electric locomotive; asynchronous traction drive;
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STUDY OF THE ASYNCHRONOUS TRACTION DRIVE'S OPERATING MODES BY COMPUTER SIMULATION
PART 1: PROBLEM FORMULATION AND COMPUTER MODEL

Summary. In this paper, the problems arising from the design of electric locomotives with asynchronous traction drive (with three-phase AC induction motors) are considered as including the debugging of control algorithms. The electrical circuit provides the individual (by axle) control of traction motors. This allows realizing the operational disconnection/connection of one or more axles in the automatic mode, with account of actual load. In perspective, the evaluation of locomotive's energy efficiency at the realization of various control algorithms must be obtained. Another objective is to research the dynamic processes in various modes of the electric locomotive operation (start and acceleration, traction regime, coasting movement, wheel-slide protection, etc). To solve these problems, a complex computer model based on the representation of AC traction drive as controlled electromechanical system, is developed in Part 1. The description of methods applied in modeling of traction drive elements (traction motors, power converters, control systems), as well as of mechanical part and of "wheel-rail" contact, is given. The control system provides the individual control of the traction motors. Part 2 of the paper focuses on the results of dynamic processes modeling in various modes of electric locomotive operation.

ИССЛЕДОВАНИЕ РЕЖИМОВ РАБОТЫ АСИНХРОННОГО ТЯГОВОГО ПРИВОДА МЕТОДАМИ КОМПЬЮТЕРНОГО МОДЕЛИРОВАНИЯ
ЧАСТЬ 1: ПОСТАНОВКА ЗАДАЧИ И КОМПЬЮТЕРНАЯ МОДЕЛЬ

Аннотация. В настоящей статье, рассматриваются проблемы, возникающие при проектировании электровозов с асинхронным тяговым приводом (АТП), в том числе отладка алгоритмов управления. В электрической схеме предусмотрено индивидуальное (поосное) регулирование тяговых двигателей, что дает возможность оперативного отключения/подключения одной или нескольких осей в автоматическом режиме, с учетом реальной нагрузки. В перспективе, должна быть получена оценка энергетической эффективности электровоза при реализации различных алгоритмов управления. Другой целью исследования является изучение динамических процессов в различных режимах работы электровоза (трогание с места, тяга, выбег, подавление боксования и т.д.). Для решения указанных проблем, в части 1 разработана комплексная компьютерная модель, основанная на представлении АТП как управляемой электромеханической системы. Приводится описание методов, использованных при моделировании элементов тягового привода (тяговых двигателей, силовых преобразователей, систем управления), также как механической части и контакта «колесо-рельс». Система управления обеспечивает индивидуальное регулирование тяговых двигателей. В части 2 сосредоточены результаты моделирования динамических процессов в различных режимах работы электровоза.

1. INTRODUCTION

Currently, the improvement of electric locomotive's traction properties occurs due to using of brushless traction motors and improving their control systems.

The use of brushless traction motors (three-phase AC induction motors) complicates the system of electric power converting and is characterized by a high degree of interaction and mutual influence of processes between the elements of the traction drive. This requires in-depth research at the design stage, it is necessary to study the interconnected electro-mechanical processes arising at various modes of functioning, and to find optimal control algorithms [1].

One of the perspective methods for studying processes in traction drive is the use of mathematical modeling methods, for example, [2]. Especially effective is the use of computer models in the design stage, as in the early stages of a new electric locomotive design allows to get answers to many questions, not making complex and costly prototypes [3-5]. We draw attention to the fact that in the cited papers and in this article, the full-size model of a locomotive having multi-motors traction drive is considered. The main feature of this article is that the electrical circuit provides the individual (by axle) control of traction motors. It allows in increasing its energy efficiency by automatic disconnection/connection of one or more axles.

The use of computer models of electromechanical processes in traction drive takes on particular significance during the control system elaboration. This allows forming its structure and parameters in parallel with the development of the rest of the equipment. Thus, there is an opportunity to take into consideration the revealed features of the traction drive functioning during the designing of its individual elements or entire subsystems.

2. PROBLEM FORMULATION

Structure and regulatory principles of traction drive do not differ if you use one or other type of traction motor. This is why the questions of developing the mathematical model of traction drive will be considered further by the example of the traction drive with asynchronous traction motors (ATM) as it is the most common [6] at the present time.

