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The method of limitation of dynamic loads of nonlinear electromechanical systems under state vector robust control

Aim. *Development of the method of limitation of dynamic loads of nonlinear electromechanical systems under state vector robust control.* ***Methodology.*** *Limitation of dynamic loads of nonlinear electromechanical systems is carried out using the minimum selector of choosing the minimum value of the control vector from formed with the help of local controllers and with the vector of maximum control values. Calculation of the gain coefficients of nonlinear robust controllers and observers are based on solutions of the Hamilton–Jacob–Isaacs equations.* ***Results****. The results of computer simulation of transitional processes of main roll drives of the rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» with limitation of dynamic loads are given.* ***Originality.*** *For the first time the method of limitation of dynamic loads of nonlinear electromechanical systems under state vector robust control based on minimum selector and nonlinear robust control of state variables which is needed limitation is developed.* ***Practical value.*** *Examples of transitional processes of main roll drives of the rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» with limitation of dynamic loads are given.* References 35, figures 6.

Key words: **nonlinear electromechanical systems, state vector robust control, Hamilton–Jacobi–Isaacs equations, limitation of dynamic loads, computer simulation.**

Мета*. Розробка методу обмеження динамічних навантажень нелінійних електромеханічних систем при векторному робастному управлінні.* ***Методологія****. Обмеження динамічних навантажень нелінійних електромеханічних систем здійснюється за допомогою селектора вибору мінімального значення вектора керування із сформованого за допомогою локальних регуляторів та вектора максимальних значень керування. Розрахунок коефіцієнтів підсилення нелінійних робастних контролерів і спостерігачів базується на рішеннях рівнянь Гамільтона–Якобі–Айзека.* ***Результати.*** *Наведено результати комп'ютерного моделювання перехідних процесів головних приводів валків прокатного стану 950 Запорізького заводу «Дніпроспецсталь» із обмеженням динамічних навантажень.* ***Оригінальність****. Вперше розроблено метод обмеження динамічних навантажень нелінійних електромеханічних систем при робастному управлінні за вектором стану на основі селектору мінімуму та нелінійних робастних регуляторів змінних стану, які необхідно обмежуват.* ***Практична цінність****. Наведено приклади перехідних процесів головних приводів прокатного стану 950 Запорізького заводу «Дніпроспецсталь» із обмеженням динамічних навантажень.* Бібл. 35, рис. 6.

Ключові слова: **нелінійні електромеханічні системи, робастне керування за вектором стану, рівняння Гамільтона–Якобі–Айзека, обмеження динамічних навантажень, комп'ютерне моделювання.**

Introduction. The use of optimal and modal controllers that implement control over the full state vector makes it possible to significantly increase the speed of electromechanical systems compared to traditional slave control systems [1, 2]. Especially effective is the use of state control for controlling electromechanical systems with the presence of elastic connections in the kinematics chain from the drive motor to the working body of the electromechanical system [3, 4].

Mathematical models of such systems are accepted in the form of two, three and more mass electromechanical systems. The control of such multi-mass systems becomes much more complicated if there are nonlinear elements in the bottom. In most mass electromechanical systems, it is necessary to take into account the nonlinear dependence of friction on the shafts of the drive motor, gearbox and working body. The task of control becomes even more complicated for a multi-ton electromechanical system with non-linear connections between individual motors through the control object.

To implement high-speed operation in such systems, significant torques and speeds are required, and possibly even higher derivative changes in the drive motor shafts and transmission elements. When working out the setting influences, the limitation of dynamic loads in such systems is implemented using intensity generators.

However, in the process of compensating for disturbances in the system, it is necessary to limit the dynamic loads. Note that the extremely widespread use of slave control systems is due precisely to the simplicity of limiting dynamic loads by limiting the rate of change and current of the drive motor, as well as speed and position using slave control loops.

One example of such multi-motor electromechanical systems is rolling mills [5–7]. A characteristic feature of the operation of rolling mills is their heavy loading mode: dynamic load application during the period of metal gripping by rolls, roll slipping, impacts of heavy ingots on rolls, impacts in the gaps of the main line, heavy modes of non-stationary processes in electric drives with acceleration and deceleration acceleration and other factors. In difficult operating conditions of mills, cases of simultaneous action of the indicated loads in various combinations are possible [8, 9]. Then the dynamics of transient processes becomes rather complex, and its study is hampered by the nonlinearity of systems of differential equations describing the motion of the main lines. Experience shows that most accidents occur as a result of large dynamic vibration loads arising during transient and unstable operating modes, as well as in connection with a violation of rolling technology (rolled cold metal, excessive reduction, etc.).

