Проведено аналітичний синтез системи оптимального керування рухом електровозного транспорту в умовах залізорудних шахт при розвантаженні та завантаженні. Розробка обумовлена необхідністю підвищення видобування залізорудної сировини. Система побудована на базі сучасних тягових електромеханічних комплексів та засобів обчислювальної техніки. Розв'язана задача демпфування коливань, що викликають надлишкові динамічні навантаження комплексу «електровоз-вагонетки»

Ключові слова: динамічні зусилля, зчіпки вагонів, власні числа, обмеження керування, гальмівний шлях

Проведен аналитический синтез системы оптимального управления движением электровозного транспорта в условиях железорудных шахт при разгрузке и погрузке. Разработка обусловлена необходимостью повышения добычи железорудного сырья. Система построена на базе современных тяговых электромеханических комплексов и средств вычислительной техники. Решена задача демпфирования колебаний, вызывающих чрезмерные динамические нагрузки комплекса «электровоз-вагонетки»

Ключевые слова: динамические усилия, сцепка вагонов, собственные числа, ограничения управления, тормозной путь

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DEVELOPMENT OF A SYSTEM TO CONTROL THE MOTION OF ELECTRIC TRANSPORT UNDER CONDITIONS OF IRON-ORE MINES

O. Sinchuk
Doctor of Technical Sciences,
Professor, Head of Department*
E-mail: speet@ukr.net

I. Kozakevich
PhD, Associate Professor*
E-mail: aepigor@gmail.com

V. Fedotov
Senior Lecturer*
E-mail: vlad.fva@gmail.com

A. Somochkyn
PhD, Associate Professor*
E-mail: shorg@gmail.com

V. Serebrenikov
PhD, Associate Professor
Department of higher mathematics and information systems
Donetsk National University of Economics and Trade
named after M. I. Tugan-Baranovsky
Tramvayna str., 16, Kryvyi Rih, Ukraine, 50005
E-mail: argen.edson@yandex.ua

*Department of automation electromechanical systems in the industry and vehicles
Kryvyi Rih National University
Vitaliy Matusevych str., 11, Kryvyi Rih, Ukraine, 50027

1. Introduction

Ukraine is one of the countries of sustainable development of natural resources. What is more, about 70 % of the country's annual currency reserves are replenished due to the export of iron ore raw material, one of the variety of country's mineral resources which is supplied to more than 50 countries. An optimistic fact is that according to a long-run prediction, the world's economy demand for it will continue to grow up to 2035 with an average annual growth rate of 1.5 % [1].

The change in world prices for iron ore is devoid of a positive trend. Over the past 4 years, the world market prices for this product fell by almost 60 %. The situation is also aggravated by the fact that the cost price of the raw materials extracted by all Ukrainian mining enterprises grows from year to year. The study of the components of the cost price of iron ore extracted by Ukrainian mining enterprises [2] indicates that the largest share in the cost price belongs to energy costs and costs for the transportation of raw materials from the place of their extraction to the place of lifting to the surface [3].

2. Literature review and problem statement

Analysis of publications shows that in order to increase profitability of extraction of this raw material, the technology into which delivery complex organically enters must be supplemented by an efficient transportation scheme [4]. Over the past ten years, all Ukrainian iron ore enterprises have been experiencing a process of falling productivity of the mine transport, in particular electric locomotive transport [5]. Solution of its numerous problems is achievable by creation of an automated control system [6]. This process is complicated by the fact that the line of mine electric locomotives manufactured by machine-building enterprises is outdated and far from being perfect [7]. It is the type of electric locomotive and its traction drive that can become an "elevator" that will raise the mine transport to the level of up-to-date automated control systems.

With the aim of elimination of the abovementioned negative moments in the design of mine electric locomotives, activities in creation of their modern types and development of effective electromechanical traction systems for them experience revival in Ukraine [8]. Efficiency of the electric traction drive along with other indicators should be understood as the ability to automatically control it with its integration into the technological structure of production automation.

At the same time, first studies of new solutions showed some drawbacks in their functionality. In particular, this refers to the problem of minimizing "locomotive – wagons" complex collisions caused by the design of their coupling devices. These "collisions" disturb dynamics of the train movement and adversely affect operation of the traction electric drive [9]. As it was established, this situation is peculiar to electric trains of Ukrainian mines. Because of the specific technology of unloading iron-ore raw materials, coupling devices of a simplified design are used and not automatic couplings as in coal mines.

