Визначено параметри, що впливають на нерівномірність струморозподілу в силовому колі при ведені вантажних поїздів. Розроблено метод аналітичного розрахунку сукупного впливу всіх факторів на струморозподіл, що дозволило підвищити тягові властивості локомотивів при взаємодії з вантажними вагонами. Результати дослідження можуть бути використані при ремонті вантажного рухомого складу постійного струму та при проектуванні систем керування

Ключові слова: транспортна механіка, тяговий двигун, коефіцієнт зчеплення, тягове зусилля, ресурсозбереження, струморозподіл

Определены параметры, влияющие на неравномерность токораспределения в силовой цепи при ведении грузовых поездов. Разработан метод аналитического расчета совокупного влияния всех факторов на токораспределение, что позволило повысить тяговые свойства локомотивов при взаимодействии с грузовыми вагонами. Результаты исследования могут быть использованы при ремонте грузового подвижного состава постоянного тока и при проектировании систем управления

Ключевые слова: транспортная механика, тяговый двигатель, коэффициент сцепления, тяговое усилие, ресурсосбережение, токораспределение

UDC 629.4.016
DOI: 10.15587/1729-4061.2018.121713

STUDY OF THE INFLUENCE OF ELECTRIC TRANSMISSION PARAMETERS ON THE EFFICIENCY OF FREIGHT ROLLING STOCK OF DIRECT CURRENT

O. Gorobchenko
Doctor of Technical Sciences, Associate Professor
Department of traction rolling stock of railways*
E-mail: gorobchenko.a.n@gmail.com

O. Fomin
Doctor of Technical Sciences, Associate Professor
Department of cars and carriage facilities*
E-mail: fomin1985@ukr.net

V. Fomin
Postgraduate student**
E-mail: fomin1971@ukr.net

V. Kovalenko
Postgraduate student**
E-mail: kkaterina@ukr.net

*State University of Infrastructure and Technology
Kyrylivska str., 9, Kyiv, Ukraine, 04071
**Department of railway, road transport and handling machines
Volodymyr Dahl East Ukrainian National University
Tsentralnyi ave., 59-a, Severodonetsk, Ukraine, 93400

1. Introduction

The task to improve operation efficiency of traction rolling stock has remained relevant over the entire period of existence of railways. Scientific research and new technical solutions have led to significant progress in this direction in recent years. Given the advances in the fields of chemistry, materials science, industrial electronics, etc., the latest element base and materials became available for rolling stock and significantly decreased the costs of transportation, increased speed and reliability of rolling stock. It is worth noting that an up-to-date locomotive is a complex, multi-purpose developed system. This predetermines the relevance of research into improvement of rolling stock via determining and formal description of internal relations between elements of a given system.

2. Literature review and problem statement

At present, most research aimed at enhancing effectiveness of rolling stock operation are conducted in the following main areas: improvement of efficiency of energy conversion and power transmission [1], improvement of onboard control systems, enhancement of conditions for implementation of traction and braking efforts of rolling stock [2]. One of the main factors for increasing the quality of traction of wheels and rails is the development of more advanced structures of crew pieces of rolling stock [3–5]. Today, introduction of new locomotive control systems as the factor of energy efficiency is directly related to intelligent technologies [6, 7].

However, despite a wide range of issues, addressed in these and many other scientific papers, there are still reserves for an increase in efficiency of rolling stock. One of these reserves is the improvement of interaction between traction elements of the power circuit. The grounds for such problem statement include modern technological requirements for traction electric motors, wheelsets, traction reducers and other sections of power transmission [8]. During manufacturing and operation of these elements, the difference in their characteristics is sure to occur. To eliminate the harmful effect of this difference, a number of systems, such as the system of axial regulation of traction effort [1], dynamic redistribution of loadings from wheelsets on rails [9], alignment of currents by parallel branches of the power circuit [10], were developed and implemented, the design of bearing elements of rolling stock [11] was improved, interaction of the wheel rolling surface with rails and brake pads [12] was improved and so on. However, these developments have not enabled the full use of the traction mass of locomotives and maximal efficiency of their operation under all modes of operation [13, 14]. A possible cause of this situation is the lack of a comprehensive approach to increasing the coefficient of traction mass in the existing studies. In other words, high quality methods for elimination of particular harmful influences on implementation of traction effort were developed. But their relationship with the design features of certain locomotives, which can both increase and decrease effectiveness of each method, has not been determined yet. Thus, the problem of a comprehensive consideration of particular transmission parameters and their overall impact on the traction effort of direct current locomotives has not been sufficiently solved so far.

3. The aim and objectives of the study

The aim of present research is to develop a comprehensive mathematical model of current distribution in the power circuit of a direct current locomotive for substantiation of improvement of traction conditions and enhancing efficiency of locomotive operation.

To accomplish the set goal, it is necessary to solve the following problem:

– to explore the influence of non-uniformity of current distribution in a power circuit on power efficiency of operation of locomotives;

– to define parameters of wheel-motor units that affect non-uniformity of current distribution;

– to develop the method for analytical calculation of the total impact of design, technological and operational factors on current distribution in a power circuit;

– to determine a condition for elimination of non-uniformity of current distribution.

4. Materials and methods of research

4. 1. Study of influence of the non-uniformity of current distribution in a power circuit on energy efficiency of locomotive operation

The study of current distribution was performed at the locomotive DE1 using the on-board diagnostics systems "Magistral-DE1", which is installed in each section. It was determined that the non-uniformity of current distribution occurs in parallel (P) and series-parallel (SP) connections of a power circuit. Distribution of currents with variable speed is represented in Fig. 1, 2. Here, I1, I2, I3, I4 are the currents in their respective branches.

According to research, at an increase in motion speed, the difference in powers of parallel branches decreases (Fig. 3).

Deviation of currents influences the locomotive's traction power, in particular contributes to an increase. This is proved by the curve in Fig. 4. Magnitude ΔF here is the difference between calculated traction power for a given mode and readings of traction power of the diagnosis system. ΔF is positive, i. e. at an increase in non-uniformity of current distribution, the implemented locomotive traction power decreases.