Experimental studies of the ingot gripping process on the operating equipment have shown that the dynamic loads in the main line of the mill differ significantly depending on the state of the ingot surface, the shape of the front and rear ends of the ingot, gripping conditions, etc. In fact, the change in the moment of resistance during the capture of the ingot does not occur instantaneously, and in a number of works it is proposed to approximate the change in the moment of resistance by an exponential curve. In this case, depending on the value of the exponential time constant, the excess of the current in the optimal controller can be 2–4 maximum permissible current values [5–7]. With such an excess, the coordinate limiting system is stable and reliably limits the state and control variables.

The purpose of the work is to develop the method of limitation of dynamic of loads of nonlinear electromechanical systems under state vector robust control.

Problem statement. Let us consider the limitation of loads in nonlinear multi-mass systems with robust control over the state vector. First, consider the limitation in an electromechanical system with only one single motor [10, 11].

To limit the state and control variables, consider the scheme of such a system. This system uses separate controllers for the main control coordinate and the same state variables that need to be limited. Using the minimum selector, we apply a voltage to the input of the thyristor converter, which corresponds to the minimum value of the outputs of all regulators.

Consider the limitation on the vector of output coordinates $\vec{y}(k)$ system at a given level of maximum permissible values $\vec{y}_{\max}$. For this purpose, we construct optimal nonlinear controllers that minimize criteria in which the integrands $\psi(\vec{x}(k), \vec{y}(k))$ are selected from the condition of ensuring the specified requirements for the speed of operation of the controllers, with the help of which the vector of output variables $\vec{y}(k)$ maintained at the level of maximum permissible values $\vec{y}_{\max}(k)$. As a result of the solution, the optimal controls are found $\vec{u}_i(k)$, ensuring the maintenance of i component $y_i(k)$ vector of output variables $\vec{y}(k)$ at the level of maximum permissible values $y_{\max i}(k)$ vector of maximum permissible values of the output coordinates $\vec{y}_{\max}(k)$. The choice of control entering the input of the system is carried out using the minimum selector, as shown in Fig. 1.

Naturally, the circuit shown in Fig. 1 for limiting the state and control variables is only an illustration of the operation of the algorithm implemented with the help of a control computer.

The control vectors defined in this way $\vec{u}(k)$ from the conditions for working out the required reference influences and compensating for disturbances, as well as maintaining the vector $\vec{y}_{\max}$ the maximum permissible values of the state variables are fed to the minimum selector, with the help of which the control is formed $\vec{u}(k)$, supplied to the input of the control system. In the course of choosing the minimum value of the control components from those formed with the help of various controllers, a comparison is also made with the maximum control value $\vec{u}_{\max}$ and thus, the limitation is carried out not only on the vector of state variables, but also on the control.

Let us now consider the limitation of loads in multi-channel nonlinear multi-mass systems, with robust control by the state vector with many electric drives connected through the control object [12–15]. In particular, such a problem arises in the joint control of the speeds of rotation of the upper and lower rolls with individual drive of the rolls and their mutual influence through the rolled metal. In addition, such a problem arises with joint coordinated control of the speeds of the main drives of multi-stand rolling mills with their mutual influence on each other through the rolled strip [5–7].

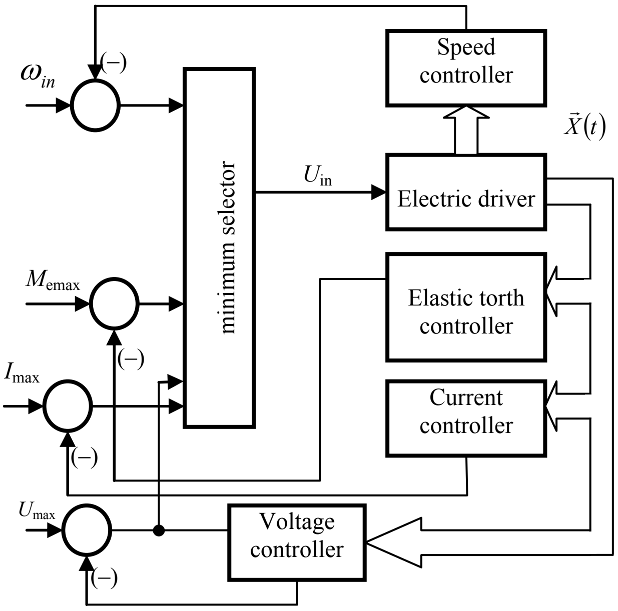


Fig. 1. Scheme of limitation of dynamic of loads of only single motor electromechanical systems

