Reducing Power Losses by Voltage Stabilization at the DC Rolling Stock Current Collector

Dmitry Tugay , Alina Trotsai , Olexandr Shkorpela , and Ivan Kostenko

O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine

Article History

Received:
17 November 2021
Accepted:
29 December 2021
Published online:
30 December 2021

Keywords

Voltage Stabilization;
Electric Rolling Stock;
Traction Substations;
Efficiency;
Power Supply System;
Current Collector

Abstract

The invention relates to an energy-efficient method for voltage stabilization at the electric rolling stock current collector through traction substation control means which provide a nominal voltage value during the electric train movement by an interstation section. The dependence of potential distribution in the contact wire during the electric rolling stock movement by an interstation section was investigated. Also researched and developed are the new ways of voltage stabilization at the current collector of the electric rolling stock based on synchronous (the same for two adjacent traction substations) and asynchronous paths of voltage regulation at DC buses of traction substations related to one synchronous and two asynchronous ways of voltage stabilization in the contact network with obtaining the energy performance describing them. The energy performance of the investigated methods of voltage stabilization in the contact network is compared, and the energy efficiency of each of them is determined. It is proved that the use of modern types of semiconductor converters such as an active rectifier – voltage source in the power equipment of DC traction substations will enable to implement adaptive voltage stabilization systems at the rolling stock current collector, providing nominal voltage values of traction motors on the interstation section without using additional equipment on the rolling stock and, as a consequence, justification and application of these methods is suitable for upgrading the existing and designing new traction substations.

INTRODUCTION

The annual volume of electrical power consumption on railroads in Ukraine is 6 billion kWh/year [1]. A considerable part of energy is used for operation of electric traction systems. Currently, power supply systems for rolling stock are commonly divided according to the type of current in the contact network into DC and AC electric traction systems. DC electric traction systems, which began to be used earlier, occupy 40% of the electrified sections of Ukrainian railroads [1, 2]. Despite the low value of contact network voltage, which results in energy losses in the system itself, although the distance between the substations is 15–20 kilometers, the modernization of the DC current use on the railroads remains possible.

The proposed option for improving the operation of DC traction systems is the use of modern semiconductor converters in traction substations and rolling stock devices, allowing not only to pro-

vide the required electrical power qualitative indicators, but to likewise stabilize the voltage at the current collector or traction motors [3–7]. The wanted performance for fulfillment of the staged purpose is inherent in the ARVS semiconductor converters – active rectifier – voltage source. In contrast to uncontrolled rectifiers, operated in rectifying units of traction substations, ARVS makes it possible to regulate the output voltage within the limits, set by parameters of the power circuit elements and load, providing practically a sinusoidal form of network currents at power factor close to unity [2, 8–11].

In the study, the efficiency of approaches for stabilizing the DC traction network voltage corresponding to a conservative voltage value at the rolling stock current collector on the interstation section was evaluated. One synchronous and two asynchronous stabilization methods were considered, the performance of which is fully analyzed and can be useful to provide modernization of the available and design of new traction substations.

Corresponding author: tugay@kname.edu.ua (Dmitry Tugay)

© 2021 The Author(s). Published by O. M. Beketov National University of Urban Economy in Kharkiv
Use permitted under [Creative Commons Attribution 4.0 International \(CC BY 4.0\)](https://creativecommons.org/licenses/by/4.0/)

Cite as: Tugay, D., Trotsai, A., Shkorpela, O., & Kostenko, I. (2021). Reducing power losses by voltage stabilization at the DC rolling stock current collector. *Lighting Engineering & Power Engineering*, 60(3), 103–111. <https://doi.org/10.33042/2079-424X.2021.60.3.03>