More than 50 % of the cycle time of movement in underground excavations of the iron ore mines is spent for the work in the locations where raw material handling operations are performed. Exactly there the most negative effects of "locomotive – wagon" collisions manifest themselves [10]. Analysis of the dynamic forces occurring in couplings during train acceleration and deceleration is presented in work [11], but the influence of the system parameters on emergence of oscillatory processes taking place in it was not shown. The conditions of underground hauling make it practically impossible to manage these works in a manual way. Therefore, a problem of the synthesis of an automated control system for traction electric drives of electric locomotives with the prospect of their inclusion in the integrated system of production automation arises with all acuteness. In [12], a variant of constructing a system for automated control of the electric transport movement was proposed but the proposed mathematical calculations do not allow one to study the entire variability of the system operation conditions since many physical quantities are considered as generalized coefficients. Thus, the first step in the creation of traction electromechanical systems for mine electric locomotives should be the analytical synthesis of the system for optimal motion control.

3. The aim and objectives of the study

This work objective was the synthesis of a system for an optimal controlling the electric locomotive traction drive during material handling operations.

To achieve this objective, it was necessary to solve the following tasks:

– obtaining a procedure for estimating and study of real operating conditions of the traction electric drives of electric vehicles in conditions of Krivbass iron ore mines (Kryvy Rig, Dnipropetrovsk region, Ukraine);

– analytical construction of a mathematical model for assessing influence of transient processes in an electromechanical system on functioning of mine locomotives;

– determination of possible principles of constructing a system for controlling traction electric drives of mine locomotives with the possibility of suppressing fluctuations in the transient processes.

4. Materials and methods for studying dynamics of electric transport for iron ore mines

4. 1. Analysis of the properties of the control object

In the analytical construction of the system for controlling electric traction drives of locomotives during loading of wagons with iron ore raw material and their unloading, it is necessary to investigate properties of the "locomotive – wagons" complex as a control object. These properties are important from the point of view of the formulated control objective. The need for a mathematical model of the dynamic processes in the "locomotive - wagons" complex as a control object is obvious since the required control can only be realized with the help of the model. With no model available, the management process can only be implemented by a trial and error method which requires too much time and often leads to erroneous actions [8].

Schematic diagram of an automatic control system for iron ore electric transport is shown in Fig. 1. According to this diagram, vectors of uncontrollable $\vec{Y}$ and controllable $\vec{U}$ variables are the input of the control object and the vector of wagon displacement $\vec{X}$ is its output.

Besides, a vector of uncontrollable disturbances $\vec{E}$ acts on the control object. Information on the input and output variables is entered to the model of dynamic processes of the "locomotive – wagons" complex where parametric identification is carried out on the a priori chosen model structure. Further on, a control algorithm is realized on the model with the help of which an optimal value of the control action $\vec{U}^*$ is calculated. According to the diagram shown in Fig. 1, the model of dynamic processes of the complex under study is its required element. Therefore, the next step is to construct a mathematical model of the dynamic processes in the "locomotive – wagons" complex.

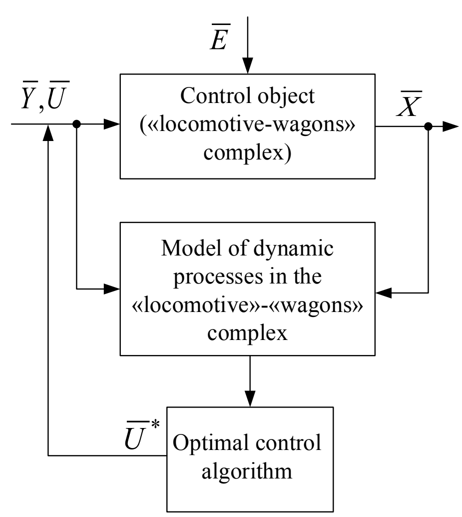

Fig. 1. Schematic diagram of an automated system for controlling electric mine transport

Analysis of dynamic processes in the "locomotive – wagons" complex as a control object requires allocation of input uncontrollable and controllable variables. The input uncontrollable variables naturally include the state of the tracks and the contact wire, the coefficient of adhesion of wheels with rails, weight of the wagons. The controlling input variable is the force action from the locomotive to the wagons. The output variables are the wagon displacement. In addition, the system is affected by unobservable disturbances by which all external and internal factors affecting this process are implied [9]. The process of the model synthesis was carried out in two stages. At the first stage, structural identification was made the meaning of which was to choose the dependence of the input and output variables of the control object without taking into account the values of its parameters [7]. In drawing up the system equations, it is natural to assume that the "locomotive – wagons" system can be represented in a form of a structure consisting of several masses connected by elastic (coupling) and rigid (rails) joints. At the same time, it is assumed that when the force is transferred from the traction motors and reducers to the wheel pairs of the locomotive, no additional dynamic loads appear. Then the mathematical model of the "locomotive – wagons" complex can be represented as a system of second-order differential equations [8].