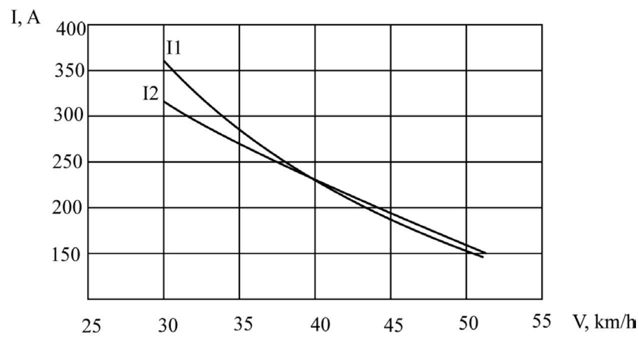

Fig. 1. Dependence of load currents (I) on motion speed (V) at series-parallel connection of motors of power circuit of locomotive

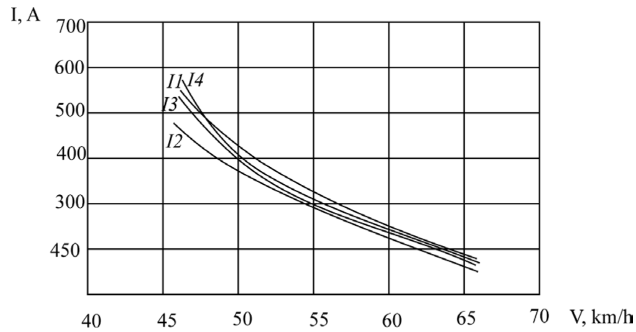

Fig. 2. Dependence of load currents (I) on motion speed (V) at parallel connection of motors of power circuit of a locomotive

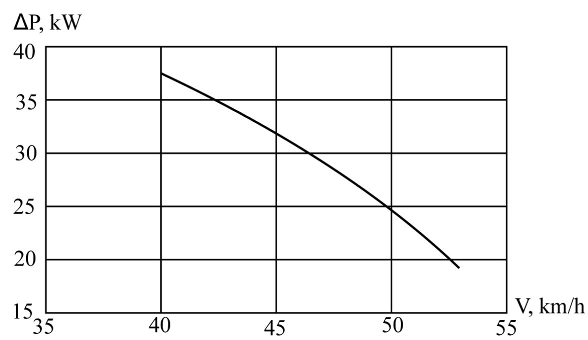

Fig. 3. Dependence of difference of powers of parallel branches of a power circuit (ΔP) on motion speed (V)

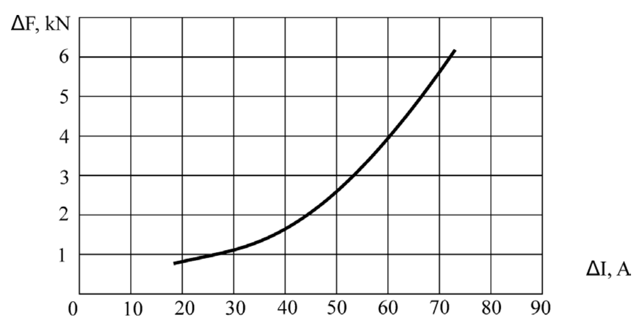

Fig. 4. Mean value of a decrease in traction power (ΔF) of locomotives DE1 depending on difference of currents (ΔI) for modes that are close to nominal

Thus, the results of study of the non-uniformity of current distribution indicate that there is a relationship between the magnitude of deviation of current of traction motors and traction effort and energy efficiency of a locomotive. In addition, the difference of powers, which are implemented by traction motors, leads to non-uniformed wear of wheel-motor units and a decrease in serviceability of rolling stock.

4. 2. Determining the parameters of wheel-motor units that affect the non-uniformity of current distribution

Difference of magnetic characteristics. In [15], it is indicated that the deviation of speed characteristic of the traction motor from the calculated one, like the difference between characteristics of motors between one another, is determined by a number of factors. These include asymmetry of magnetic system of motors and the position of brushes relatively to the neutral.

This component, in turn, depends on magnetizing longitudinal force and degree of saturation of the magnetic system.

With displacement of brushes from the neutral in the direction of rotation of the armature of the traction motor, magnetic flux increases and rotation frequency of the armature of the traction motor decreases. Displacement of brushes opposite the direction of rotation of the armature, in contrast, leads to a decrease in the resulting flow of the motor, and rotation frequency of the armature increases. Experience shows that the 1 mm displacement of brushes, for example, of the traction motor NB-406 B, at the hourly mode causes a change in rotation frequency of armature on average by 4.3 rpm. This proportion remains until the brush is displaced approximately by 10 mm.

For motors of series excitation, at relative rigidity of speed characteristics of 2–2.5 load deviation reaches 15–20 %. It significantly increases at more strict characteristics of motors of mixed and independent excitation.

Boundary deviations of parameters of traction motors with different operation modes are regulated by the standard on their production. Tolerance of the armature rotation frequency when operating at nominal power and full field is ±3 %; when operating on a weakened field of up to 50 %, it is ±3.5 %; larger than 50 %, it is ±6 %.

Tolerances on rotation frequencies when operating with minimal and maximal speeds are respectively ±3.0; ±3.0; ±5 %, as well as, ±3.5; ±5.0; ±7.0 % on the full field, on weakening of the field of up to 50 % and weakening of the field of larger than by 50 %.

Non-uniformity of current distribution on divergence of magnetic characteristics of traction motors is determined by the graphic-analytical method in the following way.