Mathematical modeling of the processes occurring in asynchronous traction drive (ATD) in dynamic modes is associated with a number of features:

• ATD is a complex dynamic system. It is composed of interacting subsystems – electrical, mechanical and control. In addition, the capacity of traction substationis comparable to the one of electric locomotive, so for adequate representation of the processes they need to be co-simulation;

• the range of rotor speed variation is quite wide – from zero to several thousand rpm;

• the power semiconductor devices in circuits of static converters have nonlinear characteristics;

• the ATM are highly-used machines, during the study of processes in them, the saturation of the magnetic circuit must be taken into account;

• the speed of the processes occurring in the individual subsystems of the traction drive differs by several orders of magnitude;

• the load of traction drive is determined by the creep force (adhesion) in "wheel-rail" contact, which has essentially nonlinear dependence on the speed of wheel slip and have the hysteresis;

• when designing the traction drive, the various structures of the electric energy converters with different algorithms and laws of control can be used; moreover, it is possible to use different versions of the mechanical parts.

When analyzing the complex systems with nonlinear characteristics and load, traditionally the simulation methods are used, allowing to investigate the existing or newly created system options. This is particularly important during the design stage. Therefore, the computer model must be complete in the sense of solving the principal problems, convenient to use, reliable and adaptive.

3. THE MATHEMATICAL MODEL OF ELECTRIC LOCOMOTIVE WITH ASYNCHRONOUS TRACTION DRIVE

3.1. The mathematical model structure

The complex computer model of ATD as controlled electromechanical system (CES), presented in this paper, is a further development of previously created models [3-5].

The electric locomotive is considered as a CES which includes the mechanical part as multibody system, the electric part (energy conversion devices and traction motors) and the control system (control algorithms and their realization).

There are direct and feedback communications between the processes in the mechanical and electric parts. Values of electromagnetic torque at the traction motor shafts are included in the right-hand side of the motion equations; values of wheelset angular velocities obtained from the mechanical part are included into the electromagnetic equations [7].

Fig. 1 shows the structure of six-axle locomotive with individual control of traction motors (individual axle drive) as CES. The structure of the electrical part includes human interface, main locomotive control system, electric power conversion devices: main transformer, 4q-S converter, DC-link, self-commutated voltage inverter (VI), ATM. The structure of the mechanical part includes car body, three bogies and suspension elements.

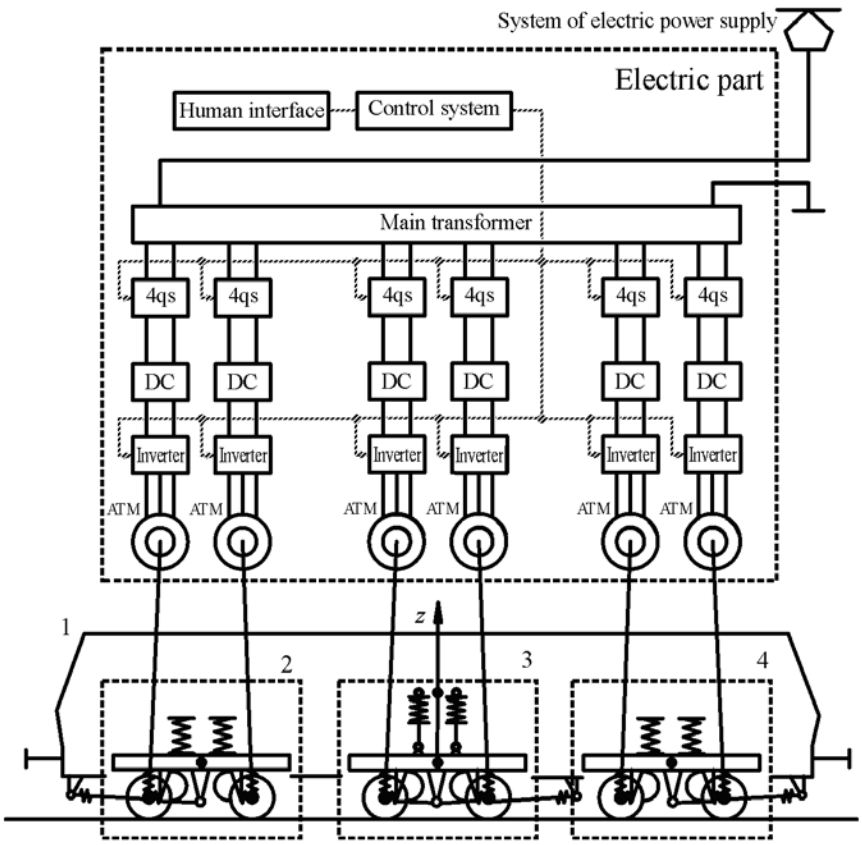


Fig. 1. Electric locomotive as controlled electro-mechanical system: 1 – car body; 2, 3, 4 – bogies
Рис. 1. Электровоз как управляемая электромеханическая система: 1 – кузов; 2, 3, 4 – тележки

The processes in separate subsystems and elements of the locomotive are modeled using various methods. The authors would like to emphasize that their main aim was to develop an adequate model of the rather complicated CES based on well-known modern methods and approaches.