PROBLEM FORMULATION

In Fig. 1 shown the diagram of the power supply of traction substations on the electrified DC railroad when the electric train moves by the substation section and its equivalent circuit, where the following values are taken: R_d is the resistance in which the energy being emitted corresponds to the rolling stock energy input; $k = L/L_0$ is the ratio of the distance from the first traction substation, L to the length of the interstation section L_0 ; R is the reduced resistance of the traction circuit, which is calculated by the following formula [1]:

$$R = \frac{\rho_c L_0}{S}, \quad (1)$$

where $\rho_c = \rho_{20c}(1 + \alpha_c(t - 20))$ is the volume resistivity of copper;

$$S = \frac{S_{st}(k_{al}S_c + S_{al})}{k_{al}S_{st} + k_{st}(k_{al}S_c + S_{al})} \quad (2)$$

is the cross-sectional area of the traction circuit in copper equivalent; S_c , S_{al} , S_{st} is the cross-section of copper and aluminum conductors of the contact hanger, respectively, and the rail track cross-section; $k_{al} = \rho_{al}/\rho_c = \rho_{20al}(1 + \alpha_{al}(t - 20))/\rho_{20c}(1 + \alpha_c(t - 20))$, $k_{st} = \rho_{st}/\rho_c = \rho_{20st}(1 + \alpha_{st}(t - 20))/\rho_{20c}(1 + \alpha_c(t - 20))$ are the ratio of volume resistivity of both aluminum and steel to the volume resistivity of copper.

Figure 1. Conditional diagram of the electrified DC railway power supply (a); equivalent diagram of the interstation section of the traction network (b)

Let us consider an example when the section is unloaded and one rolling stock moves from the first substation to the second one with a speed equal to *const*. We take the following parameters as the initial data: $L_0 = 20$ km, $\rho_c = 0.018 \Omega \cdot \text{mm}^2/\text{m}$, $\rho_{al} = 0.0295 \Omega \cdot \text{mm}^2/\text{m}$, $\rho_{st} = 0.21 \Omega \cdot \text{mm}^2/\text{m}$, $t = 20^\circ\text{C}$, contact suspension type is the M-95 + 2MF-100 + A-185, $S_{st} = 9510 \text{ mm}^2$, the electric locomotive type is the VL10K, hour capacity of traction motors is the 5360 kW, hour mode speed $V = 48.7 \text{ km/h}$, $R_d = 1.68 \Omega$, nominal voltage of the contact network $U_H = 3 \text{ kV}$.

The greatest voltage loss for the rolling stock with the corresponding voltage value at the transformer sub-station busbars occurs in the middle of the driving distance, when $L = L_0/2$.

Based on Fig. 1, let's make a system of equations according to Kirchhoff's laws:

$$\begin{cases} I_1 + I_2 - I_d = 0, \\ I_1 Rk + I_d R_d = E_1, \\ I_2 R(k-l) + I_d R_d = E_2. \end{cases} \quad (3)$$

From the ratio of the solution of the system of linear equations and the formula for calculating the reduced resistance [1]:

$$U = \frac{E_2 - \frac{(E_1 - E_2)R_d S}{\rho_c L}}{\frac{\rho_c L_0}{R_d S} \left(\frac{L}{L_0} - \frac{L^2}{L_0^2} \right) + 1} + \frac{(E_1 - E_2)R_d S}{\rho_c L}. \quad (4)$$

Based on this relationship in Fig. 2, the dependence between the voltage at the RS current collector and the position of the train on the interstation section is plotted.

From the constructed dependence it can be seen that in the middle of the rolling stock driving distance, the voltage value decreases to a minimum, which causes additional losses [12-17].

Figure 2. Dependence of the rolling stock current collector voltage on the electric train position at the interstation section

METHODS OF VOLTAGE STABILIZATION IN THE CONTACT NETWORK

The solution of the problem related to significant currents flow when reducing the voltage value in the contact network with uncontrolled rectifiers and traction electric motor voltage stabilization is possible by using active rectifiers of voltage sources for current collector voltage stabilization [8, 11, 18]. Fig. 3 shows the family of dependences $E_1 = f(L)$ at fixed values of E_2 , as well as the dependences $E_2 = f(L)$ at fixed values of E_1 , plotted accordingly (5) at $U = U_H = \text{const} = 3000$ V. And Fig. 4 presents only the curves $E_1 = f(L)$ and $E_2 = f(L)$ at fixed values of the voltage at the busbars of the second substation $E_1 = E_2 = 3300$ V. The cross-section of the curves $E_1 = f(L)$ and $E_2 = f(L)$ at the nominal voltage of the second traction substation with a straight line $E = 3300$ V makes it possible to determine the coordinates of the two points on the interstation section (points L_1 and L_2 in Fig. 4), which form a track segment, within which the electric rolling stock current collector voltage will be less than the nominal value. Substituting $U = \text{const} = 3000$ V under the condition $E_1 = E_2 = E = 3300$ V, we find the roots of the quadratic equation.

