**UDC 629.423.14**

**Yu.O. Slobodenyuk**,
**O.V. Bialobrzeski**, PhD,
**T.O. Smirnova**
Kremenchuk Mykhailo Ostrohradskyi National University, 20 Pershotravneva Str., 39600 Kremenchuk, Ukraine; e-mail:
jul.alexandrovna@gmail.com

# SIMULATION MODEL OF INSTANTANEOUS ELECTRICAL AND POWER PARAMETERS OF MODE AND QUALITY OF ELECTRICITY FOR DC TRACTION POWER SYSTEMS

*Ю.О. Слободенюк, О.В. Бялобржеський, Т.О. Смірнова.* **Імітаційна модель розрахунку миттєвих електричних та енергетичних параметрів режиму системи тягового електропостачання постійного струму.** Характер споживання електричної енергії в системах тягового електропостачання зумовлює завантаження тягових підстанцій. На підставі аналізу попередніх досліджень якісних характеристик роботи системи тягового електропостачання постійного струму виявлено недоліки, пов'язані з роботою керованих силових перетворювачів на тяговій підстанції постійного струму та на електровозі. В свою чергу, подальше збільшення рухомого складу з регульованими перетворювачами ставить задачу дослідити вплив його роботи на величину гармонік напруги й струмів у контактній мережі. ***Мета:*** Метою роботи є розробка імітаційної моделі розрахунку миттєвих електричних, енергетичних параметрів режиму та показників якості електричної енергії для системи тягового електропостачання постійного струму за умов спотворення струму. ***Матеріали і методи:*** З використанням методів теорії електротехніки розроблено модель для безперервного розрахунку миттєвих параметрів режиму систем тягового електропостачання постійного струму. ***Результати:*** На підставі аналізу структури тягової електричної частини сучасних електровозів, які отримують енергію контактною мережею постійного струму, встановлено, що електроенергетичний режим можливо якісно охарактеризувати тільки з урахуванням вищих гармонійних параметрів режиму. Вплив параметрів контактної мережі, зважаючи на наявність гармонійних складових у струмі та напрузі, вимагає врахування при розрахунках режиму як омічного опору, так і індуктивності елементів мережі. Отримані результати можуть бути використані при формуванні вимог до систем обліку електричної енергії на ділянках залізниць, де експлуатують електровози з тяговим електротехнічним комплексом, який має напівпровідникові перетворювачі.

*Ключові слова*: система тягового електропостачання постійного струму, графік руху, показники якості електроенергії.

*Yu.O. Slobodenyuk, O.V. Bialobrzeski, T.O. Smirnova.* **Simulation model of instantaneous electrical and power parameters of mode and quality of electricity for DC traction power systems.** The nature of the electricity consumption in TPS makes the loading of traction substations. On the basis of previous studies of qualitative characteristics of the DC traction power system, the shortcomings related to work of driven power transformers at DC substation and at the electric locomotives were identified. Thus, further increasing of electric railway equipment with adjustable converters sets the problem to investigate the influence of its work on the magnitude of harmonic of voltage and current in the catenary system. ***Aim:*** The aim of this research is to develop a simulation model of instantaneous electrical and power parameters of mode and quality of electricity for DC traction power systems under conditions of current distortion. ***Materials and Methods:*** Using the methods of the theory of electrical engineering, the model for continuous calculation of instantaneous mode parameters of the DC traction power systems is developed. ***Results:*** Based on the analysis of the structure of modern traction electric part of electric locomotives that get energy via DC catenary system, we found that the electricity regime may be described qualitatively only considering the higher harmonic settings of the operation mode. Influence of parameters of a catenary system, due to the presence of harmonic components in the current and voltage requires consideration in the calculation regime the effective resistance as well as the inductance of circuit elements. The obtained results can be used in the formation of the requirements for electricity metering at sites of railways where operated electric locomotives with traction electrical complex, which has a semiconductor converters.

*Keywords*: DC traction power supply system, timetable, quality indicators of electricity.

**Introduction.** The traction power system (TPS) is electrical circuit, areas of which are connected by wires of 3.3 kV power traction substations. The nature of the electricity consumption in TPS makes the loading of traction substations. The main reasons that influence the deterioration of the quality of electric energy (QEE) in TPS, include: operation of electric railway equipment with adjustable transducer [1], which generate improper harmonic components in catenary system; presence at the site TPS of electric railway equipment moving in regenerative braking mode; the difference in voltage levels on the tires of adjacent traction substations; various modes and equipment characteristics of related traction substations [2, 3]. Deterioration of QEE leads to additional technical power losses and thereby degrades the performance of TPS and electric locomotive.

**DOI 10.15276/opu.1.51.2017.13**

Further increasing of electric railway equipment with adjustable converters sets the problem to investigate the influence of its work on the magnitude of harmonic of voltage and current in the catenary system. This problem is compounded by the fact that at one site of a power system that receives power from neighboring substations can run several electric locomotives with adjustable converters [4]. Therefore, to solve this issue we set the task to develop of simulation model for calculating of the instantaneous parameters of DC TPS that can use to explore the electrical, power parameters of system and power quality distortion.