$$\begin{aligned}
&m_1\ddot{u}_1+\beta_1\dot{u}_1+k_1u_1-\beta_2(\dot{u}_2-\dot{u}_1)-k_2(u_2-u_1)=F(t),\\
&m_2\ddot{u}_2+\beta_2(\dot{u}_2-\dot{u}_1)+k_2(u_2-u_1)-\beta_3(\dot{u}_3-\dot{u}_2)-k_3(u_3-u_2)=0,\\
&m_3\ddot{u}_3+\beta_3(\dot{u}_3-\dot{u}_2)+k_3(u_3-u_1)-\beta_4(\dot{u}_4-\dot{u}_3)-k_4(u_4-u_3)=0,\\
&\ldots\\
&m_{n-1}\ddot{u}_{n-1}+\beta_{n-1}(\dot{u}_{n-1}-\dot{u}_{n-2})+k_{n-1}(u_{n-1}-u_{n-2})-\beta_n(\dot{u}_n-\dot{u}_{n-1})-\\
&-k_n(u_n-u_{n-1})=0,\\
&m_n\ddot{u}_n+\beta_n(\dot{u}_n-\dot{u}_{n-1})+k_n(u_n-u_{n-1})=0,
\end{aligned} \tag{1}$$

where m_i is the weight of the i-th wagon, kg; F (t) is force acting on the side of the locomotive on the wagons, H; β_i are damping coefficients, kg/s; k_i is rigidity coefficients, kg/s^2; u_i is displacement of the i-th wagon, m;

$$\dot{u}_i=\frac{du_i}{dt}$$

is speed of wagons, m/s;

$$\ddot{u}_i=\frac{d^2u_i}{dt^2}$$

is wagon acceleration, m/s^2; n is the number of wagons; i=1, 2, ... n.

For unambiguous solution of the resulting system of differential equations, it is necessary to add the initial conditions, which determine the coordinates and velocities of the wagons at the initial time, respectively:

$$\begin{aligned}
&u_i(t=t_0)=u_{i0},\\
&\dot{u}_i(t=t_0)=\dot{u}_{i0},
\end{aligned} \tag{2}$$

where i=1, 2, ..., n.

4. 2. Compiling a mathematical model of the electric train

As a rule, in underground operating conditions, the train includes, up to 8 wagons. Besides, it is natural to assume that the train is motionless at the initial instant of time. Therefore, the mathematical model of the "locomotive – wagons" complex will be represented by a system of differential equations with zero initial conditions:

$$\begin{aligned}
&m_1\ddot{u}_1+(\beta_1+\beta_2)\dot{u}_1+(k_1+k_2)u_1-\beta_2\dot{u}_2-k_2u_2=F(t),\\
&m_i\ddot{u}_i-\beta_i\dot{u}_{i-1}-k_iu_{i-1}+(\beta_i+\beta_{i+1})\dot{u}_i+\\
&+(k_i+k_{i+1})u_i-\beta_{i+1}\dot{u}_{i+1}-k_{i+1}u_{i+1}=0,\\
&m_n\ddot{u}_n-\beta_{n-1}\dot{u}_{n-1}-k_{n-1}u_{n-1}+\beta_n\dot{u}_n+k_nu_n=0,
\end{aligned} \tag{3}$$

where i=2,...n–1.

$$u_i(t=0)=0,\quad \dot{u}_i(t=0)=0, \tag{4}$$

where i=1, 2, ... n, n=1, 2, ... 8.

Taking into account real conditions of operating electric vehicles, it is natural to assume that the wagon couplers are of the same type, that is, the equality of the corresponding parameters takes place

$$\begin{aligned}
&k_1=\ldots=k_n=k,\\
&\beta_1=\ldots=\beta_n=\beta,
\end{aligned} \tag{5}$$

where n=1,...8.

Then system (3) takes form:

$$\begin{aligned}
&m_1\ddot{u}_1+2\beta\cdot\dot{u}_1+2k\cdot u_1-\beta\cdot\dot{u}_2-ku_2=F(t),\\
&m_i\ddot{u}_i-\beta\cdot\dot{u}_{i-1}-k\cdot u_{i-1}+\\
&+2\beta\cdot\dot{u}_i+2k\cdot u_i-\beta\cdot\dot{u}_{i+1}-k\cdot u_{i+1}=0,\\
&m_n\ddot{u}_n-\beta\cdot\dot{u}_{n-1}-k\cdot u_{n-1}+\beta\cdot\dot{u}_n+k\cdot u_n=0,
\end{aligned} \tag{6}$$

where i=2,...n–1, n=1,2,...8.

As a result of structural identification, system (6) contains unknown parameters. In order to find values of these parameters, it is necessary to carry out parametric identification at the second stage. Its idea consists in finding such parameter values that will approximate the object and the model in the chosen sense. Taking into account the fact that the mathematical model (6) describes dynamic conditions, a functional characterizing proximity of the model and the object is written in an integral form. The purpose of parametric identification is to minimize this functional according to the specified parameters [9]:

$$\Phi(k,\beta)=\int_0^T\left(u_i(\tau)-u_i^{м}(\tau,k,\beta)\right)^2d\tau\to\min_{k,\beta}, \tag{7}$$

where $u_i(\tau)$, $u_i^{м}(\tau,k,\beta)$ are values of the i-th output variable of the object and the model at time instant τ; [0; T] is the time interval during which the parametric identification is done; k, β are adjustable parameters of the model (6).

