DOI: https://doi.org/10.15276/aait.03.2020.5
UDC 622.625.28-83

COMPUTER SIMULATION OF MOVEMENT AND ACCURATE POSITIONING OF MINING ELECTRIC LOCOMOTIVES TRAINS WHEN UNLOADING CARS

Oleg N. Sinchuk[1)]
ORCID: http://orcid.org/0000-0003-2366-1920, speet@ukr.net. Scopus ID: 6602755095
Vladyslav A. Fedotoff[1)]
ORCID: http://orcid.org/0000-0001-8305-2217, fedotov@knu.edu.ua. Scopus ID: 57194700789
Albert B. Somochkyn[1)]
ORCID: https://orcid.org/0000-0002-9160-5982, a.syomochkyn@knu.edu.ua. Scopus ID: 57194694864
Igor A. Kozakevich[1)]
ORCID: http://orcid.org/0000-0002-0482-2656, kozakevych@knu.edu.ua. Scopus ID: 57193446217
Svitlana V. Somochkyna[1)]
ORCID: https://orcid.org/0000-0002-9160-5982, somochkyna@knu.edu.ua
[1)]Kryvyi Rih National University, 11, Vitaly Matusevich Str. Kryvyi Rih, 50027, Ukraine

ABSTRACT

The article discusses one of the options for solving the problem of precise control over the 14KA mine electric locomotive when rearranging cars for unloading into a tipper. VG-4.5 cars are unloaded by turning around the axis of drawbars designed with gaps of up to 0.2 m. The gaps and elastic shock-absorbers make it possible to present a mining train as a model of a chain of connected oscillators with gaps. The system of equations of such a model is very difficult to solve analytically. The authors propose to automate the operation of precise positioning of cars in the tipper using a given diagram of the electric locomotive movement. If you prevent the wheels of an electric locomotive from slipping on the rails during skidding and slipping, then, knowing instantaneous speed of the electric locomotive and the basic laws of rectilinear movement, it is easy to stop the electric locomotive in the required place. The stop of each car in the right place can be ensured by forcibly removing all the gaps. The intensity of braking of the electric locomotive should be such that the cars catch up with each other, but do not bounce back. Therefore, the locomotive at the end of travel should have a sufficient amount of kinetic energy. High rigidity of rubber shock-absorbers contributes to accuracy of car positioning in this way. To determine the required diagram for a moving mining locomotive, consisting of eight cars, a computer model is developed and implemented in the MATLAB environment. Thus, the required schedule of the electric locomotive movement determined as a result of studies and carried out on a computer model under the conditions specified in the model, enables moving the entire mining locomotive with arbitrary loading and high accuracy for unloading into the tipper. Therefore, further research should be aimed at finding ways to obtain data on the position of an electric locomotive relative to loading and unloading devices of cars, which are reliable in operation under real environmental conditions.

Keywords: Computer Model; Mining Electric Locomotive; Efficient Diagram of Movement; Accurate Positioning; Car Unloading

For citation: **Oleg N. Sinchuk, Vladyslav A. Fedotoff, Albert B Somochkyn, Igor A. Kozakevich, Svitlana V. Somochkyna. Computer Simulation of Movement and Accurate Positioning of Mining Electric Locomotives Trains when Unloading Cars.** ***Applied Aspects of Information Technology.*** **2020; Vol.3 No.3: 165–178. DOI: https://doi.org/10.15276/aait.03.2020.5**

INTRODUCTION

Biaxial electric locomotives come in the largest mass range of 20 types amounting to over 3 thousand units in total [1, 2]. They can be exploited at a variety of places – building companies, industrial enterprises, etc. However, the majority of electric locomotives of these types operate in underground mining conditions and at enterprises specialized in mining minerals, including coal, iron and manganese ore, etc. Unfortunately, currently operating biaxial electric locomotives are of an obsolete technological type, this fact being the reason for their low reliability and unsatisfactory power and electromechanical traction properties.

Yet, the latter characteristics of these locomotives including biaxial ones are determined by the type and structure of their traction electromechanical complex (TEMC).

As for biaxial electric locomotives, the TEMC structure is a system with a single power source (a traction electric grid) and two modules: a traction electromotor – a reducer – a wheel set [1, 2].

LITERATURE REVIEW

Much attention has been paid to the issues of analyzing dynamics of various locomotive types with a variety of input data, approaches applied and purposes set [3, 4], [5, 6], [7, 8], [9, 10], [11,12], [13, 14].

Electrified main railway vehicles have been studied to the fullest, their mechanical components – wheel sets, drawbars, etc. – being focused on [3, 4], [5, 6], [7, 8]. Industrial electric locomotives have been understudied to some extent. Thus, [9] contains the results of testing updated open pit electric locomotives with an asynchronous drive.

The papers [10], [15] are the closest to the research aims of the given paper.

Yet, the above-mentioned conditions, in spite of their fundamental character, cannot be applied to open pit electric locomotives because of a number of principal differences in the design of both locomotives and their cars. Concerning open pit electric locomotives, the results of the research into vibrations of trains should be noted as well as search for ways to decrease their impacts on mechanical parts of locomotives. The results of the mentioned researches deal with relevant changes in designs of the mechanical part of drawbars and other elements of open pit electric locomotives, which are or can be under the negative action of dynamic processes.

At [12] analyzes the problem of improving dynamics of open pit electric locomotives considering the factors of both iron ore and coal underground mines. Yet, TEMC dynamics is treated skin-deep here, as there are different researches aims to achieve which the authors use relevant tools.

To sum up the known research results, including the above-mentioned ones, let us indicate the fact relevant to our further research. Most of the researches concern automatic coupling devices (hitches) connecting cars with each other and the locomotive respectively. Meanwhile, the difference in the design of drawbars greatly impacts transfer processes occurring in them and the whole electromechanical system, thus determining a relevant approach to analyzing these processes in operation.

We can assume that the research results continue the studies into dynamics of electric locomotives, yet on a deeper level. The authors mean that in recent years, there have been resumed researches into designing efficient TEMCs in Ukraine [13, 14], [15]. It is essential that along with other elements of improving operation efficiency, there are studies into dynamics of open pit electric locomotives with TEMCs based on the "invertor-traction asynchronous motor" driver.

THE PURPOSE OF THE ARTICLE

The research aims to investigate into dynamics of a mining electric locomotive by using computer simulation of accelerating and precise positioning at car unloading and develop an efficient schedule of changing the speed of an electric locomotive equipped with a variable-frequency drive of the "voltage inverter-traction asynchronous motor" structure with scalar control.

Biaxial electric locomotives transport a locomotive with 8-10 cars connected by drawbars of an appropriate design [2]. The design of drawbars of operating car types (VG-4.5) provides process gaps of 0.2 m intervals as is shown in Fig. 1.

Fig. 1. **Photographic evidence of conditions of drawbars of VG-4.5 cars (for two extreme positions)**
***Source*: compiled by the author**

The total length of a train (without an electric locomotive) can vary from 39.5 m (all the drawbars are closed) to 41.5 m (all the drawbars are opened). The two-meter variation of the train length indicates the necessity to control accurate positioning of cars in unloading points. One should take into account that at Ukrainian iron ore mines, car tippers are designated for simultaneous unloading of two VG-4.5 cars.

For this reason, accuracy of positioning is determined by the size of a tipper and two cars inside the tipper. With two closed 7.9 m cars and 0.2 m gaps of car drawbars at the tipper edges, accuracy of car positioning should be no less than 0.2 m (0.1 m at each tipper edge).

Thus, the necessity of accurate positioning affects the time period of loading-unloading operations and the mode of the train movement. The basic source of inaccuracy in cars positioning during

ISSN 2617-4316 (Print)
ISSN 2663-7723 (Online)

unloading is ambiguity of current conditions of drawbars. In the last resort, the state when all the cars do not contact with each other is probable.

In this case, there are inevitable jerks caused by shocks in drawbars at selecting gaps during acceleration and deceleration. All the above-mentioned complicates control over car positioning in unloading. For this reason, when designing an effective TEMC of biaxial electric locomotives, the requirement of maintaining speed and controlling properties of the drive should be considered to provide accurate positioning.

