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АВТОМАТИЗОВАНІ СИСТЕМИ УПРАВЛІННЯ НА ТРАНСПОРТІ

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POTENTIALS RAILWISE PROPAGATION STUDY

Purpose. The article deals with conducting the study of the potentials and currents propagation along the rails to evaluate the potential difference and the current asymmetry in the rails that may have an impact on the work of railway automatics and supervisory systems. **Methodology.** To compass the purpose, the author applies methods of analysis and synthesis of track circuit electrical engineering calculations, mathematical modeling and methods of homogeneous and heterogeneous ladder circuits. **Findings.** The conducted theoretical studies indicate that in the mountainous sections of DC traction railways there are very high-level currents, whereby even at nominal asymmetry ratio the asymmetry current will be unacceptably high. The re-equipment of running line with the automatic blocking system with tonal rail circuits resulted in reduction of the number of impedance bonds, the equalizing functions of which required further advanced research, that allowed obtaining the potential railwise propagation curves when installing the impedance bonds every 6 and 5 km. The resulting potential difference was too high for railway automation systems, so the potential propagation study was conducted with impedance bonds placed every 3 and 3.5 km, which greatly improved the operation conditions of track circuits. **Originality**. The proposed method for calculating the propagation of potentials and currents in the rail network of DC traction line is characterized by the representation of the common ladder circuit of each rail as a series of T-shaped four-poles connected in cascade, taking into account the grounding of the contact-line supports on the nearer rail. It has allowed estimating the levels of asymmetry currents that branch into the equipment of track circuits and have a negative impact on their operation. **Practical value.** The obtained results can be used in designing and re-equipping the running lines with new railway automatics and supervisory systems, as well as for evaluating the influence of high asymmetry currents on the railway automation systems operation.

Keywords: traction currents; track circuits; impedance bond; asymmetry current; potentials propagation

Introduction

Traction current has a significant impact on the operation of automatic block systems (AB) [1]. There are rail sections where it reaches very high levels, resulting in melting of track choke cables. Such are the mountain sections of railways with electric drive of direct current. In this way, the problem of railwise propagation of potentials caused by traction current becomes actual, the study of which will allow to estimate the difference between the derived potentials and the negative impact on the equipment of the track circuits (TC), in particular, the tonal ones (TTC).

Purpose

The purpose of the work is to study the propagation of potentials along the rails in order to evaluate the impact of traction current on TTC operation. This will enable us to take a number of necessary technical measures to combat asymmetry, as well as to investigate their effectiveness in advance.

Methodology

As noted, high levels of traction currents are peculiar for mountain railways. This can be ex-

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plained by the presence of steep climbs, to overcome which the locomotive requires large traction effort, provided by 2-3 electric locomotives. The work examined the mountainous section with DC electric traction of Lavochne – Beskid – Skotarskoye of Lviv Railways. As a result of the carried out researches it was established that traction currents reach 7000 A on this site and it is expedient to re-equip the section AB with 50 Hz frequency TC onto the ABTK system, which uses TTC without isolating joints [2], resulting in reduced number of impedance bonds (IB), as in fact, in the case of TTC, they are installed only for the potential alignment in the rails, while the IBs pass less current. This greatly facilitates the operation of the track circuits on the running line because the impedance bond is a weak point in the TC, especially in the presence of large traction currents [3].

If we take into account such an important parameter as the asymmetry ratio, then its limiting value according to the technical conditions is equal to $k_{\text{a}} = 0.12$. In this case, the difference in rail currents will be equal to $\Delta\text{I} = 432\ \text{A}$. In practice, the asymmetry ratio can reach 0.2. As a result of the high traction currents flow, normal operation of IBs is violated due to their inadmissible heating and magnetization [4]. As a result of thermal overheating, IB may even break down. The common occurrence is the IB core saturation, resulting in a decrease in the IB input impedance to signal current, which may lead to the voltage reduction on the track receiver up to the voltage value of non-attraction of relay armature. Consequently, the asymmetry current increase can cause a parametric failure of the TC.

Since the rails are not isolated, part of the reverse traction current flows through the ground. This fact has a significant impact on a number of phenomena, in particular, the traction network resistance and TC operation [5]. The earth leakage current from rails depends on the potential difference between the rails and the ground and the resistance of the circuit through which this current flows. The circuit consists of two consecutive parts. The first part is the resistance of the transition point of the current from the rails to the sleepers and ballast; the second part is the resistance of the ground itself on the path of leakage current.

