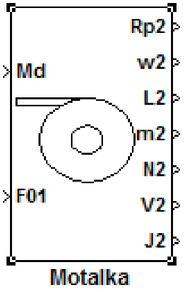
3.2. Computer models that take into account the interconnectedness of control channels

Based on the mathematical description of the electromechanical processes of rolling a strip of metal, models have been created that simulate the operation of winding-unwinding mechanisms, a working stand, a straightening machine, as well as a model of a rolled strip of metal taking into account a loop pit, changes in strip thickness and an emergency caused by strip breakage described in second chapter.

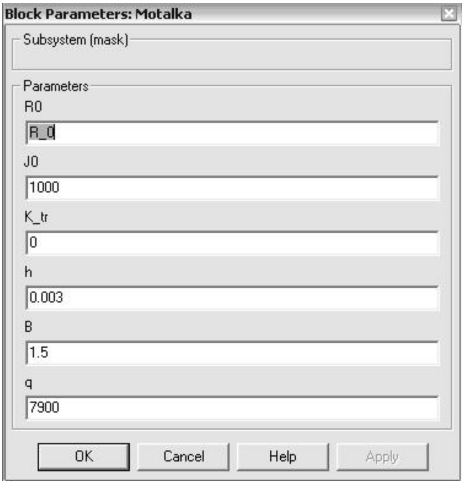
Each model is an independent subsystem with ports of input and output coordinates. For convenience, a separate logo was created, which is depicted on the model above, an interface for introducing and changing the parameters of each of the subsystems [31]. This approach has advantages, since any unit has the ability to connect to another through mechanical and electrical communication channels. Mechanical ones are speed, moment, tension force and electric ones are current, voltage, magnetic flux of the drive motor and others. There are also information channels for displaying the mill and composition of the control system, such as length, mass, elongation of the strip, number of turns, moment of inertia, radius of the roll.

One of the main units of the cold rolling mill is a winding (unwinding) mechanism. Based on dependencies (2.2) - (2.21), a model of the winding mechanism of the mill, shown in Figure 3.1, and the internal structure of the model of the unwinding mechanism, shown in Figure 3.2, are created.

In these structures, the calculation of not only linear velocity v and angular velocity ω is organized, but also the determination of the mass of metal in the roll m, the moment of inertia of the roll J, the radius of the roll Rp, the length of the wound strip l and the number of turns in the roll N.



a)


Block Parameters: Motalka

Subsystem (mask)

Parameters

R0: R_0

J0: 1000

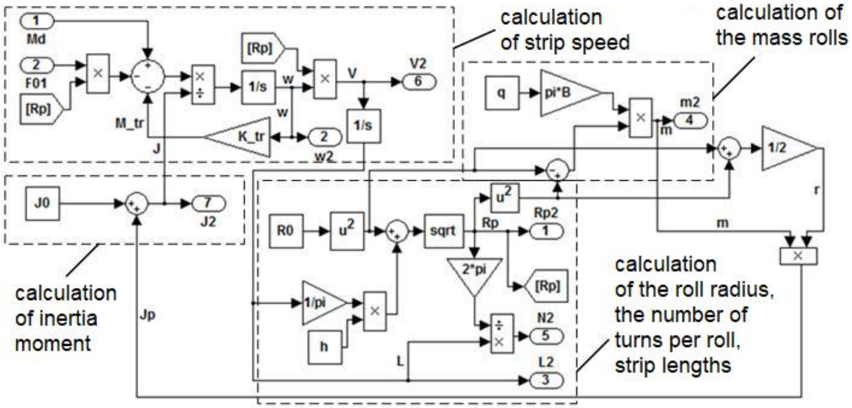
K_tr: 0

h: 0.003

B: 1.5

q: 7900

b)



calculation of strip speed

calculation of the mass rolls

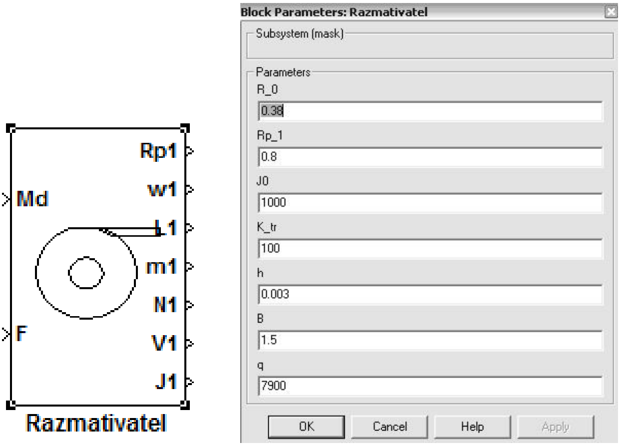
calculation of inertia moment

calculation of the roll radius, the number of turns per roll, strip lengths

c)

Figure 3.1 - Model of the winding mechanism:
a) subsystem; b) parameters; c) structure

The difference between the computer model (Figures 3.2, 3.3) of the unwinder from the one of the winder is that in the model of unwinder [26] 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.



Block Parameters: Razmativatel

Subsystem (mask)

Parameters

R_0: 0.38

Rp_1: 0.8

J0: 1000

K_tr: 100

h: 0.003

B: 1.5

q: 7900

a) b)

Figure 3.2 - Model of unwinding mechanism:
a) subsystem; b) parameters

The model of the working stand (Figure 3.4) takes into account not only the rotating masses and the balance of moments (2.24, 2.25), 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 K_{Mf} , K_{Mr} designated in the model as *Kaf0, Kaf_a*, the pressure force F_N from the side of the pressure screws is indicated by Nagim [26], 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.

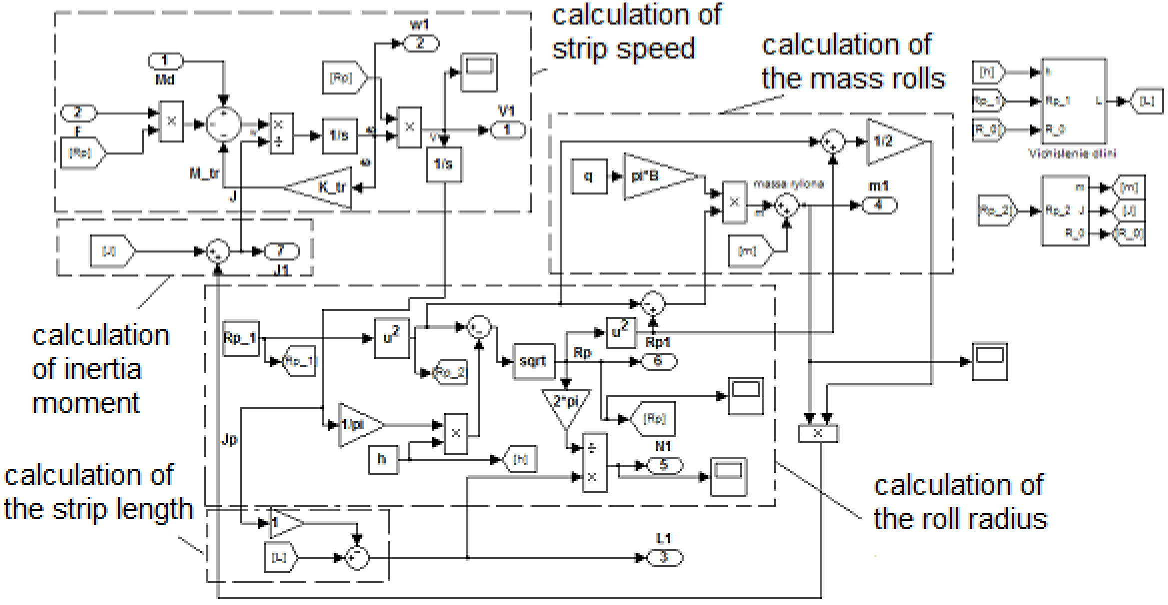
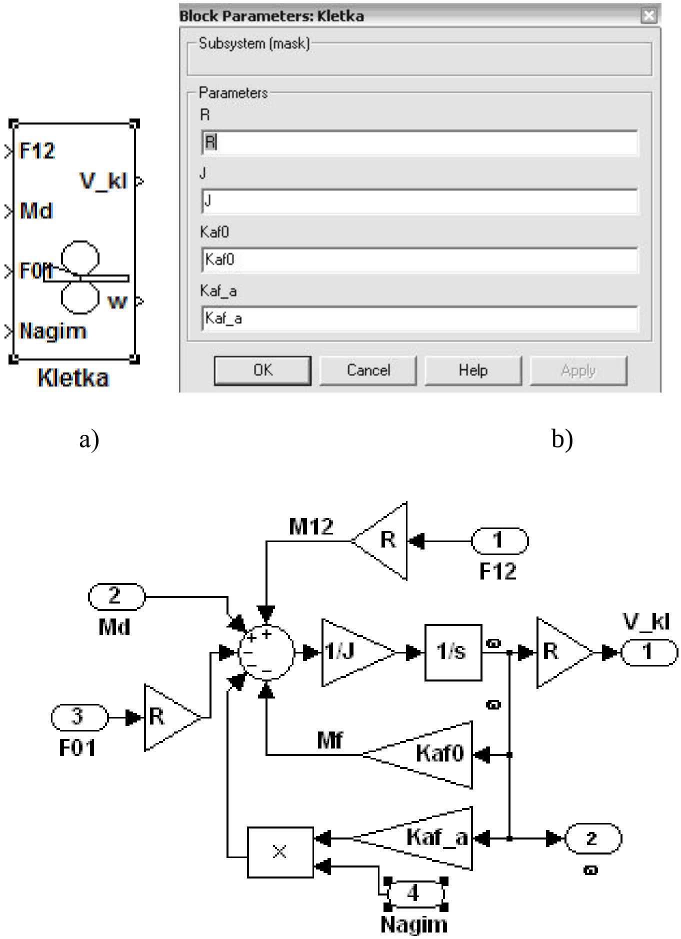


Figure 3.3 - The structure of the model of the unwinding mechanism



R: R

J: J

Kaf0: Kaf0

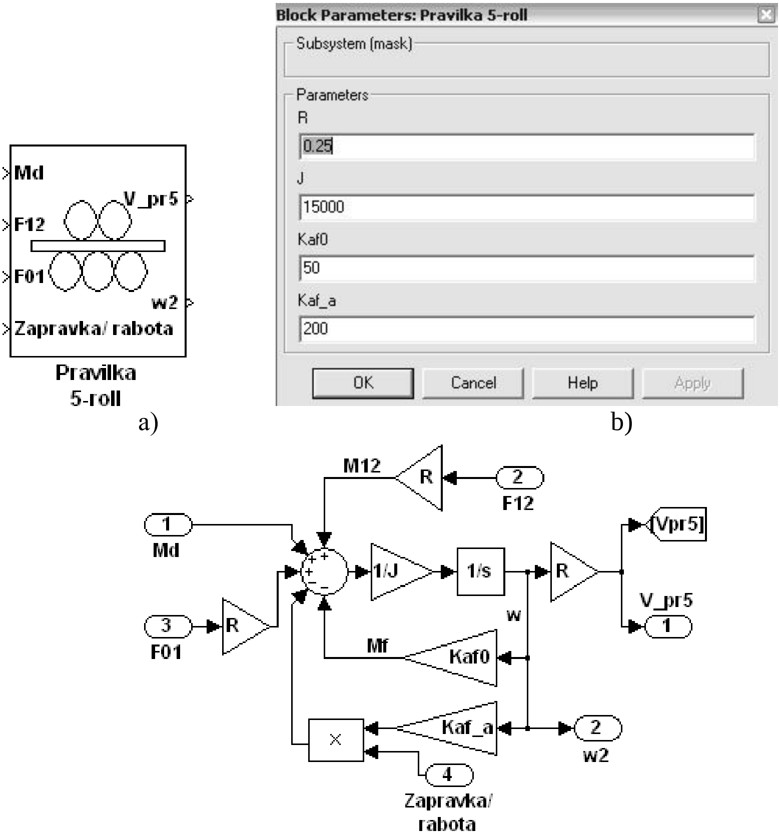
Kaf_a: Kaf_a

a) b)

c)

Figure 3.4 - Model of the working stand of the rolling mill (*Kletka*):
a) subsystem; b) parameters; c) structure

The model of the straightening machine (Figure 3.5) is based on the description of the rolling stand, as they are quite similar in functionality, except that the stand has an additional impact on the strip from the side of the pressure screws [30], and there is also an additional input port *Zapravka/rabota* to simulate the presence and absence of a strip between the rolls of the straightening machine. Using this channel, you can simulate a linear increase in the load when the metal enters the unit or a decrease in force as a function of the required coordinate (for example, rolling speed, strip length, etc.)



R

0.25

J

15000

Kaf0

50

Kaf_a

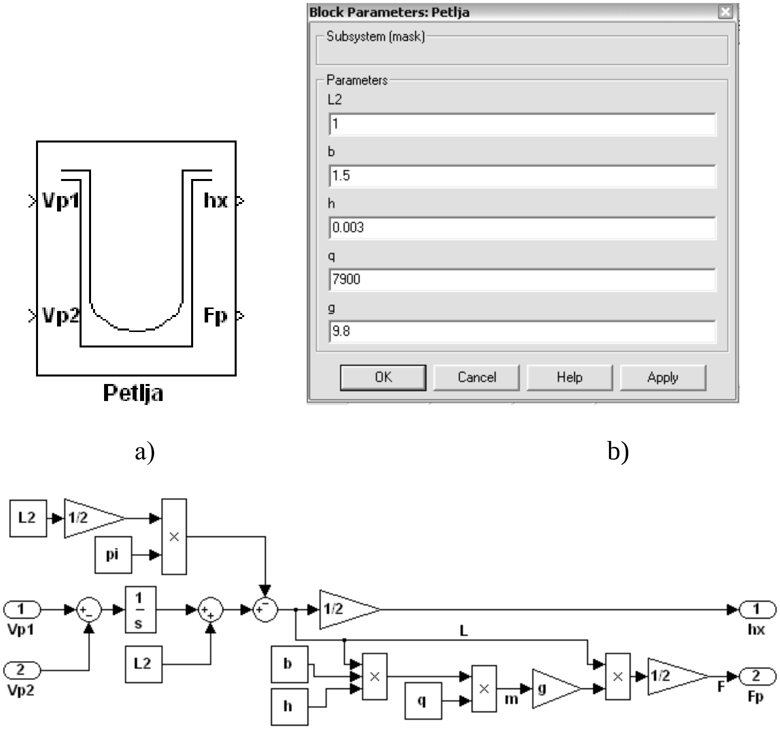
200

a) b)

c)

Figure 3.5 - Model of a five-roller straightening machine (*Pravilka 5-roll*): a) subsystem; b) parameters; c) structure

The designs of the loop pits are diverse, in a particular case it can be represented as a loop, which is formed under the influence of gravity depending on the ratio of the velocities *V1* and *V2* (Figure 2.12), the change in the length of the loop itself, or the change in mass, as shown in formulas (2.43- 2.46). If it is necessary to simulate a complicated version of a metal loop in a loop pit, this subsystem can be changed in accordance with new requirements or design features.



Block Parameters: Petlja

Subsystem (mask)

Parameters

L2: 1

b: 1.5

h: 0.003

q: 7900

g: 9.8

a) b)

c)

Figure 3.6 - Model of the loop hole (*Petlja*):
a) subsystem; b) parameters; c) structure

The constant value of the slack of the strip in the pit (indicated by *hx* in the model) is controlled by photosensors (*D1, D2, D3, D4*), discrete signals on the operation of which can be transmitted to the speed control system of the unwinding mechanism (figures 3.6, 3.7).

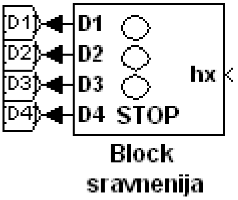
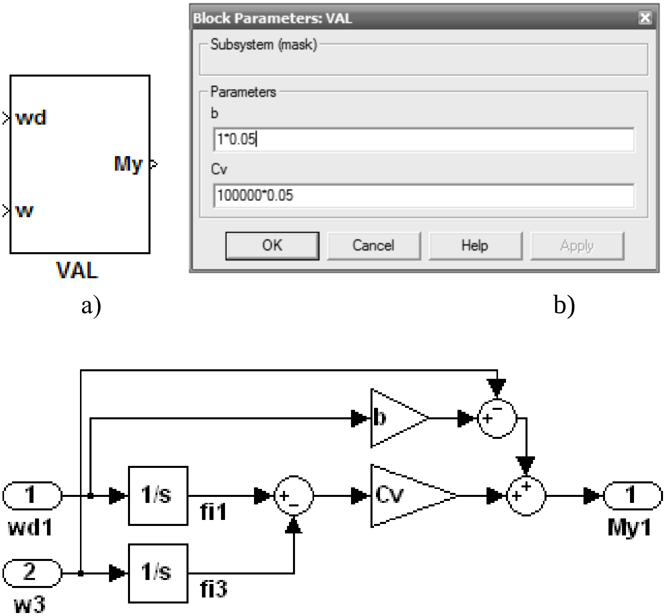


Figure 3.7 - Model of the comparison block (*Blok sravnenija*)

According to (2.33), a model was created that simulates the elastic “long shaft” connection between the engine and the drive (Figure 3.8).



b
1*0.05

Cv
100000*0.05

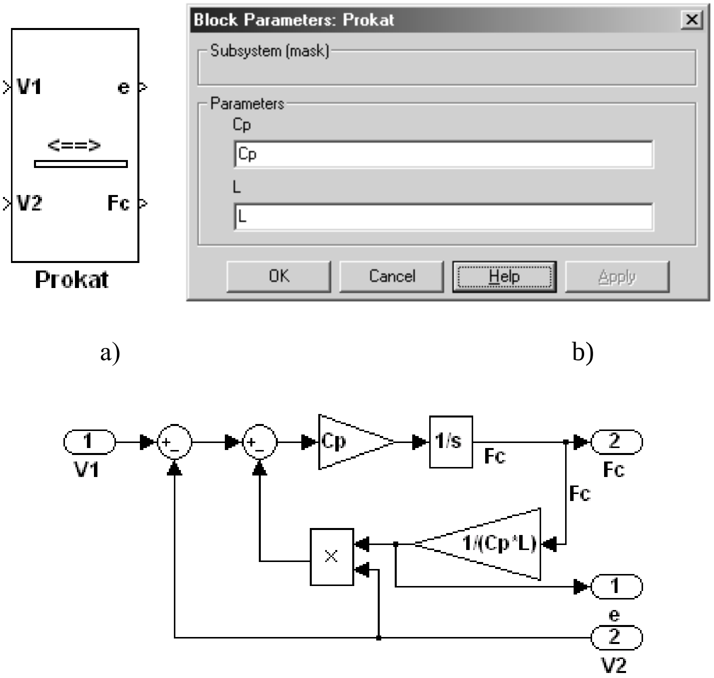
a) b)

c)

Figure 3.8 - Model of the subsystem “long shaft” (*VAL*):
a) subsystem; b) parameters; c) structure

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.

Figure 3.9 shows a metal model connecting two neighboring units [26]. Note that by its structure it is universal, suitable for all sections of the stand. This model is an elastic link of the second kind, since the force (moment) between adjacent drives is transmitted through the transported material.



Cp: Cp

L: L

a) b)

c)

Figure 3.9 - Model of rolled metal (*Prokat*):
a) subsystem; b) parameters; c) structure.

To simulate random influences from the rolled metal's side, *Motalka, Prokat, Kletka* blocks [26] can be supplemented with input ports *h* (Figure 3.10), 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* (Figure 3.11) 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 3.12 shows a model of a shaper of the thickness of a strip of random nature, the generated signal is shown in Figure 3.13. 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% (Figure 3.13).