THEORETICAL REGULATIONS AND MATHEMATICAL DESCRIPTION OF CONTROL OVER THE ELECTRIC LOCOMOTIVE TEMC

The traction electromechanical complex of a train, the diagram of which is in Fig. 2, is the object of the given research. Considering elastic properties of drawbars connecting cars, a linear chain of connected harmonic oscillators shown in Fig. 3 is relevant as a basic mathematical model [16]. Here m_0, $m_1 \ldots m_{N-1}$ are weights of material points, k_0, $k_1 \ldots k_N$ are rigidities of springs connecting material points with each other and buffer stops A and B. To approximate the calculation model to our case, we should release the end of the oscillator chain on the right by taking the condition $k_N = 0$. Accordingly, the left stop A (Fig. 4) is used as an electric locomotive here.

Considering [16], analytical solutions of equations of movement of long linear chains (N>3) can be obtained for a relatively small number of cases only (1).

As in our case, weight of cars changes in series and discretely from the beginning of the train till its end (in loading or unloading), we can draw a conclusion that the analytical solution is only for the case when car weights at the beginning/end of the train differ from those of other cars.

$$\left.\begin{array}{ll} 1. & k_0 = k_1 = \ldots = k_{N-1}, \\ & m_0 = m_1 = \ldots = m_{N-1}; \\ 2. & k_0 = k_2 = k_4 \ldots, \\ & k_1 = k_3 = k_5 \ldots, \\ & m_0 = m_1 = \ldots = m_{N-1} \\ 3. & k_0 = k_1 = \ldots = k_{N-1}, \\ & m_0 = m_2 = m_4 = \ldots, \\ & m_1 = m_3 = m_5 = \ldots; \\ 4. & k_i = k \neq k_N, i = 0,1,\ldots, N-1, \\ & m_0 = m_1 = \ldots = m_{N-1}; \\ 5. & k_i = k, i = 0,1,\ldots, N, \\ & m_i = m \neq m_{N-1}, i = 0,1,\ldots, N-2. \end{array}\right\} \quad (1)$$

For other cases of weight distribution, there is no analytical solution at all.

The model (Fig. 3) does not consider the presence of gaps between neibouring material points. In other words, the situation when a material point (in our case, a car) cannot interact with adjacent cars and be in a free movement is excluded

Assuming the above-mentioned, it is evident that the analytical solution for the system of connected oscillators with gaps is almost impossible to find. There is only a method of investigating into regularities of movement of such a system by means of computer simulation. To achieve the given goal, the model in Fig. 4 is used as the basic one, yet with gaps introduced.

.

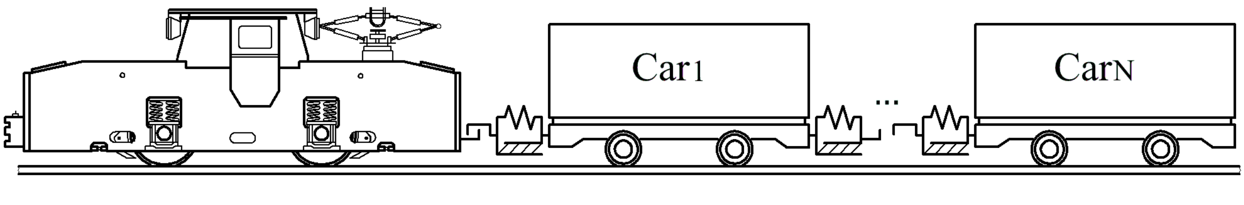


Fig. 2. **General structure of an electric locomotive and cars**
***Source*: compiled by the author**

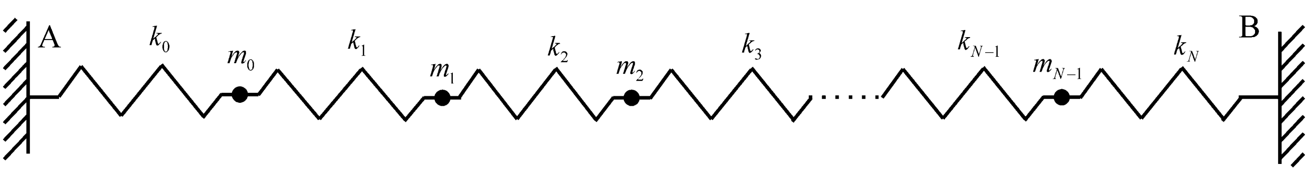


Fig. 3. **Calculation model of the mechanical part of the mining locomotive**
***Source*: compiled by the author**

According to the structure of the mining train (Fig. 2) and properties of drawbars, we apply equations describing behaviour of the mechanical system of a mining train as follows:

$$m_{ЕЛ} \cdot \frac{dV_{ЕЛ}}{dt} = F_{ДВ} - F_{CT1} - F_{У(1,2)} - F_{TP1}, \quad (2)$$

is the differential equation of the locomotive movement;

$$m_{BN} \cdot \frac{dV_{BN}}{dt} = F_{У(N,N-1)} - F_{CTN} - F_{У(N,N+1)} - F_{TPN}, \quad (3)$$

is the differential equation of the N-th cars movement

$$F_{У(1,2\ldots N-1,N)} = \begin{cases} C \cdot \left(\Delta L_N - \frac{\delta_N}{2}\right) + F_{BT1\ldots N}; \Delta L_N > \delta_N; \\ 0; \quad |\Delta L_N| \le \delta_N; \\ C \cdot \left(\Delta L_N + \frac{\delta_N}{2}\right) - F_{BT1\ldots N}; \Delta L_N < -\delta_N. \end{cases} \quad (4)$$

is the expression for modelling the elastic-viscous effort considering a gap in the N-th drawbars.
Here

$$F_{BTN} = \beta \cdot \left(V_{BN} - V_{B(N-1)}\right), \quad (5)$$

is the expression modelling viscous friction force in the N-th drawbar, β is the viscous friction factor.

$$F_{TPN} = F_{MAX} \cdot (k \cdot S_{NB} + 1)^{-1}, \quad (6)$$

is the expression modelling resistance to the shift of the N-th car with subsequent descent according the hyperbolic law

$$\frac{d\Delta L_N}{dt} = V_{BN} - V_{B(N-1)}, \quad (7)$$

is the differential equation to calculate deformation for the N-th drawbars.

Here $m_{ЕЛ}$, $m_{B1} \ldots m_{BN}$ are weights of the electric locomotive (considering reduced weights of electric motors) and cars;

C is the rigidity factor of a drawbar:

$V_{ЕЛ}, V_{1B\ldots} V_{NB}$ are linear velocities of weights of the locomotive and cars;

$F_{ДВ}$ is the moving effort affecting the mass $m_{ЕЛ}$;

F_{CT1} is static resistance affecting the locomotive;

F_{CTN} is static resistance affecting the mass m_{BN};

S_{BN} is movement of the N-th car;

k is the weight factor determining intensity of the car shift effort dropping to zero.

RESEARCH CONDITIONS

Our research is focused on a single process operation – movement of two VH-4.5 cars in the tipper as this very operation requires maximum accuracy of car positioning. Considering process requirements to unloading intensity and geometry the movement distance should be 7.9 m within 20 s. We ignore slipping of locomotive wheels along rails. Instead, we monitor dynamics of the effort in the drawbar maintained on the level of maximum shear traction force (35 kN for the 14 KA locomotive) to prevent wheel slipping.

As is known, the maximum rail tractive effort of a locomotive is calculated on the basis of the locomitive's adhesion force (14 t) and the adhison factor of the rail head with the wheel which is not exceeding $\Psi = 0.25$ for underground mines and dry rails. In other words, in our case, the sought rail tractive effort makes Fs.f. = Pc.ц.·0.25 = m_{el}·g·0.25 = 14000·9.81·0.25 = 34335 H ≅ 35 kN. Yet, one should distinguish slipping and skidding of the electric locomotive and acceleration intensity of the locomotive itself as well as a disturbing elastic effort on the locomotive drawbar. The excessive effort caused by locomotive motors and the elastic effort of the reaction on the drawbar from the stock train can equally cause skipping or slipping. Yet, in the former case, there is auxiliary circular slipping of wheels relative to rails, while in the latter – linear slipping. The specification of the 14KA electric locomotive states that nominal traction force makes 23 kN.

The factor considering resistance to linear movement of cars and the locomotive is accepted as 0.01, i.e. with the weight of the loaded car of 14200 kg, resistance to movement will make 0.01·14200 kg·9.81 m/s^2 = 1393 N.