For the analysis of the spread of traction current along the rails, regardless of the train situation and the section complexity, it is necessary to determine the load of the substations [6]. To simplify the calculation, we can accept some assumptions that will not make a tangible error. With good insulation of rails from the ground in the absence of earth leakage, the train loads can be distributed between substations in the usual way – inversely proportional to distances to the neighbouring substations (with constant area of the section of the overhead wires and the same voltage of traction substations). If the transition resistance from the rails to the ground will be minimal, then a significant part of the current will flow on the ground and, in the distribution of loads between the substations, one can neglect the resistance of the earth return [7] (rails shunted to earth), since it is much less than the resistance of the overhead wires. The latter will mostly determine the current distribution. It can be assumed that wandering currents do not significantly affect the current distribution between substations [8].

Before carrying out the research it is necessary to determine the load of the traction substations [9]. The current of the first substation – I_1, the second one – I_3, the current of the locomotive – I_2. The distances from the substation to the locomotive are known. Then the load of the traction substations (their currents) can be found, based on the distances from the locomotive to each of the substations. Thus, the traction current of the first substation is determined by: $I_1 = \frac{l_2 - l_1}{l_2} \cdot I_2 = 4\,200\ \text{A}$. Traction current of the second substation: $I_3 = \frac{l_1}{l_2} \cdot I_2 = 2\,800\ \text{A}$.

Once the load of all substations has been determined, we can go to the calculation circuit. In the calculations the following resistances play a great role: r_{t} – resistance of 1 km of track, Ohm·km; r_{T} – transient resistance from rails to earth at a length of 1 km, Ohm/km; r_e – earth resistance.

If the resistances r_{t} and r_{T} are constant over the entire length, then we obtain a circuit with constant parameters, that is, a circuit line. When calculating such circuits, the superposition method can be used. In this case, a complex contour containing several substations and loads can be replaced with a number of contours, in each of which flows a

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certain current. The calculation circuit contains one load when the earthing connector is infinitely distant. At the same time, all loads are considered in turn, taking into account the currents of substations.

The basis for analytical study of the distribution of constant voltages and currents along the rail line (RL), which is an electric long line, are differential equations of the Helmholtz type [10]. At the line input there is a source of reverse traction current leakage, herewith the expressions for the distribution of voltage and current along the line have the form, $\frac{dU}{dx} = Z_0 I$, $\frac{dI}{dx} = \varphi_0 U$. Solutions of these equations lead to the following equations:

$$\frac{d^2U}{dx^2} - \gamma^2 U = 0, \ \frac{d^2I}{dx^2} - \gamma^2 I = 0, \qquad (1)$$

Where $\gamma_0 = \sqrt{R_0 \cdot Y_0} = \alpha$, $(\mathrm{Np/km})$; α – RL propagation coefficient at constant current; R_0, Y_0 – specific rail resistance $(\mathrm{Ohm/km})$ and isolation conductivity $(\mathrm{Cm \cdot km})$ of element of the line Δx.

Each track is replaced by two two-wire homogeneous ladder circuits (HLC) «rail-earth» [11] and is presented by T-shaped four-poles sequentially connected in a cascade (Fig. 1). The estimated area of the RL can be taken of any length, we conditionally take l=3 km, it will contain N=6 identical segments of the line of 0.5 km (the quantization scale can be varied, it is determined by the line simulation accuracy).

If we neglect the resistance of IB to direct current, then both of the HLCs of the line «rail – earth» are shorted, providing alignment of the potentials of both rails with each other.

During circuit design it is taken into account that the parameters of the equivalent network (C3 EN) of the lines can vary widely, and with the relatively low isolation resistance, the input/output resistance of HLC 1, 2 are equal to characteristic ones. Then, the traction current load of each line at the boundary of the block sections is the resistance of the IB half-coils ($\approx 0.006\,\mathrm{Ohm}$), indicating the operation of each of these HLC lines in the short-circuit mode (SC).