The issue of power quality and power losses in electrical traction system is considered in several studies [1...3]. Thus, *Kashtanov* and *Komiakova* [2] considered the method for assessing the overflow capacity in DC TPS and data processing algorithms for monitoring power losses caused by overflows of power. *Slobodchikov* [1] considered the issue of electromagnetic compatibility of DC TPS and electric locomotive with adjustable converters – namely the issue of higher harmonics voltage and their influence on the work of the equipment of electric locomotive and TPS. *Mishchenko* [3] conducted the theoretical investigation of quality indicators of electricity and executed their quantitative assessment.

However, it remains an actual task of assessing the impact of harmonics generated by converters of electric locomotive in catenary system, on the value of power losses in DC TPS. Important is the ability to calculate these parameters in continuous mode in a particular area of interstation period – namely, performance calculation of system based on a simulation model that takes into account alternating position of electric locomotive, moving on the area, and power that it consumes.

The result of the simulation is the calculation of currents distribution between substations and distribution of losses of voltage and power for each electric locomotive at the connection point. Take into account the conditional constancy of the voltage and current, we selected such QEE indicators: constant components, harmonics of power loss and distortion coefficient.

**The aim** of this research is to develop a simulation model of instantaneous electrical and power parameters of mode and quality of electricity for DC traction power systems under conditions of current distortion.

**Materials and Methods**. For electrified railways mainly used MF brand contact wires with cross-sectional area of 150 mm$^2$, 100 mm$^2$ for the main tracks, and 85 mm$^2$ – for the station. In most cases at the DC ways under of current removing hung two contact wires. Sometimes, instead of two MF-100 contact wires it is possible to manage one wire with cross-sectional area of 150 mm$^2$ [5]. In this case, in the calculations of catenary system mode by known methods [5] using active resistance. Given the pulsating nature of the current, we should consider the impact of the phenomenon of electromagnetic induction by inserting into equivalent circuits of substitution the parameter which corresponds to inductance. Thus, analysis of processes in the DC power network close to analysis in AC power network.

Real voltage $u_d$ generated by the rectifier of DC traction substations and regulated electric converter has a pulsations. $u_d$ voltage can be represented as the sum of the constant component of rectified voltage $U_d$ and variable component $u_{dk}$, consisting of an infinite number of harmonics [6]. With symmetrical supply voltage for the six pulse transformers, which are used as a part of the equipment of DC traction substations, the pulsation frequency is 300 Hz.

The variable component $u_{dk}$ creates in a circle of "catenary system – electric locomotive – rail" AC current $i_{dk}$, which consists of the same harmonics as $u_{dk}$. Due to this factor, in the catenary system we need to take into account the inductance, then full resistance of catenary system can be calculated as

$$Z(\omega,l)=\sqrt{R(l)^2+X_L(\omega,l)^2}; \tag{1}$$

where $R(l)$ – full contact active resistance of catenary system area, Ohm;

$X_L(\omega,l)$ – full contact inductive resistance of catenary system area, Ohm;

$\omega$ – angular frequency of network, radians;

$l$ – length of catenary system, km

In other words, an active resistance of DC catenary system, where pulsations take place, is a function that depends on distance covered by electric locomotive, and inductive resistance is a function of length of the catenary system and frequency of pulsation of higher harmonics that when changing position of electric locomotive also changing.

By analogy to the AC TPS with duplicate electric power supply [6], we built the equivalent circuit of TPS area (Fig. 1), where $A$, $B$ – traction substations; $u_A$, $u_B$ – traction substations power supply; 1, 2 – electric locomotives that are powered by TPS; $i_1$, $i_2$ – current consumed by electric locomotive 1 and 2, respectively; $l_1$, $l_2$ – distance from the electric locomotive $l$ to the substation $A$ and from electric locomotive 2 to substation $B$ respectively; $l_{AB}$ – distance between substations; $l_{12}$ – distance between electric locomotives; $R_{A1}$, $R_{12}$, $R_{B2}$ – active resistance at sites, $L_{A1}$, $L_{12}$, $L_{B2}$ – inductance at sites. The capacitive susceptance is neglected according to [1], the values of $L$ and $r$ correspond to linear inductance and active resistance for TPS with capacity of 3.3 kV and numerically equal to $L$=0.0001 H/km and $r$=0.01 Ohm/km [3]. Distance between substations adopted $l$=25 km.