An asynchronous motor 4A250S6Y3 with the following nominal parameters is selected to be a motor of the 14 KA locomotives:

capacity $P_н = 45$ kW;

synchronous angular velocity $\omega_н = 104,7$ s^{-1};

the efficiency factor $\eta = 0,915$;

the capacity power factor

$$\cos\varphi = 0,89;$$

the maximum torque factor

$$M_{\max} / M_н = 2,0.$$

Equivalent circuit parameters of the asynchronous motor presented in Fig. 4 $X_m = 3,8$ relative unit (r.u.),

$R_1' = 0,037$ r.u., $X_1' = 0,090$ r.u.,

$R_2'' = 0,015$ r.u., $X_2'' = 0,14$ r.u.

These parameters are given in the motor specification.

ISSN 2617-4316 (Print)
ISSN 2663-7723 (Online)

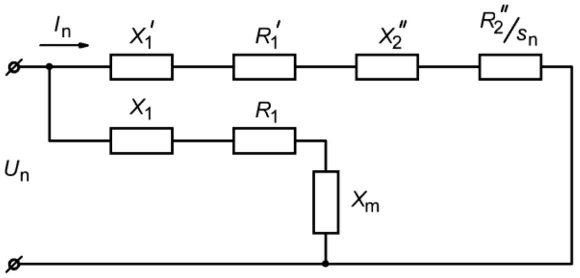


Fig. 4. **Equivalent circuit (specification) of the asynchronous motor**
***Source*: compiled by the author**

The equivalent circuit from Fig. 5 is applied to modelling in the given paper.

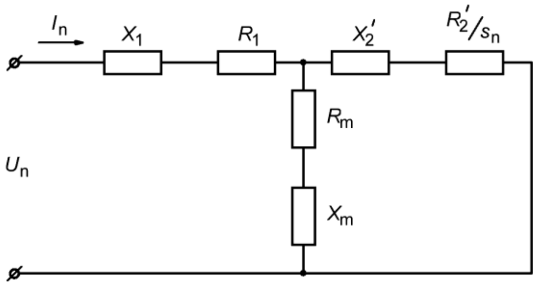


Fig. 5. **Equivalent circuit applied to modelling**
***Source*: compiled by the author**

Here are equivalent circuit parameters of Fig. 5 (in relative and physical units).

Leakage inductive reactance of the stator winding:

$$X_1 = 2X_1' \frac{X_m'}{X_m' + \sqrt{X_m'^2 + 4X_1' X_m'}} =$$

$$= 2 \cdot 0{,}09 \frac{3{,}8}{3{,}8 + \sqrt{3{,}8^2 + 4 \cdot 0{,}09 \cdot 3{,}8}} = 0{,}088 \text{ r.u.}$$

Active stator winding resistance:

$$R_1 = R' \frac{X_1}{X_1'} = 0{,}037 \frac{0{,}088}{0{,}09} = 0{,}0362 \text{ r.u.}$$

The correction factor for the L-shaped equivalent circuit:

$$b_k = \frac{X_1'}{X_1} = \frac{0{,}09}{0{,}088} = 1{,}0231 .$$

Reduced leakage inductive reactance of the rotor winding:

$$X_2' = \frac{X_2''}{b_k^2} = \frac{0{,}14}{1{,}0231^2} = 0{,}1337 \text{ r.u.}$$

Base reactance:

$$c = \frac{U_{1н}}{I_{1н}} = \frac{220}{83{,}72} = 2{,}6276 \text{ Ohm.}$$

Here are basic parameters of the equivalent circuit of the asynchronous motor in physical units.

Inductive reactance of the magnetization circuit:

$$x_m = X_m \cdot c = 3{,}8 \cdot 2{,}6276 = 9{,}985 \text{ Ohm.}$$

Leakage inductive reactance of the stator winding

$$x_1 = X_1 \cdot c = 0{,}088 \cdot 2{,}6276 = 0{,}2311 \text{ Ohm.}$$

Inductance of the magnetization branch:

$$L_m = \frac{x_m}{\omega_0} = \frac{9{,}985}{314} = 0{,}0318 \text{ H.}$$

Inductance of the stator circuit:

$$L_S = \frac{x_m + x_1}{\omega_0} = \frac{9{,}985 + 0{,}2311}{314} = 0{,}0325 \text{ H.}$$

Inductive reactance of the rotor circuit:

$$x_2' = X_2'' \cdot \frac{c}{b_k^2} = 0{,}14 \frac{2{,}6276}{1{,}0231^2} = 0{,}3514 \text{ Ohm.}$$

Active reactance of the stator winding:

$$r_1 = R_1 \cdot c = 0{,}0362 \cdot 2{,}6276 = 0{,}095 \text{ Ohm.}$$

Active reactance of the rotor winding:

$$r_2' = R_2'' \cdot \frac{c}{b_k^2} = 0{,}015 \frac{2{,}6276}{1{,}0231^2} = 0{,}0377 \text{ Ohm.}$$

Self-inductance of the rotor winding: Inductance of the rotor winding:

$$L_r = \frac{x_2'}{\omega_0} = \frac{0{,}3514}{314} = 0{,}0011 \text{ H.}$$

When simulating dynamics in AM, the following assumptions are accepted:

– the air gap is uniform;

– windings of the stator and the rotor are symmetrical and shifted by 120 degrees;

– the magnetic flow in the gap is distributed sinusoidal;

– steel saturation is ignored.

The research aims to find ways of improving accuracy of cars movement. It is topical as most of the time, a locomotive travel for short distances transporting cars for loading-unloading operations. VG-4.5 cars are unloaded in a special tipper by revolving them by 360 degrees. For this reason, drawbars are made to provide unhindered revolution of cars to any side and the gap changes within 0-0.2 m as is shown in Fig. 1.

For the rest of the model the following assumptions are taken:

– the locomotive is on the horizontal section of the way;

– distances between buffers in the expanded locomotive are equal;

– rigidity factors of rubber shock-absorbers of drawbars are equal;

– shock-absorbers are considered by Hooke's law with shock absorption [18];

– the rigidity factor of rubber shock-absorbers is 10^6 N/m,

– the vicious friction factor makes $\beta = 75000$ Ns/m for rectilinear movement. Vicious friction is considered by using (5) in the drawbar model, which is in the **Vagonetka (Car)** subsystem as is shown hereunder.

DEVELOPMENT OF A SIMULATION MODEL OF A TRACTION ELECTROMECHANICAL SYSTEM OF A BIAXIAL ELECTRIC LOCOMOTIVE

Fig. 6 presents a model of a mining locomotive with 8 cars. The motors are fed from a frequency converter with a scalar control U/f = const. Such systems are characterized by droop, which is the cause of error accumulation when determining the distance covered by the locomotive. Yet, application of an encoder on the locomotive makes the droop problem a non-issue.

The following notations are used in the model: **Signal Builder** is the signal of locomotive electrodrive operation, **Initial current limiter** is the group of blocks intended for limiting the current of locomotive motors at starting, **EMS** is the locomotive electromechanical system, **Sostav** is the structure of the model of a train of n cars, **Id** is the motor current, **Vel** is the locomotive linear velocity, **Fun** is the elastic energy of the n-th drawbar, **Vn** and **Sn** are the linear velocity and travel of the n-th car, **Zazor n** is the gap size in the n-th drawbar.

Fig. 7 presents the structure of the locomotive electromechanical system **EMS**, where **Rk** is the radius of the locomotive wheel (Rk = 0.34 m), **ired** is the reduction ratio (ired = 14.75), **massa El** is the locomotive weight (14000 kg), **g** is the free-fall acceleration, empty VG-4.5 car weight is 4200 kg, that of loaded ones is 14200 kg. The length of a car with a drawbar is 3.950 m.