Consider the limitation on the vector of output coordinates $\vec{y}(t)$ multichannel system at a given level of maximum permissible values $\vec{y}_{\max}$ [16, 17]. For this purpose, we construct optimal nonlinear controllers that minimize criteria in which the integrands $\psi(\vec{x}(t), \vec{y}(t))$ are selected from the condition of ensuring the specified requirements for the speed of operation of the controllers, with the help of which the vector of output variables $\vec{y}(t)$ maintained at the level of maximum permissible values $\vec{y}_{\max}(t)$. As a result of the solution, the optimal controls are found $\vec{u}_i(t)$, ensuring the maintenance of i component $y_i(t)$ vector of output variables $\vec{y}(t)$ at the level of maximum permissible values $y_{\max i}(t)$ vector of maximum permissible values of the output coordinates $\vec{y}_{\max}(t)$. The choice of control arriving at the input of the system is carried out using the minimum selector, as shown in Fig. 2.

For this purpose, we construct robust optimal nonlinear controllers that minimize criteria in which the integrands are selected from the condition of ensuring the specified requirements for the speed of operation of the controllers, with the help of which the vector of output variables maintained at the level of maximum permissible values. As a result of the solution, the optimal controls are found, ensuring the maintenance of component vector of output variables at the level of maximum permissible values vector of maximum permissible values of the output coordinates. The choice of control arriving at the input of the system is carried out using the minimum selector, as shown in Fig. 2.

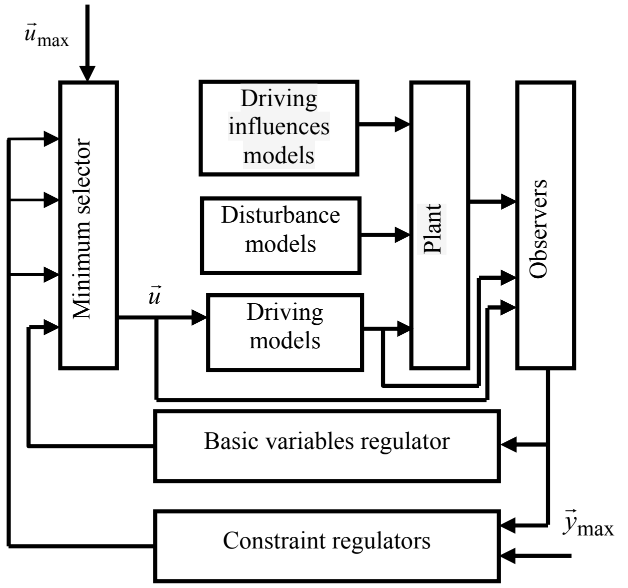


Fig. 2. Scheme of limitation of dynamic of loads of multymotor electromechanical systems

The control vectors defined in this way from the conditions of working out the required reference influences and compensation of disturbances, as well as limiting the vector of the output coordinates of the multichannel system at a given level of maximum permissible values are fed to the minimum selector, with the help of which the control vector is formed, supplied to the input of control channels. In addition, in the course of choosing the minimum value of the components of the control vector from those formed with the help of various controllers, there is also a comparison with the vector of maximum control values and thus, the limitation is carried out not only on the vector of state variables, but also on the control vector.

Method of computation of separate nonlinear robust controllers. Let us first consider the synthesis of feedback over the full state vector *x*, under the assumption that all components of the state vector can be measured without errors [18–20]. Then the original system takes the following form

$$\dot{x} = f(x) + g_{\omega}(x)\,\omega + g_u(x)u\,, \tag{1}$$

$$z = h_z(x) + k_{uz}(x)u\,. \tag{2}$$

in these expressions: *x* – state vector, *u* – control vector and *ω* – vector of external uncontrolled influences.