Figure 3. Dependencies $E_1 = f(L)$ at fixed values of E_2 (a), and dependencies $E_2 = f(L)$ at fixed values of E_1 (b) at $U = \text{const} = 3000$ V

Figure 4. Dependencies of $E_1 = f(L)$ at $E_2 = 3300$ V (a), and dependencies $E_2 = f(L)$ at $E_1 = 3300$ V (b) at $U = \text{const} = 3000$ V

One can stabilize the voltage in the contact network, when $U = \text{const} = 3000$ V, using the synchronous method, in which the control laws on the first and second substations will be equal, and two asynchronous methods, when the control laws are different. We choose a parabolic curve as the path that best meets certain requirements of synchronization of TS operation and crosses the three points: $A(L_1, E)$, $B(L_2, E)$, $C(L_0/2, E_m)$. We take E_m as the highest value of the voltage at the respective section and obtain the equation:

$$U(L) = aL^2 + bL + c, \quad (5)$$

which coefficients can be found by solving a system of three equations

$$\begin{cases} aL_1^2 + bL_1 + c = E, \\ aL_2^2 + bL_2 + c = E, \\ \frac{aL_0^2}{4} + \frac{bL_0}{2} + c = E_m, \end{cases} \quad (6)$$

$$\begin{aligned} b &= \frac{E_m - E}{\frac{L_2^2 L_1 - L_1^2 L_2}{L_1^2 - L_2^2} \left(1 - \frac{L_0^2}{4L_1^2} \right) + \frac{L_0}{2} - \frac{L_0^2}{4L_1}}, \\ c &= E + b \frac{L_2^2 L_1 - L_1^2 L_2}{L_1^2 - L_2^2}, \\ a &= \frac{E - bL_1 - c}{L_1^2}, \end{aligned} \quad (7)$$

where

$$E_m = (U - E) \frac{\left(\frac{L_2^2 L_1 - L_1^2 L_2}{L_1^2 - L_2^2} \left(1 - \frac{L_0^2}{4L_1^2} \right) + \frac{L_0}{2} - \frac{L_0^2}{4L_1} \right)}{\frac{L_2^2 L_1 - L_1^2 L_2}{L_1^2 - L_2^2}}. \quad (8)$$

The asynchronous control methods emanate from the analysis of Fig. 5 and has the following algorithm [8]:

- 1) we fix the value of $E_1 = E_2 = 3300$ V on the driving section, where $U > U_H$;
- 2) at the moment $U = U_H$ we start to increase the voltage E_1 linearly according to relation (4), until E_1 reaches the value of E_m ($E_1 = E_m$);
- 3) at the moment $E_1 = E_m$, we fix E_1 and begin to adjust E_2 along the path described by relation (4), by the time the equality $E_2 = E_m$ is fulfilled. By convention, this will occur at the midpoint of the interstation section $L = L_0/2$;
- 4) we fix $E_2 = E_m$ and adjust E_1 downwards according to relation (4) by the time the equality $E_1 = 3300$ V is fulfilled;
- 5) at the moment $E_1 = 3300$ V, we fix E_1 and adjust E_2 according to ratio (4) to the moment equality $E_2 = 3300$ V is fulfilled;
- 6) at the moment $E_2 = 3300$ V, we fix E_2 .

The voltage regulation paths of the two traction substations, described by the presented algorithm, and their corresponding voltage curve at the rolling stock current collector are shown in Fig. 5a.