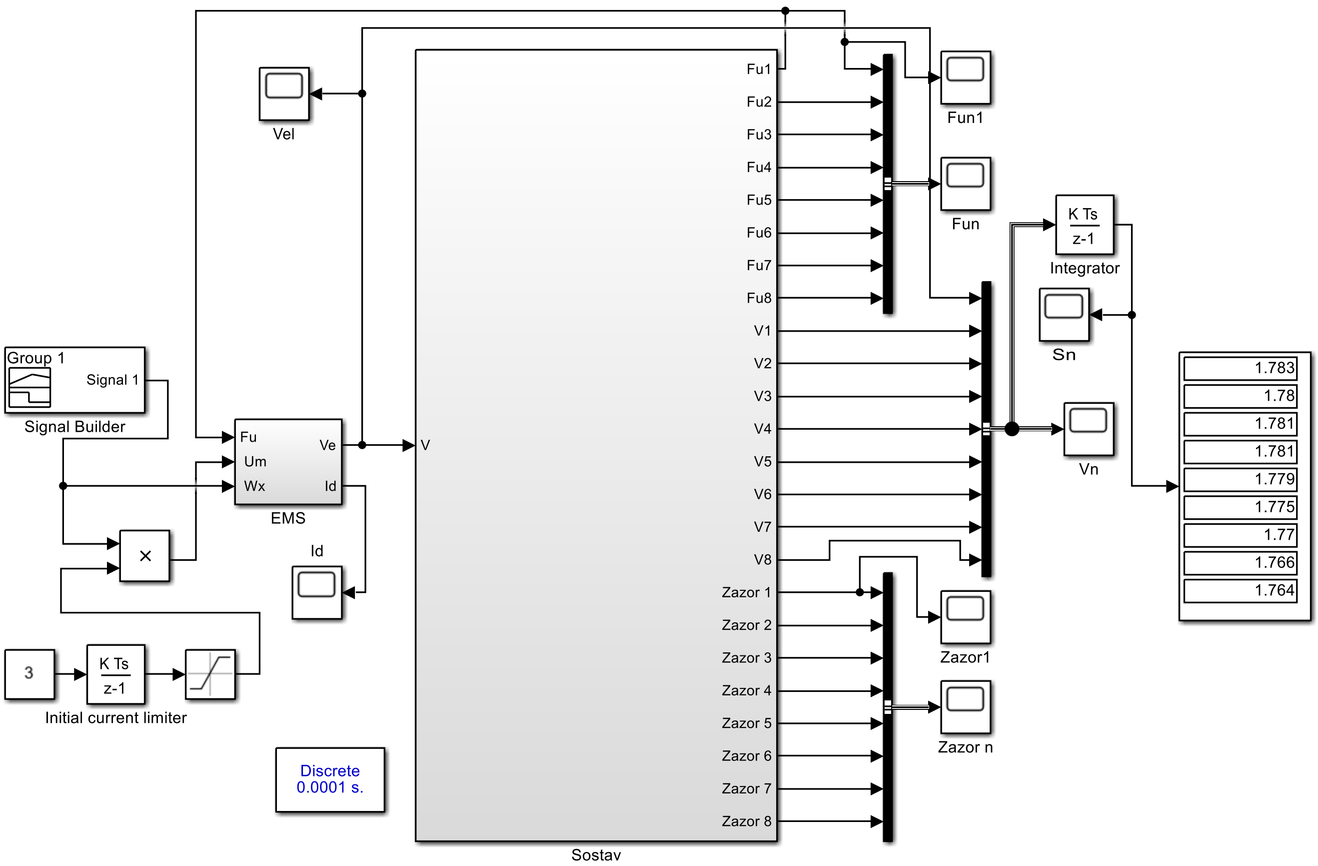


Fig. 6. **Model to study travelling and positioning of a mine electric locomotive (with 8 cars)**
***Source*: compiled by the author**

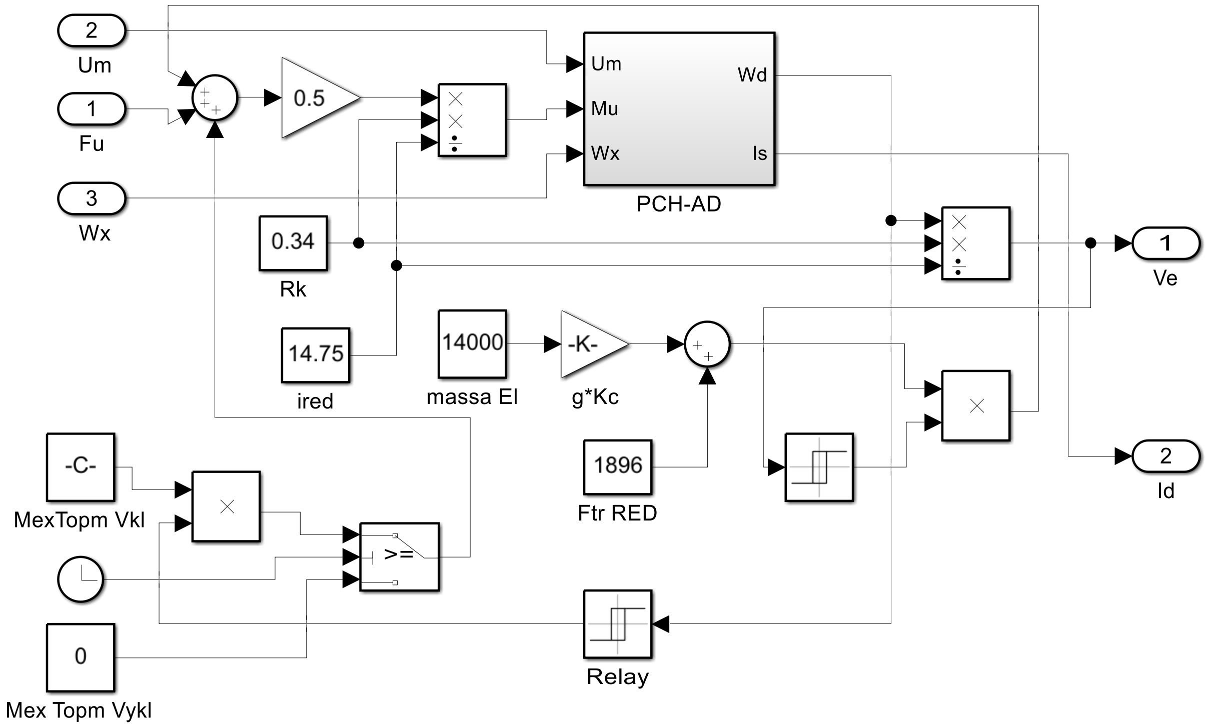


Fig. 7. **Model of the subsystem EMS (locomotive electromechanical system)**
***Source*: compiled by the author**

Relay is the block of the relay hysteresis necessary for forming the pure reactive character of loading caused by resistance to locomotive movement (bearing friction) and resistance from the reductor on the locomotive motor shaft. The factor of resistance to the rectilinear movement of the locomotive is considered in the blocks **massa El** and **g*Kc**, the output signal from which goes through the block **Relay** to the adder where it is added to elastic energy of the drawbar of the locomotive and the brake power of the drum brakes (provided by a group of blocks with **MexTormVkl** and **MexTormVkyl**). Elastic energy from the locomotive drawbar (which includes resistance to movement form cars as well) goes direct to the motor shaft considering the locomotive kinematics. When the locomotive is braking, elastic energy at its drawbar becomes active. **Ftr RED** is the resistance friction force as a response of the mechanical transmission (reductor) to the locomotive motor (1.896 kN). The coefficient 0.5 considers tha fact that the locomotive is equipped with 2 motors, i.e.
the pull-in torque of resistance is divided between them equally. **PCH-AD** is the model of a frequency electric drive (18).

Fig. 8**Ошибка! Источник ссылки не найден.** presents the structure of the subsystem **Sostav** (**Train**) with 8 cars. The model of the traction asyncronous electric drive is build on the equations (8) of the asynchronous motor [17] in the orthogonal coordinate system x, y, 0 which is fixed with respect to the feed voltage vector.

This choice is conditioned by the fact that there is no real voltage invertor in the model. The asynchronous motor model has inputs of frequency **Wx** and voltage **Um**, so we assume the motor feed voltage to be ideal and sinusoidal, this enabling its presentation as the first harmonic only.