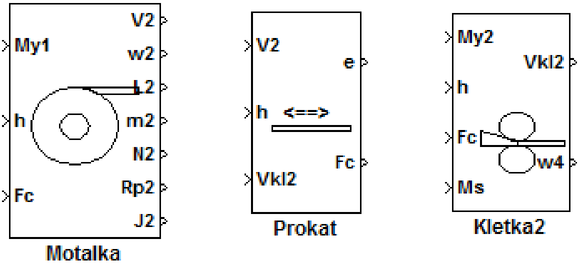


Figure 3.10 - *Motalka*, *Prokat*, *Kletka* models supplemented by the input port *h*

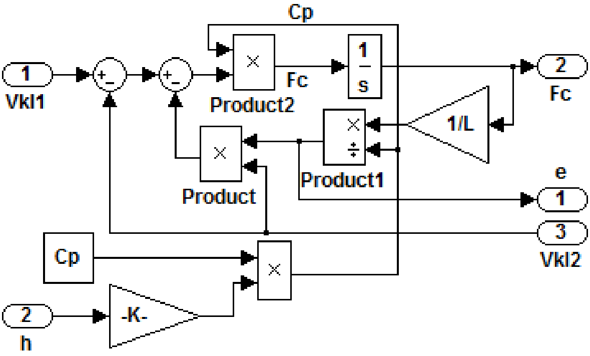


Figure 3.11 - Model of rolled strip taking into account the variation of strip thickness *h*

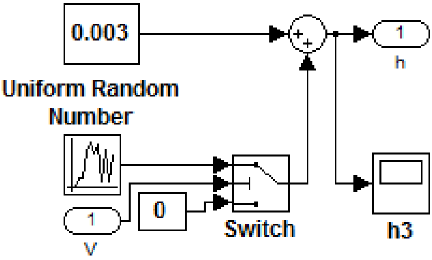


Figure 3.12 - Model of the strip thickness former

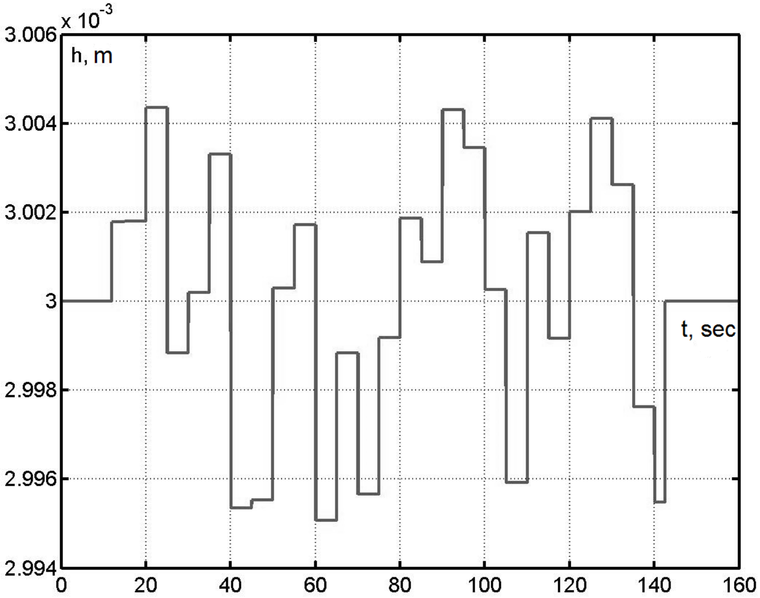
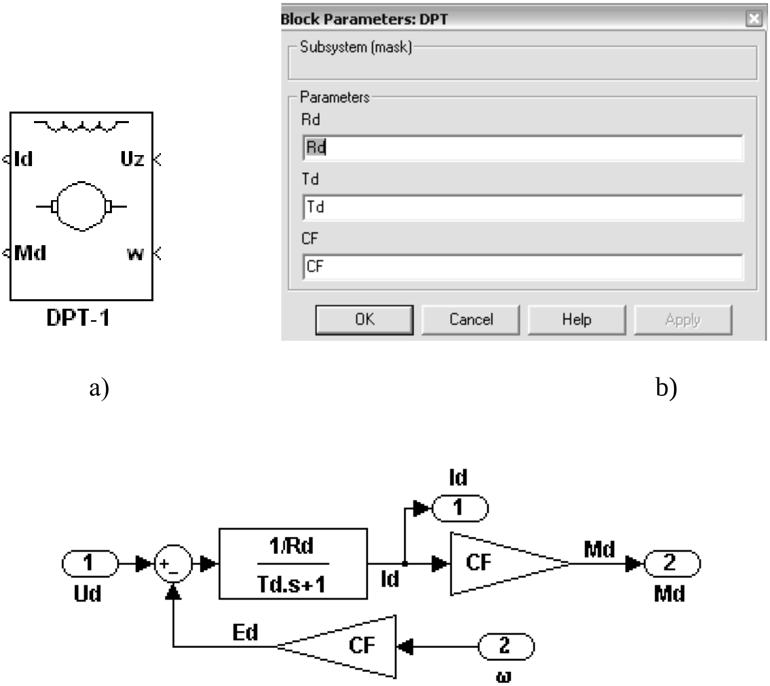


Figure 3.13 - Signal shaper thickness of a random nature

Torque *Md* is created, for example, by a DC motor of independent excitation (DCM of IE), which sets in motion the main drive units of the rolling process (Figure 3.14).

For example, in the models in Figure 3.1 and Figure 3.3, the given *Md* signal enters the *Motalka* and *Razmativatel* subsystems through the *Md* port. The formation of torque is carried out in the subsystem simulating the armature of the machine as a source of torque.

To account for the internal influence of the motor EMF, an input port *w* is provided (to which the angular velocity signal ω of the engine is supplied). In the case of engine operation in the second regulation zone, the DCM model is modified (Figure 3.15) by the appearance of two regulation channels in it (by armature voltage *Ud* and excitation flux *Uzv*). In these subsystems, the ports *Uz* and *Uzv*, respectively, are designed to control the voltage in the armature circuit and the excitation flow of the motor)



Rd: Rd

Td: Td

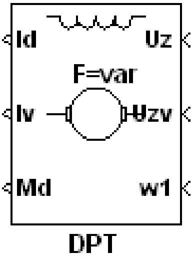
CF: CF

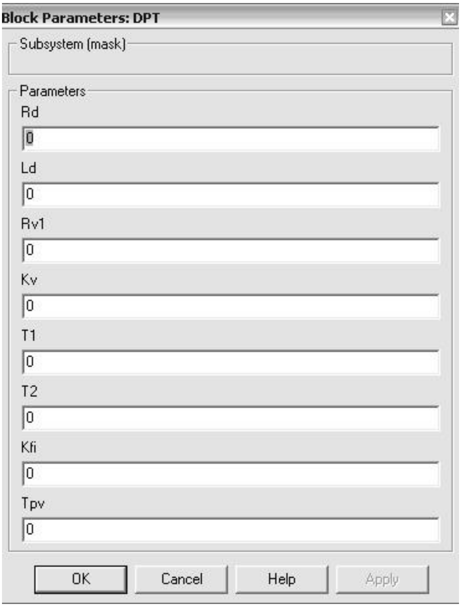
a)

b)

c)

Figure 3.14 - Model of the engine armature (DCM) during operation in the first zone:
a) subsystem; b) parameters; c) structure




Block Parameters: DPT

Subsystem (mask)

Parameters

Rd: 0

Ld: 0

Rv1: 0

Kv: 0

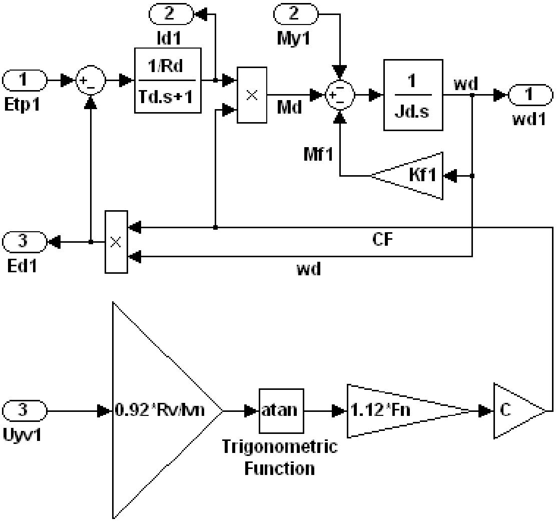
T1: 0

T2: 0

Kfi: 0

Tpv: 0

a) b)



c)

Figure 3.15 - Model of the engine armature (DPT) during operation in the second zone:

a) subsystem; b) parameters; c) structure

When the electric drive is operating in the second zone, the control object feels the action of two control signals simultaneously: U_{yd}, which determines the processes in the anchor circuit, and $U_{yв}$, which forms electromagnetic processes in the elements of the motor magnetic system (excitation current, magnetic flux, motor EMF).

Thus, a complex of computer models of the elements of rolling production was created. It can be used when working in the Power System package for modeling energy systems and devices after upgrading the ports of developed subsystems.

3.3. Four-mass models of interconnected electric drives with elastic connections of the first and second kind

For the study of electromechanical processes in interconnected electric drives of adjacent stands of a rolling mill on the basis of mathematical description and kinematic schemes (Figures 2.9, 2.12) a simulation model was developed in the package of modern applications (Figure 3.16), where *SAU-1*, *SAU-2* are the blocks that provide regulation of control signals of the engines of the first and second stands (*Kletka-1*, *Kletka-2*). The shafts connecting the rolling stands and the drive motors are simulated by *VAL-1*, *VAL-2* blocks. The metal leaving the second stand and entering the first stand is simulated by the *Prokat* block.

In the model, the torques are created by DC motors with independent excitation (*DPT-1, DPT-2*), which drive rolls of two stands through the spindles.

In the *SAU-1, SAU-2* subsystems, the control channel along the armature circuit is in and of itself a dual-circuit automatic control system in which the internal control loop is based on current, and the external one is based on speed.

In case of breakage of the rolled strip to prevent further unwinding of the roll and spoilage, it is necessary to stop rolling, that is, organize emergency braking (Figure 3.17) [32].

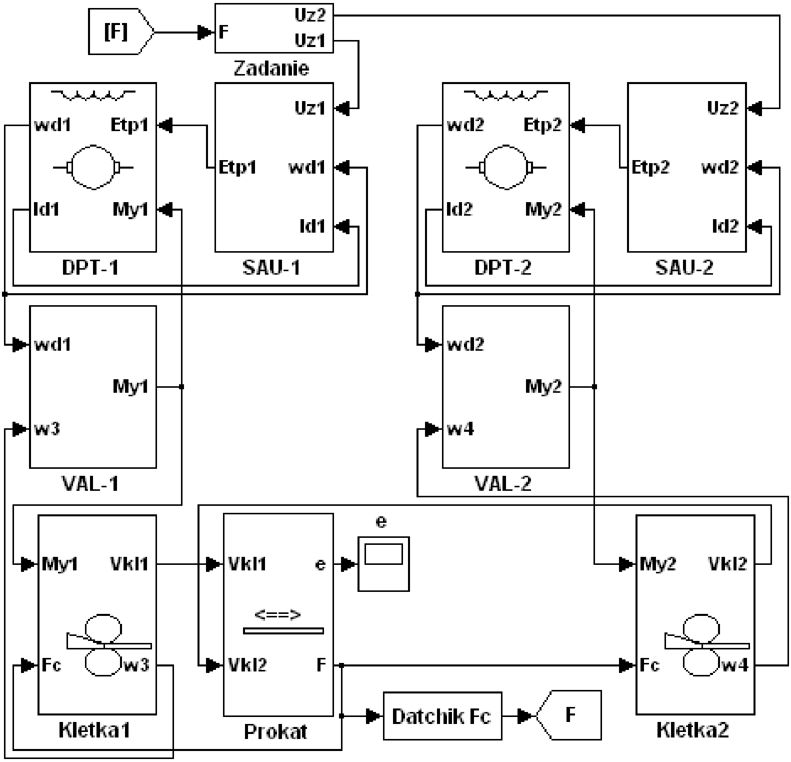


Figure 3.16 - Model of a four-mass electromechanical system of a rolling mechanism with elasticities of the first and second kind

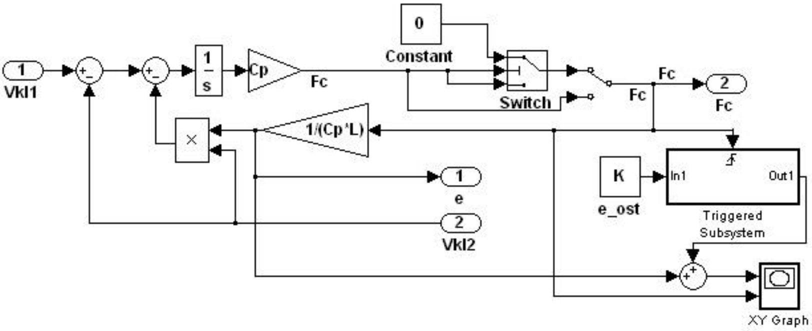


Figure 3.17 - Model of the modified subsystem “*Prokat*” taking into account the effect of band breakage

In the simulation model, the protection system is implemented according to the method of instantly disconnecting the stand electric drives from the supply network when the rolled strip is broken, information about which comes from *Datchik Fc* to the *Zadanie* block.

An analysis of the graphs obtained (Figure 3.18) shows that such a sudden stop leads to very significant jumps and fluctuations in the coordinates of the electromechanical system (EMS).

This can negatively affect the operation of real technological equipment, therefore, in emergency situations, it is necessary to make a smooth stop of the EMS (Figure 3.19).

Transient graphs obtained on the developed simulation model are shown in Figure 3.20.

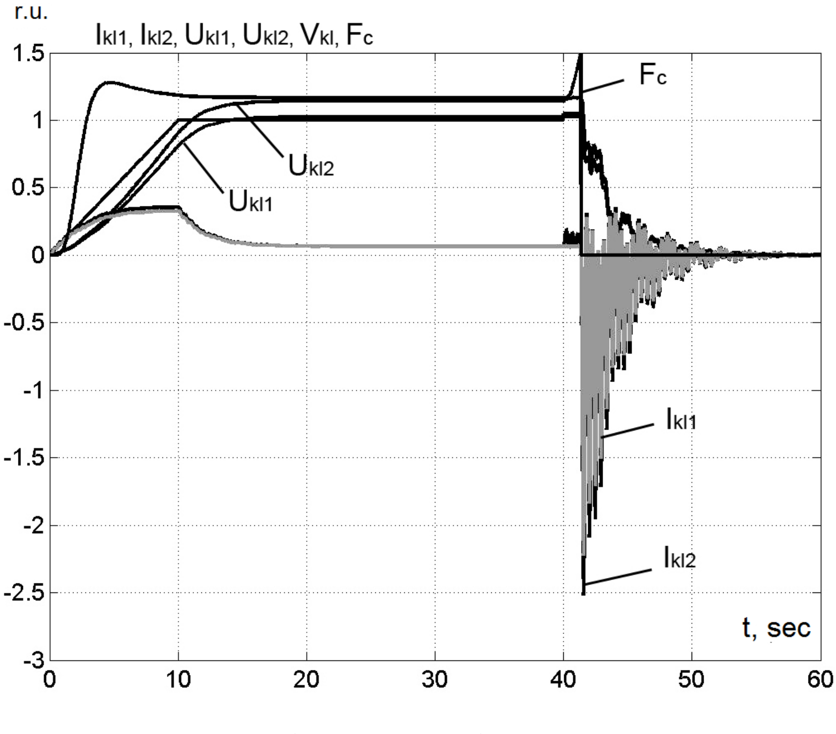


Figure 3.18 - Transients of electric drives of two adjacent stands, taking into account the elasticities of the first and second kind, taking into account the break of the strip when the EMC stops abruptly

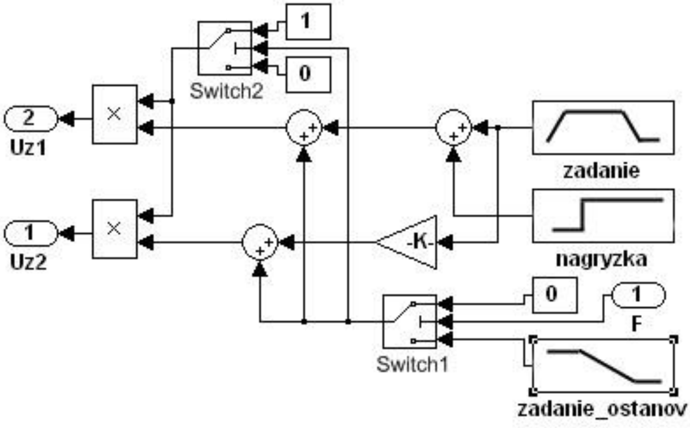


Figure 3.19 - Model of the subsystem «*Zadanie*» with a smooth stop

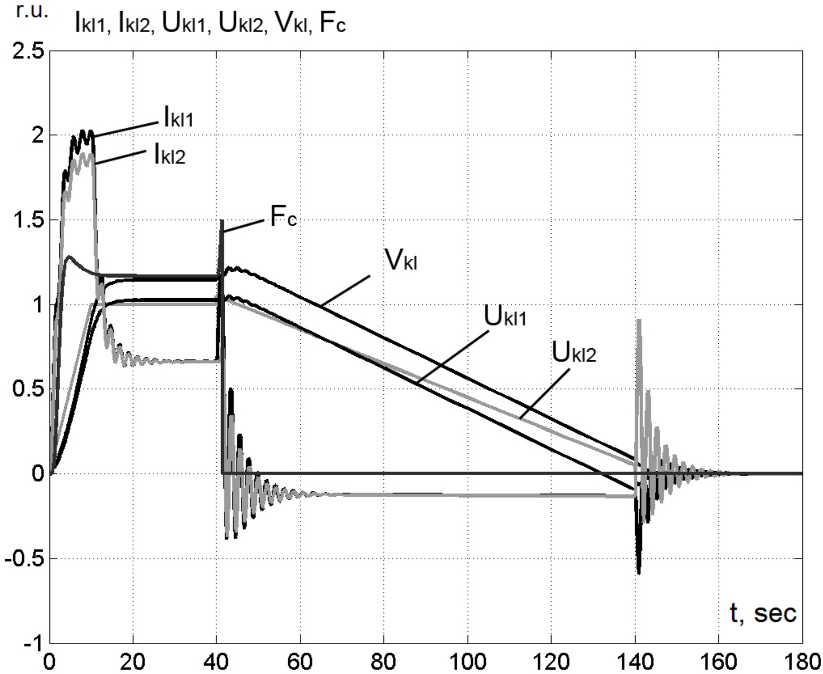


Figure 3.20 - Transient processes of electric drives of two adjacent stands, taking into account the elasticities of the first and second kind, taking into account the break of the strip when the EMS is smoothly stopped

For this purpose, an algorithm has been developed for the EMS soft stop control system provided that the rolled strip is broken [32]. In the "*Zadanie*" subsystem, driving signals are generated, and if the system works without emergency modes, block *F* sends an enable signal to the system, which is multiplied by the normal reference signal. When an unforeseen situation (accident) occurs, F_c' tends to zero and with the help of the "*zadanie_ostanov*" block, a smooth gradual decrease in the reference signal occurs until a zero appears at the output of the "*zadanie_ostanov*" block. As a result of this, switching occurs and zero appears on the output of *Switch1*. It, in turn, is the control signal for the *Switch2* unit, which feeds it to the stand control system and the units are finally stopped [32].

To illustrate the consideration of material's properties, namely the residual elongation when the strip is broken, the dependence *F* = *f(ε)* is plotted, which displays the tensile strength of the material (Figure 3.21).