The control is formed from the state vector using some nonlinear transformation *u* = *l*(*x*). Then the closed system takes the following form

$$\dot{x} = \tilde{f}(x) + \tilde{g}_{\omega}(x)\omega\,, \tag{3}$$

$$z = \tilde{h}_z(x), \tag{4}$$

where

$$\tilde{f}(x) = f(x) + g(x)l(x), \tag{5}$$

$$\tilde{g}_{\omega}(x) = g_{\omega}(x), \tag{6}$$

$$\tilde{h}_z(x) = h_z(x) + k_{uz}(x)g(x)l(x). \tag{7}$$

For this initial system (5)–(7), we write the Hamilton–Jacobi–Isaacs equation in the following form

$$\begin{aligned} &\frac{\partial}{\partial t}V(x) = V_x f + V_x g_u u + V_x g_{\omega}\omega = \\ &= V_x f + \frac{1}{2}\left\| u + g_u^T V_x^T \right\|^2 - \ldots \\ &\ldots - \frac{1}{2}\gamma^2 \left\| \omega - \frac{1}{\gamma^2} g_{\omega}^T V_x^T \right\|^2 + \ldots \\ &\ldots + \frac{1}{2}\frac{1}{\gamma^2} V_x g_{\omega} g_{\omega}^T V_x^T - \frac{1}{2} V_x g_u g_u^T V_x^T + \ldots \\ &\ldots + \frac{1}{2} h_z^T h_z + \frac{1}{2}\gamma^2 \|\omega\|^2 - \frac{1}{2}\|h_z\|^2 - \frac{1}{2}\|u\|^2 \end{aligned} \tag{8}$$

This approach can be interpreted as a zero-sum differential game of two players in which one player minimizes the accepted quality criterion for control *u*, and the other player maximizes this criterion with respect to the vector of external variables *ω*. In this case, the minimization strategy for control *u*

$$u^* = \alpha_u(x) = -g_u^T(x)V_x^T(x), \tag{9}$$

and the strategy of maximization along the vector of external influences *ω*

$$\omega^* = \alpha_{\omega}(x) = \frac{1}{\gamma^2} g_{\omega}^T(x)V_x^T(x)\,. \tag{10}$$

Previously, the issues of synthesis of nonlinear robust control (9)–(10) were considered under the assumption that the full state vector can be accurately measured. Usually, only some variables are available for measurement in the system, and they are measured with noise [21, 22]. Let us now consider the synthesis of such a robust control, when only a part of the state variables is available for measurement with noise. We will call such an approach control by the full state vector with an estimate of the state vector by the measured output. The output equation can be represented as the following expression

$$y = h_y(x) + k_{\omega y}(x)\omega + k_{\omega y}(x)u\,. \tag{11}$$

We will estimate the total state vector from the measured output vector (11) using a dynamic system – an observer, whose equation we write in the following form

$$\begin{aligned} \dot{\xi} = f(\xi) + g_u(\xi)u + g_{\omega}(\xi)\omega + G(\xi)*\ldots \\ \ldots*\bigl(y - h_y(\xi) - k_{\omega y}(\xi)\omega\bigr) \end{aligned} \tag{12}$$

The synthesis of such an observer (12) consists in determining the matrix of the gains of this observer. The perturbation is clearly not applied to the output of the observer and, in the synthesis of the guaranteed estimate, is determined during the synthesis of the observer for the worst case (worst – case disturbance), when the perturbation itself is a function of the state vector of the observer *ξ*, so the following expression holds

$$\omega = \alpha_{\omega}(\xi)\,. \tag{13}$$

Then the original system (1)–(2), closed by the total state vector, estimated with the help of such an observer (12), together with the equation of the vector of controlled coordinates (11), will take the following form

$$\dot{x} = f(x) + g_u(x)\alpha_u(\xi) + g_{\omega}(x)\omega\,, \tag{14}$$

$$\begin{aligned} \dot{\xi} = f(\xi) + g_u(\xi)\alpha_u(\xi) + g_{\omega}(\xi)\alpha_{\omega}(\xi) + \ldots \\ \ldots + G(\xi)\bigl(h_y(x) - h_y(\xi) - \ldots \\ \ldots - k_{\omega y}(\xi)\alpha_{\omega}(\xi) + k_{\omega y}(x)\omega\bigr) \end{aligned}\,, \tag{15}$$

$$z = h_z(x) + k_{uz}(x)\alpha_u(\xi)\,. \tag{16}$$

This approach can be interpreted as a zero-sum differential game of two players in which one player minimizes the accepted quality criterion (2) for matrix of gains $G(\xi)$, and the other player maximizes this criterion (2) with respect to the vector of external variables ω.