The values of the k_0, β_0 parameters found by minimization of functional (7) are optimal and provide the best approximation after their substitution into the model (6).

It is important to emphasize that the best approximation characterized by the minimum value of the functional (7):

$$\Phi(k_0,\beta_0)=\int_0^T\left(u_i(\tau)-u_i^{M}(\tau,k_0,\beta_0)\right)^2 d\tau, \quad (8)$$

may not provide desired quality of identification associated with the purpose of control. In this case, a need appears to correct the model by introducing additional parameters into the synthesized structure which will allow one to reduce the functional (8) value. The synthesized model with the quality of identification determined by the value of functional (8) required for the control problem solution is the initial model for synthesis of the control algorithm.

4. 3. Determining tactics of building a control system for the traction electric drive of a mine locomotive

Solution of the problem of eliminating oscillations in the "locomotive – wagons" complex is connected with finding necessary values of rigidity and damping coefficients for the wagon couplers. Values of these coefficients are determined from the condition that the eigenvalues of the system of differential equations (6) have to be real and negative. In a general case, finding of the eigenvalues of the system of differential equations (6) is practically unrealizable. Therefore, it seems expedient to study oscillations of the "locomotive – wagons" complex sequentially, beginning with the electric train consisting of one wagon. Since the oscillations under study are natural oscillations, there are no external actions. Then the system of differential equations (6) takes the form:

$$m\cdot\ddot{u}_1+\beta\cdot\dot{u}_1+k\cdot u_1=0. \quad (9)$$

To solve the set problem, write down the characteristic equation for (9) as:

$$m\cdot p^2+\beta\cdot p+k=0. \quad (10)$$

Roots of the quadratic equation (10), which are eigenvalues (9), are found from the formula:

$$p_{1,2}=\frac{-\beta\pm\sqrt{D}}{2m}, \quad (11)$$

where $D=\beta^2-4mk$.

For absence of oscillations, it is necessary to satisfy the condition $D=\beta^2-4mk\geq 0$ or:

$$\beta\geq 2\sqrt{mk}. \quad (12)$$

If condition (12) is satisfied, the roots of the characteristic equation (11) will be real and negative which ensures that there are no oscillations in the case under consideration.

If the electric train includes two wagons, the system of differential equations (6) takes the form:

$$m_1\ddot{u}_1+2\beta\cdot\dot{u}_1+2k\cdot u_1-\beta\cdot\dot{u}_2-k\cdot u_2=0,$$

$$m_2\ddot{u}_2-\beta\cdot\dot{u}_1-k\cdot u_1+\beta\cdot\dot{u}_2+k\cdot u_2=0. \quad (13)$$

In this case, it is expedient to write down the system of differential equations (13) in the Cauchy form:

$$\dot{X}=A\cdot X, \quad (14)$$

where

$$X=\begin{pmatrix}x_1\\x_2\\x_3\\x_4\end{pmatrix},$$

$$A=\begin{pmatrix}0 & 1 & 0 & 0\\ -\frac{2k}{m_1} & -\frac{2\beta}{m_1} & \frac{k}{m_1} & \frac{\beta}{m_1}\\ 0 & 0 & 0 & 1\\ \frac{k}{m_2} & \frac{\beta}{m_2} & -\frac{k}{m_2} & -\frac{\beta}{m_2}\end{pmatrix},$$

$$x_{2n-1}=u_n,\quad x_{2n}=\dot{u}_n,\quad n=1,2.$$

By varying coefficients of rigidity k and damping β, it is possible to achieve such result that eigenvalues of A matrix are real and negative which will ensure absence of oscillations in the "locomotive – wagons" complex consisting of two wagons. Fig. 2 shows a block diagram of an algorithm enabling elimination of oscillations in the "locomotive – wagons" complex. The input data which are entered to block 1 include the following:

n is the number of wagons in the electric train;

m_i is weight of the i-th wagon (i=1,2, ... n);

k_0, $\underline{k}$, Δk are initial and minimum values and the interval of variation of the rigidity coefficient, respectively;

β_0, $\overline{\beta}$, $\Delta\beta$ are initial and maximum values and the interval of variation of the damping coefficient, respectively.