3.2. The modeling of the asynchronous traction motor

The transformation of electromagnetic energy into mechanical energy is carried out in the ATM. The ATM is a key element of the traction drive, the parameters and design features of the motor have a direct impact on the technique and economic characteristics of the electric locomotive.

The model is based on the presentation of ATM as a system of magnet-connected contours. Determination of the motor's magnetic system parameters is carried out by the field theory methods (using finite-element method). In the mathematical model, the saturation and nonhomogeneity of the active layer of the stator and rotor, as well as the displacement of current in the stator and rotor windings, are taken into consideration [9]. This enables us to analyze various modes including stopping/starting and running with at a low speed.

The equation that describes the electromagnetic processes in the contours can be written as follows:

$$\left[\dot{\Psi}\right]=\left[U\right]-\left[R\right]\times\left[I\right], \quad (1)$$

where: $\left[\Psi\right]$ is the contour flux linkage's vector; $\left[U\right]$, $\left[I\right]$ are the vectors of the contour voltages and currents; $\left[R\right]$ is the diagonal matrix of the contour active resistance.

Connection between the flux linkage and currents in contours is defined by the algebraic equations

$$\left[\Psi\right]=\left[M\right]\times\left[I\right], \quad (2)$$

where: $\left[M\right]$ is the matrix of the contour internal and mutual inductances.

Equations (1) – (2) are DAE describing the processes in the system comprising of magnetically connected contours. The state of each contour is characterized by two values: flux linkage and current.

The contour flux linkage and inductances matrix are calculated using field theory methods. According to the conventional approach of the electrical machine theory, the ATM's magnetic field is considered to be plane-parallel. The magnetic system of the electric machine is peculiar in having a complex configuration, large number of areas with current and air-gap clearance. Besides, the magnetic system is closed and it can be assumed that the field is negligible in the outside area. The finite-element method proves to be efficient in such a case.

The developed model can adequately represent the processes in ATM in steady state and transient conditions, including low-speed and emergency modes.

To analyze the processes in ATM at angular speeds above 10-15% of the nominal, it is expedient to use the models based on the Park-Gorev equations [9].

3.3. The modeling of the processes in energy conversion system

The energy conversion system provides the operation of the electric locomotive by feeding from catenary network of 3 kV DC and of 25 kV, 50 Hz AC.

The energy conversion system is modeled as an electric circuit, it consists of a main transformer, input converters (4q-S), a DC link and self-commutated voltage inverters (VI) for feeding the traction motors [6]. The principal scheme of the power circuit of an electric locomotive that feeds from the AC network is shown in Fig. 1.

The 4q-S converters connected to the traction transformer windings function in parallel to the general filter of the DC link. The inverter works as the filter load and feeds the ATM. The processes in the electric traction drive of all three bogies under the condition of feeding from the main transformer are considered in the model.

The locomotive is equipped with three power converters; each one feed the motors of two-axle bogie. Each power converter includes 4qs-converters, DC link and VI. The individual control of traction motors (individual axle drive) was realized (see Fig. 1).

The processes in the power circuits are described by the automatically generated differential-algebraic equations derived on Kirchhoff's laws base:

$$f\left(\boldsymbol{x}_{n+1}, \dot{\boldsymbol{x}}_{n+1}, t_{n+1}\right) = 0\,, \tag{3}$$

where: $\boldsymbol{x}_{n+1}$ is the state variable of the electric circuit (currents through inductances, voltage at condensers) at time point t_{n+1}. The solution of Eq. (3) is carried out with the backward differentia tion formula.

The locomotive traction characteristics are mostly defined by the structure, principles and algorithms of the traction drive control system. A number of specific demands is usual for the control system of the ATM. The regulation of the ATM torque should be carried out without pulsations and self-exciting oscillations and its performance should be sufficient to prevent wheel slippage. It is necessary to strive for reduce torque ripple and electrical losses in the elements.

3.4. The control system

The electric locomotive driver uses control handles to set the traction or braking effort (manual mode), or to set the speed (automatic control mode). In the first case, the target effort is converted into the reference for electromagnetic torque on motors shafts. In the second case, the automatic speed controller regulates the electromagnetic torque, in order to maintain the reference speed.

Thus we developed a two-channel automatic control system with independent control of rotor flux and electromagnetic torque. The stabilization of rotor flux magnitude in all modes eliminates the excessive saturation of the magnetic system [10 - 12].

Processes in a squirrel-cage asynchronous motor are considered in a d - q rotating coordinate system. The d - q rotating coordinate system associated with rotor. The angular speed ω relative to the $\alpha - \beta$ fixed coordinate system is calculated as

$$\omega = 2\pi \frac{d}{dt}\theta(t),$$

where: $\theta(t)$ is the angle between $\alpha - \beta$ and $d - q$ coordinate system.