In addition to synthesizing the observer in the form of a matrix of gains $G(\xi)$ of this observer, it is also necessary to synthesize the controller in the form of a matrix of gains of this controller $\alpha_u(\xi)$ by the observer state vector ξ. Calculation of the gain coefficients of nonlinear robust controllers and observers are based on solutions of the Hamilton–Jacobi–Isaacs equations [23, 24].

Mathematical models of the blooming main drives. Let us consider the control system for the individual main drives of the upper and lower rolls of a rolling mill, taking into account their mutual influences through the rolled metal. During the capture of the ingot or normal rolling, slip of the rolls relative to the rolled metal is possible. The system takes into account the nonlinear nature of the dependence of the friction torque in the slip mode on the speed of the roll slip relative to the rolled metal. In this case, various combinations of operating modes of the upper and lower rolls are possible: both rolls are in normal rolling modes: one roll is skidding, and the second roll is in normal rolling mode, and finally, both rolls are in skidding mode [25–27]. It should be noted that even in the normal rolling mode, when both rolls are in the rolling mode and there is no slip relative to the rolled metal, a deep rolling asymmetry is possible in which a significant redistribution of the rolling moments between the upper and lower rolls takes place. Cases are known when the motor of one roll operates in a motor mode, and the motor of the other roll operates in a generator mode. In some cases, such asymmetric rolling is organized specifically for technological reasons. In this case, of course, the rolls rotate at different speeds and a different advance of the rolled metal relative to the upper and lower rolls is created. The breakdown of the roll in the slip mode occurs when it exceeds the critical slip relative to the rolled metal, which depends mainly on the state of the rolled metal surface. In particular, the presence of scale even in a localized area can cause the roll to slip during normal rolling.

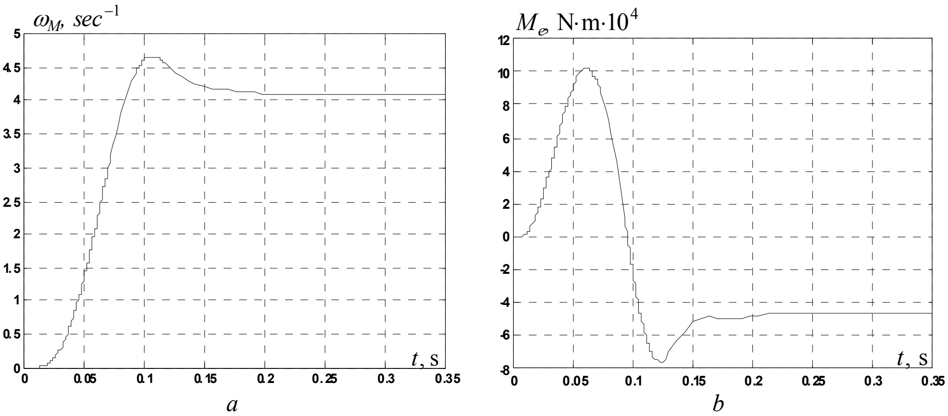
Let us take mathematical models of the channels for a short blooming line in the form of a two-mass system, and a long blooming line in the form of a three-mass system and take into account the presence of a cross-connection between the main drives of the rolls in the form of a moment proportional to the difference between the rotation speeds of the upper and lower rolls. The moment of mutual influence is the driving moment for the roll rotating at a lower speed, and this moment is braking for the roll rotating at a higher speed. Depending on the rolling conditions, the value of this moment, which characterizes the mutual influence of the rolls on each other through the rolled metal, can be a different fraction of the rolling moment, which is the moment of resistance for the main blooming drives [28, 29]. Transient processes in the short and long lines of the mill differ significantly from each other, and as the mutual coupling through the rolled ingot increases, the transients become significantly more oscillatory [30–35].

With a stepwise change in the magnitude of the moment of resistance, for the implementation of optimal control, more than tenfold forcing of the armature current and voltage of the thyristor converter is required. In this case, the limiting system goes into a self-oscillating mode of current limiting at the maximum positive and negative values.