In blocks 2 and 3, initial values are assigned to the rigidity and damping coefficients. Block 4 calculates eigenvalues of the A matrix composed of coefficients of the system of differential equations (6) represented in the Cauchy form. In block 5, check is done for existence of complex numbers among the eigenvalues of the A matrix an imaginary part of which are responsible for the oscillations. If there are no complex numbers among the eigenvalues of the A matrix, hence oscillations of the "locomotive – wagons" complex are eliminated and a transition is done to block 10 where the found eigenvalues are visualized. Otherwise, if there are complex numbers among the eigenvalues of the A matrix, block 6 increases the damping coefficient β by Δβ and then check for constraint is done in block 7. If the constraint is not satisfied, then transition to block 4 is done where the eigenvalues of the A matrix are again calculated and the process is repeated. If the restriction is satisfied in block 7, then the value of the rigidity coefficient k is reduced in block 8 by an amount of Δk followed by a check for the restriction in block 9.

If the restriction is not fulfilled, a transition is made to block 3 from which a cycle is performed for the damping parameter β. When the restriction is satisfied, a transition to block 10 is made, where the found magnitudes of the eigenvalues are visualized. In this case, minimization of oscillations in the "locomotive - wagons" complex takes place since complex numbers exist among the eigenvalues of the A matrix.

After elimination (or minimization) of oscillations in the "locomotive – wagons" complex, in order to construct the automatic control system, it is necessary to synthesize an algorithm for optimal control of the traction electric drive which will ensure loading of the wagons with iron ore and their unloading.

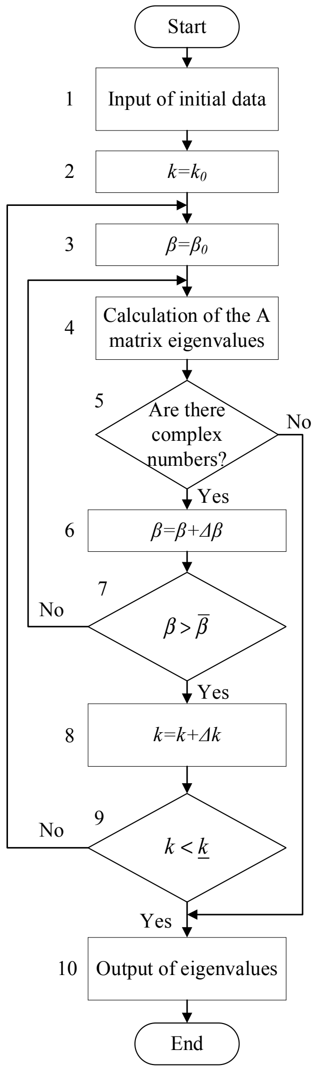

Fig. 2. Block diagram of the algorithm for eliminating oscillations in the "locomotive – wagons" complex

At the stations of loading and unloading of electric transport, the purpose of control is to move the wagons beneath a hopper from which ore comes (when loading) or delivery of the wagons to the tipping station (when unloading). Therefore, the main task in both cases is the timely advance of the electric train for a set distance to perform corresponding technological operations. From an operational point of view, the operations of wagon moving should be carried out in a minimum time which will increase productivity. Thus, it is necessary to synthesize an electric train control algorithm which is optimal for speed of operation [11]. The equation of the train movement is described by the differential equation:

$$m\cdot\ddot{x}+\beta\cdot\dot{x}+k\cdot x=F, \qquad (15)$$

where x=x(t) is travel of the electric train, m; $\dot{x}=\dot{x}(t)$ is speed of the electric train, m/s; $\ddot{x}=\ddot{x}(t)$ is acceleration of the electric train, m/s^2.

Besides, when $x(0)=\dot{x}(0)=0$, i. e. movement starts at the initial instant of time from zero speed, m is weight of the electric train, kg, β is the damping coefficient, kg/s, k is the elasticity coefficient, N/m, F=F(t) is the locomotive tractive power, N. The locomotive tractive power affects the wagons within the limits $\underline{F}\le f\le\overline{F}$, where $\underline{F}<0$ is maximum braking force (depends on the brakes and adhesion to the rails), $\overline{F}>0$ is maximum force (depends on the engine power).

Let T be the time of motion for a set distance. This quantity is a functional with its value determined by the control law F(t). To find the value of this functional, it is necessary to solve equation (15) with the boundary conditions:

$$x(0)=\dot{x}(0)=\dot{x}(T)=0, \qquad (16)$$

$$x(T)=L,$$

where L is the specified distance of movement of the electric train, m.