Another asynchronous method of voltage stabilization at the rolling stock current collector results from the algorithm of voltage regulation on the buses of each traction substation, regardless of half of the interstation section, with a fixed voltage value

Figure 5. Paths of voltage regulation at the output of traction substations with asynchronous methods of voltage stabilization

of the other substation. It is easy to prove that the highest efficiency of the traction power supply system can be achieved by fixing the voltage of the second substation at the E_m level, which is the value of the energy optimum, on half of the propulsion interval.

Fig. 5b shows the path of voltage regulation at the output of traction substations using the specified method of voltage stabilization, and in Fig. 6 – the dependence of traction network efficiency from the voltage value of the second substation fixed at half of the interstation interval, corresponding to the second asynchronous stabilization method. Fig. 6 shows that it is at $E = E_m$ that the energy maximum of stabilization is achieved.

Fig. 7 shows the curves describing the current change paths as well as the powers of the electric traction system on the interstation section for the three cases: without stabilization (conventional EPSS) – Fig. 7a; using the synchronous stabilization method – Fig. 7b; using the first asynchronous stabilization method – Fig. 7c; using the second asynchronous stabilization method – Fig. 7d.

The Table 1 shows the results of energy profile calculation data of the three studied cases of the electric traction system, corresponding to Fig. 7 and the previously adopted system's characteristics. The energy profile calculations are performed in accordance with the ratios:

- the mean voltage at the current collector within the driving distance:

$$U_{AV} = \frac{1}{L_0} \int_0^{L_0} U dL; \quad (9)$$

- the mean voltage at traction substation buses within the driving distance (without stabilization):

$$E_{AV} = E; \quad (10)$$

- the mean voltage at traction substation buses within the driving distance (with synchronous stabilization):

Figure 6. Dependence of the electric traction network efficiency on the voltage value of another substation fixed at half of the interstation section using the second asynchronous method of voltage stabilization

$$E_{AV} = \frac{1}{L_0} \int_0^{L_0} U(L) dL; \quad (11)$$

- the mean voltage at traction substation buses within the driving distance (with asynchronous stabilization (method 1)):

$$E_{AV} = \frac{1}{L_0} \int_0^{L_0} E_{a1} dL =$$

$$= \frac{1}{L_0} \int_0^{L_0} \left(\begin{aligned} &\text{if } (0 \leq L \leq L_1, E, 0) + \\ &+ \text{if } \left(L_1 < L \leq \frac{L_0}{2} \wedge E_1(E) \leq E_m, E_1(E), 0 \right) + \\ &+ \text{if } \left(L_1 < L \leq \frac{L_0}{2} \wedge E_1(E) > E_m, E_m, 0 \right) + \\ &+ \text{if } \left(\frac{L_0}{2} < L \leq L_0 \wedge E_1(E_m) \geq E, E_1(E_m), 0 \right) + \\ &+ \text{if } \left(\frac{L_0}{2} < L \leq L_0 \wedge E_1(E_m) < E, E, 0 \right) \end{aligned} \right) dL; \quad (12)$$

Figure 7. Paths of current change and electric traction system power on the interstation section: (a) – without stabilization, (b) – with synchronous method of stabilization, (c), (d) – with asynchronous method of stabilization

Table 1. Energy profile of the electric traction system operation

Profile	The method of voltage stabilization			
	Without stabilization	Synchronous	Asynchronous 1	Asynchronous 2
Mean voltage at the current collector within the driving distance, U_{AV} , V	2922	3040	3040	3040
Mean voltage on the busbars of traction substations within the driving distance, E_{AV} , V	3300	3439	3422	3449
Mean value of current in the traction network within the driving distance, I_{AV} , A	942	905	905	905
Mean value of TED current within the driving distance, $I_{\partial AV}$, A	1885	1810	1810	1810
Mean power of the electric train within the driving distance, $P_{\partial AV}$, kW	5506	5506	5506	5506
Mean power of the traction network within the driving distance, P_{AV} , kW	6304	6220	6232	6228
Mean power loss within the driving distance, ΔP_{AV} , kW	789	714	726	722
Mean efficiency within the driving distance, η_{AV}	0.873	0.885	0.884	0.884
Energy consumed within the driving distance, W , kW·h	2589	2554	2559	2558
Energy losses within the driving distance, ΔW , kW·h	328	293	298	297