Speed characteristics of the traction motor applying dependences [16] are calculated

$$n=\frac{0.5U_{cn}-IR_g}{c_e\Phi}, \qquad (1)$$

where U_{cn} is the current of the contact network, W; I is the current of motor loading, A; c_e is the constant of the motor by emf; R_g is the total resistance of the hot traction electric motor, Ohm; Φ is the main magnetic flux, Wb;

Total active resistance of a hot traction motor is determined from expression

$$R=(R_{a20}+R_{mp20}+R_{gn20})\beta_t, \qquad (2)$$

where R_{a20} is the resistance of winding of the armature of the traction electric motor at 20 °C, Ohm; R_{mp20} is the resistance of winding of main poles and shunting resistors at 20 °C, Ohm; R_{gn20} is the resistance of winding of additional poles of the electric motors at 20 °C, Ohm; β_t is the temperature coefficient of resistance of copper of winding of electric motor

In this case

$$R_{\mathrm{mp}20}=\frac{R_{\mathrm{mp}}\cdot R_{\mathrm{m}}}{R_{\mathrm{mp}}\cdot R_{\mathrm{m}}}=\frac{R_{\mathrm{mp}}\dfrac{\alpha}{1-\alpha}}{1+\dfrac{\alpha}{1-\alpha}}, \qquad (3)$$

where R_{mp} is the resistance of winding of main poles of traction electric motors at 20 °C, Ohm; R_m is the resistance of the shunting resistor, Ohm; α is the coefficient of field weakening.

$$\Phi=\Phi_{ir}-\Phi_{ar}, \qquad (4)$$

where Φ_{ir}, Φ_{ar} are the magnetic fluxes of idle running and the reaction of the armature of the traction electric motor, Wb.

Deviation of resistances of armature circuits. A branch of the power circuit of modern direct current locomotives consists of many elements. Considering non-uniformity of current distribution at a parallel connection of traction motors, it may be noted that it depends on two groups of factors:

– structural, caused by the location of traction electric motors, and hence the difference in lengths of connecting wires and magnitudes of resistance of resistors;

– technological, dependent on tolerances on the elements of the armature circuit, resistances in electric contacts.

Calculation of non-uniformity of current distribution on divergence in resistances groups of armature circuits of traction electric motors is performed in the graphic-analytic way. A number of values of resistances of the armature circuit, equal to nominal and increased by 5, 10, 15 and 20 %, are accepted. For each selected value of current and resistance, rotation frequencies, magnetic fluxes are calculated from formulas and characteristics are constructed.

The value of non-uniformity of current distribution in characteristic points is determined and dependences of maximum possible values of non-uniformity of current distribution ΔI on deviations of resistances ΔR_g of armature circuit are constructed.

On the full field of excitation, minimum value of resistance of one power circuit that affects non-uniformity of current distribution is calculated by the formula (for DE1)

$$R_{minFF}=R_{\mathrm{Cmin}}+2R_g+9R_{k\mathrm{min}}+R_{cont}, \qquad (5)$$

where $R_{\mathrm{min}FF}$ is the minimal resistance of the power circuit of the full field, Ohm; R_{Cmin} is the resistance of cables, Ohm; $R_{k\mathrm{min}}$ is the minimal resistance of contacts of the armature field, Ohm; R_g is the resistance of the armature circuit of the traction motor, Ohm; R_{cont} is the resistance of elements of control and automation (contacts of the linear contactor, load current sensors, shunts of amperemeters, contacts of braking switch, etc.)

For other series of direct current locomotives, calculation is similar, it differs only by the coefficient at $R_{k\mathrm{min}}$, depending on the layout of the scheme.

Maximum resistance $R_{\mathrm{max}FF}$ of the power circuit on full field of excitation is found in a similar way.

Boundary minimum resistance of circuit R_{minWF} at operation of the electric motor on a weakened field of excitation is

$$R_{\text{minWF}} = (R_{\text{minFF}} - 2R_{\text{WE}}) - \\ - \frac{(R_{\text{rwmin}} + R_{\text{mmin}} + R_{\text{kmmin}})2R_{\text{WE}}}{R_{\text{rwmin}} + R_{\text{mmin}} + R_{\text{kmmin}} + 2R_{\text{WE}}}, \quad (6)$$

where R_{WE} is the resistance of winding of excitation of a traction electric motor, Ohm; R_{rwmin} is the minimum resistance of wires, Ohm; R_{mmin} is the minimal resistance of shunting resistor, Ohm; R_{kmmin} is the minimal resistance of contactor of shunting, Ohm.

Maximal value of resistance of armature circuit at weakening of field R_{maxWF} is determined in a similar way.

Deviation of resistances of excitation circuits. The circuit of excitation of the traction electric motor consists of a winding of excitation of a traction electric motor, connecting wires, inductive shunt, resistors of field weakening, contactors, shunting.

Non-uniformity of current distribution for different coefficients of shunting is determined by the graphical-analytical method. Values of resistances of shunting resistors that provide regulated magnitudes of coefficients of field weakening are calculated. Operation characteristics of a motor are determined for five selected values of currents and coefficients of shunting. After assigning deviations of magnitudes of shunting resistors, that cause deviations of field weakening by 10, 20, 30 % of the calculated, working characteristics for these deviations are determined. In this case, the characteristic that corresponds to calculated coefficient of shunting is accepted as basic.

In coordinates of the difference of currents ΔI and percentage deviation of value of resistance of shunting resistors, we construct dependences of non-uniformity of current distribution ΔI on percentage deviation of the value of resistance of a shunting resistor, which provides field weakening.

Minimum and maximum values of resistance of the motor due to changes in resistances in the circuit of excitation are determined

$$R_{\min} = 2\left[R_a + R_{gn} + \frac{(R_{\text{mmin}} + R_{\text{im}} + R_{\text{rwmin}} + R_{\text{kmin}})2R_{\text{WE}}}{R_{\text{mmin}} + R_{\text{im}} + R_{\text{rwmin}} + R_{\text{kmin}} + 2R_{\text{WE}}}\right], \quad (7)$$

$$R_{\min} = 2\left[R_{\text{a}} + R_{gn} + \frac{(R_{\text{mmax}} + R_{\text{im}} + R_{\text{rwmax}} + R_{k\text{max}})2R_{\text{WE}}}{R_{\text{mmax}} + R_{\text{im}} + R_{\text{rwmax}} + R_{k\text{max}} + 2R_{\text{WE}}}\right]. \quad (8)$$

Minimum and maximum deviations of resistances of excitation circuit, taking into account tolerances for different stages of field weakening are determined. The values of non-uniformity of current distribution are determined as the difference between maximum and minimum values of the currents of motors.