Considering that rate of variable component of the catenary system current, the occurrence of which is due to work of converters, is higher than the speed of the an electric locomotive, a feeder current of traction substation and corresponding voltage drop on the line of the catenary system calculated by the formula [4]:

$$i_A = i_1 - \frac{i_1 l_{A1}}{l_{AB}} + \frac{i_2 l_{B2}}{l_{AB}}; \quad i_B = \frac{i_1 l_{A1}}{l_{AB}} - \frac{i_2 l_{B2}}{l_{AB}} + i_2; \quad i_C = \frac{i_1 l_{A1}}{l_{AB}} - \frac{i_2 l_{B2}}{l_{AB}}, \tag{2}$$

$$\Delta u_{A1} = \left| \begin{array}{l} \left( i_1 - \frac{i_1 l_{1A}}{l_{AB}} + \frac{i_2 l_{2B}}{l_{AB}} \right) R_0 l_{A1} + L_0 l_{A1} \frac{d}{dt} \left( i_1 - \frac{i_1 l_{1A}}{l_{AB}} + \frac{i_2 l_{2B}}{l_{AB}} \right), \text{ if } l_{1A} \le l_{2B}; \\ \left( i_2 - \frac{i_2 l_{2B}}{l_{AB}} + \frac{i_1 l_{1A}}{l_{AB}} \right) R_0 (l_{AB} - l_{A1}) + L_0 (l_{AB} - l_{A1}) \frac{d}{dt} \left( i_2 - \frac{i_2 l_{2B}}{l_{AB}} + \frac{i_1 l_{1A}}{l_{AB}} \right), \text{ if } l_{A1} \le l_{2B} \end{array} \right. \tag{3}$$

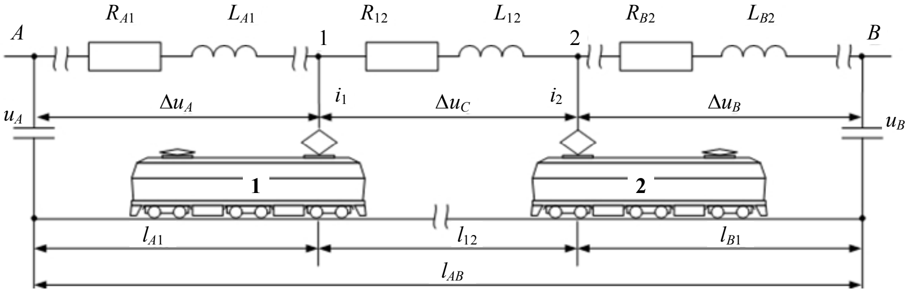

*Fig. 1. TPS replacement scheme*

Thus, in general, current and voltage of a catenary system are different from constant value, due to the operation of power equipment of traction substation and electric stock. By analogy with [7], they can be presented by two components: fundamental parameters $i_1$, $u_1$, and rest parameters $i_H$, $u_H$:

$$\begin{gathered} i = i_1 + i_H = \sqrt{2} I_1 \sin(\omega t + \psi_{i1}) + I_0 + \sum_{k \ne 1} \sqrt{2} I_k \sin(k\omega t + \psi_{ik}); \\ u = u_1 + u_H = \sqrt{2} U_1 \sin(\omega t + \psi_{i1}) + U_0 + \sum_{k \ne 1} \sqrt{2} U_k \sin(k\omega t + \psi_{uk}), \end{gathered} \tag{4}$$

where $U_0$, $I_0$ – constant components of voltage and current, respectively;

$U_k$, $I_k$ – amplitudes of harmonic components of voltage and current, respectively;

$\psi_{ik}$, $\psi_{uk}$ – initial phase of harmonic of voltage and current, respectively.

Power is defined as the product

$$p = ui; \tag{5}$$

and divided into active and inactive components

$$p = p_a + p_q; \tag{6}$$

where inactive component does not ensure the transfer of power and only causes the additional losses in the power system [8]. These power components are the product of voltage by current with further division as follows:

$$\begin{aligned} p_a &= U_0 I_0 + \sum_k U_k I_k \cos\varphi_k \left[1 - \cos(2k\omega t + 2\psi_{ik})\right]; \\ p_q &= -\sum_k U_k I_k \sin\varphi_k \sin(2k\omega t + 2\psi_{uk}) + 2\sum_{k\neq n} U_k I_n \sin(n\omega t + \psi_{in}) \sin(k\omega t + \psi_{uk}) + \\ &+ \sqrt{2} U_0 \sum_k I_k \sin(k\omega t + \psi_{ik}) + \sqrt{2} I_0 \sum_k U_k \sin(k\omega t + \psi_{uk}). \end{aligned} \tag{7}$$

where $\psi_k = \psi_{uk} + \psi_{ik}$.

This presentation of power components substantiated in studies [8, 9]. It should be noted that the active power is determined only by scalar product of working values of current and voltages harmonic which vary with the same frequency. This power $P$ is divided into components – fundamental $P_1$ and non-fundamental $P_H$ as follows:

$$\begin{cases} P = \dfrac{1}{kT} \displaystyle\int_{\tau}^{\tau+kT} p\,dt = \dfrac{1}{kT} \displaystyle\int_{\tau}^{\tau+kT} p_a\,dt = P_1 + P_H \\ P_1 = \dfrac{1}{kT} \displaystyle\int_{\tau}^{\tau+kT} u_1 i_1\,dt = U_1 I_1 \cos\varphi_1 \\ P_H = U_0 I_0 + \displaystyle\sum_{k\neq 1} U_k I_k \cos\varphi_k = P - P_1 \end{cases} \tag{8}$$

Fundamental reactive power [7] is defined as

$$Q_1 = \frac{\omega}{kT} \int_{\tau}^{\tau+kT} i_1 \left[\int u_1\,dt\right] dt = U_1 I_1 \sin\varphi_1. \tag{9}$$

Also, used the concept of apparent power

$$S = UI \tag{10}$$

where $U$, $I$ – current value of voltage and current.