- the mean voltage on the traction substation buses within the driving distance (with asynchronous stabilization (method 2)):

$$E_{AV} = \frac{1}{L_0} \int_0^{L_0} E_{a2} dL = \frac{1}{L_0} \int_0^{L_0} \left(\begin{array}{l} \text{if } (0 \leq L \leq L_1 \wedge L_2 < L \leq L_0, E, 0) + \\ \text{+if } \left(L_1 < L \leq \frac{L_0}{2}, E_1(E_m), 0 \right) + \\ \text{+if } \left(\frac{L_0}{2} < L \leq L_2, E_m, 0 \right) \end{array} \right) dL; \quad (13)$$

- the mean current value in the electric traction network within the driving distance (with synchronous and asynchronous stabilization):

$$I_{AV} = \frac{1}{L_0} \int_0^{L_0} \left(\frac{E_2 - \frac{E_1 - E_2}{\rho_c L} R_d S}{\frac{\rho_c L_0}{S} \left(1 - \frac{L}{L_0} \right) + \frac{R_d L_0}{L}} \right) dL; \quad (14)$$

- the mean value of the TEM current within the driving distance (with synchronous and asynchronous stabilization):

$$I_{dAV} = 2I_{AV}; \quad (15)$$

- the mean value of the TEM current within the driving distance (without stabilization):

$$I_{dAV} = \frac{1}{L_0} \int_0^{L_0} \frac{P_d}{U} dL; \quad (16)$$

- the mean value of current in the traction network within the driving distance (without stabilization):

$$I_{AV} = \frac{1}{L_0} \int_0^{L_0} \left(\frac{P_d}{U} \frac{L}{L_0} \right) dL; \quad (17)$$

- the mean power of the electric train within the driving distance:

$$P_{dAV} = \frac{1}{L_0} \int_0^{L_0} P_d dL = \frac{1}{L_0} \int_0^{L_0} \left(U \frac{E_2 - \frac{E_1 - E_2}{\rho_c L} R_d S}{\frac{\rho_c L_0}{S} \left(1 - \frac{L}{L_0} \right) + \frac{R_d L_0}{L}} \right) dL; \quad (18)$$

- the mean power of the traction network within the driving distance (with synchronous stabilization):

$$P_{AV} = \frac{2}{L_0} \int_0^{L_0} \left(U(L) \frac{E}{\frac{\rho_c L_0}{S} \left(1 - \frac{L}{L_0} \right) + \frac{R_d L_0}{L}} \right) dL; \quad (19)$$

- the mean power of the traction network within the driving distance (with asynchronous stabilization (mode 1)):

$$P_{AV} = \frac{2}{L_0} \int_0^{L_0} \left(E_{a1}(L) \frac{E_2 - \frac{E_1 - E_2}{\rho_c L} R_d S}{\frac{\rho_c L_0}{S} \left(1 - \frac{L}{L_0} \right) + \frac{R_d L_0}{L}} \right) dL; \quad (20)$$

- the mean power of the traction network within the driving distance (with asynchronous stabilization (mode 2)):

$$P_{AV} = \frac{2}{L_0} \int_0^{L_0} \left(E_{a2}(L) \frac{E_2 - \frac{E_1 - E_2}{\rho_c L} R_d S}{\frac{\rho_c L_0}{S} \left(1 - \frac{L}{L_0} \right) + \frac{R_d L_0}{L}} \right) dL; \quad (21)$$

- the mean power of the traction network within the driving distance (without stabilization):

$$P_{AV} = \frac{2}{L_0} \int_0^{L_0} \left(P_d \frac{L}{L_0} + \left(\frac{P_d}{U} \frac{L}{L_0} \right)^2 \frac{\rho_c L}{S} \right) dL; \quad (22)$$