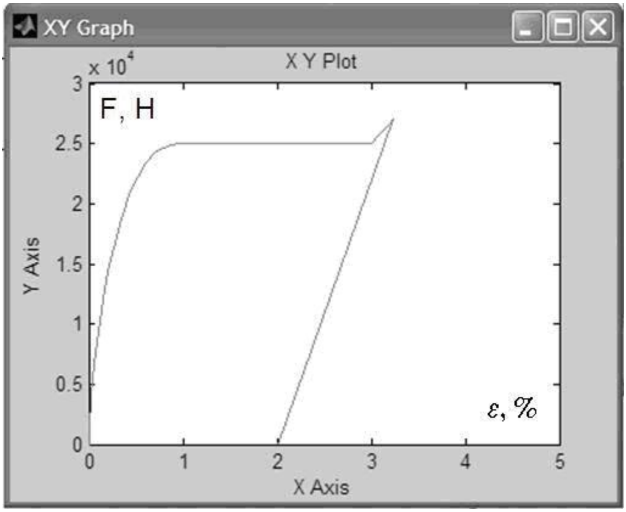


Figure 3.21 - Dependence F=f(ε) representing the tension of the material

Comparing the obtained dependence with the stretching diagram of the rolled strip (Figure 2.11), it can be seen that it corresponds to sections 0-A-B-K-L, namely, in the 0-A section of the diagram and in the range of 0-1% of the obtained dependence, the rolled strip obeys the Hooke law, in the section A-B of the diagram and in the range of 1-3%, the rolled strip passes the material yield zone, that is, the length of the gap increases significantly with a constant load. The next section of the diagram is B-K and the dependence range *F=f(ε)* of *3-3.3%* corresponds to a short-term increase in the load and the subsequent sharp decrease in the load, which leads to a decrease in the elongation of the rolled strip without destroying the strip material, while a residual elongation of the strip is observed, which is required during rolling.

From the above listed blocks, a simulation model of interconnected ED was compiled with joint control of the main coordinates of the rolling [27], for example, Figure 3.22 shows the EMS, consisting of a winder and a working stand, also with individual engines and ACSs. Communication between drive motors and mechanisms is carried out through a long shaft (blocks *VAL-1*, *VAL-2*). The control system is based on the “master-slave” principle, where the stand drive was the master and the winder drive was the slave [27]. The created simulation models allow us to study the dynamics of the EMS regulation of inter-stand tension in the rolling industry.

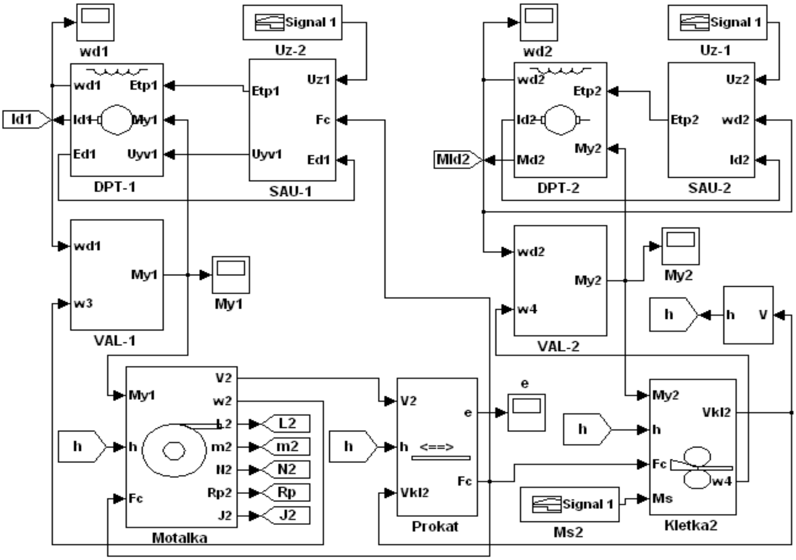


Figure 3.22 - Model of interconnected electric drives of the rolling process taking into account the elasticities of the first and second kind

Figure 3.23 shows the electromechanical processes (*Ikl, Imot, ωmot, Vmot, Vkl, Fc, Uzv, UzFc* - currents in the armature chain of the stand and winder motors, angular speed of the winder, linear speeds of the rolled strip at the exit of the winder and at the exit of the stand, band tension force, reference signals for speed and strip tension, respectively) in the following operating modes of the mill: acceleration to operating speed, rolling in steady state with constant operating speed, braking, stopping.

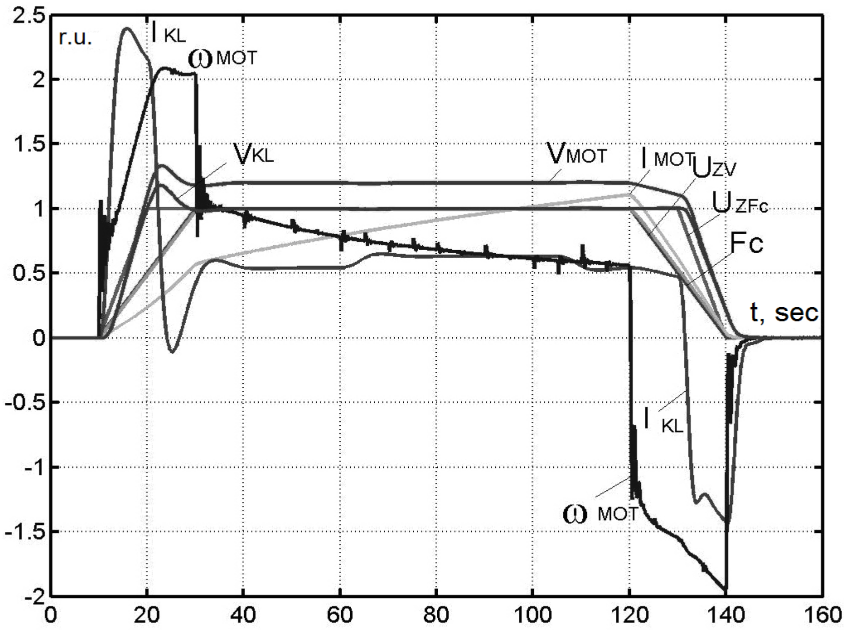


Figure 3.23 - Electromechanical processes of a model of interconnected electric drives of the rolling process, taking into account elasticities of the first and second kind

The presented graphs (Figure 3.23) are reduced to the basic values. A trapezoidal disturbance is presented as a load surge in the working stand. The random nature of the change in the thickness of the metal manifested itself more in the "coiler-crate" system, which manifested itself more on the graph of the angular speed of the coiler, since the metal thickness significantly affects the radius and moment of inertia of the roll.

The considered set of equipment is inherent in most rolling units, therefore, it can be used in modeling the entire technological complex of rolling as an integral part.

3.4. Computer model of a reversible single-chamber cold rolling mill

The single-cell reversible rolling mill consists of such technological units: two winding-unwinding devices, a working stand. To study the electromechanical processes in a single-chamber reversible rolling mill, a simulation model is developed in the package of modern applications, shown in Figure 3.24.

In the single-cell reversible CRM model, *SAU-1, SAU-2, SAU-3* are units that provide control signals for the winding, stand and unwinder engines (*DPT-1, DPT-2, DPT-3*), respectively. The unwinder is represented by the *Razmativatel* unit. The metal coming out of the unwinder and entering the stand (in direct rolling) is simulated by the *Prokat1* block. The working stand of the reversible single-chamber mill in the model is displayed by the *Kletka* block. The metal coming out of the crate and wound on a winder is represented by the *Prokat2* block. The winder is simulated by the *Motalka* unit.

During the rolling process, the strip is unwound from one winder and wound onto another, while the diameters of the rolls are constantly changing. To maintain a constant linear rolling speed, it is necessary to reduce or increase the angular frequency of the engine of the unwinding mechanism depending on the operating mode of the mill.

The change in the diameters of the rolls during the entire rolling cycle should be taken into account while maintaining the constant tension of the strip of rolled metal.

To account for changes in the radius of the roll during the rolling process, a connection is made with the angular frequency of rotation of the coiler. In the *SAU* subsystem, regulation is provided through two channels: along the motor armature and through excitation. The control channel along the armature is represented by a double-circuit ACS (internal control loop is based on current, external is based on voltage). Regulation of excitation takes into account changes in the flow of the engine.

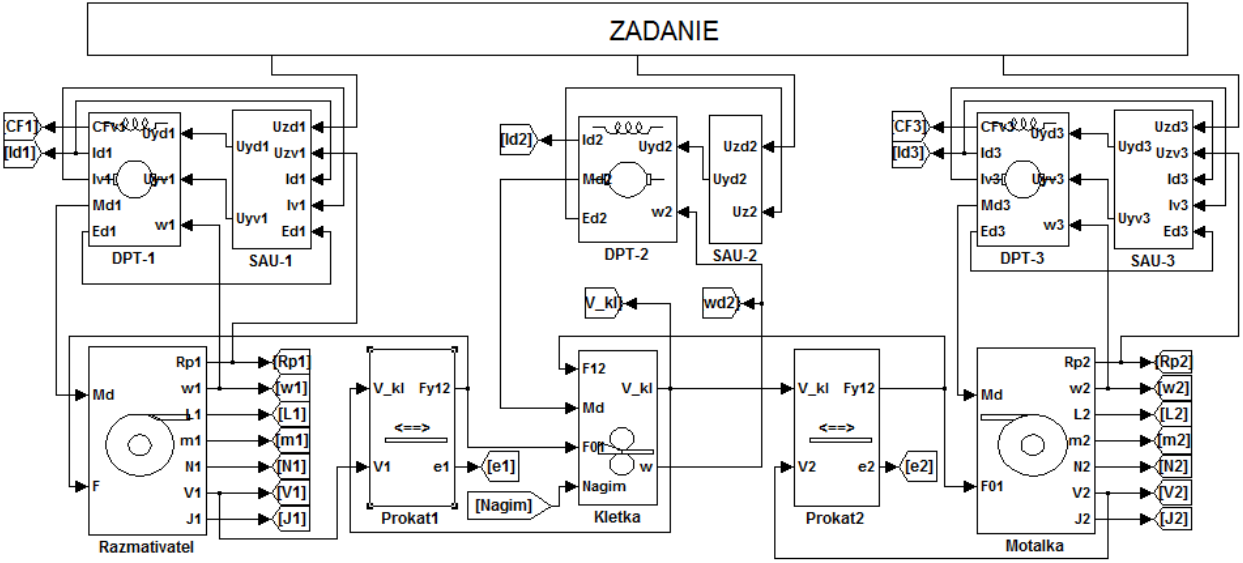
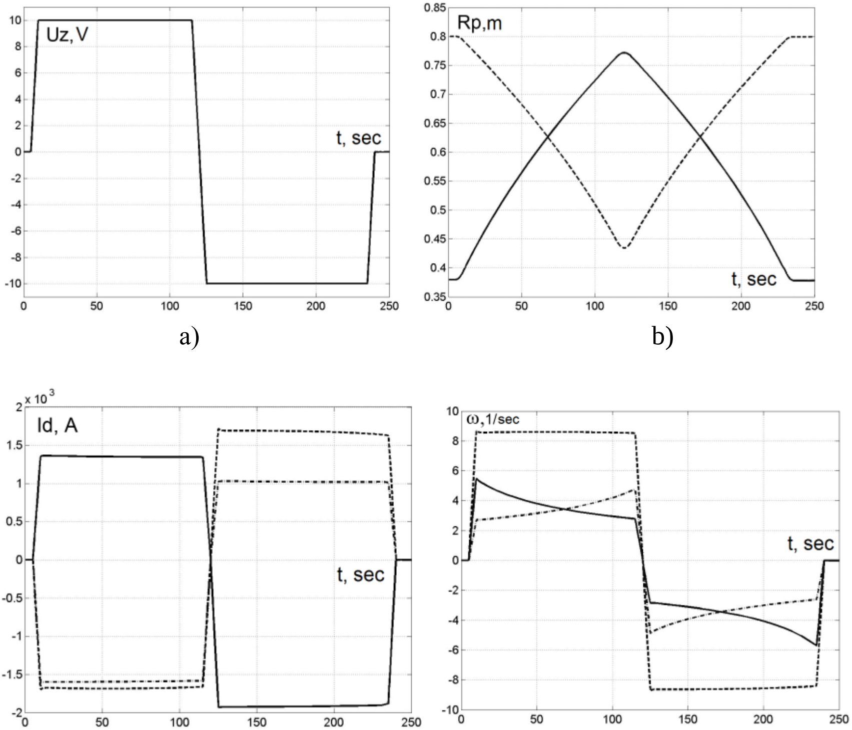


Figure 3.24 - Single-cell reversible CRM model



a) b)

c) d)

Figure 3.25 - Graphs of transients of the mill

The simulation results are shown in Figure 3.25 (reference signal for electric drives (a), roll radius (b), currents of armature circuits of electric drives of the winder, stand, unwinder (c), angular speeds of electric drives of the winder, stand, unwinder (d). The dashed line denotes the processes related to the unwinder: in figure 3.25, b - the radius of the unwinding roll is reduced to the minimum possible, and after that the strip is reversed and the radius of the roll increases to a full roll.

The analysis of the results of modeling the mechanical motion of metal for a single-cage rolling mill and their comparison with experimentally obtained data on the existing single-cage reversing mill of the workshop 1680 of CRW-1 of Zaporizhstal OJSC testifies to the reliability of the developed simulation model (with a deviation between each other not more than 5 - 8%)

3.5. Computer model of the 4-stand cold rolling mill “Tandem”

Continuous rolling mills contain several working stands in which metal is simultaneously rolled. The metal moves in one direction, and its successive compression occurs in each working stand. All stands, unwinder and coiler are equipped with electric drives.

When simultaneously rolling metal in several stands, the amount of metal leaving the previous stand should equal the amount of metal entering the subsequent stand. The same amount of metal passes through each stand in a unit of time.

To study the electromechanical processes in the four-stand cold rolling mill “Tandem”, its computer model was developed (Figure 3.26). 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).

In figure 3.27, 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 3.27 d, e, f.

Comparison of the transient graphs obtained during the simulation with the data of the operating equipment of Zaporizhsal OJSC confirmed the adequacy of the developed model of the four-stand mill “Tandem”.

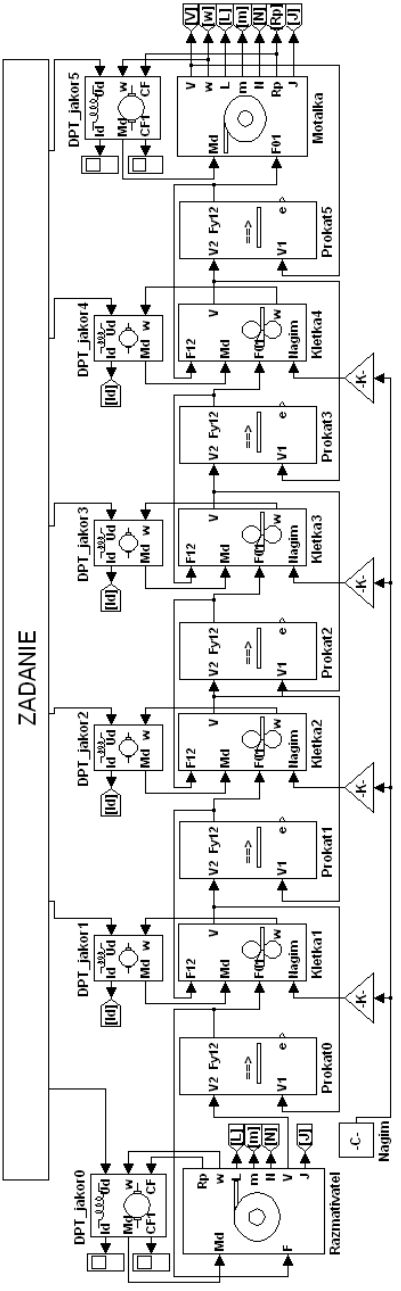
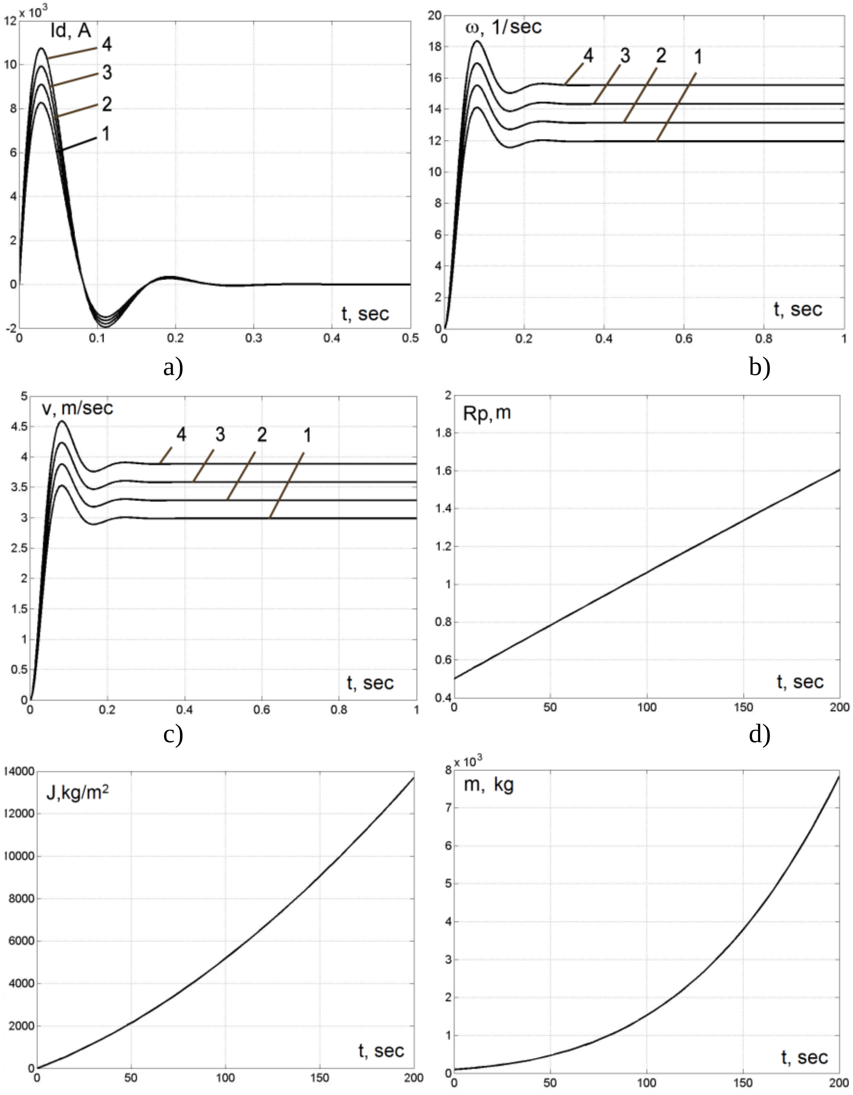


Figure 3.26 - Model of a four-stand cold rolling mill “Tandem”



a) b)

c) d)

e) f)

Figure 3.27 - Graphs of transients on 4 stands:
a) currents of armature windings of engines; b) angular velocities of the motors of the stands; c) linear speeds of the strip movement;
d) changing the radius of the roll on the winder;
e) and f) a change in the mass and moment of inertia of each of the stands.

3.6. Computer model of the transverse cutting unit

For analysis and synthesis of the TCU control system, a simulation model was developed in a package of modern application programs (Figure 3.28), the automatic control system of which was built on the basis of transfer functions, which were used to calculate a number of assumptions that greatly simplify the system [30]. In *Uz-1, Uz-2, Uz-3,* a task is formed on the pace and speed of rolling. The *DPT-1* has a dual-zone speed control system that provides constant linear strip speed and tension. In *DPT-2*, *DPT-3*, *DPT-4*, a subordinate speed control system is implemented, where the linear speed of the strip at the output and entrance to the loop pit is synchronized using the *Sinhron* unit, ensuring a constant loop length. The force from the unwinder is transmitted to the straightening machine through the metal. The block simulating the operation of the straightening machines represents the inertial mass of all rotating parts of the machine, brought to the motor shaft. The block takes into account the front and rear tension of the strip, obtaining the linear velocity of the metal at the exit of the machine. The tension between the 13-roller straightening machine and the flying shears, which causes longitudinal deformation of the metal, is non-existent, therefore only linear velocity of the strip should be taken into account correctly. The model of flying shears implements the principle of cutting the strip into sheets, depending on the feed speed of the strip.