However, apparent power is divided into fundamental [7]

$$\begin{aligned} S_1 &= U_1 I_1; \\ S_1^2 &= P_1^2 + Q_1^2, \end{aligned} \tag{11}$$

which corresponds to known representation of power for monoharmonic currents and voltages, and non-fundamental

$$S_N^2 = S^2 + S_1^2. \tag{12}$$

Non-fundamental apparent power, in turn, divided into three parts

$$S_N^2 = D_I^2 + D_U^2 + S_H^2, \tag{13}$$

where $D_I$ – current-distortion power

$$D_I = U_1 I_H, \tag{14}$$

$D_U$ – voltage-distortion power

$$D_U = U_H I_1, \tag{15}$$

$S_H$ – harmonic apparent power

$$S_H = U_H I_H = \sqrt{P_H^2 + D_H^2}, \tag{16}$$

where $D_H$ – harmonic-distortion power

$$D_H = \sqrt{S_H^2 - P_H^2}\,. \tag{17}$$

Summarizing the effects of distortion and reactive power we injected an inactive power

$$N^2 = S^2 - P^2\,. \tag{18}$$

The above mentioned power components are numerous assessment of the process of transport of electricity at the circuit point where the control and monitoring take place. But the use of these integrated performances for the analysis of the causes of distortions electricity is not possible.

Due to the fact that the indicators that are used to describe the rage mode of direct DC (working values of current and voltage; power) in this case are not informative, we should identify indicators that certain way reflect the nature of electricity consumption and the impact on catenary system of electric rolling stock. In a certain sense, the “traction substation – catenary system – electromotive force (EMS)” structure corresponds to the “rectifier – nonlinear load” structure. So, rationally to use similar indicators [10]. It should be borne in mind the impact of the current position of EMS (load) on the parameters of an equivalent system of replacement and therefore setting mode. It should be noted that in a result of calculation of mode by circuit shown in Fig. 1, for the analysis are available instantaneous values of current ($i$) and voltages ($u$) in the circuit elements and nodes on basis of which we determined amplitude ($U_k$, $I_k$) and phase ($\psi_{uk}$, $\psi_{ik}$) of harmonic components

$$\begin{gathered} U_k = \sqrt{U_{\cos.k}^2 + U_{\sin.k}^2}\,;\ \psi_{uk} = \operatorname{arctg}\frac{U_{\sin.k}}{U_{\cos.k}};\ U_{\cos.k} = \frac{2}{T}\int_0^T u\cos(k\omega t)dt;\ U_{\sin.k} = \frac{2}{T}\int_0^T u\sin(k\omega t)dt; \\ I_k = \sqrt{I_{\cos.k}^2 + I_{\sin.k}^2}\,;\ \psi_{ik} = \operatorname{arctg}\frac{I_{\sin.k}}{I_{\cos.k}};\ I_{\cos.k} = \frac{2}{T}\int_0^T i\cos(k\omega t)dt;\ I_{\sin.k} = \frac{2}{T}\int_0^T i\sin(k\omega t)dt. \end{gathered} \tag{19}$$

The working values of non-sinusoidal currents and voltages are defined as

$$U_{RMSn} = \sqrt{\sum_{k=0}^{\infty}\frac{U_{nk}^2}{2}};\quad I_{RMSn} = \sqrt{\sum_{k=0}^{\infty}\frac{I_{nk}^2}{2}}, \tag{20}$$

where $I_{nk}$, $U_{nk}$ – working values of current and voltage of *k-th* harmonic of *n-th* electric locomotive.

According to these values the coefficients of current and voltage distortion are determined

$$d_I = \frac{\sqrt{\sum_{k=1}^{\infty} I_k}}{I_0};\quad d_U = \frac{\sqrt{\sum_{k=1}^{\infty} U_k}}{U_0}, \tag{21}$$

where $I_{Ak}$ – working value of higher harmonic components of feeder current:

$I_{A0}$ – working value of constant component of feeder current;

$U_{nk}$ – working value of higher harmonic components of voltage at the connection point of the *n-th* electric locomotive;

$U_{n0}$ – working value of constant component of voltage at the connection point of the *n-th* electric locomotive.

Instantaneous power loss during pulsing voltage is determined at the connection point of electric locomotive regarding substation $A$ by the formula

$$\Delta p_{nA} = \Delta u_{nA} i_{nA}, \tag{22}$$

where $\Delta u_{nA}$ – instantaneous power loss at the connection point of *n-th* electric locomotive regarding of substation $A$;

$i_{nA}$ – instantaneous value of current consumed by *n-th* electric locomotive regarding of substation $A$.