- the mean loss power within the driving distance:

$$\Delta P_{AV} = \Delta P_{AV} - \Delta P_{dAV}; \quad (23)$$

- the mean efficiency within the driving distance:

$$\eta_{AV} = \frac{P_{dAV}}{P_{AV}}; \quad (24)$$

- the energy consumed within the driving distance:

$$W = P_{AV} \frac{L_0}{V} 10^{-6}; \quad (25)$$

- the energy loss within the driving distance:

$$\Delta W = \Delta P_{AV} \frac{L_0}{V} 10^{-6}. \quad (26)$$

Analysis of the results shown in the table makes it possible to estimate the limits of efficiency increase and loss power reduction when using the two considered methods of voltage stabilization at the rolling stock current collector. So, while the electric locomotive VL10K moves with constant speed by the twenty-kilometer interstation section, the traction motors of which operate in the hour mode, the synchronous method of voltage stabilization on the current collector allows increasing the efficiency of the traction network by 1.18%. It should be noted that the overall efficiency of the rolling stock power supply system will increase by several percent more due to the practical exclusion of reactive power and higher harmonics of the power-grid [19–22]. The basic technical and economical effect, when using the proposed methods of voltage stabilization at the rolling stock current collector, is to provide a favorable thermal operating mode of traction motors [23, 24], which enable to avoid overheating and wear of their structural elements, while the speed of electric trains on the interstation section as well as the developed traction force is maintained.

CONCLUSIONS

To implement adaptive voltage stabilization systems at the rolling stock current collector, it is appropriate to use semiconductor converters, such as the active rectifier – voltage source, in the power equipment of DC traction substations, which makes possible the operation without additional equipment on both the rolling stock or amplifier points.

Voltage stabilization on the rolling stock current collector allows reducing the loss power in the traction network. If we consider the synchronous method of voltage stabilization, the efficiency of traction network can be increased by more than 1%.

Methods of voltage stabilization at the current collector of the electric rolling stock, based on regulation of voltage on DC buses of two adjacent traction substations, have been developed. The synchronous stabilization method, which implements the same law of voltage regulation of the two traction substations according to the parabolic curve, the abscissa of the top of which corresponds to a point located inside the interstation section, and the ordinate corresponds to the energy maximum E_m . Also developed are two asynchronous stabilization methods, implementing different laws of voltage regulation of the two traction substations, at which the maximum voltage value within the regulation interval does not exceed E_m .

The use of the above stabilization methods makes it possible to enhance the traction network efficiency as well as stabilize the temperature mode of traction motors, which results in the increase of the service life of motors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

REFERENCES

1. Bozhko, V.V. (2015). Analysis of operations modes of strengthening direct-current power supply traction system. *Collection of Scientific Works of Kharkiv National University of the Air Force*, 4(45), 89–91. (in Ukrainian)
2. Shcherback, Y., Ivakina, K., & Plakhtii, O. (2021). Analysis of the energy characteristics of the traction substation rectifier. In *2021 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek)* (pp. 477–481). IEEE. <https://doi.org/10.1109/KhPIWeek53812.2021.9570092>
3. Zhemerov, G., Plakhtii, O., & Mashura, A. (2020). Efficiency analysis of charging station for electric vehicles using the active rectifier in microgrid system. In *2020 IEEE 4th International Conference on Intelligent Energy and Power Systems (IEPS)* (pp. 37–42). IEEE. <https://doi.org/10.1109/IEPS51250.2020.9263182>