Equations of the asynchronous motor are topologically reflected in the model of the **PCH-AD** subsystem (Fig. 9) which is in its turn integrated in the EMS model (Fig. 6). The structures of each of the subsystems **F1**, **F2**, **F3**, **F4**, **F5** and **Me** are not presented here.

$$\left.\begin{aligned}
\frac{d\psi_{x1}}{dt} &= u_{x1} - \alpha_s'\psi_{x1} + \alpha_s' k_r \psi_{x2} + \Omega_0 \psi_{y1};\\
\frac{d\psi_{y1}}{dt} &= u_{y1} - \alpha_s'\psi_{y1} + \alpha_s' k_r \psi_{y2} + \Omega_0 \psi_{x1};\\
\frac{d\psi_{x2}}{dt} &= -\alpha_s'\psi_{x2} + \alpha_r' k_s \psi_{x1} + (\Omega_0 - \Omega)\psi_{y2};\\
\frac{d\psi_{y2}}{dt} &= -\alpha_s'\psi_{y2} + \alpha_r' k_s \psi_{y1} - (\Omega_0 - \Omega)\psi_{x2};\\
M &= \frac{3}{2} p \frac{k_r}{\sigma L_s}(\psi_{x2}\psi_{y1} - \psi_{x1}\psi_{y2});\\
M - M_c(\Omega) &= \frac{J}{p}\frac{d\Omega}{dt}.
\end{aligned}\right\} \quad (8)$$

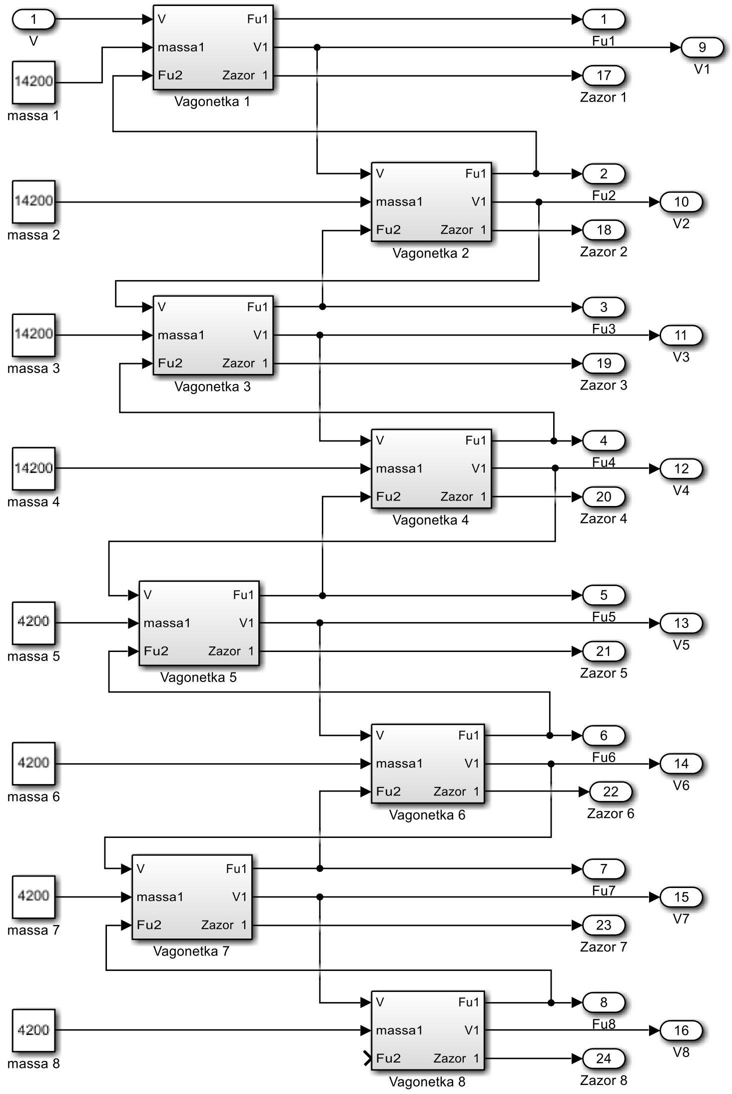


Fig. 8. **Model of the subsystem Sostav of a mining electric locomotive (with 8 cars)**
***Source*: compiled by the author**

Here, Ω_0 is cyclic frequency of stator voltage, $\frac{d\psi_{x1}}{dt}$, ψ_{x1} is the x-projection of the vector derivative and the stator linkage vector itself, $\frac{d\psi_{y1}}{dt}$, ψ_{y1} is the y-projections of the linkage vector derivative and the stator vector itself, u_{x1}, u_{y1} are the x- and y-projections of feed voltage, $\frac{d\psi_{x2}}{dt}$, ψ_{x2} are the x-projection of the vector derivative and the rotor linkage vector itself, $\frac{d\psi_{y2}}{dt}$, ψ_{y2} are the y-projection of the vector derivative and the rotor linkage vector itself, p is the number of pole pairs, $\sigma = 1 - k_r k_s = 1 - L_m^2 / L_s L_r$ is the total leakage factor, $L_s = L_m + L_1$, $L_r = L_2'$ is total inductance of the rotor and the stator, L_1, L_2', L_m are stator leakage inductance, rotor leakage inductance normalized to the stator, and magnetization circuit inductance respectively, $T_s = L_s / r_1$, $T_r = L_r / r_2'$ is the electromagnetic time constant of the stator and the rotor respectively; $\alpha_s' = 1/\sigma T_s$, $\alpha_r' = 1/\sigma T_r$ are the inverses of transient time constants (attenuation factors), $k_s = L_m / L_s$, $k_r = L_m / L_r$ are the feedback factors of the stator and the rotor respectively, Ω is electric angular velocity of the rotor, J is the inertia moment of the motor and the mechanism.

ISSN 2617-4316 (Print)
ISSN 2663-7723 (Online)

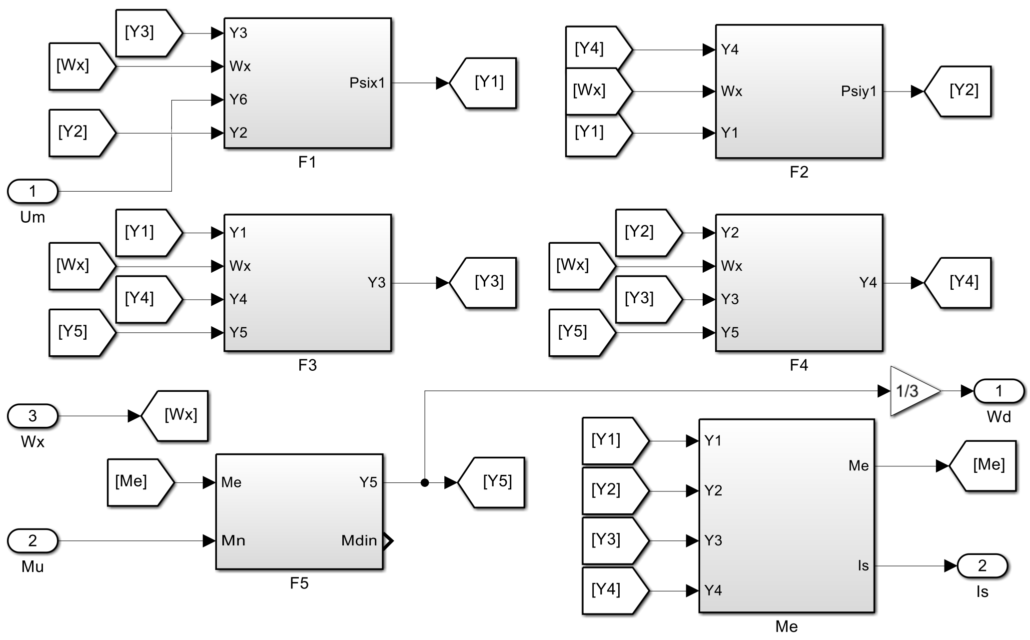


Fig. 9. **Model of the subsystem PCH-AD**
***Source*: compiled by the author**

DEVELOPMENT OF THE CONTROL ALGORITHM FOR ACCURATE POSITIONING

As considerable gaps in the train complicate analitycal solution of the task, the solution for accurate positioning of cars through shocking cars by each other is suggested. At that, this concerns both acceleration and braking. Experiments demonstrate efficiency and viability of the method.

However, this requires a special tachogram of a locomotive movement [19] of the type presented in *Fig. 9.* The tachogram is received on the model in *Fig. 7.* First, elastic energy in drawbars is limited by the marginal tractive power value at which slipping or skidding is excluded – 35 kN. The first stage of the steady motion (1-3 s) provides starting of a fully loaded and long train with a zero gap in all drawbars. This is the most difficult case. Duration of the stage is selected in the way so that all the cars start moving. On completion of the stage, transition to the second stage of the steady motion (4-10 s) is performed.

Speed values of the first and second stages of the steady motion are selected not to let elastic energy in the drawbars exceed the maximum permissible value of 35 kN (at the first speed – with the initial opened position of the drawbars, at the second speed – with the initial closed position). The second stage of the steady motion finishes when the last car starts moving. After that, the speed is smoothly increasing (10-17s) up to the moment the entire train gets the sufficient amout of kinetic energy. This kinetic energy is required for all the cars to catch up with each other, but not bounce back. The latter is achieved through limiting the maximum target speed of the train acceleration (for electric locomotives 14 КА – a little more than 0.6 m/sec).