If the rotor flux vector $\vec{\Psi}_r$ is along an axis d, then

$$\Psi_{rd} = \left|\vec{\Psi}_r\right|; \quad \Psi_{rq} = 0\,.$$

The position of $\vec{\Psi}_r$ relative the $\alpha - \beta$ fixed coordinate system is defined by an angle θ. In this case, the location of vectors is as shown in Fig. 2, where δ – angle between the vectors of stator current $\vec{I}_s$ and the rotor flux $\vec{\Psi}_r$, φ – the angle between $\vec{I}_s$ and stator voltage $\vec{U}_s$.

Processes in the squirrel-cage asynchronous motor are described by the equations:

$$\begin{cases} \vec{U}_s = \vec{I}_s r_s + \dfrac{d\vec{\Psi}_s}{dt} + j\omega\vec{\Psi}_s, \\ 0 = \vec{I}_r r'_r + \dfrac{d\vec{\Psi}_r}{dt} + j\omega\vec{\Psi}_r. \end{cases} \tag{4}$$

where: r_s, r'_r – stator and rotor resistances, $\vec{I}_r$ – rotor current vector, $\vec{\Psi}_s$ – stator flux vector.

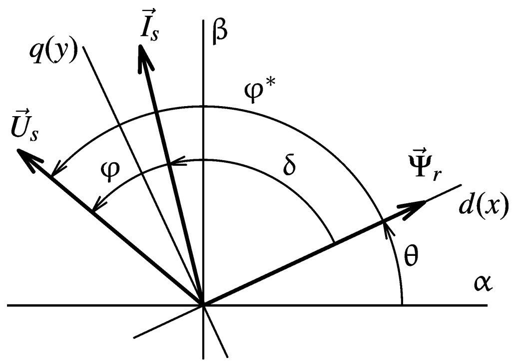


Fig. 2. Location of stator voltage, stator current and rotor flux vectors
Рис. 2. Положение векторов напряжения статора, тока статора и потокосцепления ротора

The relationship between the currents and fluxes of stator and rotor described by the equations:

$$\begin{cases} \vec{\Psi}_s = L_s\vec{I}_s + L_m\vec{I}_r, \\ \vec{\Psi}_r = L_m\vec{I}_s + L'_r\vec{I}_r. \end{cases} \tag{5}$$

where: L_s, L'_r – stator and rotor inductances, L_m – mutual inductance.

The electromagnetic torque is equal to the imaginary part of vector product of the rotor flux and the stator current:

$$M_{em} = \frac{3}{2} p \frac{L_m}{L'_r} \operatorname{Im}\left[\vec{\Psi}_r \times \vec{I}_s\right]. \tag{6}$$

where: M_{em} – electromagnetic torque, p – number of pole pairs.

After substitution of the rotor current from (5) to (4), the second equation becomes:

$$\vec{I}_s \frac{L_m r'_r}{L'_r} = \frac{d\vec{\Psi}_r}{dt}\left(\frac{L'_r}{r'_r} + j\omega\right)\vec{\Psi}_r. \tag{7}$$

Obtained equations are the basis of the structure of the vector control system. The control system is a dual-channel. The first channel controls the rotor flux by regulating projection of the stator current in the *d*-axis. The second channel controls the electromagnetic torque by regulating projection of the stator current in the *q*-axis.

But motor powered by the voltage inverter, therefore the control system must control the voltage vector [13]. To regulate the voltage vector channels have double circuit structure. The outer circuit sets the value of the current vector; inner circuit controls the voltage vector by performing a task of outer circuit. Voltage vector is calculated by first equation from (4):

$$\vec{U}_s = r_s\vec{I}_s + \frac{d\vec{\Psi}_s}{dt} + j\omega\vec{\Psi}_s. \tag{8}$$

The structure of control circuits of the stator current is determined based on the equation (8). Block diagram of the control system with independent control of rotor flux and electromagnetic torque is shown in Fig. 3

The reference signal of rotor flux and electromagnetic torque on the motor shaft is the input of the control system. The difference between the reference and the actual value of the rotor flux is applied to the input of the flux regulator. Projection of the stator current in the *d*-axis is the output of the control system. Projection of the stator current in the *d*-axis is summed with the voltage compensation signal. Voltage compensation signal is generated by cross-links compensation block [14].

The electromagnetic torque control channel has a similar structure.