Change in diameters of wheelsets' threads. Taking into account the influence of diameters of wheelsets' threads is carried out with the assumption that velocities of operating slip of all wheelsets are the same, and velocities of excessive slips are equal to zero.

Characteristics of traction electric motor for full field and their respective degrees of weakening the magnetic flux are constructed (Fig. 5).

Deviations of rotation frequencies (Δn) by 1.2 and 3 % from the original value are marked on the ordinate axis. From the obtained characteristic points, we draw parallels to the intersection with the appropriate operation characteristics of the electric motor. From the points of intersection of the parallels and the characteristics, we mark perpendiculars to the intersection with the axis of the currents. The sections that are deviating on the axis of the current, are equal to non-uniformities of current distribution. Boundary deviations of diameters of wheelsets' threads (ΔD), expressed as percentage, are marked on the plotted diagrams. The sum of deviations of current from influences of motor characteristics and the deviation of the diameter of the thread will be the actual value of deviation of current in an assembled wheel-motor unit.

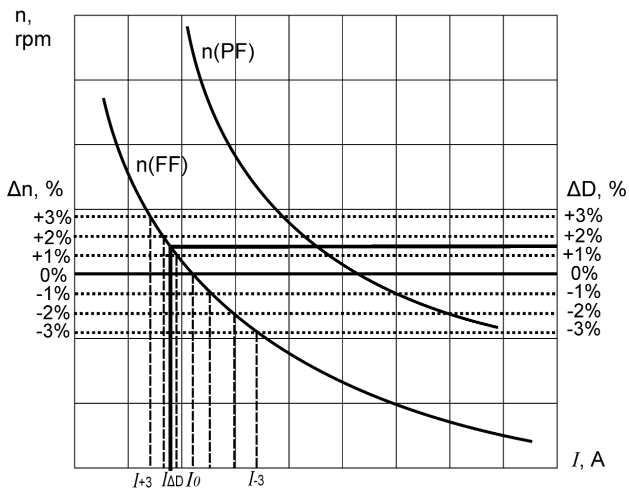

Fig. 5. Diagram of graphical-analytical method for determining the influence of deviation of diameter of thread (ΔD) on current of the motor (I) with regard to its characteristics

4. 3. Development of the method for analytical calculation of total influence of structural, technological and operational factors on current distribution

The difference of currents in parallel-connected motors of sequential excitation is expressed through

$$\Delta I = I_1 - I_2, \quad (9)$$

where I_1 is the load current of motor 1, A; I_2 is the load current of motor 2, A.

According to [16], current of the motor equals to

$$I = \frac{U - c_e \cdot \Phi \cdot n}{R_{\text{ekv}}}, \quad (10)$$

where U is the voltage, applied to the motor, W; c_e is the structural constant of a machine with emf; Φ is the magnetic flux, Wb; n is the rotation frequency of the armature, rpm; R_{ekv} is the total resistance of the windings of a traction motor, Ohm.

Substituting expression (10) in expression (9), we will obtain:

$$\Delta I = \frac{U - c_e \cdot \Phi_1 \cdot n_1}{R_{\text{ekv1}}} - \frac{U - c_e \cdot \Phi_2 \cdot n_2}{R_{\text{ekv2}}}. \quad (11)$$

Based on the calculation task, we accept that in a general case, the motors have a difference in magnetic fluxes, rotation frequencies, and supports. That is why magnetic flux of motor 2 can be represented as

$$\Phi_2 = \Phi_1 - \Delta\Phi. \quad (12)$$

Rotation frequency of motor 2

$$n_2 = n_1 - \Delta n. \quad (13)$$

Resistance of windings of motor 2

$$R_{ekv} = R_{ekv1} + \Delta R_{ekv}. \quad (14)$$

Then (11) will take the form

$$\Delta I = \frac{U - c_e \cdot \Phi_1 \cdot n_1}{R_{ekv1}} - \frac{U - c_e \cdot (\Phi_1 + \Delta\Phi) \cdot (n_1 + \Delta n)}{R_{ekv1} + \Delta R_{ekv}} =$$
$$= \frac{U \cdot \Delta R_{ekv} - \Delta R_{ekv} c_e \cdot \Phi_1 \cdot n_1 + \Delta n \cdot R_{ekv1} \cdot c_e \cdot \Phi_1 + n_1 \cdot R_{ekv1} \cdot c_e \cdot \Delta\Phi + \Delta n \cdot R_{ekv1} \cdot c_e \Delta\Phi}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} =$$
$$= \frac{U \cdot \Delta R_{ekv} - \Delta R_{ekv} \cdot c_e \cdot \Phi_1 \cdot n_1}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} + \frac{\Delta n \cdot c_e \cdot \Phi_1 + n_1 \cdot c_e \cdot \Delta\Phi + \Delta n \cdot c_e \cdot \Delta\Phi}{R_{ekv1} + \Delta R_{ekv}}. \quad (15)$$

Let us represent magnetic flux through load current. For motors of series excitation at full field

$$\Phi_1 = k_1 I_1, \quad \Phi_2 = k_2 I_2. \quad (16)$$

Here k_1 and k_2 are the variable coefficients, the values of which vary depending on currents I_1 and I_2.

From formula (12)

$$\Delta\Phi = k_1 I_1 - k_2 I_2. \quad (17)$$

Then expression (15) will take the form

$$\Delta I = \frac{U \cdot \Delta R_{ekv} - \Delta R_{ekv} \cdot c_e \cdot k_1 \cdot I_1 \cdot n_1}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} +$$
$$+ \frac{\Delta n \cdot c_e \cdot k_1 \cdot I_1 + n_1 + c_e \cdot (k_1 \cdot I_1 - k_2 \cdot I_2) + \Delta n \cdot c_e \cdot (k_1 \cdot I_1 - k_2 \cdot I_2)}{R_{ekv1} + \Delta R_{ekv}}.$$