Based on the above, the locomotive control algorithm can be outlined [19].

It is well known that any body with its known instantaneous speed moves for the distance:

$$L = \int_{0}^{t_{ел}} v_{мит} dt \quad , \qquad (9)$$

where: – L is the current travel of the locomotive;
– $t_{ел}$ is the current travel time of the locomotive;
– $v_{мит}$ is the instantaneous speed of the locomotive.

Special attention should be paid to the last part of the tachogram. Braking should be started at the moment that lets the locomotive stop in a certain place.

This moment can be easily determined by expression (9) concerning the last part of the movement tachogram as the drooping speed part is relatively straight, the travel at braking makes:

$$L_{гал} = \frac{v_{поч}\, t_{гал}}{2} = \frac{0,63 \cdot 2,5}{2} = 0,7875 \text{ m.}$$

Hence, if it is necessary to move all train units for x meters (providing x is not less than 7.9 m), acceleration and steady movement should first be performed till the moment the locomotive reaches the point x – 0,7875 m, and rectilinear braking should start from that moment.

Additional requirement in the end of acceleration is immediate use of air brake on the locomotive wheels as the cars catching each other and impacting the locomotive may move it a little and affect positioning accuracy.

The disadvantage of this method is its impossible application to moving cars for less than 7.9 m.

Thus, the car movement process is visually divided into four stages: the two-stage one (the first stage limits speed for the cases when gaps are completely opened, the second one – for the cases when gaps are completely closed) acceleration for limiting tractive power by the rail tractive effort, further acceleration to the initial braking speed and braking until stop.

It is obvious that to implement the set special movement tachogram, an electric drive system able to provide high accuracy of the tachogram tasks fulfillment should be applied. When using this tachogram in the model, the following diagrams of the transition process of movement of the locomotive with fully loaded cars for 7.9 m (i.e. for the length of two cars) are obtained (Fig. 10, Fig. 11, Fig. 12, Fig. 13, Fig. 14, Fig. 15 & Fig. 16).

Fig. 10 presents the diagram of locomotive movement and it differs slightly in the form from the set movement tachogram (small fluctuations of speed at the first acceleration stage can be observed).

Fig. 11 shows speed of all cars and the locomotive. Speed of the cars is seen to fluctuate to a varying degree around the locomotive speed.

Fig. 12 shows that each zero gap makes still moving cars travel a longer and longer distance.

Fig. 13 shows elastic energy at each drawbar.

Fig. 14, Fig. 15 & Fig. 16 demonstrate that for both initially closed and initially opened drawbars elastic energy never exceeds the maximum permissible value of 35 kN, thus preventing slipping and skidding.

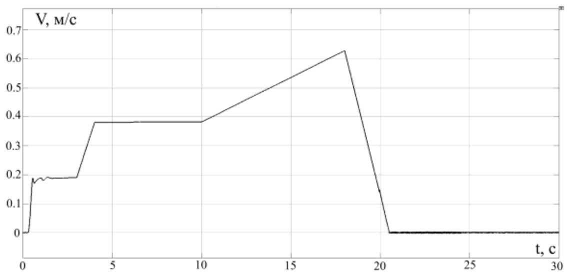


Fig. 10. **The locomotive movement diagram**

***Source*: compiled by the author**

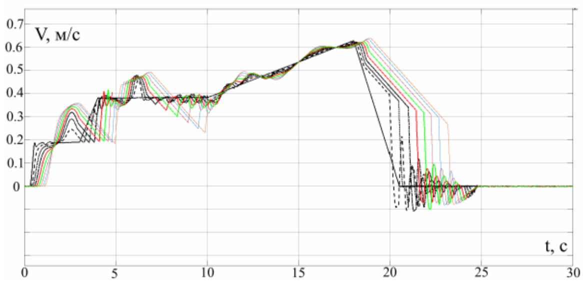


Fig. 11. **Linear speed of train units**

***Source*: compiled by the author**

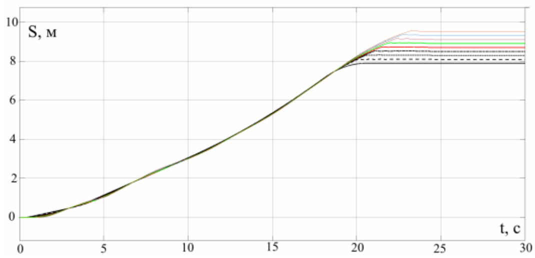


Fig. 12. **Travel of the locomotive and 8 cars**

***Source*: compiled by the author**

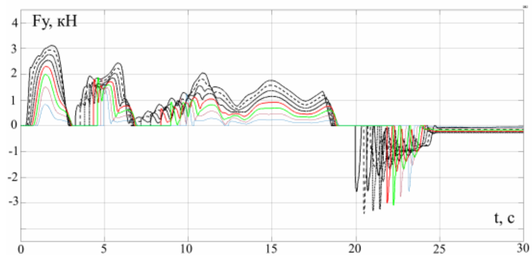


Fig. 13. **Elastic energy in drawbar**

***Source*: compiled by the author**

ISSN 2617-4316 (Print)
ISSN 2663-7723 (Online)

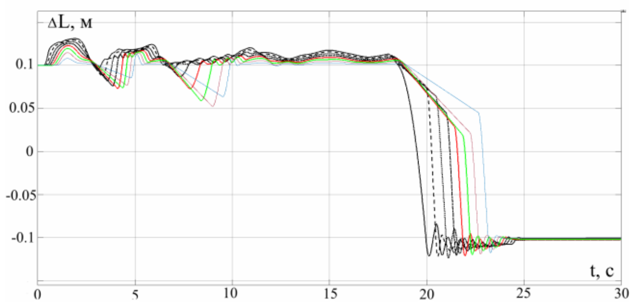


Fig. 14. **Values of gaps in drawbars of the mining train(opened initial state)**
***Source*: compiled by the author**

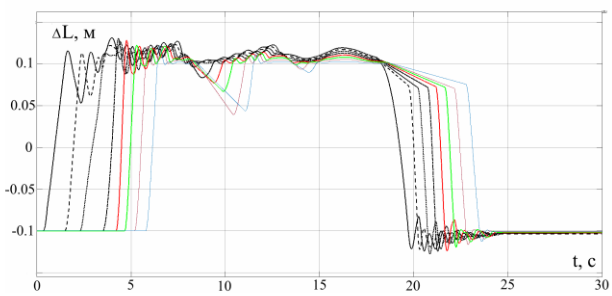
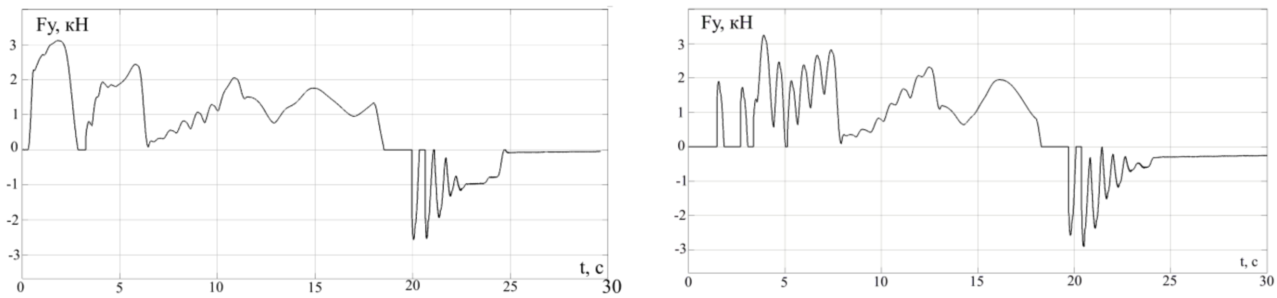


Fig. 15. **Sizes of gaps in drawbars of the mining train (closed initial state)**
***Source*: compiled by the author**



a b

Fig. 16. **The value of elastic energy of a locomotive drawbar: a) opened initial state of the gap; b) closed initial state of the gap**
***Source*: compiled by the author**

CONCLUSIONS

1. The paper substantiates possibility of building a strictly determined automated system for controlling accurate movement of cars applying the set movement tachogram with the initial state of a train being arbitrary, i.e. drawbars may be in an arbitrary initial state.