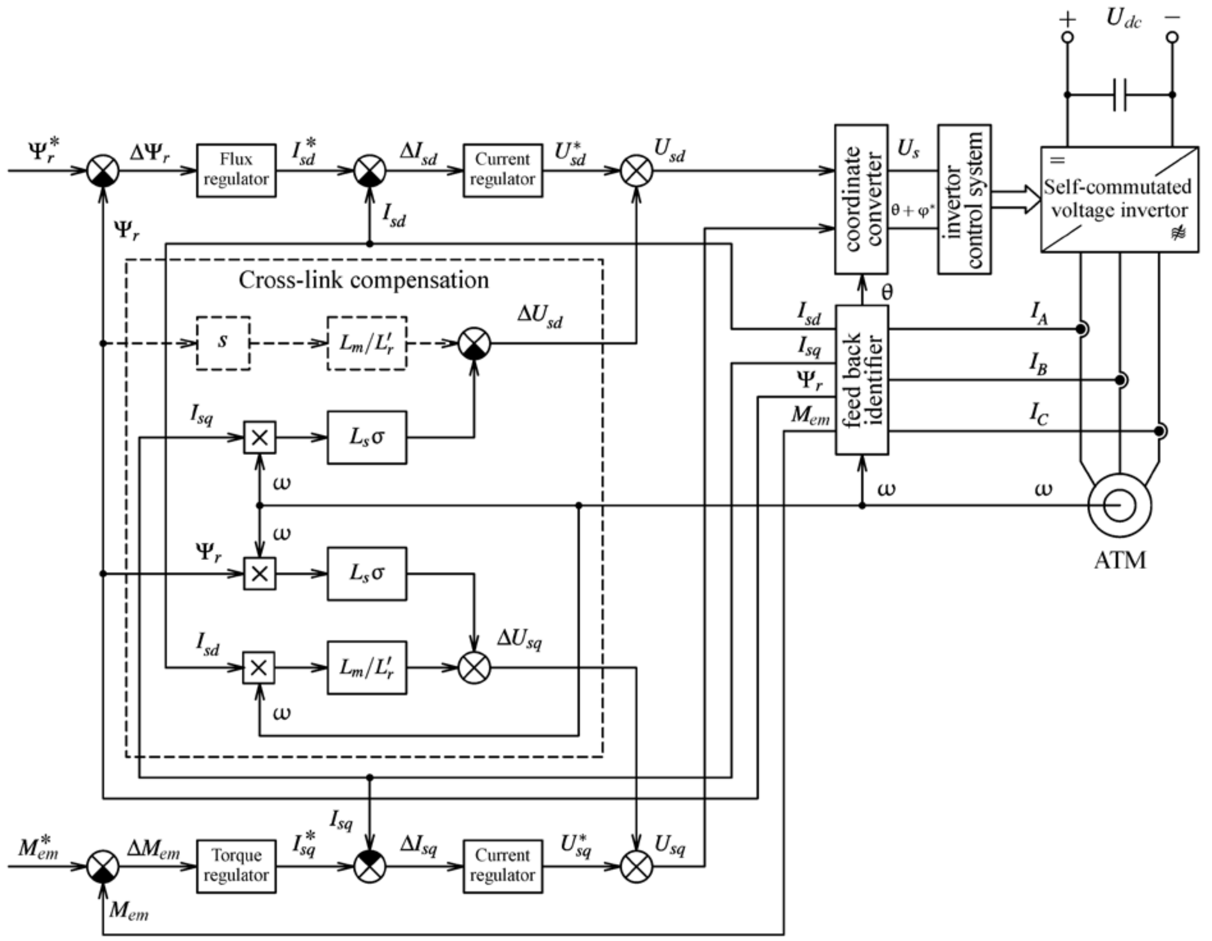


Fig. 3. Block diagram of the control system with independent control of rotor flux and electromagnetic torque
Рис. 3. Блок-схема системы управления с независимым управлением потокосцеплением ротора и электромагнитным моментом

3.5. The modeling of mechanical part

The mechanical part of the electric locomotive considered as a multi body structure consists of a car body and three two-axle bogies (see Fig. 1). The electric locomotive's axle formula is Bo-Bo-Bo. The inclined traction rods carry out the transmission of the traction and brake efforts from the bogies to the locomotive's car body. The traction motors and reducers are bogie-mounted. In total, the model contains 28 rigid bodies.

The equations of motion are generated based on the Newton – Euler formalism [15]

$$\begin{gathered} \boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}}+\boldsymbol{k}(\boldsymbol{q},\dot{\boldsymbol{q}})=\boldsymbol{Q}(\boldsymbol{q},\dot{\boldsymbol{q}})+\boldsymbol{G}(\boldsymbol{q})^T\lambda, \\ \boldsymbol{g}(\boldsymbol{q})=0, \end{gathered} \tag{9}$$

where: $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$, $\ddot{\boldsymbol{q}}$ are the column matrices of Lagrange coordinates, velocities and accelerations; $\boldsymbol{M}$ is the mass matrix; $\boldsymbol{k}$, $\boldsymbol{Q}$ are the column matrices of inertia and applied forces; λ is the vector of Lagrange multipliers corresponding to the cut joints; g are the algebraic constraint equations; m is the number of constraints; $\boldsymbol{G}=\partial\boldsymbol{g}/\partial\boldsymbol{q}^T=\{\partial\boldsymbol{g}_i/\partial\boldsymbol{q}_j\}_{i=\overline{1,m}}^{j=\overline{1,n}}$ is the constraint Jacobi matrix.