Instantaneous power loss is the result of interaction between current and voltage, and its harmonic composition is greater [10], but according to (19) may be represented by respective harmonic components:

$$\Delta P_k = \sqrt{\Delta P_{\cos k}^2 + \Delta P_{\sin k}^2}; \quad \psi_{\Delta pk} = \operatorname{arctg}\frac{\Delta P_{\sin k}}{\Delta P_{\cos k}};$$
$$\Delta P_{\cos k} = \frac{2}{T}\int_0^T \Delta p \cos k\omega t \cdot dt; \quad \Delta P_{\sin k} = \frac{2}{T}\int_0^T \Delta p \sin k\omega t \cdot dt. \tag{23}$$

Thus, distortion coefficient of power losses can be defined as

$$d_P = \frac{\sqrt{\sum_{k=1}^{\infty}\Delta P_k^2}}{\Delta P_0}, \tag{24}$$

where $\Delta P_{nk}$ – effective value of the higher harmonic components of power losses at the connection point of the *n-th* electric locomotive;

$\Delta P_{n0}$ – effective value of the constant component of power losses at the connection point of the *n-th* electric locomotive.

The energy losses at the connection point of the *n-th* electric locomotive calculated by the formula:

$$\Delta W_n = \int \Delta p_n dt. \tag{25}$$

The energy losses caused by the influence of the *k-th* harmonic at the connection point of the *n-th* electric locomotive, calculated by the formula:

$$\Delta W_{nk} = \int \Delta p_{nk} dt. \tag{26}$$

**Results.** For the analysis of TPS can be applied the simulation modeling method of calculation, which directly reflects the processes in a real sequence of events. Using the results obtained in previous studies (for example, operating parameters, calculated using a simulation model [4]) the initial data for calculation of energy performance is the current and speed of electric locomotives. According to equations obtained in [4], the simulation model of calculation of DC TPS (Fig. 2) is developed using in MATLAB/Simulink, where entered the blocks to ensure implementation of expressions (3...26).

There are time diagrams of the current, speed and distance from traction substation to each electric locomotive in Fig. 3.

Parameters of equivalent circuit of catenary system used in simulation model for calculation of DC TPS (see Fig. 2), and calculation results are shown in Fig. 4 and 5. In this case, each electric locomotive voltage (Fig. 4, *a*, *c*) has pulsation caused by pulsating current in the catenary system that causes pulsating voltage drop (Fig. 4, *b*, *d*).

In view of the pulsations in parameters of researched DC system mode, performed a preliminary analysis of the spectrum of pulsations, at this case the main harmonic frequency of 50 Hz is selected. The analysis showed that dominant is harmonic pulsations with the multiplicity of frequencies 1, 3, 7 and 13 of the principal. In this harmonic voltage distribution when driving follows the distribution of working voltage (Fig. 5, *b*) on form. Some uneven distribution observed during the electric locomotive starter (Fig. 5, *c*, *d*) on the time interval 0...4 s. This raises a significant growth of coefficient of current distortion (Fig. 5, *e*) and causes insignificant influence on rate of voltage distortion (Fig. 5, *c*). Taking into account that with increasing distance from traction substation to the connection point of electric locomotive increases the voltage pulsations it is rationally assume that changes in the current in this case will cause the significant changes in voltage.