Let us express I_2 through I_1:

$$I_2 = I_1 + \Delta I.$$

Then

$$\Delta I = \frac{U \cdot \Delta R_{ekv} - \Delta R_{ekv} \cdot c_e \cdot k_1 \cdot I_1 \cdot n_1}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} +$$
$$+ \frac{\Delta n \cdot c_e \cdot k_1 \cdot I_1 + n_1 + c_e \cdot (k_1 \cdot I_1 - k_2 \cdot (I_1 + \Delta I)) + \Delta n \cdot c_e \cdot (k_1 \cdot I_1 - k_2 \cdot (I_1 + \Delta I))}{R_{ekv1} + \Delta R_{ekv}}.$$

We decompose the first fraction into two, open the brackets in the numerator of the second fraction and separate the fractions, which contain in numerator I_1 from those that contain ΔI.

$$\Delta I = \frac{U \cdot \Delta R_{ekv}}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} - \frac{\Delta R_{ekv} \cdot c_e \cdot k_1 \cdot I_1 \cdot n_1}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} +$$
$$+ I_1 \cdot c_e \cdot \frac{2\Delta n \cdot k_1 + n_1 \cdot k_1 - k_2 \cdot n_1 + \Delta n \cdot k_2}{R_{ekv1} + \Delta R_{ekv}} + \Delta I \cdot c_e \cdot \frac{-n_1 \cdot k_2 - \Delta n \cdot k_2}{R_{ekv1} + \Delta R_{ekv}}.$$

We solve the equation relative to ΔI:

$$\Delta I \left(1 + c_e \cdot k_2 \frac{n_1 + \Delta n}{R_{ekv1} + \Delta R_{ekv}}\right) = \frac{U \cdot \Delta R_{ekv}}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} +$$
$$+ I_1 \cdot c_e \cdot \left(-\frac{\Delta R_{ekv} \cdot k_1 \cdot n_1}{R_{ekv1} \cdot (R_{ekv1} + \Delta R_{ekv})} + \frac{2\Delta n \cdot k_1 + n_1 \cdot k_1 - k_2 \cdot n_1 + \Delta n \cdot k_2}{R_{ekv1} + \Delta R_{ekv}}\right),$$

or

$$\Delta I = \frac{U \cdot \Delta R_{ekv}}{R_{ekv}^2 + R_{ekv1} \cdot \Delta R_{ekv} + R_{ekv1} \cdot c_e \cdot k_2 \cdot (n_1 + \Delta n)} +$$
$$+ I_1 \cdot c_e \cdot \begin{pmatrix} -\dfrac{\Delta R_{ekv} \cdot k_1 \cdot n_1}{R_{ekv}^2 + R_{ekv1} \cdot \Delta R_{ekv} + R_{ekv1} \cdot c_e \cdot k_2 \cdot (n_1 + \Delta n)} + \\ + \dfrac{2\Delta n \cdot k_1 + n_1 \cdot k_1 + k_2 \cdot n_1 - \Delta n \cdot k_2}{R_{ekv}^2 + R_{ekv1} \cdot \Delta R_{ekv} + R_{ekv1} \cdot c_e \cdot k_2 \cdot (n_1 + \Delta n)} \end{pmatrix}. \quad (18)$$

Dependence of magnitude of magnetic flux on current of the motor will be represented in the analytical form. As a result of breaking the curve of dependence $\Phi(I)$ into three sections, approximations of the middle curvilinear part, we can write down the formula of magnetic flux of the motor. For the motor of series NB-406B, it would be in the following form:

$$\Phi = \begin{cases} 0{,}000588I \text{ if } 0 \le I \le 200, \\ 1{,}54321 \cdot 10^9 \cdot I^3 - 1{,}74537 \cdot 10^6 I^2 - \\ -0{,}000768241 \cdot I + 0{,}021421 \text{ if } 200 < I < 380, \\ 0{,}00008955 \cdot I + 0{,}11197 \text{ if } 380 \le I \le 600. \end{cases} \quad (19)$$

For the motors of series ED141AU1 (locomotive DE1), dependence of magnetic flux on load current is determined in the similar way based on its characteristics.

Formula (19) describes the standard (reference) traction electric motor that has no deviations from the passport data. However, in actual motors, there are deviations in characteristics, which have different causes. It is possible to judge about these deviations, based on the bench test data, from the passports of motors.

Let us assume that bench measurements revealed that rotation frequency n_i of a tested TEE is different from the standard. Assuming all other parameters being equal, we will find magnetic flux for n_i.

$$\Phi_i = \frac{U - IR_a}{n_i c_e}, \quad (20)$$

where n_i is the frequency, measured during bench tests.

It is not difficult to see that

$$\Phi_i = \frac{n_n}{n_i} \Phi_n. \quad (21)$$

Magnitude

$$k_n = n_n / n_i \quad (22)$$

will be called coefficient of deviation of magnetic flux, which shows by how many times the magnetic flux of the reference motor differs from the magnetic flux of the actual motor. Then

$$\Phi = k_{ni} \Phi_n. \quad (23)$$

In accordance with these considerations, the formula of rotation frequency for each actual motor is

$$n_i = \frac{U - R_a \cdot I}{c_e \cdot k_n \cdot \Phi_n} \quad (24)$$

$$n=\begin{cases}\dfrac{U-R\cdot I}{c_e\cdot k_n\cdot 0{,}000588\cdot I} & \text{if } 0\le \mathrm{I}\le 200,\\[2mm] \dfrac{U-R\cdot I}{c_e\cdot k_n\cdot(1{,}54321\cdot 10^{9}\cdot I^3-1{,}74527\cdot 10^{6}\cdot I^2-0{,}000768241\cdot I+0{,}021421} & \text{if } 200< I< 380,\\[2mm] \dfrac{U-R\cdot I}{c_e\cdot k_n\cdot(0{,}00008955\cdot I+0{,}11197)} & \text{if } 380\le I\le 600.\end{cases}$$

Returning to formulas (16), magnetic flux can be represented in the form of

$$\Phi_1=k_{n1}k_{\mathrm{et1}}I_1,$$

$$\Phi_2=k_{n2}k_{\mathrm{et2}}I_2, \tag{25}$$

where k_{n1}, k_{n2} are the coefficients of deviations of fluxes of motor 1 and motor 2; k_{et} is the coefficient of proportionality between magnetic flux and load current of the reference motor.