Equations (9) are differential-algebraic equations (DAE). The values to determine are the generalized coordinates $\boldsymbol{q}(t)$ and the Lagrange multipliers $\lambda(t)$.

Simulation of the mechanical part was carried out in the software package «Universal Mechanism» [16-18]. The computer animation of locomotive's movement is shown in Fig. 4.

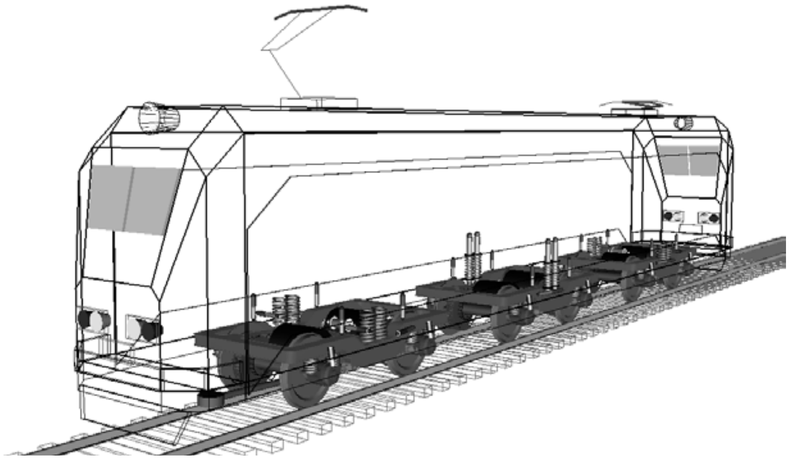


Fig. 4. Model of mechanical part (computer animation)
Рис. 4. Модель механической части (компьютерная анимация)

Coasting movement. The modeling of processes during coasting movement was executed by numerical integration of differential equations of motion (9) on the assumption that the torques on the traction motor shafts is zero.

The parameters of calculation scheme of the locomotive's mechanical part (dimensions, inertia characteristics, stiffness coefficients of elastic elements, damping coefficients of dampers, etc.) were taken from publications in the technical literature.

The FASTSIM algorithm [18] and its modification devoted to an unsteady contact model that provides the correct solution also for the case of zero vehicle velocity, were used for computation of creep forces. When modeling, the macro geometry of track on which the locomotive moving (the vertical profile and the plan of the railway) and the presence of rail's vertical and horizontal micro-irregularities are taken into account. The rail's micro-irregularities were constructed according to the UIC materials.

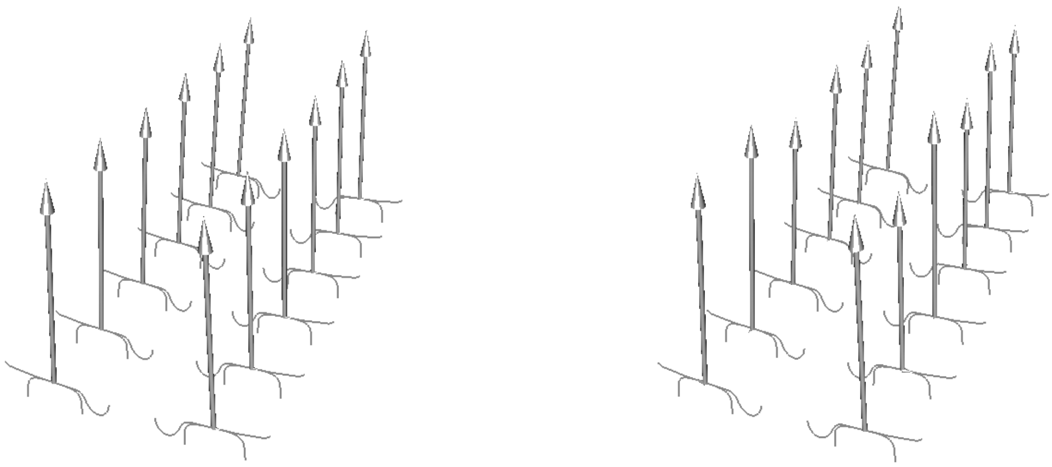
The mechanical part's full-size model allows taken into account the redistribution of load between the axles in the traction and braking modes, to investigate the interaction in the side wheel-rail contact during the passage of the curves, and so on.

The modeling was done in the velocity range of 10 to 60 m/s (i.e. from 36 to 216 km/h) with the step of 10 m/s.