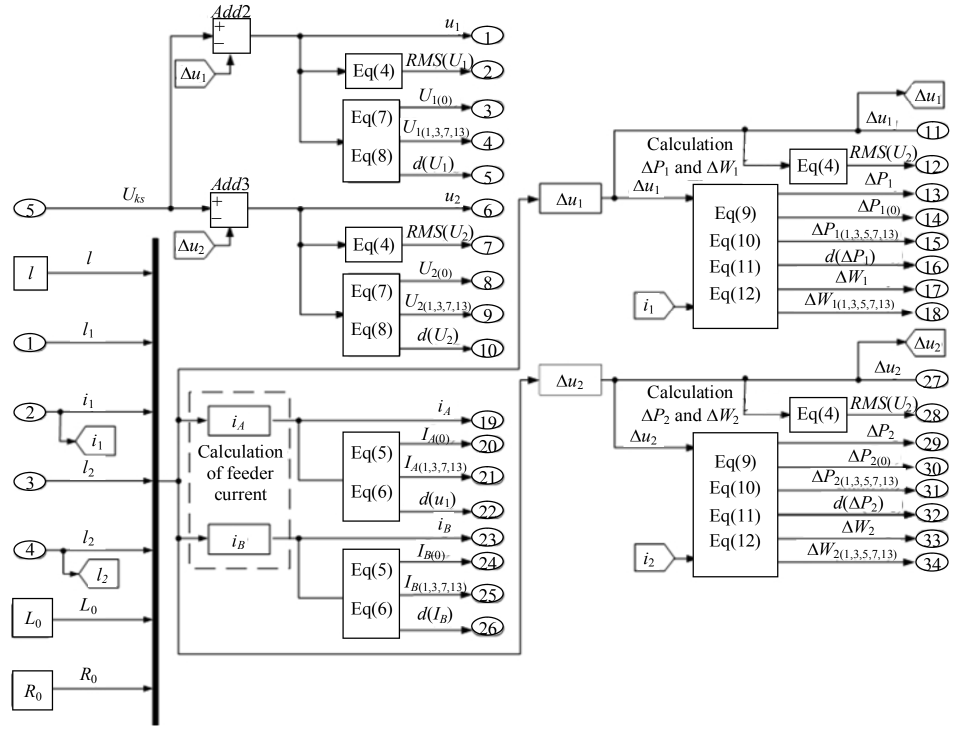

*Fig. 2. Simulation model of DC TPS calculation*

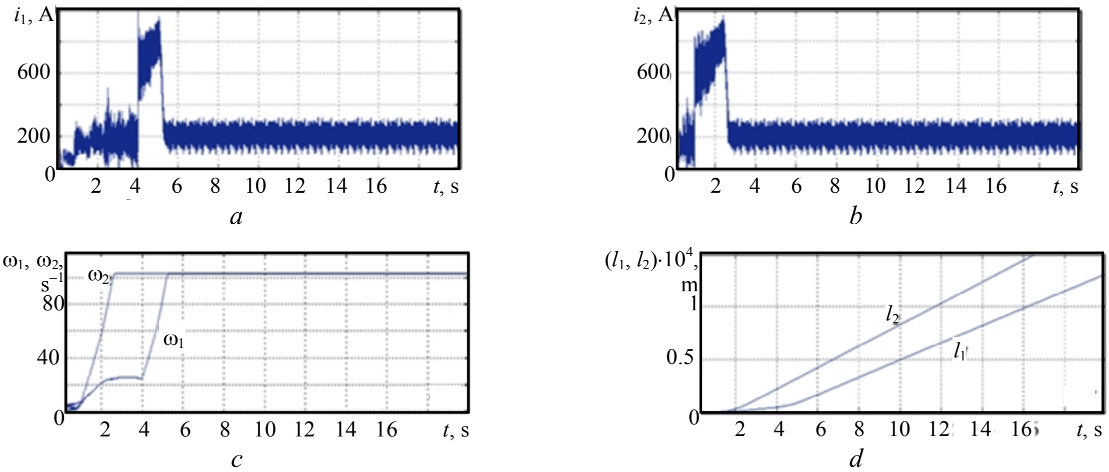

*Fig. 3. Initial data for modeling: a – 1st electric locomotive current; b – 2nd electric locomotive current; c – speeds of 1st and 2nd electric locomotives; d – distance covered by 1st and 2nd electric locomotives*

Mentioned above distribution of mode settings of investigated scheme corresponding to distribution of power flows of electrical energy (Fig. 6), which can be characterized by parameters (23...26). The level of power loss caused by the action of 1, 3, 7 and 13 of harmonics (Fig. 6, *a*) is commensurate with the level of power losses of constant component (Fig. 6, *b*), as evidenced by their relation (Fig. 6, *c*). The energy loss is obtained by integrating the constant power and full power range are identical (Fig. 6, *d*), and the energy caused by the influence of higher harmonics is insignificant (Fig. 6, *e*).

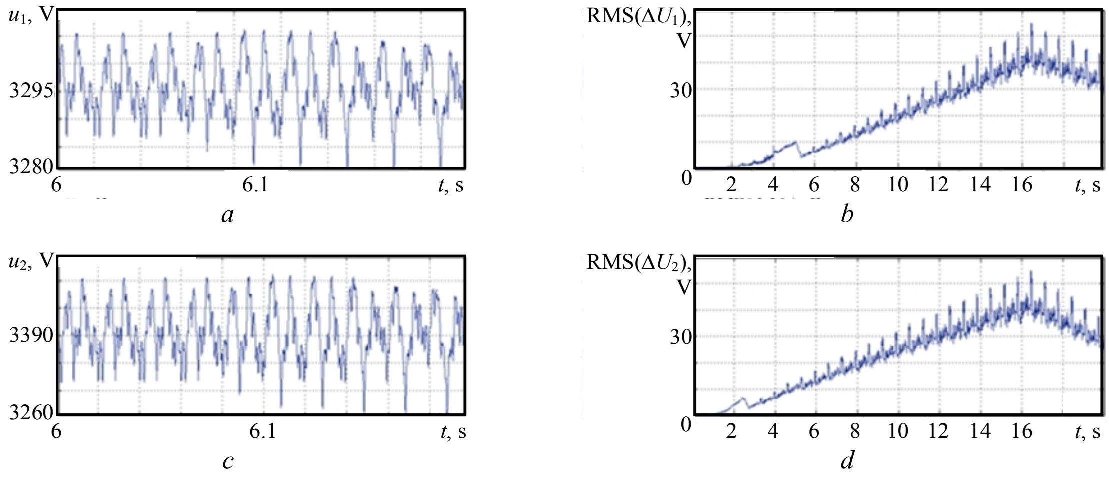

*Fig. 4. Simulation results: a – voltage at the connection point of 1st electric locomotive; b – voltage losses at the connection point of 1st electric locomotive; c – voltage at the connection point of 2nd electric locomotive; d – voltage losses connection point of 2nd electric locomotive*