In formula (18), we give the values of coefficients k_1 and k_2 to k_{et}, k_{n1}, k_{n2}.

$$\Delta I=\frac{U\cdot\Delta R_{\mathrm{ekv}}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{et}\cdot k_{n2}\cdot(n_1+\Delta n)}+$$
$$+I_1\cdot c_e\cdot\left(-\frac{\Delta R_{\mathrm{ekv}}\cdot k_{et}\cdot k_{n1}\cdot n_1}{R^2_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{et}\cdot k_{n2}\cdot(n_1+\Delta n)}+\right.$$
$$\left.+\frac{2\Delta n\cdot k_{et}\cdot k_{n1}+n_1\cdot k_{et}\cdot k_{n1}-k_{et}\cdot k_{n2}\cdot n_1-\Delta n\cdot k_{et}\cdot k_{n2}}{R_{\mathrm{ekv1}}+\Delta R_{\mathrm{ekv}}+c_e\cdot k_{et}\cdot k_{n2}\cdot(n_1+\Delta n)}\right),$$

$$\Delta I=\frac{U\cdot\Delta R_{\mathrm{ekv}}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{et}\cdot k_{n2}\cdot(n_1+\Delta n)}+$$
$$+I_1\cdot c_e\cdot k_{et}\cdot\left(-\frac{\Delta R_{\mathrm{ekv}}\cdot k_{n1}\cdot n_1}{R^2_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{et}\cdot k_{n2}\cdot(n_1+\Delta n)}+\right.$$
$$\left.+\frac{2\Delta n\cdot k_{n1}+n_1\cdot k_{n1}-k_{n2}\cdot n_1-\Delta n\cdot k_{n2}}{R_{\mathrm{ekv1}}+\Delta R_{\mathrm{ekv}}+c_e\cdot k_{et}\cdot k_{n2}\cdot(n_1+\Delta n)}\right). \tag{26}$$

It is appropriate to express rotation frequencies in (25) for calculation through motion speed. According to [17],

$$n=\frac{V\cdot i\cdot 60}{\pi\cdot D_{\mathrm{t}}}, \tag{27}$$

where V is the motion speed, km/h; i is the gear ratio of the traction reducer; D_{t} is the diameter of the thread, m.

Then, given (27) and that $\Delta n=n_1-n_2$,

$$\Delta I=\frac{U\cdot\Delta R_{\mathrm{ekv}}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi}\left(\dfrac{2}{D1}-\dfrac{1}{D2}\right)}+$$
$$+I_1\cdot c_e\cdot k_{\mathrm{et}}\cdot\left(-\frac{\Delta R_{\mathrm{ekv}}\cdot k_{n1}\cdot V\dfrac{i\cdot 60}{\pi\cdot D_1}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi}\left(\dfrac{2}{D1}-\dfrac{1}{D2}\right)}+\right.$$
$$\left.+\frac{2\cdot V\dfrac{i-60}{\pi}(D_1-D_2)\cdot k_{n1}+V\dfrac{i\cdot 60}{\pi\cdot D_1}\cdot k_{n1}-k_{n2}\cdot V\dfrac{i\cdot 60}{\pi\cdot D_1}-V\dfrac{i\cdot 60}{\pi}(D_1-D2)\cdot k_{n2}}{R_{\mathrm{ekv1}}+\Delta R_{\mathrm{ekv}}+c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi}\left(\dfrac{2}{D1}-\dfrac{1}{D2}\right)}\right),$$

$$\Delta I=\frac{U\cdot\Delta R_{\mathrm{ekv}}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi}\left(\dfrac{2}{D1}-\dfrac{1}{D2}\right)}+$$
$$+I_1\cdot V\frac{i\cdot 60\cdot c_e\cdot k_{\mathrm{et}}}{\pi\cdot D_1}\left(-\frac{\Delta\sum R\cdot k_{n1}\dfrac{1}{D_1}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi}\left(\dfrac{2}{D1}-\dfrac{1}{D2}\right)}+\right.$$
$$\left.+\frac{2\cdot(D_1-D_2)\cdot k_{n1}+\dfrac{1}{D_1}\cdot k_{n1}-k_{n2}\cdot\dfrac{1}{D_1}-\dfrac{1}{D_2})\cdot k_{n2}}{R_{\mathrm{ekv1}}+\Delta R_{\mathrm{ekv}}+c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi}\left(\dfrac{2}{D1}-\dfrac{1}{D2}\right)}\right). \tag{28}$$

Expression (28) demonstrates the structure of occurrence of non-uniformity of current distribution in the power circuit of locomotives. It takes into account the basic factors influencing deviation of current – the difference of electrical resistances, diameter of tires and magnetic fluxes.

5. Results of research into current distribution in a power circuit

Summing up the above calculation order, it is possible to represent deviations of currents in a general form as

$$\Delta I=\rho+I_1\cdot\varepsilon, \tag{29}$$

where

$$\rho=\frac{U\cdot\Delta R_{\mathrm{ekv}}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi\cdot D_2}};$$

$$\varepsilon=V\frac{i\cdot 60\cdot c_e\cdot k_{\mathrm{et}}}{\pi}\cdot\left(-\frac{\Delta R_{\mathrm{ekv}}\cdot k_{n1}\cdot\dfrac{1}{D_1}}{R^2_{\mathrm{ekv1}}+R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}+R_{\mathrm{ekv1}}\cdot c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi\cdot D_2}}+\right.$$
$$\left.+\frac{2\cdot\left(\dfrac{1}{D_1}-\dfrac{1}{D_2}\right)\cdot k_{n1}+\dfrac{1}{D_1}\cdot k_{n1}-k_{n2}\cdot\dfrac{1}{D_1}-\left(\dfrac{1}{D_1}-\dfrac{1}{D_2}\right)\cdot k_{n2}}{R_{\mathrm{ekv1}}\cdot\Delta R_{\mathrm{ekv}}\cdot c_e\cdot k_{\mathrm{et}}\cdot k_{n2}\cdot V\dfrac{i\cdot 60}{\pi\cdot D_2}}\right).$$