General solutions for equation (1) can be written for a symmetric four-pole in x coordinate system and in A-parameters. We consider the voltage U_{n+1} and current I_1 at HLC input ($x = l$) as given. Then the equation of the four-pole for the entire circuit can be written as follows:

$$\begin{aligned} U_2 &= U_1 \cdot \mathrm{ch}\Gamma N - I_0 \cdot R_\mathrm{c} \cdot \mathrm{sh}\Gamma N; \\ I_2 &= -U_1 \cdot \frac{\mathrm{sh}\Gamma N}{R_\mathrm{c}} + I_1 \cdot \mathrm{ch}\Gamma N. \end{aligned} \qquad (2)$$

The equations (2) correspond to the equations of symmetrical four-poles in A-parameters, if adopted:

$$\begin{aligned} &A_{11} = \mathrm{ch}\Gamma N; \ A_{12} = R_\mathrm{c} \cdot \mathrm{sh}\Gamma N; \\ &A_{21} = \frac{\mathrm{sh}\Gamma N}{R_\mathrm{c}}; \ A_{22} = \mathrm{ch}\Gamma N. \end{aligned}$$

For one link HLC can be recorded

$$\frac{U_{n+1}}{U_n} = e^{\Gamma}; \ \frac{I_{n+1}}{I_n} = e^{\Gamma},$$

Whence $\Gamma = \ln\left(\frac{U_{n+1}}{U_n}\right) = \ln\left(\frac{I_{n+1}}{I_n}\right)$ – transfer constant (weakening) of the link (in long lines it is the analogue of $\gamma \cdot l$), herewith

U_{n+1}, I_{n+1} – voltage and current at the input of $n+1$-th link; U_n, I_n – voltage and current at the input of n-th link; $R_\mathrm{c} = \sqrt{\frac{R_0}{Y_0}}$ – characteristic resistance of the line.

Permanent transfer of the entire HLC is characterized by the ratio of voltages at the beginning and at the end of the HLC:

$$\Gamma_\mathrm{c} = \ln\left[\left(U_1 / U_{1.2}\right)\left(U_{1.2} / U_{2.3}\right) \ldots \left(U_{n-1} / U_2\right) \right],$$

where U_n, U_{n+1} – voltage at the input of the link N, counting from end to start; U_{n+1}, U_{n+2} – voltage at the input of the link $n+1$, counting from end to start.

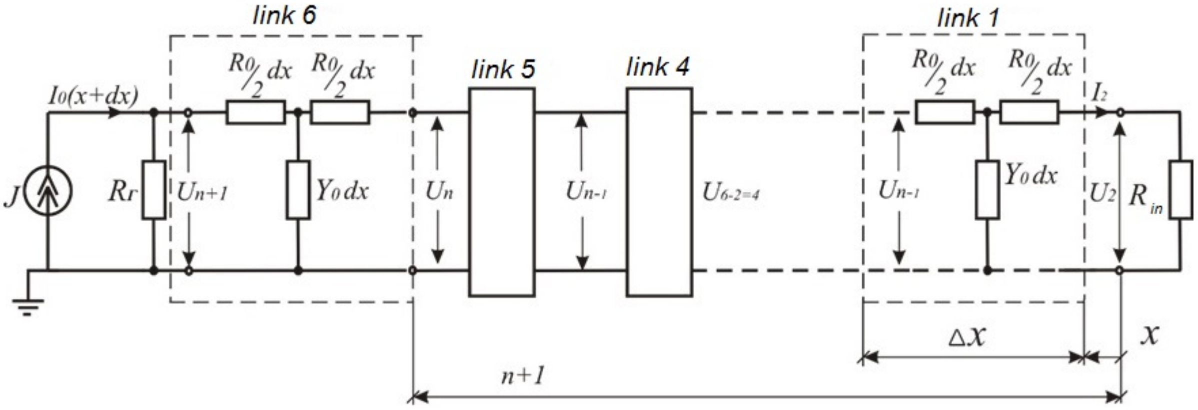

Fig. 1. Homogeneous circuit «rail-earth» with T-links

Consequently, the transfer constant $\Gamma_c = \Gamma \cdot N$. The calculated parameters of the T-shaped circuit «rail-earth» of the HLC-1 track are R_0 and Y_0. The resistance of the rail loop to direct current is $0.1\ \text{Ohm/km}$ (with copper rail bonds or steel duplicated ones) then the resistance of one rail is $0.05\ \text{Ohm/km}$. Herewith, the resistance of the rail of the (butting) link track consists of two components. As the practice of operation shows, both of these components are random variables and depend on a number of random factors such as ambient temperature, specific resistance of the steel, bond resistance, which depends on the quality of weld, the number of torn wire ropes, etc. The calculations adopt the regulatory values of the parameter R_0. The rail insulation conductivity Y_0 is also a parameter that depends on many random factors: ballast material (crushed stone, sand), type of sleepers and term of their operation, humidity and ambient temperature, foreign impurities clogging the ballast section (mineral salts, coal, etc.). The operation experience shows that Y_0 can vary from 10 to $0.02\ \text{Cm} \cdot \text{km}$.