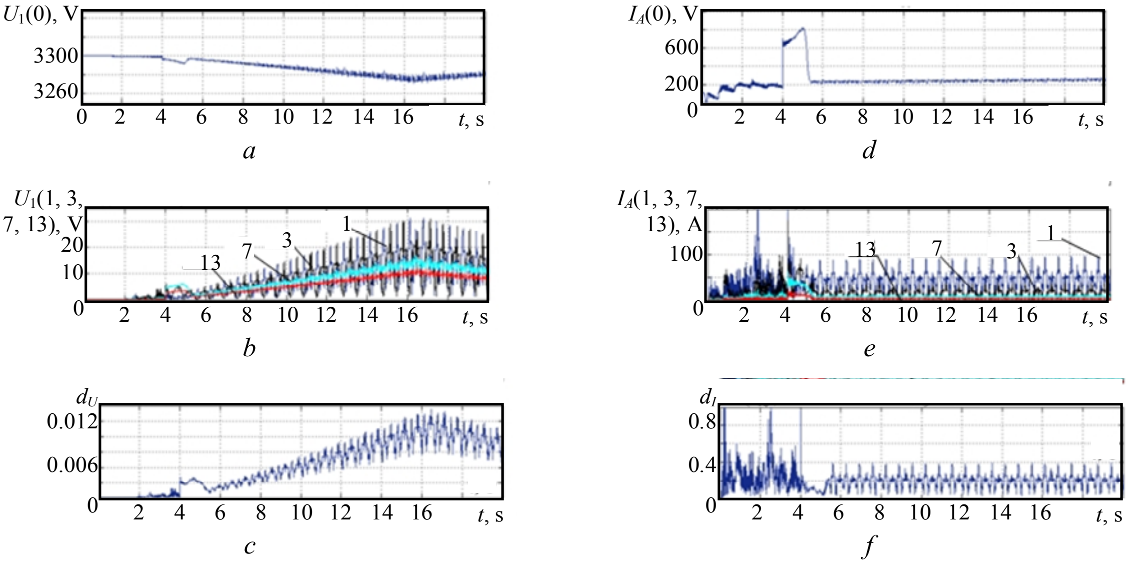

*Fig. 5. Simulation results: a – constant component of voltage at the connection point of 1st electric locomotive; b – voltage variation in time for 1, 3, 7 and 13 harmonics of 1st electric locomotive; c – variation in time of distortion coefficient of voltage loss for 1st electric locomotive; d – variation in time of constant component for "feeder A" current; e – variation in time of 1, 3, 7 and 13 harmonics for "feeder A" current; f – variation in time of distortion coefficient for "feeder A" current*

**Conclusions**. Based on the analysis of the structure of modern traction electric part of electric locomotives that get energy via DC catenary system, we found that the electricity regime may be described qualitatively only considering the higher harmonic settings of the operation mode. Influence of parameters of a catenary system, due to the presence of harmonic components in the current and voltage requires consideration in the calculation regime the effective resistance as well as the inductance of circuit elements. To analyze the power of electricity in the DC catenary system the polyharmonic representation of power was applied that allows for a schedule of electric locomotive movement assess its impact on level of voltage and the quality by parameters of its speed and current. Also, polyharmonic representation of power allows to estimate its components, which are used in existing international standards.

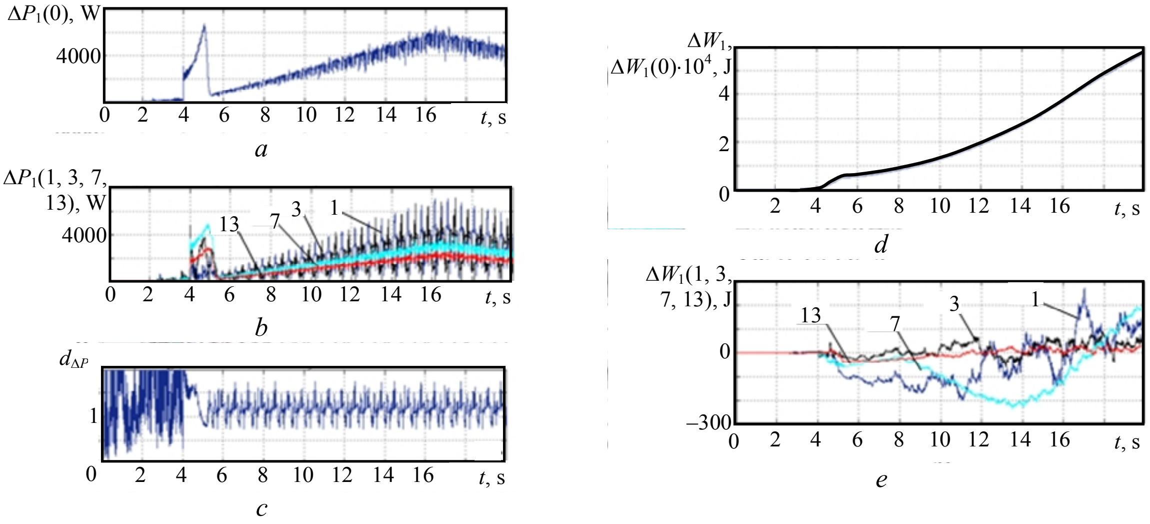

*Fig. 6. Simulation results: a – constant component of power losses at the connection point of 1st electric locomotive; b – working value of power losses for 1, 3, 7 and 13 harmonics at the connection point of 1st electric locomotive; c – distortion coefficient of power losses at the connection point of 1st electric locomotive; d – complete power loss for 1, 3, 7 and 13 harmonics at the connection point of 1st electric locomotive; e – energy loss for 1, 3, 7 and 13 harmonics at the connection point of 1st electric locomotive*

The obtained results can be used in the formation of the requirements for electricity metering at sites of railways where operated electric locomotives with traction electrical complex, which has a semiconductor converters.