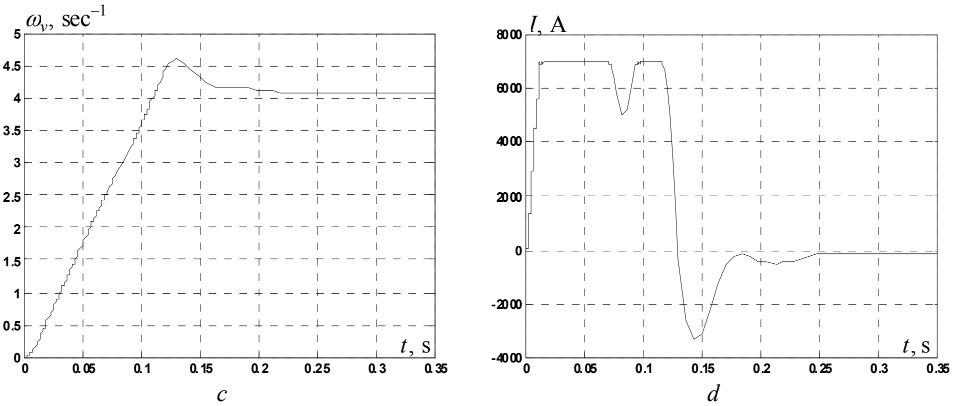
The mathematical model of the disturbing effect is adopted in the form of an exponential application of the load on the roll.

To implement optimal control of the main variable and variables that must be limited in the considered electromechanical system, a complete state vector is required. In a three-mass system, the moments of elasticity are not directly measured $M_{e1}(t)$ and $M_{e2}(t)$, as well as the speed of rotation of the reducer $\omega_R(t)$ and mechanism $\omega_{mech}(t)$, in a two-mass system, the elastic moment and the rotation speed of the mechanism are not measured. To reconstruct these directly not measurable state variables, we construct an optimal observer of reduced dimension in comparison with the original system, such that the input of this observer will be the armature currents $I_M(t)$, and the measured outputs of this observer will be the rotational speeds of the motors $\omega_M(t)$.

Computer simulation. As an example, in Fig. 3 are shown transient processes on references in a nonlinear control system with limiting the output value of the motor armature circuit current and voltage at the output of the thyristor converter of the upper roll of rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» with an exponential application of the load on the roll. In the figure are shown transient processes of ω_M – motor rate speed (a), M_e – the moment of elasticity of the shaft (b), ω_v – roll rotation speed (c) and I – motor armature current (d). In the figure are shown the characteristic sections of constant current, held by the current regulator at the level of maximum permissible values.



a *b*

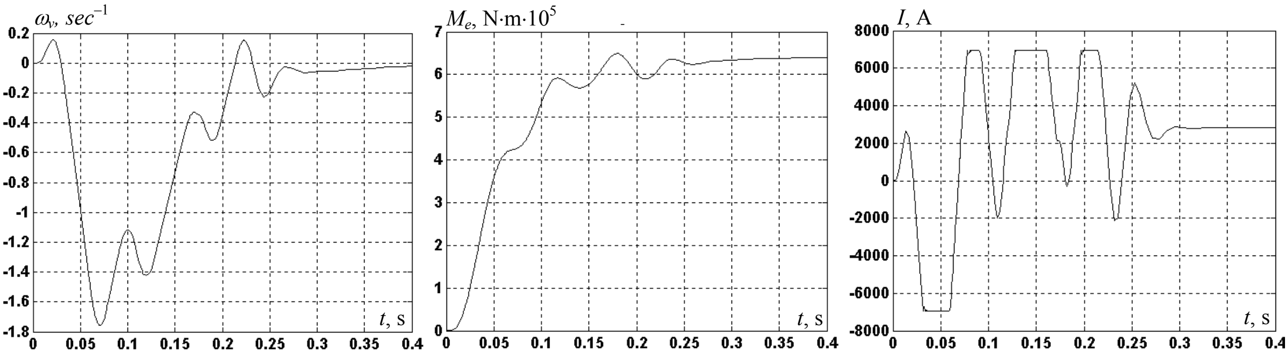


c *d*

Fig. 3. Transient processes on references

As an example, in Fig. 4 are shown the transient processes on moment of resistance of the upper roll control system (dual-mass control system) with the limitation of the output value of the motor armature circuit current and the voltage at the output of the thyristor converter of the rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» with an exponential application of the load on the roll due to the disturbing effect. In the figure, the following designations of the system state variables are adopted: ω_v – roll rotation speed (*a*), M_e – the moment of elasticity of the shaft (*b*) and I – motor armature current (*c*). In the figure also are shown the characteristic sections of constant current held by the current regulators at the level of maximum permissible values.