The following figure 3.29 shows graphs of changes in the basic coordinates obtained on a simulation model of a transverse metal cutting unit. Namely, graphs of changes in the angular speeds of rotation of the engines of the unwinder, 5-roller and 13-roller straightening machines are shown. The linear speed of the strip at the output of the 5-roller straightening machine is slightly higher than the linear speed of the strip at the output of the 13-roller straightening machine, due to which a loop is formed.

The gravity of the loop *Fp* increases as the mass of the loop increases. The tension force *F12* is kept constant. On the graphs of the moments of the engines of the unwinder, 5-roller and 13-roller straightening machines, the dynamic components of the transient processes (acceleration, speed change, braking) are visible. The obtained results confirm the adequacy of the model when compared with experimental data on the transverse cutting unit of the Cold Rolling Shop No. 1 of Zaporizhstal JSC.

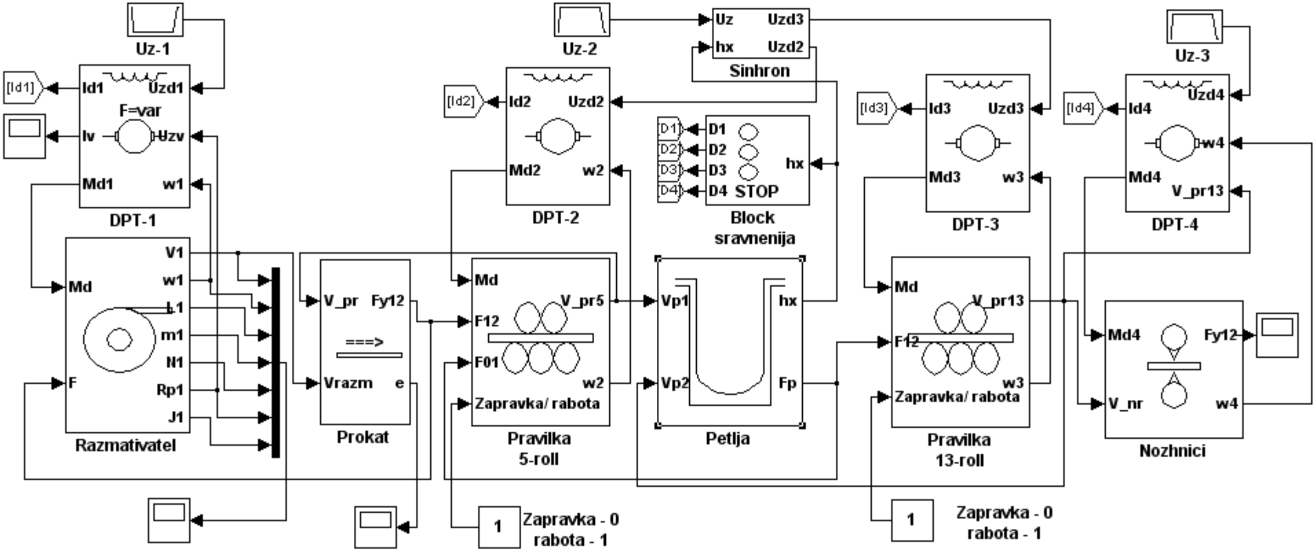
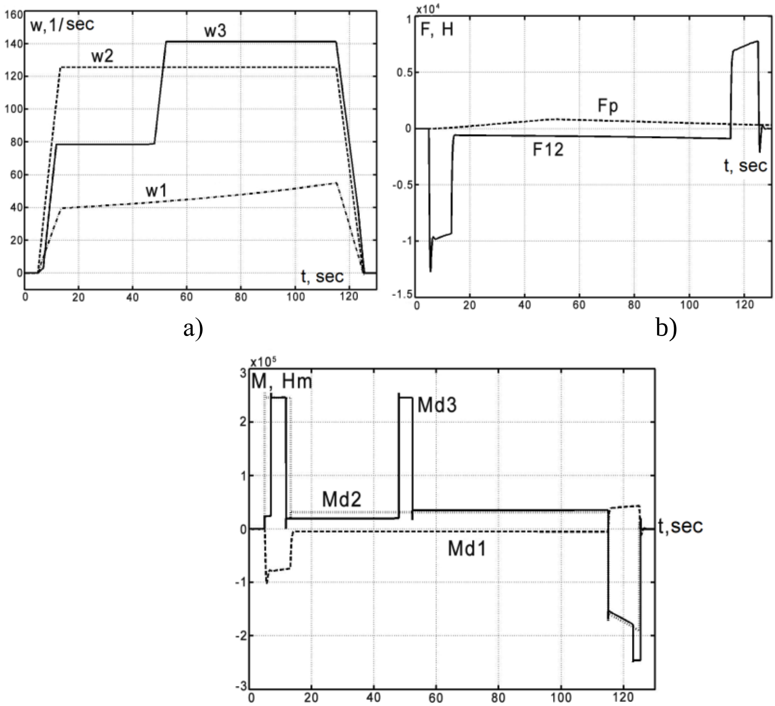


Figure 3.28 - Model of the transverse cutting unit



a) b)

c)

Figure 3.29 - Graphs of electromechanical processes of TCU:
a) angular velocity; b) forces acting in the metal;
c) engine moments

Thus, a complex of interconnected computer models of rolling production elements is proposed that takes into account the elasticities of the first and second kind, reversing, looping, changing the thickness of the rolled strip and the possibility of an emergency in connection with the strip breakage. Implementation of the proposed complex of computer models is recommended, which will provide a rational approach to the design and study of electromechanical systems of cold rolling mills. The universality of the developed complex of models of elements of rolling production was confirmed in the study of electromechanical systems with various structures, namely, a reversible single-chamber cold rolling mill, four-stand cold rolling mill “Tandem”, a transverse cutting unit.

Chapter 4.
MULTI-CHANNEL DIAGNOSTIC COMPLEX OF THE COLD ROLLING MILL

4.1. Hardware

During the control and research of the technological process, conclusions about the operating conditions of the equipment and the nature of the technological process are made on the basis of an analysis of the values obtained by measuring its parameters. The measurement usually implies receiving and displaying information about some of the coordinates of the process. The measurement process consists of the experimental determination of the numerical relationship between the measured physical quantity and the value taken as the unit of measurement. However, in practice it is technically difficult to control some parameters directly, therefore, when creating a reliable model of a rolling mill, they can be calculated using the indirect method, implementing them on microprocessor systems [21].

Methods for measuring linear displacements, even if they are small, are not very difficult and are quite well developed. However, when measuring the electromechanical parameters of rolling mills, the known direct methods for measuring linear displacements cannot be used due to the short duration of the measured loads and the need to transmit a signal proportional to the measured electromechanical parameter to the mill control panel or to the automatic control system. Therefore, when measuring the electromechanical parameters during rolling, small linear displacements are converted into a value that is easy to amplify and measure or record with electrical signals.

When using measuring and diagnostic devices, several parameters are usually measured simultaneously. Therefore, light-beam oscilloscopes are used as the information fixation, allowing several parameters to be simultaneously recorded on photosensitive paper. The measurement results are obtained only after processing and decoding the waveforms, which significantly slows down the process of diagnosing rolling. Known literature sources describe the two-channel measuring and computing complex IND-7681, which receives information from specially developed sensors MAD-7681. However, this does not address issues related to the creation of a common diagnostic complex that allows you to continuously monitor the operation of the rolling mill according to several current technological electromechanical parameters, and not just tension.

Modern microprocessor systems also allow you to diagnose and transmit various signals for analysis through information channels. With the development of microprocessor electric drives of both direct and alternating current, it became possible to create a common diagnostic multi-channel complex of the entire technological process (in particular, a training rolling mill), in which almost all available electromechanical parameters can be controlled.

In order to reduce the thickness of the metal, to obtain the necessary surface strength of the metal and the quality of the strip surface, the strip is subjected to tempering (rolling with small reductions of up to 1.5% and a relatively high coefficient of friction), which results in hardening of the surface layer. Tempering is carried out in the forward direction.

The layout of the equipment of a single-stand tempering mill for cold rolling workshop No. 1 of Zaporizhstal JSC is shown in Figure 4.1. In this picture it is indicated: 1 - unwinder; 2 - tension rollers; 3 - pressure device; 4 - crate; 5 - strain gauge rollers; 6 - winder; 7, 8, 10 - gearboxes of engines for unwinding and winding devices, tension rollers, respectively; 9 - gear stand; 11-14 - motors of electric drives of the unwinding device, tensioner, stand and winder device; ω1, ω2 - angular speeds of the unwinder and winder; υ1, υ2 - linear speed of the strip at the input and output of the stand; U - unwinding device, TR - tension rollers, S - stand, W - winding device.

To solve the problem of measuring the electromechanical parameters in the conditions of metal rolling, a diagnostic multi-channel complex was developed. The complex uses information received from speed, current and voltage sensors. For each of the four electric drives [33], the following coordinates are controlled: motor voltage, excitation current, armature current, as well as the stand speed, which is taken into account in accordance with the calibration coefficient in proportion to the tachogenerator voltage.

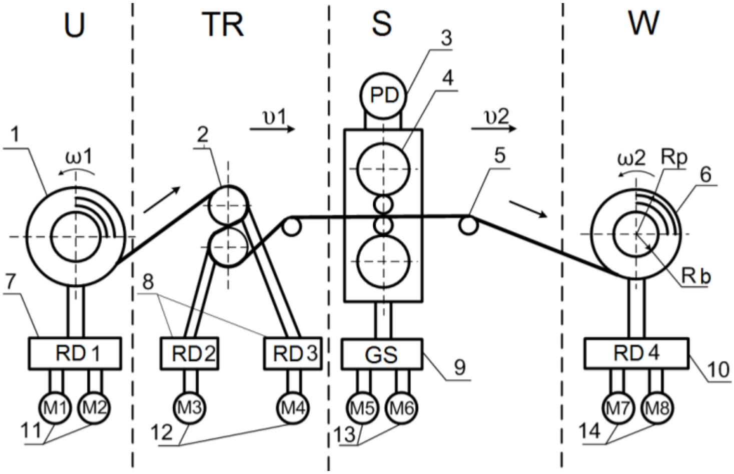


Figure 4.1 - Layout of the equipment of the rolling mill

The block diagram of the diagnosing multichannel complex is shown in Figure 4.2.

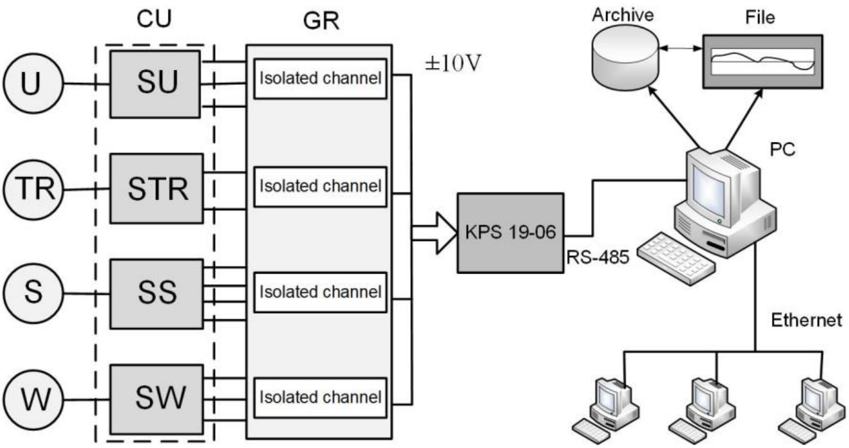


Figure 4.2 - Structural diagram of a diagnosing multichannel complex

Table 4.2 - The main technical characteristics of the diagnostic multi-channel complex

Parameter	Value
1 Number of measurement channels, pcs	16
2 Number of monitored quantities, pcs	12
3 Supply voltage from a network of an alternating (50±1 Hz) current, V	220
4 Analog inputs, DC voltage, V	-10…+10
5 Digital channel	RS-485
6 Data transfer rate, kB/s	19200
7. The execution time of one command by the processor, μs	0,5
8. The speed of the complex as a whole, μs	5

The signals from the current and voltage sensors enter the conversion unit (CU), which is represented by voltage dividers. Next, the signals are fed to the galvanic isolation unit (GR). A stabilized constant voltage equal to ± 10 V is supplied to the analog input block B16.2 of the KPS19-06 microcontroller (Figure 4.3). The KPS19-06 controller is designed to collect measurement information in the form of analog signals: direct current and voltage. It is also possible to pre-process information and issue control actions on the control object to build automated systems for measuring, controlling, regulating and controlling production processes, technology production lines [22]. This is done according to the programs recorded in the controller memory using the programming and debugging tools provided to the consumer. The KPS19-06 programmable controller is shown in Figure 4.3.

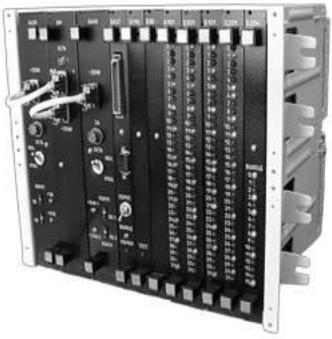


Figure 4.3 - KPS19-06 Programmable Controller

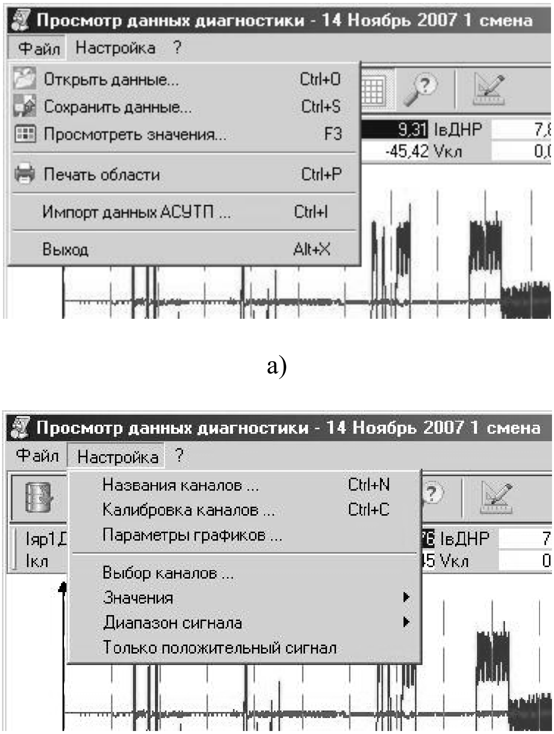
The functionality of the KPS19-06 microcontroller meets the technical requirements set during the development of the diagnosing multichannel complex. This module has a fairly high processor speed and implements analog-to-digital conversion of input signals. Thanks to the use of port B16.2, it is possible to connect all the sensors of the diagnostic complex to the microcontroller.

Further, the signals are transmitted by a serial communication channel RS-485 with a speed of 19200 kB/s to a personal computer with the WindowsXP operating system, where the process of recording and archiving the current values of electromechanical parameters takes place [15, 21]. The controller provides programming and debugging systems: “RKS” - a tool of a technologist who does not speak the programming language “ASSEMBLER” (extended by functional blocks); "WINTS" is intended for users who know the languages "SI" and "ASSEMBLER", as well as for writing programs with complex algorithms (including support for network, serial port and remote control, interruptions).

4.2. Software

In this case, the software of the complex was specially developed based on the built-in microcontroller system KPS19-06. To write the program, the programming languages Borland Delphi 5.0 and CROSS-ASSEMBLER ASM51 were used, with which it is possible to organize input/output of information and which have a number of reserves. The main menu of the created program (Figure 4.4) contains both the familiar options for opening a file for viewing data, saving data, viewing values, printing a value area, as well as specific ones, for example, importing process control data.

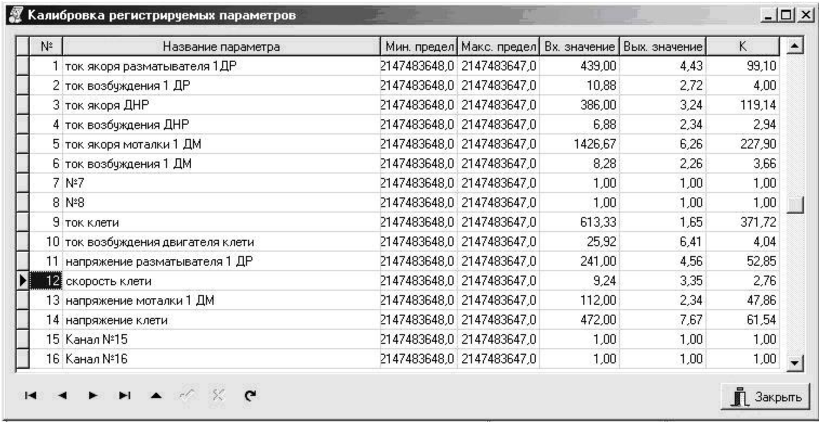
The developed program allows the user to enter the necessary channel names, calibrate the channels (Figure 4.5), change the parameters of the graphs. To adjust the image of graphs, the program provides the ability to change the color, thickness of the graph lines; for the convenience of studying the curves, a grid can be displayed and its step can be set; To study the graphs in general form (without displaying the effect of noise on the signal), an averaging function is provided. Program users can select the curves of the necessary signals to display on the coordinate axes [33].



a)

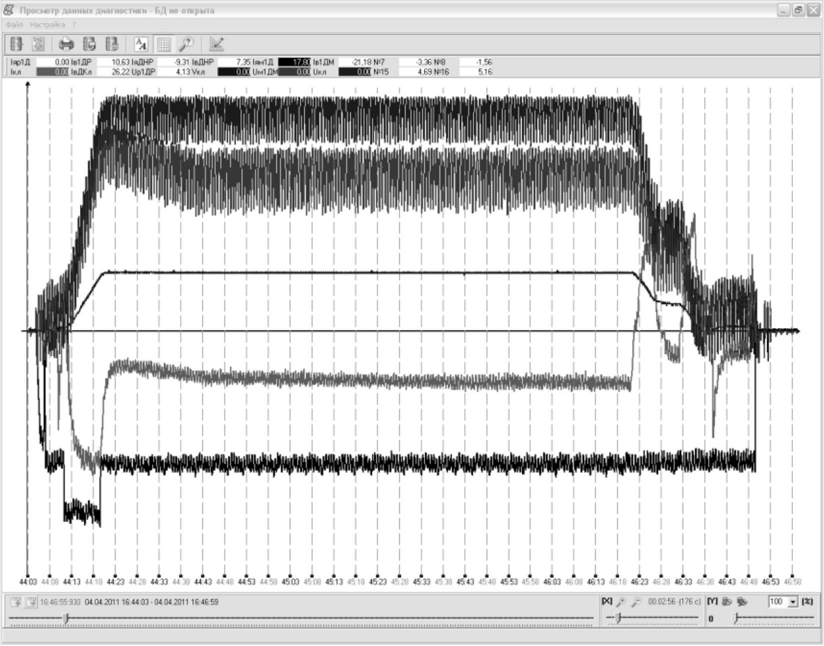
b)