4. Ooagu, R., Taguchi, K., Yashiro, Y., Amari, S., Naito, H., & Hayashiya, H. (2019). Measurements and calculations of rail potential in D.C. traction power supply system. In *2019 11th Asia-Pacific International Conference on Lightning (APL)* (pp. 1–6). IEEE. <https://doi.org/10.1109/APL.2019.8816070>
5. Mariscotti, A. (2003). Distribution of the traction return current in AC and DC electric railway systems. *IEEE Transactions on power delivery*, 18(4), 1422–1432. <https://doi.org/10.1109/TPWRD.2003.817786>
6. Wojciechowski, J., Lorek, K., & Nowakowski, W. (2018). An influence of a complex modernization of the DC traction power supply on the parameters of an electric power system. *MATEC Web of Conferences*, 180, 02001. <https://doi.org/10.1051/mateconf/201818002001>
7. Hayashiya, H., Masuda, M., Noda, Y., Suzuki, K., & Suzuki, T. (2017). Reliability analysis of DC traction power supply system for electric railway. In *2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe)* (pp. 1–6). IEEE. <https://doi.org/10.23919/EPE17ECCEEurope.2017.8098953>
8. Tugay, D.V., & Zemerov, G.G. (2018). The overhead line voltage stabilization to increase the efficiency of the DC electric rail traction system. *Technical Electrodynamics*, 2018(5), 88–91. <https://doi.org/10.15407/techned2018.05.088> (in Ukrainian)
9. Pahlevani, M., & Jain, P.K. (2020). Soft-switching power electronics technology for electric vehicles: A technology review. *IEEE Journal of Emerging and Selected Topics in Industrial Electronics*, 1(1), 80–90. <https://doi.org/10.1109/JESTIE.2020.2999590>
10. Simiyu, P., & Davidson, I.E. (2021). MVDC railway traction power systems; state-of-the art, opportunities, and challenges. *Energies*, 14(14), 4156. <https://doi.org/10.3390/en1414156>
11. Zhang, G., Tian, Z., Tricoli, P., Hillmansen, S., Wang, Y., & Liu, Z. (2019). Inverter operating characteristics optimization for DC traction power supply systems. *IEEE Transactions on Vehicular Technology*, 68(4), 3400–3410. <https://doi.org/10.1109/TVT.2019.2899165>
12. Tugay, D.V., Zemerov, G., Korneliuk, S., & Kotelevets, S. (2019). Three theorems of the instantaneous power theory. In *2019 IEEE 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON)* (pp. 289–294). IEEE. <https://doi.org/10.1109/UKRCON.2019.8879901>
13. Sychenko, V., Danylov, O., Petro, B., Kosariev, Y., Liashuk, V., & Drubetskaya, T. (2020). Asymmetric power supply circuit design for electric rolling stock on the electrified DC rail. In *2020 IEEE 7th International Conference on Energy Smart Systems (ESS)* (pp. 326–329). IEEE. <https://doi.org/10.1109/ESS50319.2020.9160312>
14. Fast Traffic. (2005). *Rules of arrangement of the traction power supply system of the railways of Ukraine* (Instruction CE0009). (in Ukrainian)
15. Mariscotti, A. (2021). Critical review of EMC standards for the measurement of radiated electromagnetic emissions from transit line and rolling stock. *Energies*, 14(3), 759. <https://doi.org/10.3390/en14030759>
16. Chen, Y., Tian, Z., Roberts, C., Hillmansen, S., & Chen, M. (2021). Reliability and life evaluation of a DC traction power supply system considering load characteristics. *IEEE Transactions on Transportation Electrification*, 7(3), 958–968. <https://doi.org/10.1109/TTE.2020.3047512>
17. Popescu, M., Bitoleanu, A., Suru, V., & Dobriceanu, M. (2017). Increasing power quality in a 6-pulse DC-traction substation. In *2017 International Conference on Electromechanical and Power Systems (SIELMEN)*, (pp. 483–488). IEEE. <https://doi.org/10.1109/SIELMEN.2017.8123376>
18. Kosarev, E.M. (2015). Voltage control in a contact network of dc electrified railways. *Electrification of Transport*, (9), 37–43. (in Ukrainian)
19. Pliuhin, V., Teterev, V., & Lapko, A. (2021). Smart Grid technologies as a concept of innovative energy development: initial proposals for the development of Ukraine. *Lighting Engineering & Power Engineering*, 60(2), 47–65. <https://doi.org/10.33042/2079-424X.2021.60.2.02>
20. Ilisiu, D., & Dinu, E.D. (2019). Modern reactive power compensation for smart electrical grids. In *2019 22nd International Conference on Control Systems and Computer Science (CSCS)* (pp. 353–357). IEEE. <https://doi.org/10.1109/CSCS.2019.00063>
21. Botte, M., D'Acierno, L., & Pagano, M. (2020). Impact of railway energy efficiency on the primary distribution power grid. *IEEE Transactions on Vehicular Technology*, 69(12), 14131–14140. <https://doi.org/10.1109/TVT.2020.2998153>
22. Verdicchio, A., Ladoux, P., Caron, H., & Courtois, C. (2018). New medium-voltage DC railway electrification system. *IEEE Transactions on Transportation Electrification*, 4(2), 591–604. <https://doi.org/10.1109/TTE.2018.2826780>
23. Hao, F., Zhang, G., Chen, J., Liu, Z., Xu D., & Wang, Y. (2020). Optimal voltage regulation and power sharing in traction power systems with reversible converters. *IEEE Transactions on Power Systems*, 35(4), 2726–2735. <https://doi.org/10.1109/TPWRS.2020.2968108>
24. Ramsey, D., Letrouve, T., Bouscayrol, A., & Delarue, P. (2021). Comparison of energy recovery solutions on a suburban DC railway system. *IEEE Transactions on Transportation Electrification*, 7(3), 1849–1857. <https://doi.org/10.1109/TTE.2020.3035736>