As can be seen from Fig. 5 (20 m/s), the presence of track micro-irregularities leads to the fact that normal reactions in the wheel-rail contact for all wheels obtain the dynamic components and deviate from their quasi-static values occurring when driving on the track without irregularities.

The spots of wheel-rail contact for all the wheels are shown in Fig. 6 (20 m/s). The shaded area corresponds to the material's adhesion, the area without coloring – to the slip. The resultant force of interaction in the wheel-rail contact is shown as a vector which value and direction vary during wheel rolling on the rail. The scale in Fig. 6, *a* and *b* is the same.

It is seen, that the presence of track micro-irregularities leads to the fact that the resultant force within the wheel-rail contact varies considerably in magnitude and direction.



a *b*

Fig. 5. Normal reactions in the wheel-rail contact during coasting movement for the track without irregularities (*a*) and with irregularities (*b*)

Рис. 5. Нормальные реакции в контакте «колесо-рельс» при движении на выбеге по ровному пути (*a*) и по пути, имеющему неровности (*b*), скорость 20 м/с

Amplitud-frequency characteristics (AFC). The AFC (or frequency response) was built by spectral analysis of the harmonic track profile (perturbation) and the corresponding vibration (response). The horizontal axis shows the frequency of perturbation (Hz). The vertical axis shows the dimensionless dynamic coefficient k_{dyn} (amplification ratio). It means in how many times the amplitude of the forced oscillations is greater than static deformation.

Thus obtained AFC of the car body bouncing vibrations is shown in Fig. 7, *a*. The AFC for pitching and rolling oscillations of the car body are shown in Fig. 7, *b* and *c*.

The experimentally determined values of natural frequencies are as follows: for car body bouncing vibrations 1.89 Hz, for lateral rolling vibrations 0.64 Hz.

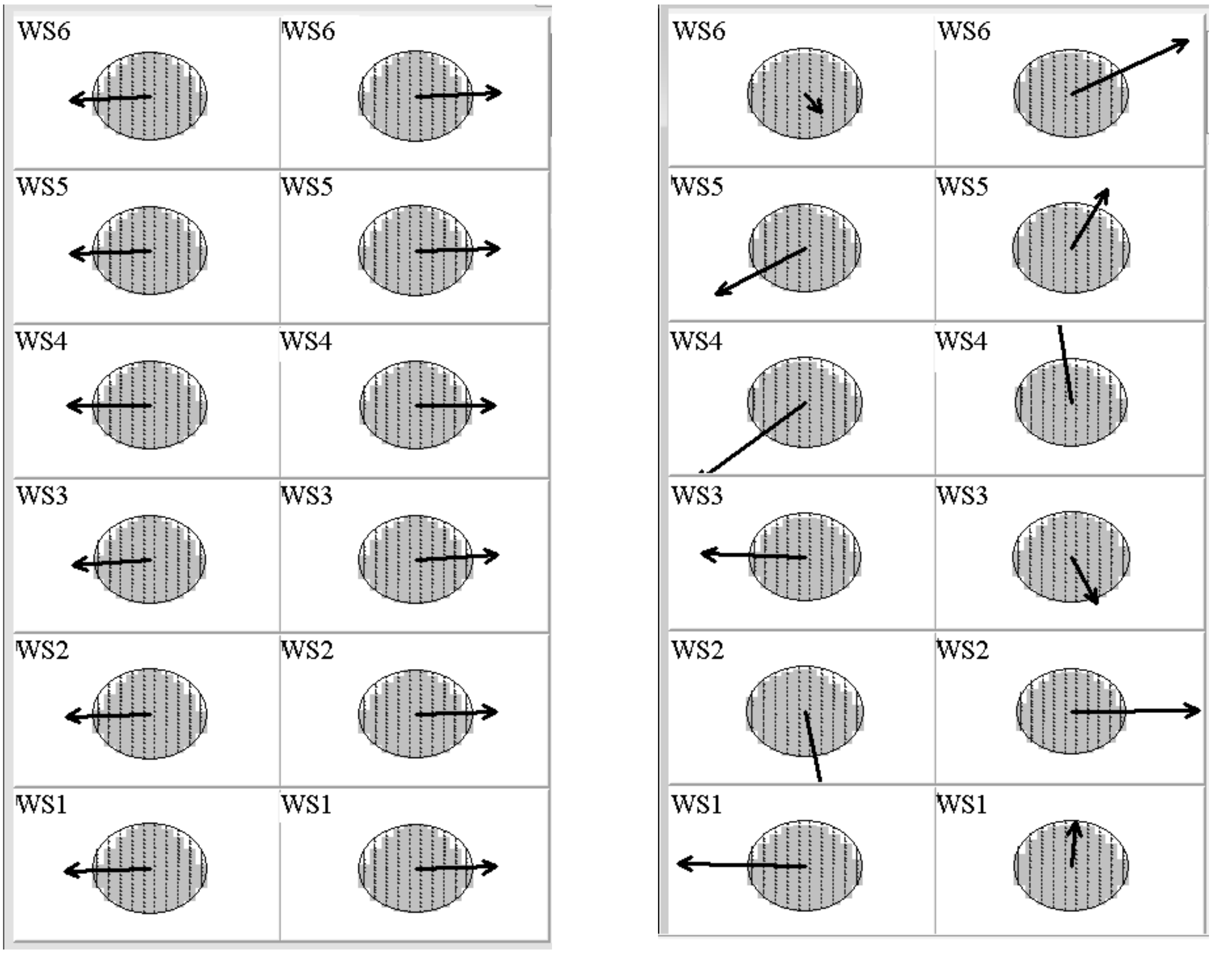
The features of dynamic behavior. We also note some qualitative features of the dynamic behavior, which have been identified in the coasting movement simulation. First of all, the significant increase of the oscillation frequencies with augmenting velocity is evident. However, the vibration amplitudes, starting from a speed of 72 km/h, have only the insignificant changes.