The obtained value of the functional T=T(F(t)) is the minimized goal. As a result, the problem of optimal control of the electric locomotive drive can be written as:

$$T\big(F(t)\big)\to\min_{F(t)\in\Omega}, \qquad (17)$$

$$\Omega:\begin{cases}\underline{F}\le F(t)\le\overline{F},\\ m\cdot\ddot{x}+\beta\cdot\dot{x}+k\cdot x=F(t),\\ x(0)=\dot{x}(0)=\dot{x}(T)=0,\\ x(T)=L,\\ \dot{x}(t)\le v_0.\end{cases} \qquad (18)$$

The last line of (18) contains a condition limiting the speed of the electric train by the value v_0 proceeding from the technical conditions of operation. It was mathematically proven that the optimal control F*(t) of the electric train as a solution of the problem (17), (18) is of a relay nature and consists of switchings. In other words, the train should be maximally accelerated in the beginning, then it should move with an allowable velocity v_0 and finally abruptly decelerated to a full stop. Thus, the problem of synthesis of the optimal control F*(t) is reduced to finding the instants of time, namely the end of acceleration (t_1) and the beginning of deceleration (t_2). Fig. 3 shows the diagrams of thrust and speed of movement of mine electric locomotive during reloading operations. In what follows, the problem (17), (18) will be transformed to the following form for convenience of solution:

$$T\big(u(t)\big)\to\min_{u(t)\in\Omega}, \qquad (19)$$

$$\Omega:\begin{cases}\underline{u}\le u(t)\le\overline{u},\\ \ddot{x}+a\cdot\dot{x}=u(t),\\ x(0)=\dot{x}(0)=\dot{x}(T)=0,\\ x(T)=L,\\ \dot{x}(t)\le v_0.\end{cases} \qquad (20)$$

where $u(t)=F(t)/m$, $\underline{u}=\underline{F}/m$, $\overline{u}=\overline{F}/m$, $a=\beta/m$.

According to the diagram shown in Fig. 3, the path traversed by the electric train is written as:

$$\int_0^{t_1}\dot{x}(t)dt+\int_{t_1}^{t_2}\dot{x}(t)dt+\int_{t_2}^{T}\dot{x}(t)dt=L. \qquad (21)$$

Consider the train movement at each of the three sections of the path.

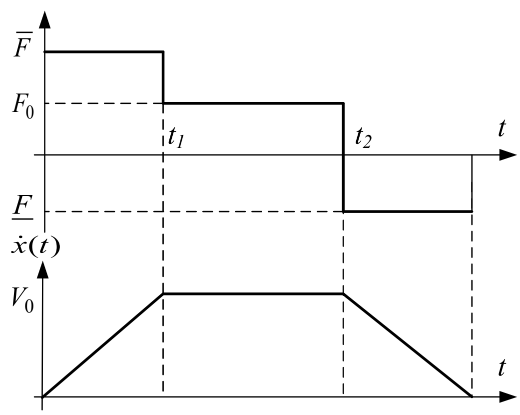

Fig. 3. Representation of diagrams of thrust and speed of movement of mine electric locomotive during reloading operations

The first section.

$$\left[0;t_1\right],\quad u=\overline{u}.$$

The equation of the train motion is:

$$\ddot{x}(t)+a\cdot\dot{x}(t)=\overline{u}.$$

Use the method of the integrating factor and find successively:

$$\dot{x}(t)=\frac{\overline{u}}{a}+C_1e^{-a\cdot t},\tag{22}$$

where C_1 is an arbitrary constant.

To find C_1, make use of the initial condition:

$$\dot{x}(0)=0,$$

whence it follows that:

$$\dot{x}(0)=\frac{\overline{u}}{a}+C_1=0,$$

$$C_1=-\frac{\overline{u}}{a}.\tag{23}$$

Then, substitute equation (23) into (22) to find the train speed at the first section:

$$\dot{x}(t)=\frac{\overline{u}}{a}\left(1-e^{-a\cdot t}\right).\tag{24}$$

Taking into account the fact that the train speed should not exceed the value of v_0, find the instant of time of switching control in order to maintain this speed:

$$t_1=-\frac{1}{a}\ln\left(1-\frac{av_0}{\overline{u}}\right).\tag{25}$$

The path covered at this section is determined by the formula:

$$l_1=\int_0^{t_1}\left(\frac{\overline{u}}{a}\left(1-e^{-a\cdot t}\right)\right)dt=$$

$$=\frac{\overline{u}}{a}\left(t+\frac{1}{a}e^{-at}\right)\Bigg|_0^{t_1}=\frac{\overline{u}}{a}\left(t_1+\frac{1}{a}e^{-a\cdot t_1}-\frac{1}{a}\right).\tag{26}$$

$$l_1=-\frac{\overline{u}}{a}\left(\frac{1}{a}\ln\left(1-\frac{av_0}{\overline{u}}\right)+\frac{v_0}{\overline{u}}\right).\tag{27}$$

The second section:

$$\left[t_1;t_2\right],$$

$$u_0=a\cdot v_0.\tag{28}$$

The equation of the train movement is:

$$\dot{x}(t)=v_0.\tag{29}$$

The path covered in this section is determined by the formula:

$$l_2=\int_{t_1}^{t_2}v_0dt=v_0\left(t_2-t_1\right)=v_0\left(t_2+\frac{1}{a}\ln\left(1-\frac{av_0}{\overline{u}}\right)\right).\tag{30}$$