Figure 4.4 The program menu bar:
a) File menu; b) Setup menu



№	Название параметра	Мин. предел	Макс. предел	Вх. значение	Вых. значение	K
1	ток якоря разматывателя 1ДР	2147483648,0	2147483647,0	439,00	4,43	99,10
2	ток возбуждения 1 ДР	2147483648,0	2147483647,0	10,88	2,72	4,00
3	ток якоря ДНР	2147483648,0	2147483647,0	386,00	3,24	119,14
4	ток возбуждения ДНР	2147483648,0	2147483647,0	6,88	2,34	2,94
5	ток якоря моталки 1 ДМ	2147483648,0	2147483647,0	1426,67	6,26	227,90
6	ток возбуждения 1 ДМ	2147483648,0	2147483647,0	8,28	2,26	3,66
7	№7	2147483648,0	2147483647,0	1,00	1,00	1,00
8	№8	2147483648,0	2147483647,0	1,00	1,00	1,00
9	ток клети	2147483648,0	2147483647,0	613,33	1,65	371,72
10	ток возбуждения двигателя клети	2147483648,0	2147483647,0	25,92	6,41	4,04
11	напряжение разматывателя 1 ДР	2147483648,0	2147483647,0	241,00	4,56	52,85
12	скорость клети	2147483648,0	2147483647,0	9,24	3,35	2,76
13	напряжение моталки 1 ДМ	2147483648,0	2147483647,0	112,00	2,34	47,86
14	напряжение клети	2147483648,0	2147483647,0	472,00	7,67	61,54
15	Канал №15	2147483648,0	2147483647,0	1,00	1,00	1,00
16	Канал №16	2147483648,0	2147483647,0	1,00	1,00	1,00

Figure 4.5 - Window for calibration of recorded parameters



Iяр1Д 0,00 Iв1ДР 10,63 IяДНР -9,31 IвДНР 7,35 Iям1Д 17,80 Iв1ДМ -21,18 №7 -3,36 №8 -1,56

Iкл 0,00 IвДКл 26,22 Up1ДР 4,13 Vкл 0,00 Uм1ДМ 0,00 Uкл 0,00 №15 4,69 №16 5,16

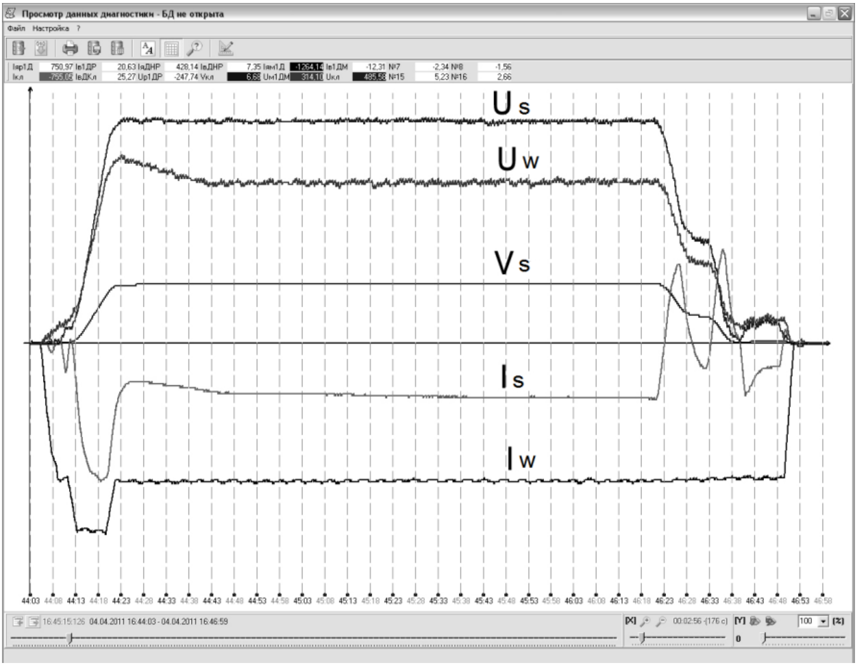
16:46:55:930 04.04.2011 16:44:03 - 04.04.2011 16:46:59

00:02:56 (176 c)

Figure 4.6 - Electromechanical processes of a tempering mill

For a detailed study of the rolling processes in the complex, the possibility of scaling along the X and Y axes was specially provided. To simplify the perception of the graphs of the displayed signals, it is possible to use a function that allows you to sign graphs on the coordinate plane in the same color as the graph curve.

To visualize the instantaneous values of parameters, display them in the form of a waveform and archive them there is a monitoring program that is installed on a personal computer (server) and connected to the diagnostic system via Ethernet. Data is written into a file that contains information: date and time of measurement; number of signals; array of signals - which makes it easier to orient the file archive.



Iяр1Д 750,97 Iв1ДР 20,63 IяДНР 428,14 IвДНР 7,35 Iям1Д -1264,14 Iв1ДМ -12,31 №7 -2,34 №8 -1,56

Iкл -755,05 IвДКл 25,27 Uр1ДР -247,74 Vкл 6,68 Uм1ДМ 314,10 Uкл 485,58 №15 5,23 №16 2,66

16:45:15:126 04.04.2011 16:44:03 - 04.04.2011 16:46:59

00:02:56 -(176 c)

Figure 4.7 - Averaged electromechanical processes of the temper mill

The analysis of the results obtained can be used to configure and control the control system of both individual equipment and the electromechanical complex as a whole.

Chapter 5
MODELING OF ELECTROMECHANICAL PROCESSES ON THE EXAMPLE OF A TRAINING MILL

5.1. A brief description of the equipment of the training mill 1700

The 1700 training mill consists of a four-roll stand and its equipment: a chain conveyor with a tilter, a loading trolley with a lifting table, an unwinder, feed rollers, a tensioner, a coiler, a roll picker, a roll transfer mechanism, a chain conveyor behind the mill.

The chain conveyor with a tilter is designed to transport rolls from the thermal compartment or from the warehouse of the training compartment to the mill and tilting them from a vertical to a horizontal position.

The loading trolley with a lifting table is designed to remove the rolls from the tilter, feed them to the unwinder drum and put them on.

The unwinder is intended for the correct installation of the roll relative to the longitudinal axis of the mill and the creation of the rear tension of the strip during training. The unwinder consists of a drum (drum diameter 690-770 mm), a clamping device and a roll centering mechanism. Electric motor power 150 kW (2 engines installed), 300-1200 rpm, maximum strip tension - 1500 kg.

The feed rollers are designed to feed the end of the unwinding strip into the rolls of the tensioner, which is designed to create additional tension of the strip during training and is installed on the front side of the stand. It consists of two rolls with a diameter of 500 mm, the drive of each roll from an electric motor with a power of 180 kW, 750-1500 rpm.

The mill stand is equipped with two engines of 660 kW each, 450-1200 rpm, the permissible metal pressure on the rolls is 500 tons, and the maximum speed is 20 m/sec. The electric motors of the pressure devices are connected by a coupling to ensure joint or separate operation of the pressure screws. The movement of the screws is controlled using selsyn BD-501A.

A drum-type winder located on the back of the stand is designed to pull and wind the strip into a roll. The maximum diameter of the winder drum is 750 mm, strip winding speed - 20 m / s, winder drum speed - 207-664 rpm, strip tension - up to 5 tons, drive from an engine with a power of 630 kW, 500-1000 rpm.

Cold-rolled annealed strips of such steel groups are trained: carbon boiling and semi-quiet - high-quality and ordinary quality general-purpose; non-aging steel 08yu; low alloy steels; alloy steels.

The sizes of the strips are 0.5-2.5x850-1500 mm. The values of the deformation degree during the training of bands, according to the technological map No. 3 are given in table. 5.1.

Table 5.1 - The magnitude of the degree of deformation

Kind of steel	The magnitude of deformation
Carbon boiling and semi-quiet steel	0,8-1,2 %
Steel grade 08 yu	0,8-1,2 %
Carbon mild steel of all thicknesses	No more 1,5 %
Low alloy commercial steel	No more 2%
Alloy steel	No more 3%
Blanks for bent profiles	No more 2%

The value of the deformation degree during training is recorded by the recording devices IRO-1, installed at the posts of mills. When leaving the working stand, the front end of the strip is fed to the coiler and threaded into the throat of its drum, the hinged support is closed, then the pressure device is turned on and the upper rolls are lowered by an amount that provides the necessary compression of the strip, the necessary tension is created between the unwinder and the rollers. Engines of the tensioner are turned on, which operate in the generator mode. The unwinder motor also engages in generator mode. The lower idle roller is lowered to the lower position, and all the mechanisms of the mill are transferred to the maximum speed for this training mode. Slowing and stopping the mill is done by the roll maker. When changing the speed of training, the roller adjusts the reduction with the help of pressure screws.

5.2. Analysis of indicators of the existing tension control system (advantages and disadvantages)

Adjustable DC drives in the generator-motor system are widely used for main drives of continuous stands, reversible and temper cold rolling mills. One of the incentives for the use of such electric drives was the possibility of using powerful synchronous drive motors of converting units of these rolling mills as sources of reactive energy to improve the energy performance of the supply network [8, 23].

The DC generator is a power amplifier, the input signal of which is the excitation voltage of the generator. The main type of exciter of the generator is a valve converter, which provides high speed and power gain.

When comparing the G-D system with TP-D, it is seen [1] that an additional aperiodic link appears in the G-D system with a time constant of the excitation winding of the generator T and coefficient K. Thus, an additional large time constant T appears in the circuit, which is also subject to compensation, as well as the time constant of the anchor chain T_A [1].

One can refuse to compensate for a time constant T_A that is less than T by setting $T_M = T_\mu + T_A$. The cutoff frequency of the circuit is low enough, which corresponds to a decrease in the speed of the circuit and a decrease in the accuracy of regulation. The deterioration of the current control loop properties is the greater, the larger T_A. Therefore, to compensate for the influence of T_A on the quality of regulation of current and torque, a subordinate control circuit of the EMF of the generator is introduced in the GD system.

When training, special attention is paid to the tension of the strip. The tension of the strip is controlled at a constant speed of the mill according to the indications of ammeters and should be constant during the entire time of training the strip.

The automatic control system for each roll of the training stand includes three loops: a generator voltage chain with a PI voltage regulator, an armature current chain with a PI current regulator, and a speed chain with a proportional EMF controller.

To reliably quench the residual excitation flux of the generator and prevent the effect of creeping speed of the electric motor when it is stopped, additional feedback on the voltage of the generator is introduced into the automatic control system. It is connected by the switch to the input of the excitation regulator when one of two conditions is fulfilled - a zero signal for setting the speed at the input of the speed controller or opening the power circuit of the G-D system.

The parameters of the generator voltage feedback loop are selected in such a way as to ensure reliable damping of the residual excitation flux of the generator and at the same time stability when a closed loop for regulating the voltage of the generator is introduced in the field damping mode [8].

In the case when the requirements for ensuring high performance are not presented to the tuning of the control circuit of the motor EMF, the EMF controller is integral. Its integration constant determines the cutoff frequency of the logarithmic amplitude frequency response (LAFR) of the EMF control loop and, accordingly, the speed of this circuit.

If, in accordance with technological requirements, it is necessary to ensure high-speed response of the EMF control loop, then this problem can be solved by using the EMF PI-regulator. The forcing component of the controller should compensate for the effect of the equivalent time constant of the closed loop for regulating the excitation current of the electric motor.

5.3. Modeling an existing tension control system

The tension of the strip is created using electric winding-unwinding devices. The electric drive of the winder operates in the motor mode, providing the output tension of the strip. The unwinder engine is in generator mode. The pulling motor for the unwinder is the rolling stand motor.

Using computer models of the rolling stand mechanism, the winding-unwinding mechanism, the DC motor, blocks simulating the elastic connections of the engine and the actuator, as well as the strip being rolled, a computer model [8] for the rolling stand and winding control system was developed.

The automatic control system of winder is dual-zone. The control along the armature circuit is carried out using a dual-circuit system: internal current loop, external - EMF (Figure 5.1). The excitation circuit is controlled by a voltage control system. Dotted line indicates the structural blocks of the main parts of this system (Figure 5.2).

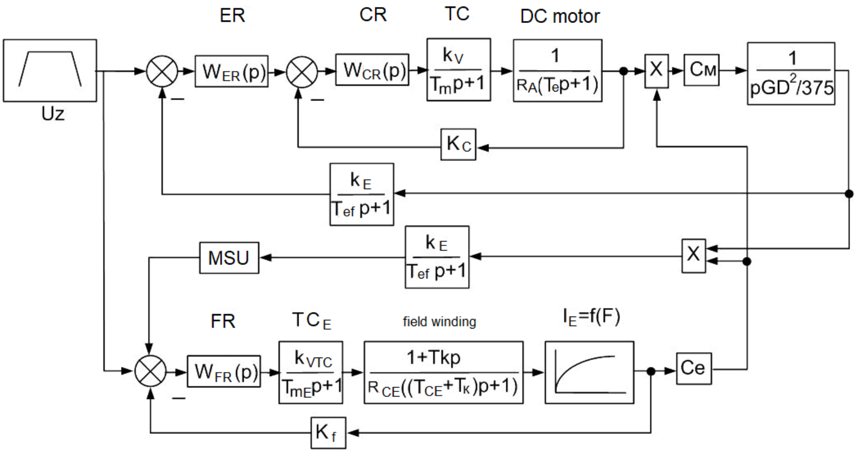


Figure 5.1 - Functional scheme of the electric winder with a dual-zone automatic control system

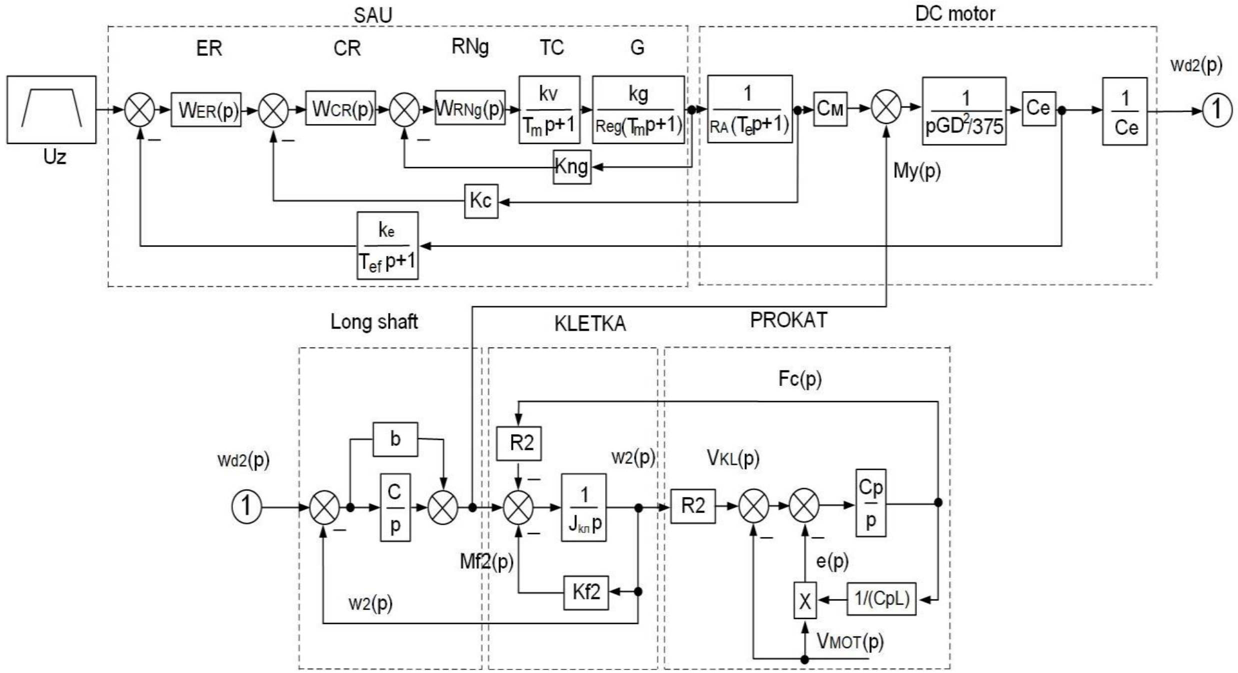


Figure 5.2 - Structural diagram of the rolling mill electric drive taking into account the elasticities of the first and second kind with the automatic control system “generator-engine”

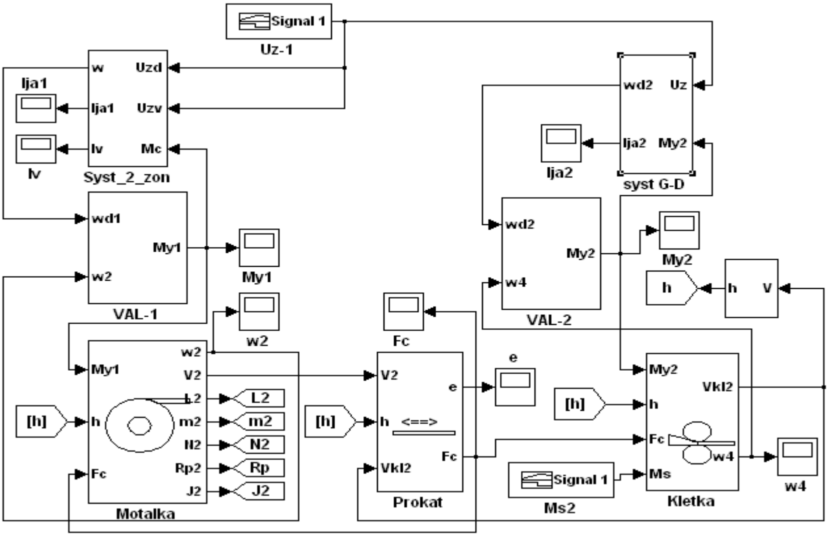


Figure 5.3 - Model of the electric drive of the winder and stand, taking into account the elasticities of the first and second kind

The automatic control system of the rolling stand consists of three loops: a generator voltage loop with a PI voltage regulator, an armature current loop with a PI current regulator and a speed loop with an EMF P-regulator (Figure 5.1).

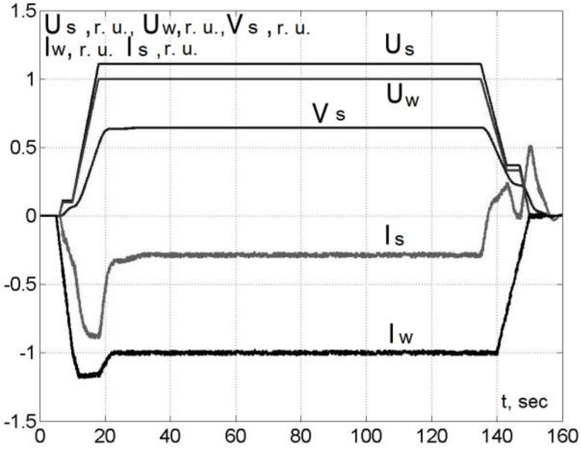


Figure 5.4 - Simulation results

Figures 5.3, 5.4 show a model of the winder and stand electric drive with existing control systems, simulation results [27] (stand anchor current, linear speed of the strip, stand motor voltage, winder motor voltage, winder armature current, winder excitation current).

5.4. Model adequacy check

By conducting a passive experiment using a diagnostic multi-channel complex, the data of the electromechanical processes of a 1700 single-trainer mill for randomly selected rolls and shifts were collected (tables 5.2 and 5.3).

To determine the reference values of the measured values, we calculate the average statistical measurement results

$$\overline{a} = \frac{1}{n}\sum_{i=1}^{n} a_i \, , \tag{5.1}$$

where n – number of measurements; a_i - measurement results under the same conditions.

The following operating modes were investigated: acceleration to the filling speed, acceleration to the operating speed, operation in the steady state, braking to a reduced speed, braking to a complete stop.

Control points selected t_1, t_2, t_3 - transition to refueling, working and reduced speeds, respectively; I_{AM}, I_{EM}, U_M – armature current, excitation current and winder voltage; I_{kl}, V_{kl}, U_{kl} – stand current, linear stand speed and stand voltage; (1) - when the filling speed is reached, (2) - when the operating speed is reached, (3) - when the reduced speed is reached. To check the adequacy of the developed models, transient processes were simulated in the main operating modes of the 1700 single-trainer mill and compared with the calculated average statistical values. Figure 5.5 shows the transients obtained on the model, and Figure 5.6 shows the averaged experimental transients most similar to the calculated average statistics. Tables 5.4, 5.5 show the coordinates of transients at control points and assess the relative error of the models.