When connecting any types of grounding devices to the rails in double rail track circuits, in order to prevent the shunting of the latter, all grounding devices must be connected to one rail line [12]. In the case of connection of grounding devices to the rail with two conductors, the distance between their connections should be minimal and should not exceed 200 mm. The last requirement is determined by the fact that the continuity fault of the rail line between the conductor connection points is not controlled. The connection of grounding devices to one rail line of double rail circuits creates a transverse asymmetry of the rail line [13]. Parameters for calculating HLC-2 (of the second rail) are selected taking into account the ground of the contact line supports (3). Conductivity and resistance of general rail ground:

$$G_{02} = Y_0 + Y_{\text{sp}},$$
$$R_{32} = \frac{R_{\text{i}} \cdot R_{\text{sp}}}{R_{\text{i}} + R_{\text{sp}}} \qquad (3)$$

where $Y_{\text{sp}}, R_{\text{sp}}$ – conductivity and resistance of the support ground.

At the same time, the conductivity Y_0 during the year to a lesser extent depends on the temperature, since the depth of landing in the soil is more than 3 m. In the summer, the conductivity of the supports can reach 0.3–0.4 cm, due to unsatisfactory maintenance of the spark gaps IPM-62. Also, the analysis of operating experience and calculations shows that the most unfavourable period of the rail line operation is winter, because then the potentials and currents can reach the highest value.

Consequently, according to the proposed method, each rail is considered separately as an HLC consisting of a certain number of T-shaped four-poles. Output parameters of one of the HLC are selected taking into account the grounding of the contact line supports. The use of the given methodology resulted in writing the program in Maple programming environment [14, 15], which allows to obtain the diagrams of the propagation of currents and potentials along the rails.

Calculations are made for each of the rails separately by the four-pole method. The output potential of one four-pole will be input for the next four-pole. While the greater the number of four-poles, the greater the accuracy of the data received.

The number of four-poles is given in the output data. The received curves of the propagation of currents and potentials along each of the rails give an opportunity to evaluate the asymmetry currents in the rails.

Findings

As can be seen from the obtained dependencies (Fig. 2, *a, b*), the potential levels for each of the rails will be different. Their difference will fall near the IBs, which align the potentials on the rails. It should be noted that the potential difference ($\Delta\varphi$) in the middle of the section between the IB onnection and the train will be maximal [16].