Coefficients ρ and ε in the general case depend on connected voltage, speed of motion, difference of ohmic resistances of motors' circuits, design of a machine, coefficients of flux deviation and diameter of threads of motor's wheelsets. That is:

$$\rho=f(\mathrm{U},\ \Delta R_{\mathrm{ekv}},\ V,\ c_e,\ k_{\mathrm{et}},\ k_{n2},\ i,\ D_2), \tag{30}$$

$$\varepsilon=f(\Delta R_{\mathrm{ekv}},\ V,\ c_e,\ k_{\mathrm{et}},\ k_{n1},\ \mathrm{k}_{n2},\ i,\ D_2,\ D_1). \tag{31}$$

At $\Delta R_{\text{ekv}}=0$, expression (29) takes the form

$$\Delta I = I_1 \cdot V \frac{i \cdot 60 \cdot c_e \cdot k_{\text{et}}}{\pi} \times$$
$$\times \frac{2 \cdot \left(\frac{1}{D_1} - \frac{1}{D_2}\right) \cdot k_{n1} + \frac{1}{D_1} \cdot k_{n1} - k_{n2} \cdot \frac{1}{D_1} - \left(\frac{1}{D_1} - \frac{1}{D_2}\right) \cdot k_{n2}}{R_{\text{ekv1}} + c_e \cdot k_{\text{et}} \cdot k_{n2} \cdot V \frac{i \cdot 60}{\pi \cdot D_2}}. \tag{32}$$

At $D_1=D_2$, expression (29) takes the form

$$\Delta I = \frac{U \cdot \Delta R_{\text{ekv}}}{R_{\text{ekv1}}^2 + R_{\text{ekv1}} \cdot \Delta R_{\text{ekv}} + R_{\text{ekv1}} \cdot c_e \cdot k_{\text{et}} \cdot k_{n2} \cdot V \frac{i \cdot 60}{\pi \cdot D_2}} +$$
$$+ I_1 \cdot V \frac{i \cdot 60 \cdot c_e \cdot k_{\text{et}}}{\pi} \times$$
$$\times \left(- \frac{\Delta R_{\text{ekv}} \cdot k_{n1} \cdot \frac{1}{D_1}}{R_{\text{ekv1}}^2 + R_{\text{ekv1}} \cdot \Delta R_{\text{ekv}} + R_{\text{ekv1}} \cdot c_e \cdot k_{\text{et}} \cdot k_{n2} \cdot V \frac{i \cdot 60}{\pi \cdot D_2}} + \frac{\frac{1}{D_1} \cdot k_{n1}}{R_{\text{ekv1}} + \Delta R_{\text{ekv}} + c_e \cdot k_{\text{et}} \cdot k_{n2} \cdot V \frac{i \cdot 60}{\pi \cdot D_2}} \right). \tag{33}$$

Thus, the approach to identification and assessment of separate factors influencing non-uniformity of current distribution in the power circuit, was developed.

6. Discussion of results of the study of power circuit of traction rolling stock

Results of the research make it possible to argue that to eliminate the magnitude of deviation of currents, it is necessary that $\rho=0$ and $\varepsilon=0$, i. e. numerators of fractions turned into 0. Let us analyze conditions of their being equal to zero.

$$U \cdot \Delta R_{\text{ekv}} = 0, \tag{34}$$

$$\Delta R_{\text{ekv}} \cdot k_{n1} \cdot \frac{1}{D_1} = 0, \tag{35}$$

$$2 \cdot \left(\frac{1}{D_1} - \frac{1}{D_2}\right) \cdot k_{n1} + \frac{1}{D_1} \cdot k_{n1} -$$
$$- k_{n2} \cdot \frac{1}{D_1} - \left(\frac{1}{D_1} - \frac{1}{D_2}\right) \cdot k_{n2} = 0. \tag{36}$$

To satisfy conditions (34) and (35), it is sufficient that there should be no deviation of ohmic resistances in circuits of motors. Under operation conditions, magnitude ΔR_{ekv} is insignificant and can be neglected. As a result of simple transformations, it is seen that to satisfy condition (36), it is necessary that the equality (37) should be satisfied

$$\frac{D_2}{D_1} = \frac{-k_{n2} + 2k_{n1}}{3k_{n1} - 2k_{n2}}. \tag{37}$$

Thus, during selection of wheel-motor units in the depot, it is necessary to try to satisfy the equation (37). If it is necessary to select a wheelset, it is required to use formula (38)

$$D_2 = D_1 \frac{-k_{n2} + 2k_{n1}}{3k_{n1} - 2k_{n2}}. \tag{38}$$

To select a motor, it is necessary to use formula (39)

$$k_{n2} = k_{n1} \frac{3D_2 + 2D_2}{2D_2 - D_1}. \tag{39}$$

If we perform calculations ΔI for a particular locomotive, magnitudes c_e, k_{et}, k_{n1}, k_{n2}, i will completely determine values, constant in operation process. Though D_1, D_2 change, they do it so slowly that for the purposes of this calculation they can be accepted as constant. ΔR_{ekv} is subject to changes under the influence of temperature of heating, i. e. $\Delta R_{ekv} = f(T)$.

In this connection, expressions (30) and (31) take the form

$$\rho = f(U, \Delta\Sigma R, V), \tag{40}$$

$$\varepsilon = f(\Delta\Sigma R, V). \tag{41}$$

Determining of a condition of the absence of difference of currents.

The difference of currents of parallel branches of the power circuit depends on current strength and coefficients ρ and ε in accordance with formulas (29).

If we assume that the $\Delta I=0$, we will obtain

$$0 = \rho + I_1 \cdot \varepsilon.$$

Hence,

$$I_1 = -\frac{\rho}{\varepsilon}. \tag{52}$$

Expression (52) can be considered a condition for the absence of difference of currents, i. e. magnitude of current in traction electric motor must be equal to a negative value of the ratio of ρ to ε for all modes of operation.