The third section:

$$\left[t_2;T\right],\quad u=\underline{u}.$$

The equation of movement has the form:

$$\ddot{x}(t)+a\cdot\dot{x}(t)=\underline{u}.\tag{31}$$

Use the method of integrating factor to find solution of equation (31):

$$\dot{x}(t)=\frac{\underline{u}}{a}+C_1e^{-a\cdot t},\tag{32}$$

where C_1 is an arbitrary constant. Taking into account condition (27), find C_1:

$$v_0=\frac{\underline{u}}{a}+C_1e^{-a\cdot t},\tag{33}$$

$$C_1=\left(v_0-\frac{\underline{u}}{a}\right)e^{a\cdot t_2}.\tag{34}$$

Then the speed of movement of the electric train at the third section will be written as:

$$\dot{x}(t)=\frac{\underline{u}}{a}+\left(v_0-\frac{\underline{u}}{a}\right)e^{-a\left(t-t_2\right)}.\tag{35}$$

Taking into account that $\dot{x}(T)=0$, find the instant of time when the train deceleration starts:

$$t_2=T-\frac{1}{a}\ln\left(1-\frac{av_0}{\underline{u}}\right).\tag{36}$$

The path that the train passes at the third section is found by integrating (37):

$$
\begin{aligned}
l_3 &= \int_{t_2}^{T}\left(\frac{\underline{u}}{a}+\left(v_0-\frac{\underline{u}}{a}\right)e^{-a(t-t_2)}\right)dt = \\
&= \frac{\underline{u}}{a}t\Big|_{t_2}^{T} - \frac{1}{a}\left(v_0-\frac{\underline{u}}{a}\right)e^{-a(t-t_2)}\Big|_{t_2}^{T} = \\
&= \frac{\underline{u}}{a}(T-t_2)-\frac{1}{a}\left(v_0-\frac{\underline{u}}{a}\right)\left(e^{-a(T-t_2)}-1\right) = \\
&= \frac{\underline{u}}{a^2}\ln\left(1-\frac{av_0}{\underline{u}}\right)+\left(v_0-\frac{\underline{u}}{a}\right)\frac{v_0}{\underline{u}}. \qquad (37)
\end{aligned}
$$

Thus, the above mathematical calculations make it possible to synthesize the system for controlling operation at the train loading and unloading stations.

5. The results obtained in studying dynamics of the iron ore mine electric transport

As a result of studying the electric train movement dynamics, a block diagram of the algorithm of controlling movement during loading-unloading operations was obtained (Fig. 4). The starting number of the loaded wagon is assigned in block 1 and then the input data are entered in block 2. These data include the following:

m: weight of the electric train, kg;
β: coefficient of damping, kg/sec;
$\overline{F}, \underline{F}$: maximum tractive and braking forces, N;
F_0: thrust of steady movement, N;
L: distance of the wagon movement, m;
n: number of wagons in the electric train;
Δm: mass of iron ore loaded into the wagon, kg.

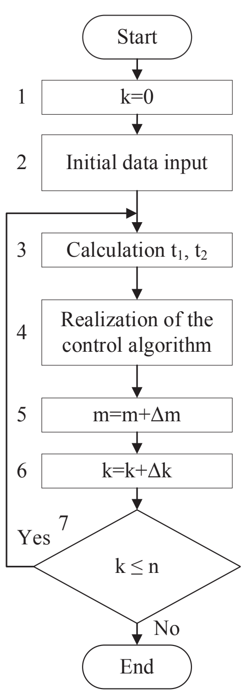

Fig. 4. Block diagram of the algorithm for controlling movement of the train during the wagon loading with raw materials

Timing of the control switching is calculated in block 3, and the control algorithm is implemented in block 4 according to the traction diagram of Fig. 3. The train weight increase by the amount of iron ore loaded in a wagon is realized in block 5. Further, the number of the loaded wagons is increased in block 6 followed by a check in block 7 for the end of loading according to the number of wagons in the train. If not all wagons were loaded, then transition to block 3 is done and the recounting cycle is repeated. Otherwise, when all wagons were loaded, exit from the algorithm is done.

When unloading the wagons, the control algorithm is modified in comparison with that shown in Fig. 4. First of all, information is entered in block 2 on the weight of the wagons loaded with raw material. The operation of subtracting unloaded weight of raw material is realized in block 5. In other respects, functioning of the optimal control algorithm remains the same.