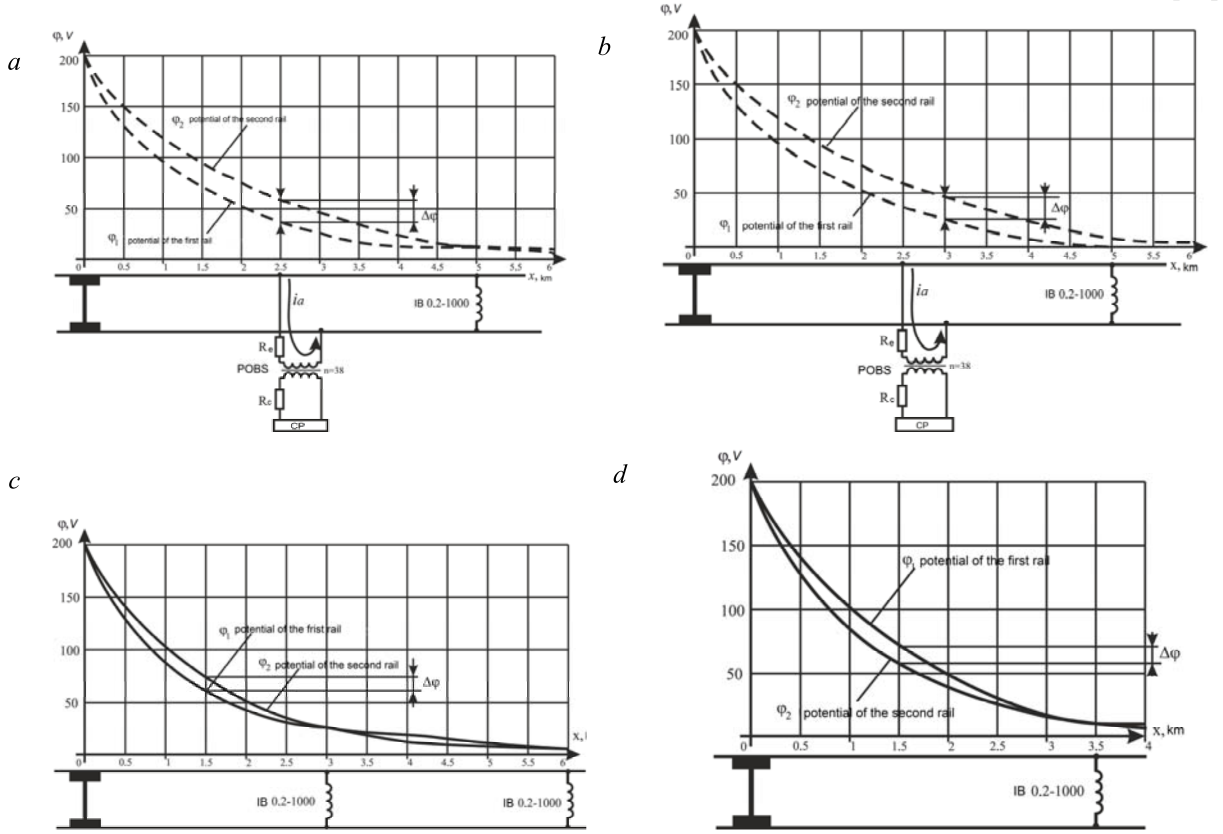

Fig. 2. Potentials railwise propagation with IB:
a – installed every 5 km; *b* – installed every 6 km;
c – installed every 3 km; *d* – installed every 3,5 km

For example, in Figure 2, *a*, which shows the potentials railwise propagation with IB installed every 5 km $\Delta\varphi = 34$ V. This indicator is quite high, since it will have a negative impact on the operation of RC equipment. When installing IB every 6 km (Fig. 2, *b*) $\Delta\varphi$ will be 37 V.

In order to reduce the potential difference, it was proposed to set equalizing IB with a smaller interval. Figures 2, *c*, *d* present the curves of potentials railwise propagation when IB installed every 3 km and 3.5 km, which show that at a distance of 1.5 km $\Delta\varphi$ will be maximum and will equal 14 V. This indicator is completely satisfactory for the operation of railway automation devices [17].

Figure 3 shows the dependence of the potential difference from the IB installation interval. Curve 1 shows the change in the potential difference with IB installed every 5 km, curve 2 – with IB installed every 3 km. This graph confirms the expediency of the proposed reduction in the IB installation interval, because the maximum values $\Delta\varphi$ between the two curves vary significantly.

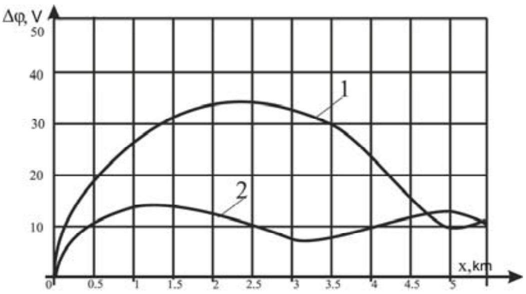

Fig. 3. Dependence of the potential difference from the IB installation interval

Originality and practical value

The proposed method for calculating the propagation of potentials and currents in the rail network of DC traction line is characterized by the representation of the common ladder circuit of each rail as four-poles, taking into account the grounding of the contact-line supports on the nearer rail. It has allowed estimating the levels of asymmetry currents that branch into the RC equipment. The obtained results can be used in designing and re-equipping the running lines with new railway automatics and supervisory systems (RAS), as well as for evaluating the influence of high asymmetry currents on RAS systems operation.

Conclusions

The study of impact of high levels of traction currents on the equipment of AB systems was carried out. The method for calculating the propagation of potentials and currents along the rails for the railway sections with DC electric traction was improved. It consists in the study of propagation of φ of each individual rail, which is represented as HLC «rail-earth» and presented as a series of T-shaped four-poles connected in cascade, taking into account the grounding of the contact-line supports on the end rail.

The proposed method allowed carrying out the potentials railwise propagation study with IB installed every 6 and 5 km (Fig. 2, *a*, *b*). The potential difference was too large for uninterrupted functioning of RAS equipment. Therefore, it was proposed to shorten the IB installation interval to 3 and 3.5 km [18]. As shown in the received diagrams and in the resulting comparative graph in Figure 3, the proposed solution is appropriate.