Зменшення втрат електроенергії шляхом стабілізації напруги на струмоприймачі рухомого складу постійного струму

Дмитро Тугай, Аліна Троцай, Олександр Шкурпела, Іван Костенко

Анотація. Розроблено та запропоновано енергоефективні способи стабілізації напруги на струмоприймачі електрорухомого складу засобами керування тягових підстанцій, що забезпечують номінальне значення напруги при русі електропоїзда міжпідстанційною ділянкою. Було досліджено залежність розподілу потенціалу в контактному проводі при переміщенні електрорухомого складу на міжпідстанційній ділянці. Також досліджено та розроблено нові способи стабілізації напруги на струмоприймачі електрорухомого складу, що засновані на синх-

ронній (однаковій для двох суміжних тягових підстанцій) та асинхронній траєкторіях регулювання напруги на шинах постійної напруги тягових підстанцій синхронних і двох асинхронних способів стабілізації напруги в контактній мережі, з отриманням енергетичних характеристик, що їх описують. Порівняно енергетичні показники досліджуваних способів стабілізації напруги в контактній мережі з визначенням енергетичної ефективності кожного з них. Доведено, що використання сучасних типів напівпровідникових перетворювачів, таких як активний випрямляч – джерело напруги, в силовому обладнанні тягових підстанцій постійного струму дозволить реалізувати адаптивні системи стабілізації напруги на струмоприймачі рухомого складу, що забезпечують номінальні значення напруги на тягових електродвигунах на міжпідстанційній ділянці без застосування додаткового обладнання на рухомому складі та, як наслідок, обґрунтування та застосування цих способів є придатним для модернізації діючих та проектуванні нових тягових підстанцій.

Ключові слова: активний випрямляч, електротяговий двигун, система електричної тяги, енергоефективність, коефіцієнт корисної дії, міжпідстанційна ділянка, струмоприймач, електрорухомий склад.

NOTES ON CONTRIBUTORS

Dmitry Tugay
tugay@kname.edu.ua

D.Sc., Professor
Department of Alternative Electric Power and Electrical Engineering
O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
<https://orcid.org/0000-0003-2617-0297>
<https://publons.com/researcher/G-3702-2018/>
<https://www.scopus.com/authid/detail.uri?authorId=35115703700>

Alina Trotsai
alina.trotsai@kname.edu.ua

Postgraduate student
Department of Alternative Electric Power and Electrical Engineering
O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
<https://orcid.org/0000-0003-3912-1929>

Olexandr Shkorpela
oleksandr.shkorpela@kname.edu.ua

Ph.D., Assistant Professor
Department of Alternative Electric Power and Electrical Engineering
O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
<https://orcid.org/0000-0002-7872-221X>
<https://www.scopus.com/authid/detail.uri?authorId=57215299718>

Ivan Kostenko
ivan.kostenko@kname.edu.ua

Ph.D., Assistant Professor
Department of Alternative Electric Power and Electrical Engineering
O. M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
<https://orcid.org/0000-0002-8170-7432>
<https://publons.com/researcher/E-9080-2019/>
<https://www.scopus.com/authid/detail.uri?authorId=57163429500>