6. Discussion of the results obtained in the study of dynamics of the iron ore mine electric transport

The presented control algorithm makes it possible to accelerate and decelerate the train with minimization of variation of the wagon linear speeds. This is ensured by changing parameters of the control system in such a way that when taking into account the values of the coefficients of rigidity k and damping β, the largest by module eigenvalues of the system matrix were real and negative. Minimization of these variations makes it possible to control more exactly wagon movement, which is especially important at the stations of their loading and unloading presenting the opportunity to shorten time for rearranging the train and decrease amount of spilled iron ore. As can be seen from Fig. 5, the initial speed-up proceeds with a high acceleration since the remaining elements of the train are separated from the locomotive by gaps. When the gaps are eliminated, the rest of the wagons start moving which leads to a decrease in speed.

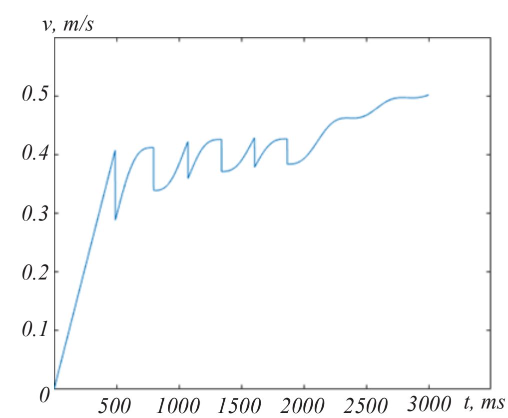

Fig. 5. Variation of the locomotive speed during acceleration and in the presence of gaps in the couplers

The control system adapts to these changes and adjusts the amount of tractive effort to eliminate oscillation in the "locomotive – wagons" system.

7. Conclusions

1. The properties of the electric train as a control object have been studied. It was shown that significant speed fluctuations and impact loads are observed during train acceleration

and stoppage. The reason for these phenomena is the presence of elasticity and gaps in the coupling devices. These loads lead to the emergence of current fluctuations (2 to 3 times exceeding the nominal rating) in the armature of the locomotive traction DC motor, which adversely affects its service life.

2. By studying mathematical description of a dynamic system consisting of an electric locomotive and a set of wagons, a model was synthesized that makes it possible to study the processes taking place in this system when parameters of motion and couplers change. Based on the mathematical dependencies obtained, an algorithm was developed that enables parametric optimization of the system. A characteristic feature of this algorithm that distinguishes it from existing ones is that the train composed of an electric locomotive and wagons is being considered taking into account available elastic couplers and gaps between the train elements. Implementation of this algorithm makes it possible to control movement of the train with minimizing collisions of the train wagons during acceleration and braking which lengthens service life of the electrical and mechanical components of the system.

3. The problem of eliminating dynamic loads caused by oscillating processes in the “locomotive-wagons” complex was solved which enabled analytical construction of an optimal control system for the material handling processes involved in operation of electric transport in conditions of iron ore mines. Application of this system makes it possible to optimally perform high-speed loading of wagons with raw materials and their unloading. It is expected that application of this approach thru shortening time spent in shifting the wagons for their loading will result in a 20 to 30 % growth of the mine transport productivity.

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DEVELOPMENT OF A METHOD FOR THE ACCELERATED TWO-STAGE SEARCH FOR AN OPTIMAL CONTROL TRAJECTORY IN PERIODICAL PROCESSES

I. Lutsenko
Doctor of Technical Sciences, Professor*
E-mail: delo-do@i.ua
O. Fomovskaya
PhD, Associate Professor, Head of Department*
I. Konokh
PhD, Associate Professor**
E-mail: icegun.ik@gmail.com
I. Oksanych
PhD, Associate Professor**
E-mail: krotuk-i-g@rambler.ru
*Department of Electronic Devices***
Department of Information and Control Systems*
***Kremenchuk Mykhailo Ostrohradskyi National University
Pershotravneva str., 20, Kremenchuk, Ukraine, 39600

Робота відноситься до області оптимізації технологічних процесів, зокрема до питань пошуку оптимальної траєкторії управління з використанням експериментального підходу. Показано, що існує клас операційних процесів, в рамках якого оптимізаційний підхід не може бути реалізований з використанням технології динамічного програмування. Запропоновано метод прискореного двоетапного визначення оптимальної траєкторії для періодичних операційних процесів

Ключові слова: оптимальна траєкторія, практичний метод оптимізації, двоетапна оптимізація, пошукова оптимізація

Работа относится к области оптимизации технологических процессов, в частности к вопросам поиска оптимальной траектории управления с использованием экспериментального подхода. Показано, что существует класс операционных процессов, в рамках которого оптимизационный подход не может быть реализован с использованием технологии динамического программирования. Предложен метод ускоренного двухэтапного определения оптимальной траектории для периодических операционных процессов

Ключевые слова: оптимальная траектория, практический метод оптимизации, двухэтапная оптимизация, поисковая оптимизация

1. Introduction

To maintain results of procedural activities of business enterprises maximally in line with their owners' goals, enterprises integrate special indicators into their control systems, the so called optimization criteria.

In theory, use of the optimization criterion capacities should ensure selection of such a mode of operation of pro-