The relative error ε_A of the measured quantity A is usually called the ratio of the absolute error ΔA to the true value of A. The ratio ΔA to the average value $\overline{a}$ is used as the best estimate of the relative error ε_A.

$$\varepsilon_A = \frac{\Delta A}{\overline{a}} \, . \tag{5.2}$$

Comparison of the model obtained and experimental values shows that the relative error does not exceed 8.12%.

According to (5.1), the average statistical relative error of the entire model was calculated $\overline{a}_m$ =3,79 %.

Table 5.2 - Winder experimental data

Control points	Numerical values of samples										Statistical average
	1	2	3	4	5	6	7	8	9	10	
$I_{AM}(1)$, (A)	180	170	190	200	180	210	220	200	190	200	194
$I_{AM}(2)$, (A)	1400	1400	1450	1500	1550	1600	1650	1550	1500	1550	1680
$I_{AM}(3)$, (A)	700	700	750	800	700	850	900	850	850	850	795
$I_{EM}(1)$, (A)	21	21	22	23	21	23	24	23	22	23	22,3
$I_{EM}(2)$, (A)	21	21	22	23	21	23	24	23	22	23	22,3
$I_{EM}(3)$, (A)	0,21	0,21	0,22	0,23	0,21	0,23	0,24	0,23	0,22	0,23	0,22
U_M (1), (V)	12	12,5	14	14	12	14	14,5	12,5	12	12,5	13
U_M (2), (V)	100	110	115	115	105	115	115	112	110	110	110,7
U_M (3), (V)	50	55	60	65	50	70	75	65	60	65	61,5
t_1, (sec)	2	3	4	5	2	6	6	5	4	5	4,2
t_2, (sec)	17	18	19	20	17	21	21	20	19	20	19,2
t_3, (sec)	145	145	146	147	145	148	148	147	146	147	146,4

Table 5.3 - Stand experimental data

Control points	Numerical values of samples										Statistical average
	1	2	3	4	5	6	7	8	9	10	
I_{kl} (1), (A)	60	61	62	63	60	64	64	63	62	63	62,2
I_{kl} (2), (A)	600	605	610	615	600	620	620	615	610	615	611
I_{kl} (3), (A)	490	495	500	505	490	510	510	505	500	505	501
U_{kl} (1), (V)	4,5	4,6	4,65	4,7	4,5	4,75	4,75	4,7	4,65	4,7	4,65
U_{kl} (2), (V)	450	460	465	470	450	475	475	470	465	470	465
U_{kl} (3), (V)	225	230	232	235	225	237	237	235	232	235	232,3
V_{kl} (1), (m/sec)	1,8	1,9	2	2	1,8	2,1	2,1	2	2	2	1,97
V_{kl} (2), (m/sec)	18	19	20	20	18	21	21	20	20	20	19,7
V_{kl} (3), (m/sec)	9	9,5	10	10	9	10,5	10,5	10	10	10	9,85
t_1, (sec)	2	3	4	5	2	6	6	5	4	5	4,2
t_2, (sec)	17	18	19	20	17	21	21	20	19	20	19,2
t_3, (sec)	145	145	146	147	145	148	148	147	146	147	146,4

Table 5.4 - The results of the verification of the adequacy of the model winder

Control points	Value on the waveform	Value on model	Relative error
I_{AM} (1), (A)	190	191	0,5 %
I_{AM} (2), (A)	1660	1650	0,59 %
I_{AM} (3), (A)	795	790	0,62 %
I_{EM} (1), (A)	22,3	21,5	3,59 %
I_{EM} (2), (A)	22,3	21,5	3,59 %
I_{EM} (3), (A)	0,22	0,21	3,59 %
U_M (1), (V)	13	14	7,69 %
U_M (2), (V)	110,7	112	1,17 %
U_M (3), (V)	61	65	6,5 %
t_1 , (sec)	4,8	5	4,76 %
t_2 , (sec)	19	20	5,2 %
t_3 , (sec)	145	150	3,41 %

Table 5.5 -The results of the verification of the adequacy of the stand model

Control points	Value on the waveform	Value on model	Relative error
I_{kl} (1), (A)	65	60	8,03 %
I_{kl} (2), (A)	605	620	2,45 %
I_{kl} (3), (A)	500	510	1,99 %
U_{kl} (1), (V)	4,3	4,5	4,3 %
U_{kl} (2), (V)	470	460	2,15 %
U_{kl} (3), (V)	230	235	2,15 %
V_{kl} (1), (м/sec)	2	1,9	5,07 %
V_{kl} (2), (м/sec)	20	19	5,07 %
V_{kl} (3), (м/sec)	9	9,8	8,12 %
t_1 , (sec)	4,7	4,9	4,76 %
t_2 , (sec)	20	21	5,2 %
t_3 , (sec)	148	147	0,68 %

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 tempering mill 1700-1 of cold rolling shop No. 1 of Zaporizhstal JSC.

Chapter 6.
OPTIMIZATION OF THE TENSION CONTROL SYSTEM OF THE ROLLING STRIP OF THE TRAINING MILL 1700

6.1. Development of an optimal control system for interconnected electric drives

A large number of electric drives according to the GD system are currently successfully operated in various industries. In metallurgy, they are used not only in cold rolling mills, but also in hot rolling crimping mills. The increase in productivity of these units, due to the reduction of unscheduled downtime, and the improvement of the quality of products due to the improvement of the process of controlling the coordinates of the electric drive, are directly related to the need for a radical modernization of the electric drives under consideration. It can be performed without significant capital outlay and is therefore preferred.

The task of controlling non-stationary objects under the action of coordinate disturbances has led to the construction of systems that are stable with an unlimited increase in gain, guaranteeing an aperiodic transient with the lowest possible time constant on the trajectories of controlled motion and zero static error. Such an approach in the field of linear control laws made it possible to significantly reduce the sensitivity of the system to external perturbations and to provide sufficiently high possibilities for compensating parametric perturbations [7].

The main requirement that is imposed on the electric drive of the driving mechanism, in the case in question for the rolling stand, is the quality of working out the control commands of the operating personnel: accelerating and decelerating the unit at a given pace and maintaining a given speed value. The last requirement significantly affects the performance of the unit. The required accuracy of maintaining the speed is determined by the absolute value of the maximum speed of the unit [7].

When compiling the equations of dynamics of a two-mass system with elastic bonds of the first kind, it is assumed that the damping of free vibrations is due to the forces of external viscous friction, which, in a first approximation, is proportional to the velocities of the corresponding masses.

Based on the well-known expressions (2.47) as applied to the two-mass control object shown in Figure 2.13, the system of equations of dynamics in element-wise form will take the form [34].

$$\left.\begin{aligned}
&p\varphi_4=\omega_4;\\
&p\omega_4=-\frac{1}{J_{kl}}M_4+\frac{C_2}{J_{kl}}(\varphi_2-\varphi_4)+\frac{b_2}{J_{kl}}(\omega_2-\omega_4)-\frac{k_{f4}}{J_{kl}}\omega_4;\\
&p\varphi_2=\omega_2;\ p\omega_2=\frac{1}{J_{d2}i_{p2}}M_{d2}-\frac{C_2}{J_{d2}}(\varphi_2-\varphi_4)-\frac{b_2}{J_{d2}}(\omega_2-\omega_4)-\frac{k_{f2}}{J_{d2}}\omega_2;\\
&pM_{d2}=-\frac{1}{T_{d2}}M_{d2}-\frac{(C\Phi_2)^2}{R_{d2}T_{d2}i_{p2}}\omega_2+\frac{C\Phi_2}{R_{d2}T_{d2}}U_{d2};\\
&pU_{d2}=-\frac{1}{T_{\mu 2}}U_{d2}+\frac{k_{B2}}{T_{\mu 2}}U_{y2},
\end{aligned}\right\}\quad(6.1)$$

where φ_2 and φ_4 - angles of rotation of the ends of the spindle; ω_2 и ω_4 – angular speeds of the spindle ends; M_4 - load moment; M_{d2} - drive motor electromagnetic moment; U_{d2} and U_{y2} - voltage at the output and input of the converter, respectively; J_{d2} - moment of inertia of the engine and speed reducer, J_{kl} - inertia moment of the rolling stand; C_2 – spindle stiffness; b_2 – internal damping coefficient proportional to the mismatch of the angular velocities of two adjacent masses; k_{f2}, k_{f4} - viscous friction coefficients; i_{p2} – gear ratio; T_{d2} – electromagnetic time constant of the electric drive; R_{d2} - anchor chain resistance; $C\Phi$ - constructive motor coefficient; $T_{\mu 2}$ - time constant of a controlled converter; k_{B2} - gain of controlled converter.

The structural scheme of the mechanical part of the stand in the form of a two-mass electromechanical system with elasticities of the first kind, compiled on the basis of the equations system (6.1), is shown in Figure 6.1.

To facilitate a generalized study of an elasto-dissipative control object, it is advisable to carry out directed normalization of system (6.1).

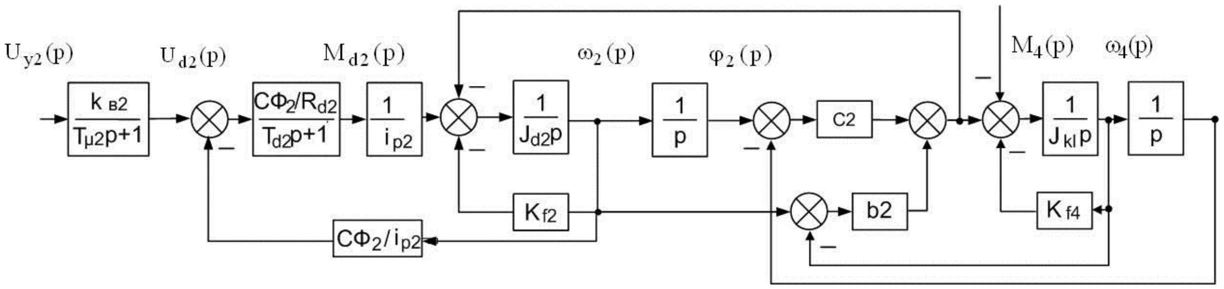


Figure 6.1 - Structural scheme of the mechanical part of the stand in the form of a two-mass electromechanical system with elasticities of the first kind

We will take as base variables U_{max} - maximum motor voltage; ω_{max} - engine idle speed; M_{max} - motor short-circuit point at a voltage U_{max}, φ_{max} - maximum angle of the shaft rotation. Basic values obey the following relations:

$$\varphi_{max} = \omega_{max} \cdot t\big|_{t=1c}; \;\; \omega_{max} = \frac{U_{max}}{C\Phi} i_p \,;$$

$$M_{max} = C\Phi_2 \frac{U_{max}}{R_{d2}}; \; U_{max} = k_{B2} \cdot U_{y2max} \,.$$

We introduce new state variables: $y_1, \ldots, y_k$, that obey the following relations:

$$y_1 = \frac{\varphi_4}{\varphi_{max}}; \; y_2 = \frac{\omega_4}{\omega_{max}}; \; y_3 = \frac{\varphi_2}{\varphi_{max}}; \; y_4 = \frac{\omega_2}{\omega_{max}}; \; y_5 = \frac{M_{d2}}{M_{max}}; \; y_6 = \frac{U_{d2}}{U_{max}}.$$

Given these state variables, the system of equations (6.1) is transformed to

$$\left.\begin{aligned}
&py_1 = y_2;\\
&py_2 = a_{21}y_1 + a_{22}y_2 + a_{23}y_3 + a_{24}y_4;\\
&py_3 = y_4;\\
&py_4 = a_{41}y_1 + a_{42}y_2 + a_{43}y_3 + a_{44}y_4 + a_{45}y_5;\\
&py_5 = a_{54}y_4 + a_{55}y_5 + a_{56}y_6;\\
&py_6 = a_{66}y_6 + m_6 u,
\end{aligned}\right\} \qquad (6.2)$$

where

$$a_{21} = -\frac{C_2}{J_{kl}}; \; a_{22} = -\frac{b_2}{J_{kl}} - \frac{k_{f4}}{J_{kl}}; \; a_{23} = \frac{C_2}{J_{kl}}; \; a_{24} = \frac{b_2}{J_{kl}}; a_{41} = -\frac{C_2}{J_{d2}}$$

$$a_{42} = \frac{b_2}{J_{d2}}; \; a_{43} = \frac{C_2}{J_{d2}}; \;\; a_{44} = -\frac{b_2}{J_{d2}} - \frac{k_{f2}}{J_{d2}}; \; a_{54} = -\frac{1}{T_{d2}}; \; a_{55} = -\frac{1}{T_{d2}};$$

$$a_{56} = \frac{1}{T_{d2}}; \; a_{66} = -\frac{1}{T_{\mu 2}}; \; m_6 = \frac{1}{T_{\mu}}.$$

From the set of trajectories of the system (6.2), we single out the unperturbed motion under the action of program control u^* as a solution to differential equations

$$\left.\begin{aligned}
&p\overset{*}{y}_1 = \overset{*}{y}_2;\\
&p\overset{*}{y}_2 = a_{21}\overset{*}{y}_1 + a_{22}\overset{*}{y}_2 + a_{23}\overset{*}{y}_3 + a_{24}\overset{*}{y}_4;\\
&p\overset{*}{y}_3 = \overset{*}{y}_4;\\
&p\overset{*}{y}_4 = a_{41}\overset{*}{y}_1 + a_{42}\overset{*}{y}_2 + a_{43}\overset{*}{y}_3 + a_{44}\overset{*}{y}_4 + a_{45}\overset{*}{y}_5;\\
&p\overset{*}{y}_5 = a_{54}\overset{*}{y}_4 + a_{55}\overset{*}{y}_5 + a_{56}\overset{*}{y}_6;\\
&p\overset{*}{y}_6 = a_{66}\overset{*}{y}_6 + m_6 u^*.
\end{aligned}\right\} \tag{6.3}$$

The actual movement of the control object differs from the desired deviation

$$\eta_k = y_k - \overset{*}{y}_k, (k = 1,\ldots,6). \tag{6.4}$$

Calculation from system (6.2) system (6.3), taking into account the notation (6.4), we obtain the system of differential equations of perturbed motion

$$\left.\begin{aligned}
&p\eta_1 = \eta_2;\\
&p\eta_2 = a_{21}\eta_1 + a_{22}\eta_2 + a_{23}\eta_3 + a_{24}\eta_4;\\
&p\eta_3 = \eta_4;\\
&p\eta_4 = a_{41}\eta_1 + a_{42}\eta_2 + a_{43}\eta_3 + a_{44}\eta_4 + a_{45}\eta_5;\\
&p\eta_5 = a_{54}\eta_4 + a_{55}\eta_5 + a_{56}\eta_6;\\
&p\eta_6 = a_{66}\eta_6 + M_6 U,
\end{aligned}\right\} \tag{6.5}$$

where $U = u - u^*$ - additional stabilizing control, which is the deviation of the real control action u from the software u^*.

To solve the problem of analytical design of regulators, it is necessary to set the quality functional.

There are no general rules for choosing quality criteria for various controlled objects, and the assignment of an optimality criterion in each specific case is an independent task. The quality functional should be chosen in such a way that, on the one hand, it best describes the control goal, and on the other hand, the specific variational problem should be analytically solvable. A functional can be considered as a function of a special kind in which another function plays the role of an independent variable.

Currently, integral functionals are widely used in the theory and practice of optimal control

$$I = \int_{t_0}^{t_1} F(\eta_1,\ldots\eta_n, U_1,\ldots U_j)\,dt = extremum. \tag{6.6}$$

For control systems whose dynamics are described by differential equations of perturbed motion (6.5), functional (6.7) defines the control goal, which is determined by the form of function F.

To give the synthesized system astatic properties, we supplement system (6.5) with the equation

$$p\eta_0 = \eta_2$$

and we take the integral quadratic functional [7] as a criterion for the optimality of the control system for the stands speed of rotation

$$I_1 = \int_0^{\infty} \left\{ \left(\left(\frac{v_{06}}{p} + v_{26} \right)\eta_2 + v_{16}\eta_1 + v_{36}\eta_3 + v_{46}\eta_4 + v_{56}\eta_5 + v_{66}\eta_6 \right)^2 + CU^2 \right\} dt\ .(6.7)$$

In the integrand of the functional (6.7) $v_{i6}, i = 0,1,\ldots,6$ - coefficients of the Lyapunov function

$$V = \sum_{i,j=0}^{6} v_{ij}\eta_i\eta_j\ , \tag{6.8}$$

which are associated with the parameters of the control object (6.5) by the relations [7]

$$v_{06} = \Delta,\ v_{i6} = M_{i2}(\Delta)\,, \tag{6.9}$$

where

$$\Delta = \begin{vmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} & 0 \\ 0 & 0 & 0 & a_{54} & a_{55} & a_{56} \\ 0 & 0 & 0 & 0 & 0 & a_{66} \end{vmatrix}, \qquad (6.10)$$

$M_{i2}(\Delta)$ - minor of the i-th element of the second column of the determinant (6.10).

The first term of the integrand of functional (6.7) is the sum of the areas weighed by the coefficients of the Lyapunov function, bounded by the squares of deviations of the coordinates of the true motion from the coordinates of the programmed motion for each state variable. The introduction of the second term under the integral, on the one hand, means achieving optimality of damping the perturbed motion while limiting the energy costs of control, and on the other hand, it provides the search for optimal control among the set of admissible linear functions subject to

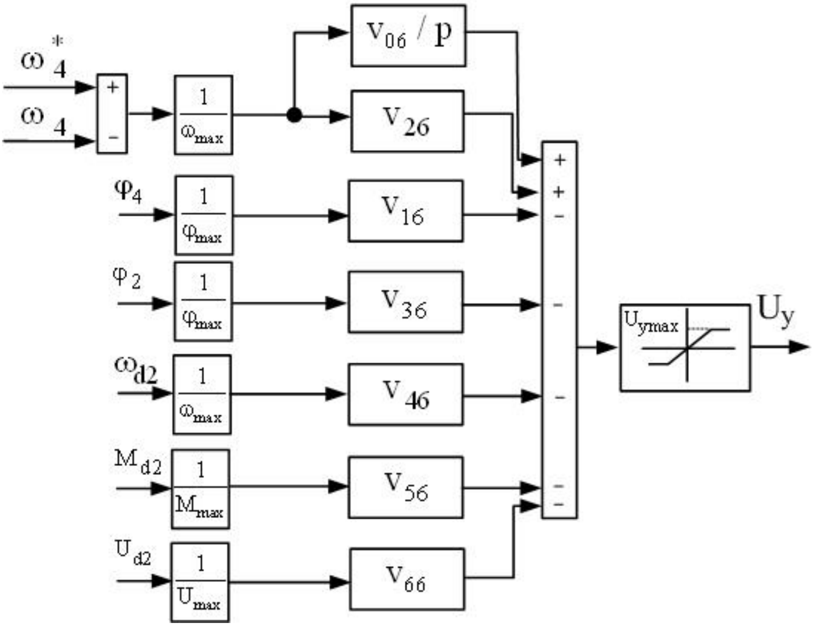


Figure 6.2 - Block scheme of the stand speed controller, implements the algorithm (6.11)

$$\left| U \right| \le 1 .$$

Such functionality is minimized by optimal control [34]

$$\begin{aligned} U_y = U_{y\,max} sat((\frac{v_{06}}{p} + v_{26})(\omega_4^* - \omega_4) - v_{16}\varphi_4 - v_{36}\varphi_2 - v_{46}\omega_2 - \\ - v_{56} I_{d2} - v_{66} U_{d2}), \end{aligned} \tag{6.11}$$

where $sat(\cdot)$ - nonlinear function of the “saturation” type.

After the transition to the source state variables of the control object, the speed controller, according to algorithm (6.11), will take the form shown in Figure 6.2.