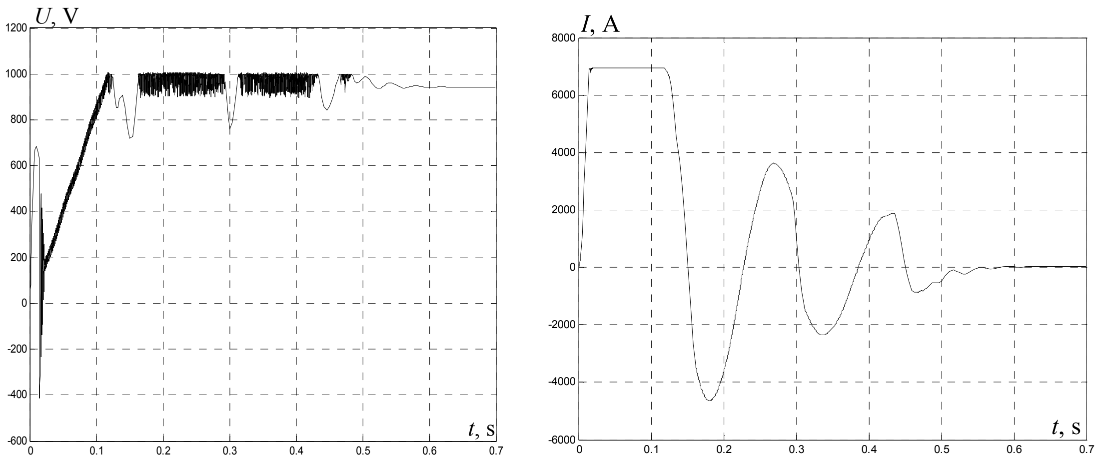
Despite armature current limitations, the roll speed control system returns the speed mismatch to zero in steady state.



a *b* *c*

Fig. 4. Transient processes on moment of resistance

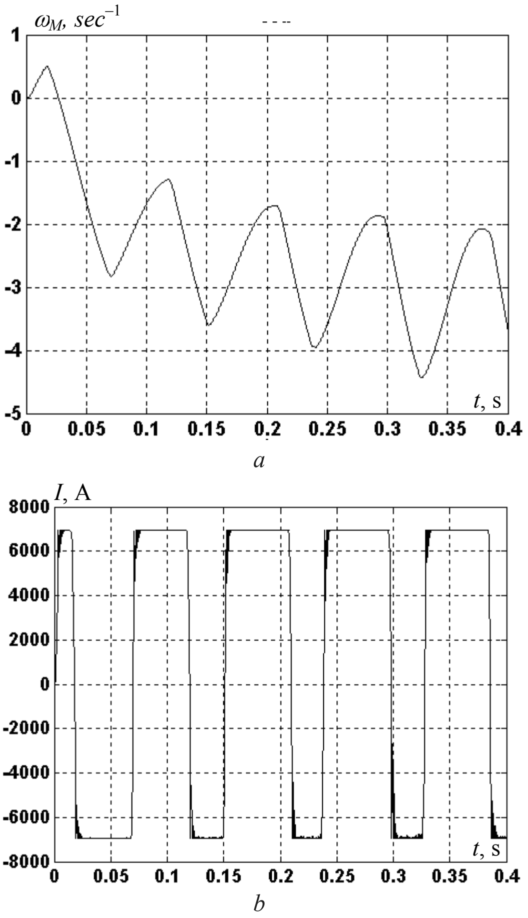
In Fig. 5 are shown the transient processes on references of the upper roll control system with simultaneous limitation of the output voltage value at the output of the thyristor converter and the current of the armature circuit of the motor of the rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» by the disturbing effect are shown. In the figure, the following designations of the system state variables are adopted: U – voltage at the output of the thyristor converter (*a*) and I – motor armature current (*b*). In the figure also are shown typical sections of constant current and voltage values, which are held by current and voltage regulators at the level of maximum permissible values.



a *b*

Fig. 5. Transient processes on references

In Fig. 6 are shown the transient processes of the ω_M motor rotation speed (*a*) and the *I* armature current (*b*) of the upper roll control system (dual-mass control system) with the restriction of the output value of the armature circuit current of the motor of the rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» by the disturbing effect.



a

b

Fig. 6. Transient processes on moment of resistance

As can be seen from these graphs, using the control system, the armature current is limited at the level of maximum permissible values when the system is working out the disturbing effect when capturing the ingot.