2. One of possible solutions of the precise car positioning task consists in stopping all the cars by their "impacting softly" each other. For this, appropriate rigidity of speed characteristics for the locomotive TEMC should be provided and the maximum rail tractive effort value should not be exceeded. Due to their small deformation, rigid dampers enable accurate car positioning.

3. The performed modelling proves operability of the control algorithm, which provides for opening or closing gaps in the kinematic circuit that enables unambiguous determination of the distance from a locomotive to a particular car (or a pair of cars). If there is information available on the locomotive position in relation to car loading-unloading equipment, the algorithms tested on the model can be implemented.

4. Considering poor accuracy of standard equipment of the locomotive, to enhance accuracy of the obtained data on locomotive movement, a spring-loaded roller with an encoder should be mounted on it. The roller does not slip on the rails. Data from the encoder will enable controlling slipping and skidding modes of locomotives to make the set movement tachogram more precise. No feedback sensors are required on cars, this being a considerable advantage of the suggested automation system.

5. The modeling results prove adequacy of the mathematical and software model. That is why; the suggested model may be a basis for further development of enhanced systems of controlling the locomotive TEMC.

REFERENCES

1. Butt, Yu. D., Gryadushchiy, V. B. & Debelyi, V. L. "Mining Locomotive and Railway Vehicles" Donetsk: Ukraine (in Russian). 2013; Vol.1: 480 p.

2. Sinchuk, I. O., Guzov, E. S., Debelyi, V. L. & Debely, L. L. "Mining Electric Locomotive Vehicles. Theory, Designs, Electric Equipment: Textbook". Sinchuk, O. N. (ed.) (in Russian) Krivoi Rog: Donetsk: Ukraine. *Publ. ChP Shcherbatyh A.V.* 2015. 428 p

3. Juan Manuel Cano Sanchiz. “Railways and Mining: the Role of the Train in the Exploitation of the CERRO MURIANO Mine”. Córdoba: Spain. 2014. p. 128–148. DOI: https://doi.org/10.1179/0309072813Z.00000000022.

4. Dovzhenko, V. P., Vakulchik, V. G. & Debelyiy, V. L. “Transistor Modules for Controlling Mining Locomotive Drives” (in Russian). *Publ. Ugol Ukrainy*. 2003. p.16–18.

5. Naysh, N. M., Beletskiy, Yu. V. & Maslov, A. V. “Modern Railway Transport” (in Russian). *Journal of East-Ukrainian National University named after Volodymyr Dal*. Severodonetsk: Ukraine. 2013; No.18 (207): 79–84.

6. Molatefi, H., Ferestade, I. & Taefi Aghdam N. Dynamic. “Modeling and Active Control of Slip Phenomenon in a Fouraxle Locomotive”. *International Journal of Railway Rasearch, IJRARE.* Tehran: Iran. 2019; No. 6(2): 153–162. URL: http://ijrare.iust.ac.ir/article-1-233-en.html.

7. Jiateng Yin, Tao Tang, Lixing Yang, Jing Xun, Yeran Huang & Ziyou Gao. “State Key Laboratory of Rail Traffic Control & Safety. Research and development of automatic train operation for railway transportation systems”. *Beijing Jiaotong University*. Beijing: 100044, China. Transportation Research Part C: *Publ. Emerging Technologies*. 2017; Vol. 85: 548–572. DOI: https://doi.org/10.1016/j.trc.2017.09.009.

8. Gerben M. Scheepmakerac, Helen Y. Willeboordsed, Jan H. Hoogenraadd, Ralph S. Luijtb, Rob M. & P.Goverdec. “Comparing Train Driving Strategies on Multiple Key Performance Indicators”. *Journal of Rail Transport Planning & Management.* 2020; Vol. 13 100163: 1–26. DOI: https://doi.org/10.1016/j.jrtpm.2019.100163.

9. Pivnev, V. A., German, A. G., Leontev, V. M. & Chernigov, V. M. “Industrial Testing of Electric Locomotives with Asynchronous Drives at the Integrated Kirov Mine the PJSC “Apatite”” (in Russian). *Journal Mining equipment and electromechanics*. 2006; 3: 37–38

10. Jon Otegui, Alfonso Bahillo, Iban Lopetegi & Luis Enrique Díez. “A Survey of Train Positioning Solutions”. University of Deusto. Bilbao, Spain: *IEEE Sensors Journal*. 2017; Vol.17 Issue 20: 6788–6797. DOI: https://doi.org/10.1109/JSEN.2017.2747137.

11. Markus Dammers, Gregor Brudek, Matthias Pütz & Andreas Merchiers. “Opportunities and Challenges of Rail Haulage Systems in Current Mining Operations”. *Journal Engineering & Mining.* Jacksonville. USA. 2016. p. 42–47.

12. Klepikov, V. B. “Dynamics of Electromechanical Systems with Nonlinear Friction: Monograph” (in Russian). Pidruchnik NTU. “KhPI”. Kharkov: Ukraine. 2014. 408 p.

13. Sinchuk, O. N., Sinchuk, I. O. & Boyko, S. N. “Power Control System at Mining Enterprises Aimed at Increasing Energy Efficiency of Iron ore Mining”(in Russian). *Journal Technical electrodynamics*. Kyiv: Ukraine. 2016. p. 60–62

14. Chernaya, V. O. “Analysis of Monitoring Systems Mine Transport and Methods Information Transfer”. Proceedings of XI International Scientific-technical Conference of Young Scholars and Specialists. *Electromechanical and Power Systems, Methods of Simulation and Optimization.* KrNU. Kremenchuk: Ukraine. 2013. 130 p.

15. Shan, W., Wei, L. & Chen, K. “Longitudinal Train Dynamics of Electric Multiple Units under Rescue”. *Journal of Modern Transportation*.2017; Vol.25:250–260. DOI: https://doi.org/10.1007/s40534-017-0142-x.

16. Porshnev, S. V. “Computer Simulation of Physical Processes in MATLAB” (in Russian). *Publ. Goryachaya liniya-Telekom. Hot line–Telecom.* 2003.

17. German-Galkin, S. G. “Computer Simulation of Semiconductive Systems in Matlab 6.0: Teaching Manual” (in Russian). *Publ. KORONA prints.* Saint Petersburg: Russian Federation. 2001.

18. Syomochkin, A. B. & Fedotov, V. O. “Control over Traction Electromechanical Complex of a Mining Locomotive with Open System AVI-AM”. *Bulletin. Problems of energy and resource saving in electrical systems. Science, education and practice* (in Russian). KrNU. Kremenchuk: Ukraine. 2018; 5: 85–88.

19. Sinchuk, I. O., Syomochkin, A. B. & Fedotov, V. A. “On Principles of Minimum Colliding and Maximum Accurate Control Over Moving Cars of Mining Locomotives” (in Russian). *Journal of Kryvyi Rih National University*. Kryvyi Rih: Ukraine. 2016; 42: 83–87.

20. Yu Jiang, Zhixiong Li, Guang Yang, Yuelei Zhang & Xiaogang Zhang. “Recent Progress on Smart Mining in China Unmanned Electric Locomotive”. *Advances in Mechanical Engineering*.2017;Vol.9(3): 1–10. DOI: https://doi.org/10.1177/1687814017695045.

Conflicts of Interest: the authors declare no conflict of interest

Received. 03.08.2020
Received after revision 16.09. 2020
Accepted 20.09 . 2020

DOI: https://doi.org/10.15276/aait.03.2020.5
УДК 622.625.28-83

КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ПРОЦЕСІВ РУХУ ТА ТОЧНОГО ПОЗИЦІОНУВАННЯ ШАХТНОГО ЕЛЕКТРОПОЇЗДІВ ПРИ РОЗВАНТАЖЕННІ ВАГОНЕТОК

Олег Миколайович Сінчук[1)]
ORCID: http://orcid.org/0000-0002-7621-9979, speet@ukr.net. Scopus ID: 6602755095
Владислав Олександрович Федотов[1)]
ORCID: http://orcid.org/0000-0002-6536-5591, fedotov@knu.edu.ua. Scopus ID: 57194700789
Альберт Борисович Сьомочкин[1)]
ORCID: http://orcid.org/0000-0002-3592-7899, a.syomochkyn@knu.edu.ua. Scopus ID: 57194694864[1)]
Ігор А. Козакевич[1)]
ORCID: http://orcid.org/0000-0003-4472-4783, kozakevych@knu.edu.ua. Scopus ID: 57193446217
Світлана В. Сьомочкина[1)]
ORCID: http://orcid.org/0000-0001-9809-0048, somochkyna@knu.edu.ua
[1)]Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027,Україна