6.2. Synthesis of speed and tension control algorithms of rolled metal strip of the training mill

Based on systems of equations describing a two-mass system with elasticities of the first and second kind (2.46, 2.54), the system of equations in element-wise form takes the form [35]

$$\left. \begin{aligned} & pFc = C_p R_1 \omega_3 - C_p R_2 \omega_4 - \frac{F_c R_2 \omega_4}{L} ; \\ & p\omega_3 = \frac{1}{J_M} M_{13} + \frac{b_1(\omega_1 - \omega_3)}{J_M} - \frac{F_c R_1}{J_M} - \frac{k_{f3}\omega_3}{J_M} ; \\ & pM_{13} = C_1(\omega_1 - \omega_3); \\ & p\omega_1 = \frac{1}{J_{d1} i_{p1}} M_{d1} - \frac{1}{J_{d1}} M_{13} - \frac{k_{f1}}{J_{d1}} \omega_1 ; \\ & pM_{d1} = \frac{C\Phi_1}{R_{d1} T_{d1}} U_{d1} - \frac{1}{T_{d1}} M_{d1} - \frac{(C\Phi_1)^2}{R_{d1} T_{d1} i_{p1}} \omega_1 ; \\ & pU_{d1} = \frac{k_{B1}}{T_{\mu 1}} U_{y1} - \frac{1}{T_{\mu 1}} U_{d1} , \end{aligned} \right\} \tag{6.12}$$

where ω_{d1} - engine angular speed M1; ω_1 , ω_3 - spindle end angular speeds; ω_4 - angular speed of rolls; J_{d1} - moment of inertia of the rotor of the engine M1 and reducer, J_M - winding moment of inertia; M_{f1}, M_{f3} - external friction moments; M_{13} - elastic moment; C_1 - stiffness of the elastic element; C_p – stiffness of the transported material; b_1 - coefficient of internal damping; F_C - tension force of rolled strip; L - the distance between the axes of the rotating mechanisms; i_p - gear ratio of reducer, R_1 - roll radius; R_2 - stand roll radius; k_{B1}, $T_{\mu 1}$ - gain and time constant of a controlled converter; U_{d1}, U_{y1} voltage at the output and input of a controlled motor power converter M1.

To facilitate a generalized study of an elasto-dissipative control object, it is advisable to carry out directed normalization of the system (6.12). As basic variables accepted U_{max} - maximum control voltage of converter; ω_{max} - engine idle speed; M_{max} - motor short circuit U_{max}; F_{max} maximum allowable strip tension by technology.

$$\omega_{max} = \frac{U_{max}}{C\Phi_1} i_{p1};\ M_{max} = C\Phi_1 \frac{U_{max}}{R_{d1}};\ U_{max} = k_{B1} \cdot U_{y1max}.$$

Then the system of equations (6.12) is transformed to the form

$$py_i = \sum_{k=1}^{6} a_{ik} y_k + C + m_6 u,\ (i=1,...,6), \tag{6.13}$$

where

$$y_1 = \frac{F_c}{F_{max}};\ y_2 = \frac{\omega_3}{\omega_{max}};\ y_3 = \frac{M_{13}}{M_{max}};\ y_4 = \frac{\omega_{d1}}{\omega_{max}};\ y_5 = \frac{M_{d1}}{M_{max}};\ y_6 = \frac{U_{d1}}{U_{max}};$$

$$a_{11} = -\frac{R_2\omega_4}{L};\ a_{12} = C_p R_1 \frac{\omega_{max}}{F_{max}};\ a_{21} = -\frac{R_1 F_{max}}{J_M \omega_{max}};\ a_{22} = -\left(\frac{b_1}{J_M} + \frac{k_{f3}}{J_M}\right);$$

$$a_{23} = \frac{M_{max}}{J_M \omega_{max}};\ a_{24} = \frac{b_1}{J_M};\ a_{32} = -\frac{C_1\omega_{max}}{M_{max}};\ a_{34} = \frac{C_1\omega_{max}}{M_{max}};$$

$$a_{44} = -\frac{k_{f1}}{J_{d1}};\ a_{45} = \frac{M_{max}}{J_{d1}\omega_{max}};\ a_{54} = -\frac{1}{T_{d1}};\ a_{55} = -\frac{1}{T_{d1}};$$

$$a_{56} = \frac{1}{T_{d1}};\ a_{66} = -\frac{1}{T_\mu};\ m_6 = \frac{1}{T_\mu}. \tag{6.14}$$

From the set of trajectories of the system (6.13), we single out the unperturbed motion under the action of program control u^* as a solution of differential equations

$$py_i^* = \sum_{k=1}^{6} a_{ik} y_k^* + C + m_6 u^* \text{ , } (i=1,...,6). \tag{6.15}$$

The actual movement of the control object differs from the desired deviation

$$\eta_k = y_k - y_k^*, \ (k=1, \ ..., \ 6). \tag{6.16}$$

Then the perturbed movement of the control object (6.12) obtained by subtracting equations (6.15) from equations (6.13) can be represented as follows

$$p\eta_i = \sum_{k=1}^{6} a_{ik} \eta_k + m_6 U \text{ , } (i=1,...,6), \tag{6.17}$$

where $U = u - u^*$ - additional stabilizing control, which is the deviation of the real control action from the software u^*; a_{ik}, m_6 - coefficients.

For a synthesized system of equations, the quality of control can be specified by the Letov functional

$$I = \int_0^{\infty} \Big(\sum_{i,k=0}^{6} w_{ik} \eta_i \eta_k + cU^2 \Big) dt, \ w_{ik} = w_{ki}, \tag{6.18}$$

the extreme value to which the optimal control delivers on the trajectories of motion (6.17)

$$U = -sat \frac{g}{m_6} \sum_{i=0}^{6} v_{i6} \eta_i \text{ ,} \tag{6.19}$$

while guaranteeing the exponential nature of the controlled movement of the controlled variable $\eta_1 = -exp\left(\frac{1}{g} t \right)$ with a trajectory of undisturbed motion

$y_1^* = 1(t)$ and providing astatic properties to the closed system due to the presence of an integral component $\eta_0 = \frac{1}{p}\eta_1$ [7].

Optimal control (6.19) in expanded form

$$U = -sat\frac{g}{m_6}(v_{06}\eta_0 + v_{16}\eta_1 + v_{26}\eta_2 + v_{36}\eta_3 + v_{46}\eta_4 + v_{56}\eta_5 + v_{66}\eta_6). \tag{6.20}$$

The coefficients of the control algorithm (6.20) are the coefficients of the function

$$V = \sum_{i,k=0}^{6} v_{ik}\eta_i\eta_k, v_{ik} = v_{ki}, \tag{6.21}$$

which are interconnected by the relations

$$v_{ik} = \frac{v_{in}v_{kn}}{v_{nn}}, (i,k=0,1,2,...,6). \tag{6.22}$$

The coefficients (6.22) are determined respectively by the minors of the i-th, k-th and n-th elements of the 1st column of the determinant of the coefficients of the system (6.17) [7]

$$\begin{aligned} v_{06} &= (-1)^6 \Delta, \\ v_{i6} &= (-1)^{i+6} M_{i1},\ i = 1,2,...6, \end{aligned} \tag{6.23}$$

where

$$\Delta = \begin{vmatrix} a_{11} & a_{12} & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 & 0 \\ 0 & a_{32} & 0 & a_{34} & 0 & 0 \\ 0 & 0 & a_{43} & a_{44} & a_{45} & 0 \\ 0 & 0 & 0 & a_{54} & a_{55} & a_{56} \\ 0 & 0 & 0 & 0 & 0 & a_{66} \end{vmatrix}. \tag{6.24}$$

Then, the desired coefficients of the optimal control algorithm are determined by the expressions

$$\begin{aligned}
&v_{06} = -a_{66}(a_{11}a_{23}a_{32}a_{55}a_{44} - a_{11}a_{23}a_{32}a_{45}a_{54} - a_{11}a_{55}a_{43}a_{24}a_{32} + \\
&+ a_{11}a_{55}a_{43}a_{34}a_{22} - a_{55}a_{43}a_{34}a_{12}a_{21}); v_{16} = -a_{22}a_{43}a_{34}a_{55}a_{66} - \\
&- a_{32}a_{23}a_{44}a_{55}a_{66} + a_{32}a_{23}a_{54}a_{45}a_{66} + a_{32}a_{43}a_{24}a_{55}a_{66}; \\
&v_{26} = -a_{12}a_{43}a_{34}a_{55}a_{66}; v_{36} = -a_{12}(a_{23}a_{44}a_{55}a_{66} - a_{23}a_{54}a_{45}a_{66} - \\
&- a_{43}a_{24}a_{55}a_{66}); v_{46} = a_{12}a_{23}a_{34}a_{55}a_{66}; v_{56} = -a_{12}a_{23}a_{34}a_{45}a_{66}; \\
&v_{66} = a_{12}a_{23}a_{34}a_{45}a_{56}.
\end{aligned} \tag{6.25}$$

It should be noted that the weight coefficients of functional (6.18) are uniquely related with the coefficients of function (6.21) by the relations with hard feedbacks

$$w_{ik} = \frac{m_6^2}{c} v_{i6} v_{k6} = g\ v_{i6} v_{k6}\ ,\ i,k = 0,1,...6. \tag{6.26}$$

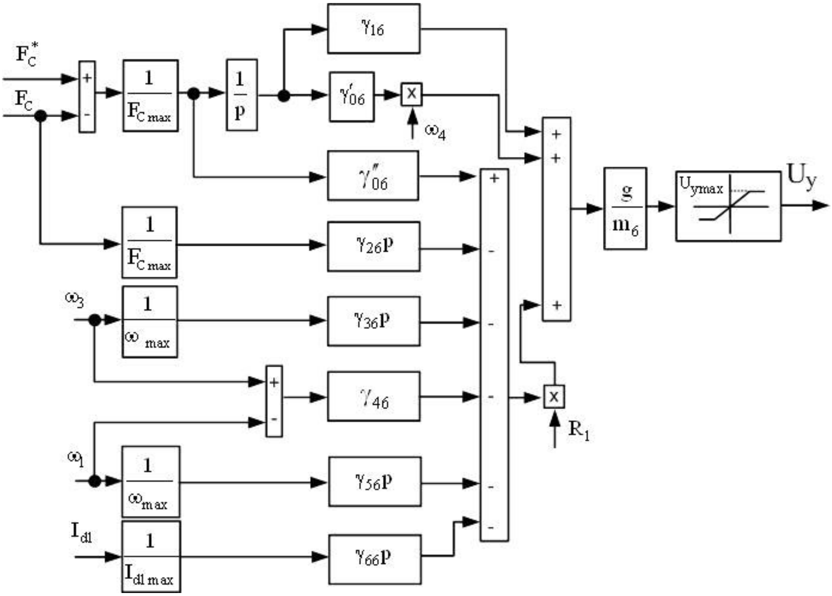


Figure 6.2 - Block scheme of the tension regulator

Having performed the change of the coordinates of the perturbed motion in the control algorithm (6.20), according to the system of differential equations (6.17), and passing from the relative values of the variable states to their named values, we obtain in the final form the algorithm for optimal control of the rolled strip tension

$$\begin{aligned} U_y = U_{ymax} sat \frac{g}{m_6}((\frac{\gamma_{06}}{p} + \gamma_{16})(F_C^* - F_C) - \gamma_{26} pF_C - \gamma_{36} p\omega_3 - \\ - \gamma_{46}(\omega_1 - \omega_3) - \gamma_{56} p\omega_1 - \gamma_{66} pI_{d1}). \end{aligned} \tag{6.27}$$

The coefficients of the algorithm for optimal control of the tension of the rolled strip include variable technological parameters: the angular speed of the stand rolls ω_4 and roll radius R_1.

According to (6.22), the tension regulator will have the form (Figure 6.2)

An analysis of the values of the coefficients (6.14) of system (6.13) shows that the stand speed ω_4 included in the coefficient a_{11}, and the radius of the roll R_1 - in the coefficients a_{12}, a_{21}. a_{12}, a_{21}. Since these coefficients of the equations of dynamics participate in the calculation of the coefficients of the Lyapunov function, we separate the terms of the coefficient γ_{06} into two parts: γ'_{06} - with the variable speed ω_4 and γ''_{06} - subject to variable roll radius R_1. Similarly, we take into account the change in the coefficients of the regulator $\gamma_{26}, \ldots \gamma_{66}$ depending on the variable radius of the roll, then the structural diagram of the tension regulator will take the final form, shown in Figure 6.2.

6.3. Modeling an optimal control system for interconnected electric drives

Using computer models of the rolling stand mechanism, DC motor, and blocks simulating the elastic connection between the motor and the rolling stand [31], we will compose a computer model of the rolling stand rotation speed control system (Figure 6.3), which is based on algorithm (6.11).

It is known, optimal speed control systems with relay controllers are widely used in various industries, utilities and electric vehicles, which confirms the prospects and relevance of their use [36-38].

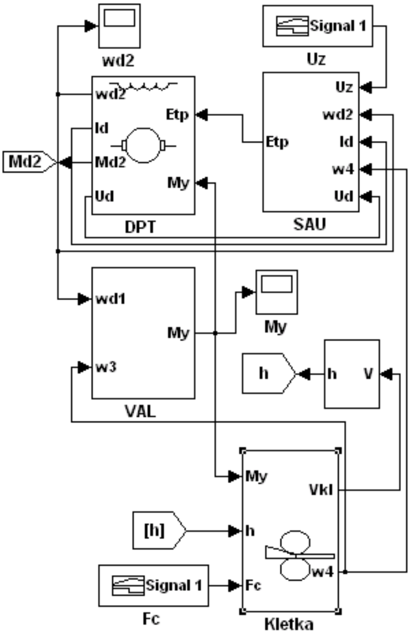
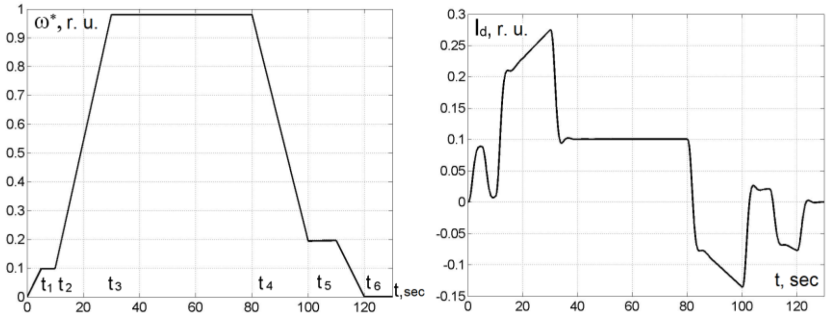


Figure 6.3 - Model of stand electric drive

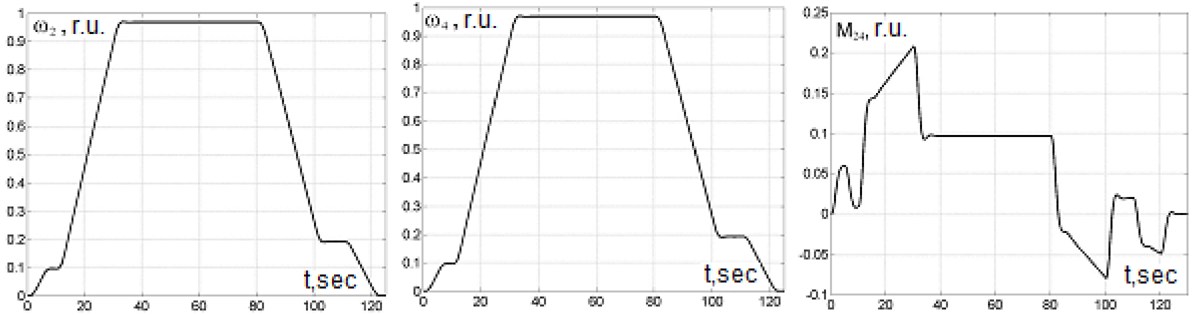
When modeling, we used the equipment data from a single-stand training mill 1700-1 of the cold rolling workshop No. 1 of JSC Zaporizhstal. The results of mathematical modeling of the synthesized optimal control system are shown in Figures 6.4 and 6.5.



а)

б)

Figure 6.4 - Simulation results of a system for optimal control of the rolling stand speed: reference signal (a), motor armature current (b)



а)

б)

в)

Figure 6.5 - The results of modeling the optimal speed control system of the rolling stand: the angular speed of the engine (a), the angular speed of the rolls of the stand (b), spindle elastic moment (c).

According to the technological features of rolling, transient processes are obtained for the following operating modes of the mill: acceleration to the filling speed $(0-t_1)$, work at this speed (t_1-t_2), acceleration to rolling speed (t_2-t_3), steady state operation (t_3-t_4), reduced speed braking (t_4-t_5), work at this speed (t_5-t_6) and braking (t_6-120c).

In Fig. 6.4, b and Fig. 6.5, d, in the time interval from 18 s to 20 s and from 83 s to 100 s, linear changes in current and elastic moment are observed, caused by a change in speed and the presence of viscous friction in the system.

The structure of the computer model of the synthesized system for optimal control of interconnected electric drives of the stand and winder is shown in Figure 6.6 [25].

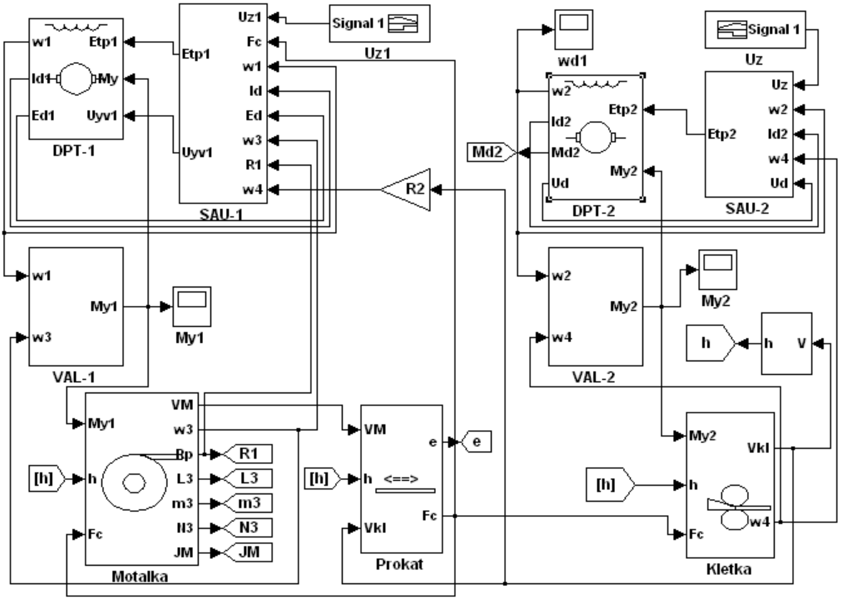


Figure 6.6 - Model of an electromechanical system for optimal control of interconnected stand and winder electric drives

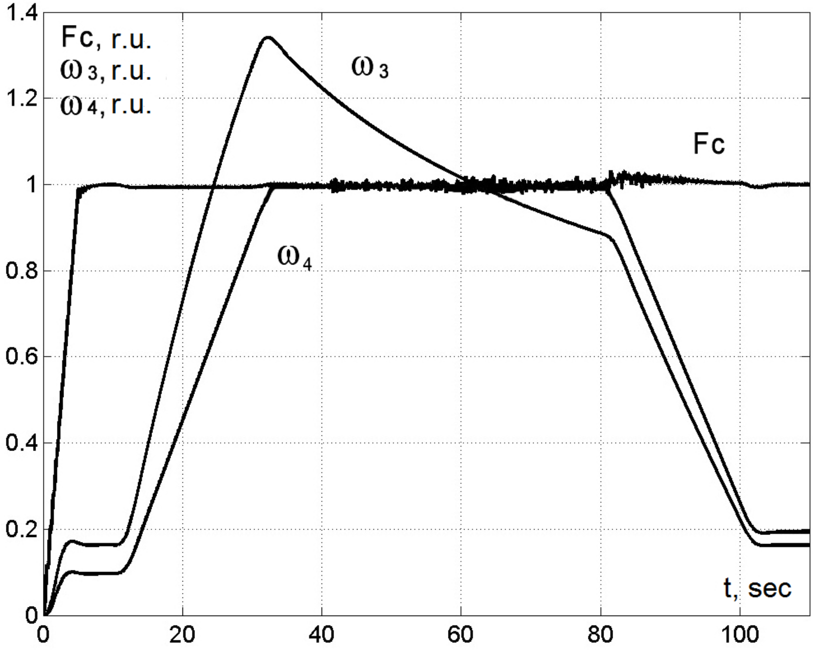


Figure 6.7 - Transients of a synthesized system

According to the technological instruction ТИ 226-П.ХЛ 1-20-05"Training cold-rolled strips on mills 1700 No. 1 and No. 2" tension is created between the cage and the unwinding device from the capture moment of the strip front endWhen leaving the working stand, the front end of the strip is fed to the winder and refueled into the throat of its drum, the necessary tension is created, all the mill mechanisms are switched to the maximum speed for this mode. When training, special attention is paid to the tension of the strip, which is controlled at a constant speed of the stand according to the readings of ammeters and should be constant during the whole time of training the strip. After the end of the training of the roll, the mill stops, the stand rolls are bred, the back end of the strip is skipped and wound into a roll.