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ДОСЛІДЖЕННЯ РОЗПОВСЮДЖЕННЯ ПОТЕНЦІАЛІВ УЗДОВЖ РЕЙОК

Мета. У науковій роботі передбачається проведення дослідження розповсюдження потенціалів та струмів уздовж рейок із метою оцінки різниці потенціалів і струму асиметрії у рейках, які можуть здійснювати вплив на роботу систем залізничної автоматики та телемеханіки. **Методика**. Для досягнення поставленої мети застосовані методи аналізу та синтезу електротехнічних розрахунків схем рейкових кіл, математичного моделювання, методи однорідних та неоднорідних ланцюгових схем. **Результати**. Проведені теоретичні дослідження свідчать про те, що на гірських ділянках залізниць з електричною тягою постійного струму протікають струми дуже високих рівнів, за яких навіть при номінальному коефіцієнті асиметрії струм асиметрії буде недопустимо великим. У результаті переобладнання перегону системою автоблокування з тональними рейковими колами скоротилася кількість дросель-трансформаторів, вирівнюючи функції яких потребували подальшого досконалого дослідження. Були отримані епюри розповсюдження потенціалів уздовж рейок при встановленні вирівнюючих дросель-трансформаторів кожні 6 та 5 км. Отримані різниці потенціалів виявилися зависокими для роботи систем залізничної автоматики, тому було проведено дослідження розповсюдження потенціалів при інтервалі розташування дросель-трансформаторів кожні 3 та 3,5 км, що значно покращило умови роботи рейкових кіл. **Наукова новизна**. Запропонований метод розрахунку розповсюдження потенціалів та струмів у рейковій мережі перегону електричної тяги постійного струму відрізняється представленням загальної цепної схеми кожної рейки у вигляді послідовно з’єднаних в каскад Т-подібних чотириполюсників із урахуванням заземлення опор контактної мережі на ближню рейку. Це дозволило оцінити рівні струмів асиметрії, які відгалужуються в апаратуру рейкових кіл та здійснюють негативний вплив на їх роботу. **Практична значимість**. Отримані результати можуть використовуватися при проектуванні та переобладнанні перегонів новими системами залізничної автоматики та телемеханіки, а також для оцінки впливу високих струмів асиметрії на роботу систем залізничної автоматики.

Ключові слова: тягові струми; рейкові кола; дросель-трансформатор; струм асиметрії; розповсюдження потенціалів

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ИССЛЕДОВАНИЕ РАСПРОСТРАНЕНИЯ ПОТЕНЦИАЛОВ ВДОЛЬ РЕЛЬСОВ

Цель. В научной работе предполагается проведение исследования распространения потенциалов и токов вдоль рельсов с целью оценки разности потенциалов и тока асимметрии в рельсах, которые могут оказывать влияние на работу систем железнодорожной автоматики и телемеханики. **Методика**. Для достижения поставленной цели применены методы анализа и синтеза электротехнических расчетов схем рельсовых цепей, математического моделирования, методы однородных и неоднородных цепных схем. **Результаты**. Проведенные теоретические исследования свидетельствуют о том, что на горных участках железных дорог с электрической тягой постоянного тока протекают токи очень высоких уровней, при которых даже при номинальном коэффициенте асимметрии ток асимметрии будет недопустимо большим. В результате переоборудования перегона системой автоблокировки с тональными рельсовыми цепями сократилось количество дроссель-трансформаторов, выравнивающие функции которых требовали дальнейшего досконального исследования. Были получены эпюры распространения потенциалов вдоль рельсов при установке уравнивающих дроссель-трансформаторов каждые 6 и 5 км. Полученные разности потенциалов оказались слишком высокими для работы систем железнодорожной автоматики, поэтому было проведено исследование распространения потенциалов при интервале расположения дроссель-трансформаторов каждые 3 и 3,5 км, что значительно улучшило условия работы рельсовых цепей. **Научная новизна**. Предложенный метод расчета распространения потенциалов и токов в рельсовой сети перегона электрической тяги постоянного тока отличается представлением общей цепной схемы каждого рельса в виде последовательно соединенных в каскад Т-образных четырехполюсников с учетом заземления опор контактной сети на ближний рельс. Это позволило оценить уровни токов асимметрии, которые ответвляются в аппаратуру рельсовых цепей и оказывают негативное влияние на их работу. **Практическая значимость.** Полученные результаты могут использоваться при проектировании и переоборудовании перегонов новыми системами железнодорожной автоматики и телемеханики, а также для оценки влияния высоких токов асимметрии на работу систем железнодорожной автоматики.

Ключевые слова: тяговые токи; рельсовые цепи; дроссель-трансформатор; ток асимметрии; распространение потенциалов

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