## Література

1. Слободчиков, И.В. К вопросу об электромагнитной совместимости подвижного состава с импульсным регулированием с тяговыми подстанциями постоянного тока / И.В. Сободчиков / Коммунальное хозяйство городов. – 2010. – № 95 – С. 379–383.
2. Каштанов, А.Л. Оценка перетоков мощности в тяговой сети постоянного тока по данным автоматизированной системы АСМУЭ ФКС / А.Л. Каштанов, О.О. Комякова // Вестник Воронежского государственного технического университета. – 2015. – Т. 11, № 3. – С. 130–133.
3. Мищенко, Т.Н. Показатели качества электроэнергии в тяговой сети на токоприемниках электровозов постоянного тока / Т.Н. Мищенко // Вісник Дніпропетровського національного університету залізничного транспорту імені академіка В. Лазаряна. – 2008. – Вип. 23. – С. 114–116.
4. Слободенюк, Ю.О. Модель розрахунку миттєвих параметрів режиму системи тягового електропостачання при русі електровозу / Ю.О. Слободенюк, О.В. Бялобржеський // Електротехніка та електроенергетика. – 2016. – № 1. – С. 42–48.
5. Марквардт, К.Г. Электроснабжение электрифицированных железных дорог / К.Г. Марквардт. – 4-е изд., перераб. и доп. – М.: Транспорт, 1982. – 528 с.
6. Слепцов, М.А. Основы электрического транспорта / М.А. Слепцов, Г.П. Долаберидзе, А.В. Прокопович [и др.]; под общ. ред. М.А. Слепцова. – М.: Academia, 2006. – 462 с.
7. IEEE Standard 1459-2010. Definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions / Institute of Electrical and Electronics Engineers. — IEEE, 2010. – 40 p.
8. Emanuel, A.E. Power Definitions and The Physical Mechanism of Power Flow / A.E. Emanuel. – Oxford: Wiley-Blackwell, 2010. – 280 p.
9. Сиротин, Ю.А. Векторная мгновенная мощность и энергетические режимы трехфазных цепей / Ю.А. Сиротин // Технічна електродинаміка. – 2013. – № 6. – С. 57–65.
10. Зиновьев, Г.С. Основы силовой электроники / Г.С. Зиновьев. – Новосибирск: НГТУ, 2003. – 664 с.

11. Сухоніс, Т.Ю. Моделювання позаштатних режимів роботи системи інвертор – асинхронний двигун тягового електротехнічного комплексу двосистемного електровоза / Т.Ю. Сухоніс, Ю.О. Миколаєнко, О.В. Бялобржеський // Гірнича електромеханіка та автоматика. – 2013. – Вип. 91. – С. 89–94.

## References

1. Slobodchikov, I.V. (2010). On the electromagnetic compatibility of rolling with impulse control with DC traction substations. *Municipal Economy of Cities*, 95, 379–383.
2. Kashtanov, A.L., & Komiakova, O.O. (2015). Evaluation of power flow in traction network DC according to the automated system of the FCC ASMAA. *The Bulletin of Voronezh State Technical University*, 11(3), 130–133.
3. Mishchenko, T.M. (2008). The quality of electricity in traction network for the DC electric locomotives pantographs. *Bulletin of Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan*, 23, 114–116.
4. Slobodenjuk, Yu.O., & Bialobrzeski, O.V. (2016). Model calculating the instantaneous mode parameter a traction power system moving electric locomotives. *Electrotechnics and Electroenergetics*, 1, 42–48.
5. Marquardt, K.G. (1982). *Power Supply of Electrified Railways*. Moscow: Transport.
6. Sleptsov, M.A. (Ed.). (2006). *Fundamentals of Electric Transport*. Moscow: Academia.
7. Institute of Electrical and Electronics Engineers. (2010). *IEEE Standard 1459-2010. Definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced, or unbalanced conditions*. Piscataway, N.J.: IEEE.
8. Emanuel, A.E. (2010). *Power Definitions and The Physical Mechanism of Power Flow*. Oxford: Wiley-Blackwell.
9. Sirotin, Yu.A. (2013). Vectorial instantaneous power and energy modes in three-phase circuits. *Tekhnichna Elektrodynamika*, 6, 57–65.
10. Zinoviev, G.S. (2012). *Fundamentals of Power Electronics*. Novosibirsk: NGTU.
11. Sukhonos, T.Yu., Nikolaenko, Yu.A., & Byalobrzheskiy, A.V. (2013). Simulation of abnormal operating conditions of the inverter-induction motor traction electrical complex dual-system electric locomotive. *Mining Electrical Engineering and Automation*, 91, 89–94.

Received November 23, 2016

Accepted January 29, 2017