The mathematical model of the change in the load moment in the process of gripping the ingot is assumed to be exponential. Analysis of transient processes shows that the nature of dynamic loads in the system during ingot capture depends significantly on the rate of change of the moment of resistance. The more abruptly the moment of resistance changes, the greater the dynamic loads occur in the main line of the mill. Moreover, in this example under consideration, due to the limitation of the armature current there is a drawdown in the speed of the rolling rolls in steady state.

Discussion. The nature of transient processes in such a system substantially depends on the operation of the system of constraints. If the system does not go beyond the limits, then the transient processes in it are determined by the operation of the optimal controller of the main variables. When processing large setpoints or compensating for disturbing influences, the nature of transient processes depends significantly on the operation of the constraint system. In general, when the system reaches the limits, the time of transients increases in comparison with transients in the system without restrictions. Moreover, this increase in the time of transient processes mainly depends on the duration of the system operation on the constraints. In addition, when the system is operating on constraints, the very nature of the system's operation can significantly change. Since in such a mode the system practically opens in relation to the main controlled coordinates and is on limitations, it is natural that there is no damping of oscillatory processes in the system and an increase in oscillations can begin until loss of stability.

In the course of modelling the synthesized system, in a number of cases, when adjusting the control loops, the system switched to a self-oscillating mode at the levels of the maximum permissible positive and negative values of the state variables. As studies of such a system have shown, it can also become unstable, depending on the level and form of external influences. The most dangerous is the mode of coordinate limitation under the action of the moment of resistance. The nature of the restrictions essentially depends not so much on the magnitude as on the steepness of the change in the moment of resistance. With a stepwise change in the magnitude of the moment of resistance, for the implementation of optimal control, more than tenfold forcing of the armature current and voltage of the thyristor converter is required. In this case, the limiting system goes into a self-oscillating mode of current limiting at the maximum positive and negative values.

During the simulation of the synthesized nonlinear optimal control system with the optimal limitation of the output value of the motor armature circuit current, the voltage at the output of the thyristor converter and the moments of elasticity in the shafts of the main roll drives of the rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» characteristic sections of constant current values were obtained, stresses and moments of elasticity held by robust regulators of current, voltage and moments at the levels of their maximum permissible values.

It should be noted that individual autonomous controllers can be unstable: for example, a current control loop in a small one, when the effect of a change in EMF can be neglected leads to an unlimited increase in position and speed in a steady state, since in this case there are integral relationships between current and speed and between speed and position. In some cases, when adjusting the control loops, the system goes into self-oscillating mode at the levels of the maximum permissible positive and negative values of the state variables.

As studies of such a system have shown, it can also become unstable, depending on the level and form of external influences. The most dangerous is the mode of coordinate limitation when the moment of resistance is applied. The nature of the restrictions essentially depends not so much on the magnitude as on the steepness of the change in the moment of resistance.

Conclusions.

1. For the first time the method of limitation of dynamic loads of nonlinear electromechanical systems under state vector robust control is developed. Limitation of control and state variables of nonlinear electromechanical systems is carried out using the minimum selector of choosing the

minimum value of the control vector from formed with the help of local controllers and with the vector of maximum control values.

2. To limit the state and control variables the separate robust controllers for the main control coordinate and the same state variables that need to be limited are used. Using the minimum selector, we apply a voltage to the input of the thyristor converter, which corresponds to the minimum value of the outputs of all separate regulators. The separate robust controllers are calculated based on solutions of the Hamilton–Jacobi–Isaacs equations.

3. Examples of transitional processes with limitation of dynamic loads of nonlinear electromechanical systems of main roll drives of the rolling mill 950 of the Zaporozhye plant «Dniprospetsstal» are given.

4. It is shown, that when the system reaches the limits, the time of transients increases in comparison with transients in the system without restrictions. Moreover, this increase in the time of transient processes mainly depends on the duration of the system operation on the constraints. In addition, when the system is operating on constraints, the very nature of the system's operation can significantly change.

Conflict of interest. The authors declare that they have no conflicts of interest.

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