Figure 6.7 shows transients (F_C – rolled strip tension, ω_3 – winder angular velocity, ω_4 – stand angular speed) at the end of the strip into the reel drum, from 0 sec to 5 sec set the necessary strip tension, from 5 sec to 120 sec constant tension training, from 120 sec to 130 sec tension task is removed. In this case, the task of the speed of the stand at a time 0 sec – 10 sec corresponds to the refueling speed of the mill, 10 sec – 30 sec stand acceleration to working speed, 30 sec – 80 sec – constant speed operation, 80 sec – 100 sec – reduced speed braking, 100 sec – 110 sec – reduced speed operation.

The quality characteristics of rolling include: the accuracy of maintaining the speed, the accuracy of maintaining the tension, the absence of overshoot without increasing the regulation time, zero static error, reduced oscillation, low sensitivity to a number of destabilizing factors.

6.4. Comparison of synthesized and existing systems with external and parametric disturbances

To study the quality of the synthesized optimal control system for interconnected stand and winder electric drives, an external disturbance was modeled in the form of a load surge of 30% of the nominal stand motor moment in the time interval from 40 sec to 60 sec (Figure 6.8), as well as parametric disturbances caused by a change in the initial moment of inertia (Figures 6.9-6.11), friction coefficients and changes in the resistance of the anchor chain of the electric drives of the winder and stand (6.12-6.15), as well as when changing the initial radius of the roll (6.16).

With a jump-like increase and a subsequent decrease in the stand load by 30% of the applied nominal moment, the amplitude of the strip tension oscillations increased by 1-2%, and the angular stand speed in the time interval from 40 s to 60 s decreased by 1-2%, which is permissible by technological process.

An increase in the initial moment of winder inertia by a factor of 1.5-2 does not lead to a change in the speeds of the coiler and stand, while in the acceleration section to the filling speed, the vibration tension of the strip slightly increases.

The increase in the initial reduced moment of inertia of the electric drive stand 3 times leads to longer transient processes of the speeds of the stand and coiler, but this does not affect the strip tension. A number of experiments on changing the friction coefficients of the winder and stand have shown that the synthesized optimal control system for interconnected electric drives is not sensitive to these changes. Changing the resistance of the anchor circuit of the electric winder drive affects the electromagnetic and electromechanical time constants, which determine the values of the auxiliary feedback coefficients of the strip tension control algorithm.

With increasing resistance there is an increase in the oscillation of tension when accelerating to refueling speed and working on it. Resistance reduction does not affect the strip tension and the angular speed of the winder.

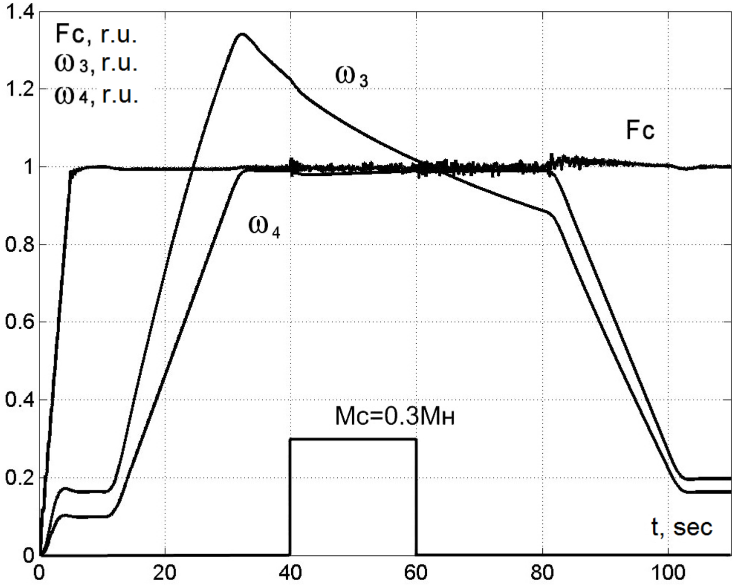


Figure 6.8 - Load surge on the stand electric drive Mc = 0,3 Mnom

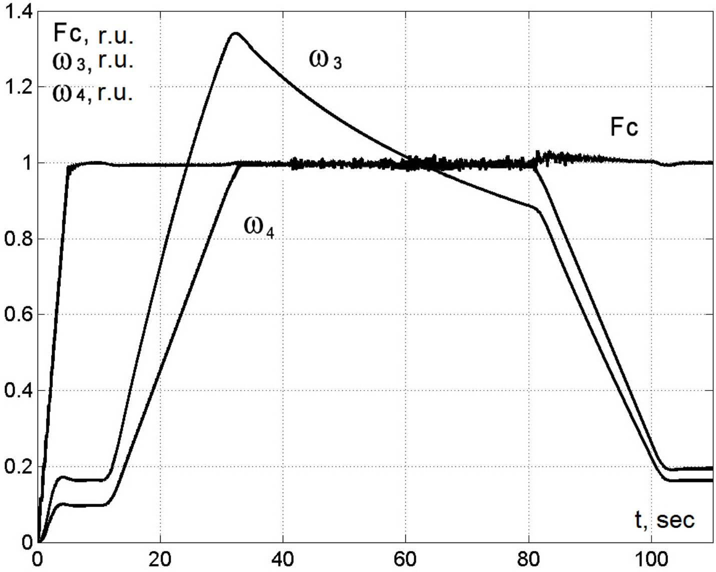


Figure 6.9 - The initial reduced moment of inertia of the winder electric drive is increased by 1.5 times

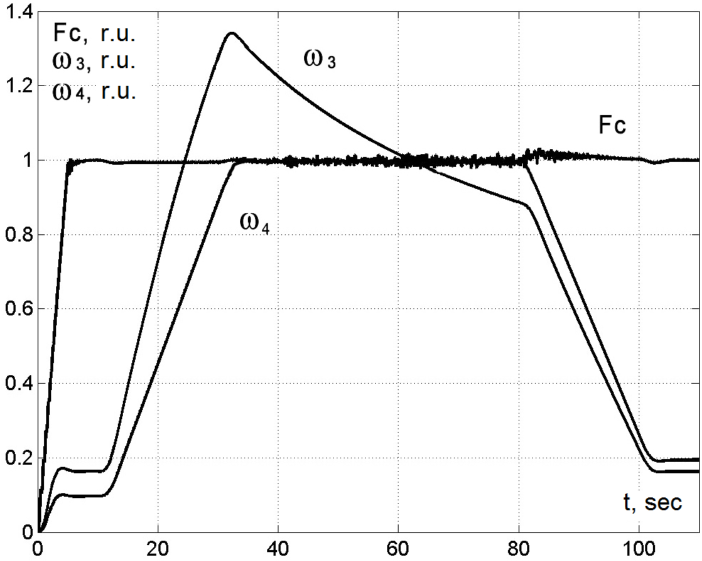


Figure 6.10 - The initial reduced moment of inertia of the winder electric drive is increased by 2 times

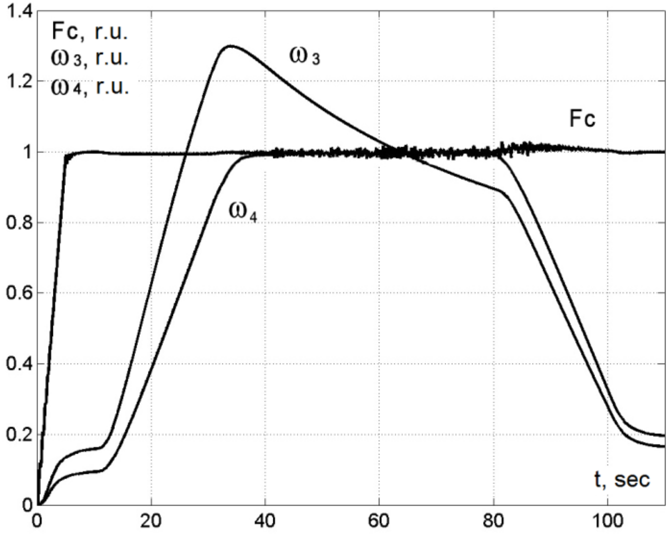


Figure 6.11 - The initial reduced moment of inertia of the stand electric drive is increased 3 times

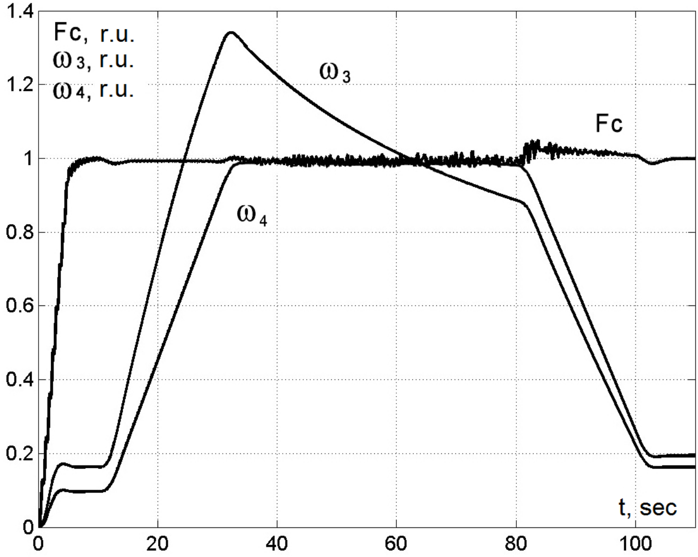


Figure 6.12 - Increase in the resistance of the anchor chain of the electric winder by 2 times

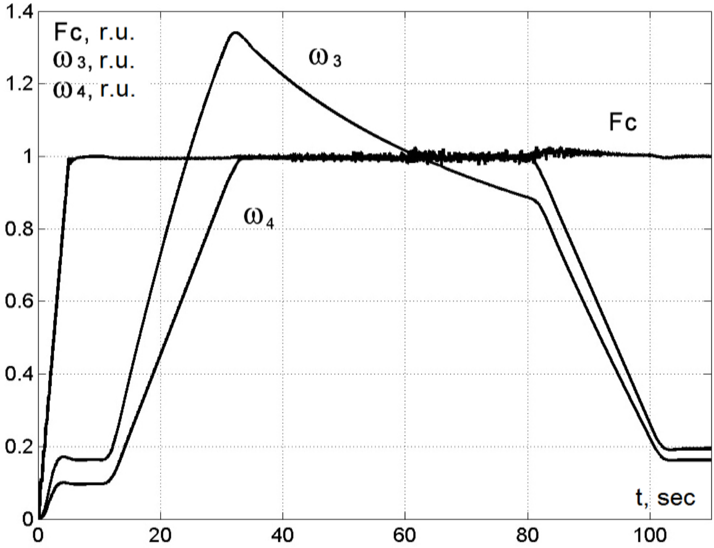


Figure 6.13 - Reducing the resistance of the anchor circuit of the electric winder by 2 times

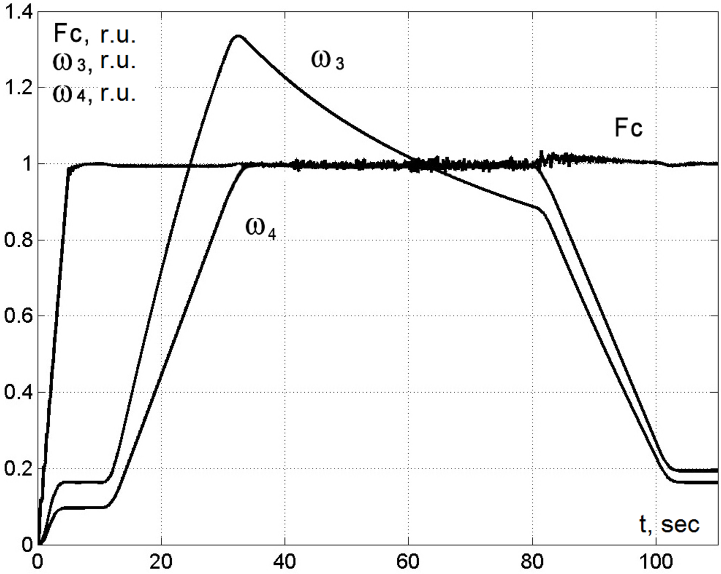


Figure 6.14 - Reduction of the resistance of the anchor circuit of the electric drive stand by 2 times

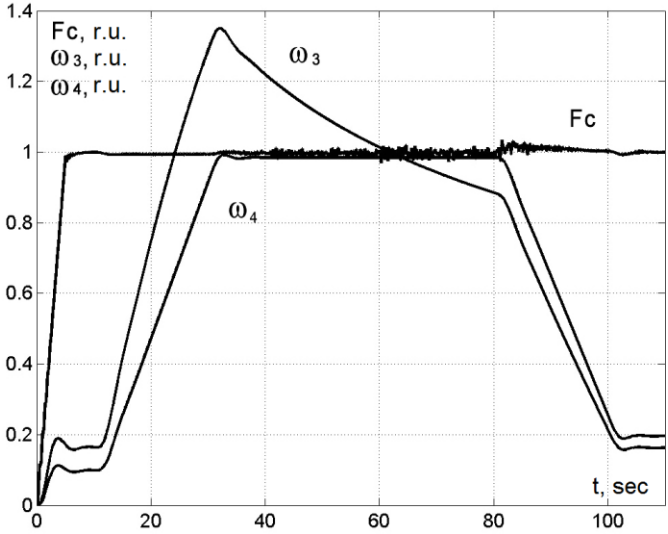


Figure 6.15 - Increase in the resistance of the anchor chain of the electric drive stand by 2 times

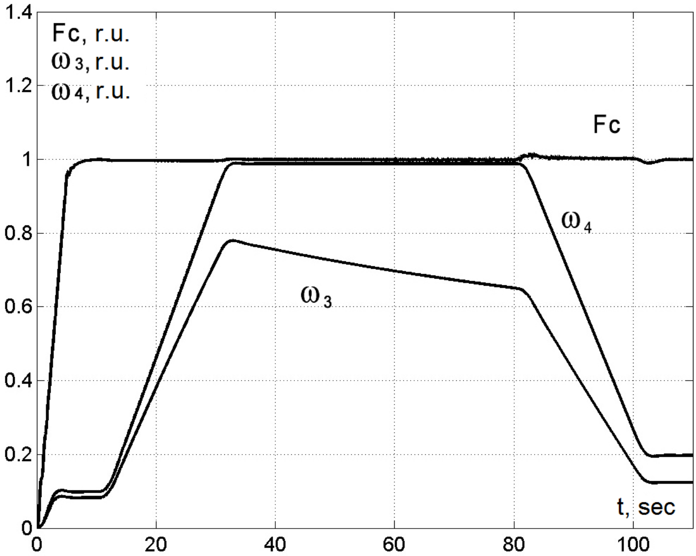


Figure 6.16 - The initial radius of the roll is increased 2 times

A change in the resistance of the anchor chain of the electric drive of the stand does not affect the angular speed of the stand, which indicates the insensitivity of the system to changes in this parameter.

When the initial radius of the roll is increased in 2 times, for example, when the rolling of the roll is forced to stop and the rolling of the same roll is subsequently started, the angular speed of the winder decreases in proportion to the radius of the roll, and the strip tension and the angular speed of the stand remain unchanged.

Based on the conducted studies, it can be said that the synthesized optimal control system of interconnected winder and stand electric drives provides the specified quality of the control process and has low sensitivity to changes in a number of parameters, which will lead to an increase in the quality of control when using this system.

The developed algorithms for optimal control of the tension of the rolled strip are the basis for the design of electric drives of metallurgical equipment with new control systems, in particular, winding and unwinding devices at the State Institute of Design of Industrial Enterprises GIPROPROM.

CONCLUSION

The book provides a new solution of actual scientific and applied problem of control systems optimization for interconnected electric drives of a rolling stand and winding-unwinding mechanisms of a cold rolling mill using a models elements complex of rolling production, which allows to improve the quality of finished products and reduce the number of emergencies caused by strip breakage during rolling.

This study is intended for engineers, scientists and specialists in the field of automated electric drives and automatic control systems, may be useful in the preparation of bachelors, masters and graduate students in the field of "Power engineering, electrical engineering, electromechanics" and "Automation and computer-integrated technologies" [39].

The most significant scientific and practical results, conclusions and recommendations are as follows.

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, which are used in the synthesis of electromechanical systems for strip tension optimal control.

For the first time, a complex of interconnected 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. The complex provides the ability to simulate a variable thickness of the rolled strip and emergency situations caused by its break.

A multi-channel diagnostic complex of electric drives of the main mechanisms of cold rolling mills was proposed and put into production, which allows real-time monitoring of electromechanical processes, recording in the archive, and also identifying the causes of emergencies.

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 interconnected models for the synthesis and study of optimal control systems for electric drives of the main mechanisms of cold rolling mills.

For the first time a method for studying multi-mass interconnected electric drives 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 mathematical models of the basic elements of rolling production is proposed.

The theory of interconnected electric drives with elastic couplings was further developed by developing a mathematical model of a four-mass electromechanical system that takes into account the mutual influence of mechanisms through two elastic couplings of the first kind and one bond of the second kind.

The possibility of improving the quality of finished products of cold rolling mills, the electric drives of the main mechanisms of which are interconnected by elastic bonds of the first and second kinds, under conditions of variable radius of the roll and the speed of stand rolls rotation, is proved by optimizing the control systems of electric drives to a minimum of integral quadratic quality functionals.

By mathematical modeling of synthesized optimal control systems for interconnected winder and stand electric drives, the possibility of eliminating the overshoot of the rolling speed and strip tension without increasing the transient time with zero static error is confirmed. The accuracy of the stabilization of tension meets the technological requirements, while the dynamic error does not exceed 5%. The systems have low sensitivity to a number of destabilizing factors, such as an increase in load of 30% of the nominal moment of the stand motor, changes in the initial moment of inertia of the winder by 1.5-3 times, resistance of the anchor chain of electric drives of the winder and stand in 2 times, increase in the initial radius of the roll 2 times.

The results of the work were introduced at Zaporizhstal JSC in the form of a diagnostic complex for electric drives of the main equipment of a single-train tempering mill 1700-1 of cold rolling workshop No. 1 and at the State Institute of Industrial Design Engineering GIPROPROM enterprise in the form of mathematical models of electromechanical systems of cold rolling mills and algorithms optimal control of strip tension.

The performed complex of theoretical and experimental studies has allowed to develop the theory and practice of multi-mass interconnected electric drives of the main equipment of cold rolling mills with elastic couplings of the first and second kinds based on the developed complex of interconnected models of rolling elements.

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