АНОТАЦІЯ

У статті розглядається один з варіантів вирішення завдання точного управління шахтним електровозом 14КА при перестановці вагонеток під розвантаження в перекидач. Вагонетки типу ВГ-4.5 розвантажуються переворотом навколо осі зчіпних пристроїв, і в конструкції зчіпних пристроїв є зазори до 20 см. Ці зазори разом з пружними амортизаторами дозволяють уявити шахтний склад як модель у вигляді ланцюжка зв'язаних осциляторів з зазорами. Систему рівнянь такої системи аналітично вирішити досить важко. Авторами пропонується автоматизувати операцію точного позиціонування вагонеток в перекидачі за допомогою заданої тахограми руху електровоза. Якщо запобігати прослизанню коліс електровоза об рейки при юзі і буксовании, то, знаючи миттєву швидкість електровоза і основні закони прямолінійного руху, неважко зупинити електровоз в потрібному місці. Зупинка ж кожної вагонетки в потрібному місці можна забезпечити, примусово вибравши всі зазори. Інтенсивність гальмування електровоза повинна *бути такою, щоб* вагонетки наздоганяли один одного, але не відскакували назад. Тому поїзд до кінця переміщення повинен мати достатню кількість кінетичної енергії. Точності позиціювання вагонеток таким способом сприяє висока жорсткість гумових амортизаторів. Для визначення необхідної тахограми руху шахтного поїзда, що складається з електровоза і восьми вагонеток, розроблена комп'ютерна модель, реалізована в середовищі МАТЛАБ. Таким чином, в результаті досліджень, проведеної на комп'ютерній моделі, визначений необхідний графік руху електропоїзда дозволяє при заданих в моделі умовах здійснити переміщення всього шахтного поїзда з довільним завантаженням і високою точністю під розвантаження до перекидачу. Тому подальші дослідження повинні бути спрямовані на пошук надійних в роботі при реальних умовах навколишнього середовища способів отримання інформації про стан електровоза щодо пристроїв завантаження і вивантаження вагонеток.

Ключові слова: шахтний електровоз; задана тахограма руху; точне позиціонування вагонетки; розвантаження в перекидувачі

DOI: https://doi.org/10.15276/aait.03.2020.5
УДК 622.625.28-83

КОМПЬЮТЕРНОЕ МОДЕЛИРОВАНИЕ ПРОЦЕССОВ ДВИЖЕНИЯ И ТОЧНОГО ПОЗИЦИОНИРОВАНИЯ ШАХТНОГО ЭЛЕКТРОПОЕЗДА ПРИ РАЗГРУЗКЕ ВАГОНЕТОК

Олег Николаевич Синчук[1)]
ORCID: http://orcid.org/0000-0002-7621-9979, speet@ukr.net. Scopus ID: 6602755095
Владислав Александрович Федотов[1)]
ORCID: http://orcid.org/0000-0002-6536-5591, fedotov@knu.edu.ua. Scopus ID: 57194700789
Альберт Б. Сёмочкин[1)]
ORCID: http://orcid.org/0000-0002-3592-7899, a.syomochkyn@knu.edu.ua. Scopus ID: 57194694864
Игорь А. Козакевич[1)]
ORCID: http://orcid.org/0000-0003-4472-4783, kozakevych@knu.edu.ua. Scopus ID: 57193446217
Светлана В. Сёмочкина[1)]
ORCID: http://orcid.org/0000-0001-9809-0048, somochkyna@knu.edu.ua
[1)]Криворожский национальный университет, ул. Виталия Матусевича, 11. Кривой Рог, 50027, Украина

АННОТАЦИЯ

В статье рассматривается один из вариантов решения задачи точного управления шахтным электровозом 14КА при перестановке вагонеток под разгрузку в опрокидыватель. Вагонетки типа ВГ-4.5 разгружаются вращением вокруг оси сцепных устройств и в конструкции сцепных устройств имеются зазоры до 20 см. Эти зазоры вместе с упругими амортизаторами позволяют представить шахтный состав как модель в виде цепочки связанных осцилляторов с зазорами. Систему уравнений такой системы аналитически решить весьма затруднительно. Авторами предлагается автоматизировать операцию точного позиционирования вагонеток в опрокидывателе при помощи заданной тахограммы движения электровоза. Если предотвратить проскальзывание колес электровоза о рельсы при юзе и буксовании, то, зная мгновенную скорость электровоза и основные законы прямолинейного движения, нетрудно остановить электровоз в нужном месте. Остановка вагонеток с требуемой точностью в существующей системе управления реализуется путем принудительного устранения зазоров в сцепных устройствах. Интенсивность торможения электровоза должна быть такой, чтобы вагонетки догоняли друг друга, но не отскакивали назад. Поэтому поезд к концу перемещения должен обладать достаточным, но не чрезмерным количеством кинетической энергии. Точности позиционирования вагонеток таким способом способствует высокая жесткость резиновых амортизаторов. Для определения рациональной тахограммы движения шахтного поезда, состоящего из электровоза и восьми вагонеток, разработана компьютерная модель, реализованная в среде МАТЛАБ. Таким образом, определенный в результате исследований, проведенных на компьютерной модели, требуемый график движения электропоезда позволяет при заданных в модели условиях осуществить перемещение всего шахтного поезда с произвольной загрузкой и высокой точностью под разгрузку к опрокидывателю. Поэтому дальнейшие исследования должны быть направлены на поиск надежных в работе при реальных условиях окружающей среды способов получения информации о положении электровоза относительно устройств загрузки и выгрузки вагонеток.

Ключевые слова: компьютерная модель; шахтный электропоезд; рациональная тахограмма движения; точное позиционирование; разгрузка вагонеток

ABOUT THE AUTHORS

Oleg N. Sinchuk – Dr. Sci. (Eng), Prof. of the Automated Electromechanical Systems in the Industry and VehiclesDepartment, Kryvyi Rih National University, 11, Vitaly Matusevich Str. Kryvyi Rih, 50027, Ukraine
speet@ukr.net. ORCID: http://orcid.org/0000-0003-2366-1920. Scopus ID: 6602755095

Олег Миколайович Сінчук – д-р техніч. наук, професор, завідувач кафедри Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027,Україна

Vladyslav O. Fedotoff – Cand. Sci. (Eng.), Associate Prof. of the Automated Electromechanical Systems in the Industry and Vehicles Department, Kryvyi Rih National University, 11, Vitaly Matusevich Str. Kryvyi Rih, 50027, Ukraine
fedotov@knu.edu.ua. ORCID: http://orcid.org/0000-0002-6536-5591

Владислав Олександрович Федотов – канд. техніч. наук, доцент каф. Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027,Україна

Albert B. Somochkyn – Cand. Sci. (Eng.), Associate Prof. of the Automated Electromechanical Systems in the Industry and Vehicles Department, Kryvyi Rih National University, 11, Vitaly Matusevich Str. Kryvyi Rih, 50027, Ukraine
a.syomochkyn@knu.edu.ua. ORCID: http://orcid.org/0000-0002-3592-7899.

Альберт Борисович Сьомочкин – канд. техніч. наук, доц. каф. Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027, Україна

Igor A. **Kozakevich –** Cand. Sci. (Eng.), Associate Prof. of the Automated Electromechanical Systems in the Industry and Vehicles Department, Kryvyi Rih National University, 11, Vitaly Matusevich Str. Kryvyi Rih, 50027, Ukraine
kozakevych@knu.edu.ua. ORCID: http://orcid.org/0000-0003-4472-4783.

Ігор Аркадійович Козакевич – канд. техніч. наук, доц. каф. Автоматизованих електромеханічних систем в промисловості та транспорті. Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027,Україна

Svitlana V. Somochkyna – Cand. Sci. (Eng.), Associate Prof. of the Department of Computer Systems and Networks, Kryvyi Rih National University, 11, Vitaly Matusevich Str. Kryvyi Rih, 50027, Ukraine
somochkyna@knu.edu.ua. ORCID: http://orcid.org/0000-0001-9809-0048.

Світлана Володимирівна Сьомочкина – канд. техніч. наук, доц. каф. Комп’ютерних систем та мереж. Криворізький національний університет, вул. Віталія Матусевича, 11. Кривий Ріг, 50027,Україна

ISSN 2617-4316 (Print)
ISSN 2663-7723 (Online)