The bouncing of middle bogie at high speeds obtain the greater amplitude than for the front and rear bogies. This is due to the installation of the softer long-stroke springs at the level of car body suspension of the middle bogie.

In contrast, the pitching of the middle bogie, in comparison with front and rear bogies, is extremely small. The reason for this is the decisive role of the car body pitching vibrations which are transmitted to the extreme bogies more intensively (due to the much greater arms) that to the middle bogie.

As for the bogie's lateral pitching oscillations, they at low speed are determined by the local irregularities of rail way. At high speeds, they are composed of the lateral pitching vibrations of the car body and the high-frequency oscillations of small amplitude.

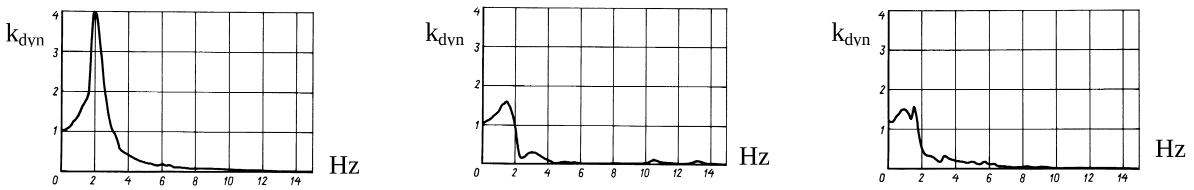
It should be noted that the results of the coasting movement modeling correspond to the actual tests [18].



a *b*

Fig. 6. The spots of wheel-rail contact and resultant forces during coasting movement on the track without irreg ularities (*a*) and with irregularities (*b*)

Рис. 6. Пятна контакта «колесо-рельс» и силы взаимодействия при движении на выбеге по ровному пути (*a*) и по пути, имеющему неровности (*b*)



a *b* *c*

Fig. 7. AFC of the car body vibrations: bouncing (*a*), pitching (*b*) and lateral rolling (*c*)

Рис. 7. АЧХ колебаний подпрыгивания (*a*), галопирования (*b*) и боковой качки (*c*) кузова

4. CONCLUSION

The six-axle electric locomotive with individual control of traction motors is considered as a controlled electromechanical system which includes the mechanical part as multi body structure, the electrical part (energy conversion devices and traction motors) and the control block (control algorithms and their realization). The full-size computer model is based on the subsystem technique.

There are direct and feedback communications between the processes in the mechanical and electrical parts.

The ATM's model is based on the presentation of induction motor as a system of magnet-connected contours. Determination of the motor's magnetic system parameters is carried out by the field theory methods (finite-element method). The saturation and non-homogeneity of the active layers of the stator and rotor, as well as the displacement of current in the stator and rotor windings, are taken into consideration.

The energy conversion system provides the operation of the electric locomotive by feeding from catenary network of 3 kV DC and of 25 kV, 50 Hz AC. It is modeled as an electric circuit, which consists of a main transformer, 4q-S input converters, a DC link and self-commutated voltage inverters for feeding the traction motors.

The two-channel automatic control system with independent control of the rotor flux and electromagnetic torque is developed. The stabilization of rotor flux magnitude in all modes eliminates the excessive saturation of the magnetic system.

The mechanical part of the electric locomotive, considered as a multi body structure, consists of a car body and three two-axle bogies. The model contains 28 rigid bodies. The processes during coasting movement was studied, the normal reactions and the forces of interaction in the wheel-rail contact is shown. The AFC was built for the car body bouncing, pitching and lateral rolling oscillations. Some qualitative features of the dynamic behavior are noted.

Results of dynamic electromechanical processes simulation in various modes of electric locomotive operation will be presented in Part 2 of this paper.

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