Analyzing the above results, it should be noted that they were obtained in order to provide a strictly uniformed distribution of currents by parallel branches of the power circuit. It is not difficult to introduce the expression (52) into the algorithm of functioning of automated regulation systems. However, with regard to the phenomena of dynamic redistribution of loadings from the locomotive's wheelsets during implementation of traction effort [18], there is a possibility of a more perfect control of currents. It is based on estimation of the current value of traction mass of separate axes: a decrease in current of a motor of unloaded wheelset and an increase in current of the motor of additionally loaded axis. However, this approach requires subsequent research. Thus, presented results so far can be recommended to use only during assembly of wheel-motor units under conditions of depot or factories.

Based on the presented models, for obtaining a dynamic condition for maximizing of coefficient of traction mass, it is necessary to carry out further research. The result can be a refined algorithm of automatic control of traction transmission, implementation of which will make it possible to increase operation efficiency of traction rolling stock even more.

7. Conclusions

1. A negative impact of the non-uniformity of current distribution in the power circuit on operation efficiency of locomotives was established. Measurement results show that overall power, implemented by a locomotive, decreases by 30–37 kW (approximately up to 1 %). Traction force also decreases by magnitude of up to 6 kN (up to 1.5 %). That is why it is possible to conclude that there are certain reserves for enhancing operation efficiency of the direct current traction rolling stock (DE1, VL8, VL10 and similar) due to alignment of currents on the motors.

2. The influence of different factors on uniformity of current distribution was detected and assessed. Under operation conditions, such factors include the difference of magnetic characteristics of traction motors (up to 5 %), deviations of resistance of armature circuits and excitation circuits of motors (up to 9 %), difference of diameters of wheelsets' threads within one carriage (up to 1 %) and within a locomotive (up to 2 %).

3. By applying the developed calculation method, it was possible to analyze the impact of various factors on current distribution and relationship between parameters of electric motors, switched on in parallel. They clearly show that deviation of currents is affected not only by certain parameters of wheel-motor units, but also by their connection. The benefit of this method is a possibility of estimation of non-uniformity of current distribution depending on the design of a machine and on connection of design parameters of a wheel-motor unit.

References

1. Koblov R., Novachuk I., Egorov P. New Interpretation of Process of Formation of Tractive Effort of the Locomotive // Procedia Engineering. 2017. Vol. 187. P. 803–808. doi: 10.1016/j.proeng.2017.04.444
2. Dincer I., Hogerwaard J., Zamfirescu C. Integrated Locomotive Systems // Clean Rail Transportation Options. Springer, 2015. P. 115–136. doi: 10.1007/978-3-319-21726-0_6
3. Slivinskiy Y. V., Yu Radin S., Gridchina I. N. The Development of Technical Solutions for the Transverse Arrangement of Wheelsets of the Triaxial Non-Pedestal Bogies for Locomotives // Indian Journal of Science and Technology. 2015. Vol. 8, Issue 34. doi: 10.17485/ijst/2015/v8i34/85275
4. Goryacheva I. G., Soshenkov S. N., Torskaya E. V. Modelling of wear and fatigue defect formation in wheel–rail contact // Vehicle System Dynamics. 2013. Vol. 51, Issue 6. P. 767–783. doi: 10.1080/00423114.2011.602419
5. Fomin O. V. Increase of the freight wagons ideality degree and prognostication of their evolution stages // Scientific Bulletin of National Mining University. 2015. Issue 3. P. 68–76.
6. Energy-Efficient Locomotive Operation for Chinese Mainline Railways by Fuzzy Predictive Control / Bai Y., Ho T. K., Mao B., Ding Y., Chen S. // IEEE Transactions on Intelligent Transportation Systems. 2014. Vol. 15, Issue 3. P. 938–948. doi: 10.1109/tits.2013.2292712
7. Tartakovskyi E., Gorobchenko O., Antonovych A. Improving the process of driving a locomotive through the use of decision support systems // Eastern-European Journal of Enterprise Technologies. 2016. Vol. 5, Issue 3 (83). P. 4–11. doi: 10.15587/1729-4061.2016.80198
8. Liudvinavičius L., Bureika G. Theoretical and practical perspectives of diesel locomotive with DC traction motors wheel-sets' slipping and sliding control // Transport. 2011. Vol. 26, Issue 4. P. 335–343. doi: 10.3846/16484142.2011.633339
9. Garg V. Dynamics of railway vehicle systems. Ottava: Elsevier, 2012. 407 p.
10. De Souza R. R., Gules R. Modeling of a high power IGBT for a 1000A DC-DC converter used to drive diesel-electric locomotive traction motors // 2016 12th IEEE International Conference on Industry Applications (INDUSCON). 2016. doi: 10.1109/induscon.2016.7874500
11. Kelrykh M., Fomin O. Perspective directions of planning carrying systems of gondolas // Metallurgical and Mining Industry. 2014. Issue 6. P. 57–60.
12. Slipping and skidding occurrence probability decreasing by means of the friction controlling in the wheel-braking pad and wheel-rail contacts / Gerlici J., Gorgunov M., Kravchenko K., Domin R., Kovtanets M., Lack T. // Manufacturing Technology. 2017. Vol. 17. P. 179–186.
13. Gorobchenko O. Determination of the parameters of the utility function of the DSS solutions for locomotive brigades // Collection of scientific works of the Ukrainian State University of Railway Transport. 2014. Issue 149. P. 80–87.
14. Butko T. V., Babanin O. B., Horobchenko O. M. Rationale for the type of the membership function of fuzzy parameters of locomotive intelligent control systems // Eastern-European Journal of Enterprise Technologies. 2015. Vol. 1, Issue 3 (73). P. 4–8. doi: 10.15587/1729-4061.2015.35996
15. Pyrhönen J., Jokinen T., Hrabovcová V. Design of rotating electrical machines. New York: John Wiley & Sons, 2013. doi: 10.1002/9781118701591
16. Tong W. Mechanical design of electric motors. Boca Raton: CRC press, 2014.
17. Hetman H. The theory of electric traction. Vol. 1: monograph. Dnipropetrovsk: Makovetsky Publishing House, 2011. 456 p.
18. Simson S. A., Cole C. Simulation of curving at low speed under high traction for passive steering hauling locomotives // Vehicle System Dynamics. 2008. Vol. 46, Issue 12. P. 1107–1121. doi: 10.1080/00423110701883163