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

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

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

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 switching 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 switching converters in traction substations and rolling stock devices, allowing not only to provide 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.
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]:

\[
R = \frac{\rho_c L_0}{S},
\]

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

\[
S = \frac{S_{al} (k_{al} S_c + S_{st})}{k_{al} S_{al} + k_{st} (k_{al} S_c + S_{st})}
\]

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

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 \( v = 20 \) km/h, \( R_d = 48.7 \text{ km/h} \), contact suspension type is the M-95 + 2MF-100 + A-185, \( S_{al} = 9510 \text{ mm}^2 \), 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:

\[
\begin{align*}
I_1 + I_2 &= 0, \\
I_1 R_k + I_d R_d &= E_1, \\
I_2 (1-k) + I_d R_d &= E_2.
\end{align*}
\]

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

\[
U = \frac{\rho_c L_0}{R_d S} (\frac{L}{L_0} - \frac{L^2}{L_0^2}) + (\frac{E_1 - E_2}{R_d S}).
\]

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 1](image1.png)

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

![Figure 2](image2.png)

**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 $U = U_H = const = 3000$ 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 $L_4$ and $L_5$ 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 $U = const = 3000$ V under the condition $E_1 = E_2 = E = 3300$ V, we find the roots of the quadratic equation:

$$U(L) = AL^2 + bL + c,$$

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

$$\begin{align*}
aL_1^2 + bL_1 + c &= E,
\frac{aL_2^2}{4} + bL_2 + c &= E_m,
\frac{b}{L_2} &= E_m - E
\end{align*}$$

where

$$E_m = (U - E)\left(\frac{L_3}{L_4} - \frac{L_1^2}{L_2} - \frac{L_2^2}{L_4} - \frac{L_0^2}{4L_4}\right).$$

One can stabilize the voltage in the contact network, when $U = const = 3000$ 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:

$$U(L) = AL^2 + bL + c,$$

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

$$\begin{align*}
aL_1^2 + bL_1 + c &= E,
\frac{aL_2^2}{4} + bL_2 + c &= E_m,
\frac{b}{L_2} &= E_m - E
\end{align*}$$

where

$$E_m = (U - E)\left(\frac{L_3}{L_4} - \frac{L_1^2}{L_2} - \frac{L_2^2}{L_4} - \frac{L_0^2}{4L_4}\right).$$

Figure 3. Dependences $E_1 = f(L)$ at fixed values of $E_2$ (a), and decencies $E_2 = f(L)$ at fixed values of $E_1$ (b) at $U = const = 3000$ V

Figure 4. Dependencies of $E_1 = f(L)$ at $E_2 = 3300$ V (a), and decencies $E_2 = f(L)$ at $E_1 = 3300$ V (b) at $U = const = 3000$ V
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 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:

\[
U_{AV} = \frac{1}{L_0} \int_0^{L_0} UdL;
\]  

(9)

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

\[
E_{AV} = E;
\]  

(10)

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

\[
\eta = \text{Figure 5. Paths of voltage regulation at the output of traction substations with asynchronous methods of voltage stabilization}
\]  

\[
\text{Figure 6. Dependence of the electric traction network efficiency on the voltage value of another substation fixed at half of the interstation section using the second asynchronous method of voltage stabilization}
\]
\[ E_{AV} = \frac{1}{L_0} \int_0^{L_0} U(L) dL; \]  

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

\[ E_{AV} = \frac{1}{L_0} \int_0^{L_0} E_{dl} dL = \]

\[
\begin{align*}
\text{if } (0 \leq L \leq L_1, E, 0) + \\
\text{if } \left( L_1 < L \leq \frac{L_0}{2} \right) \land E_1(E) \leq E_m, E_1(E, 0) + \\
\text{if } \left( \frac{L_0}{2} < L \leq L_0 \right) \land E_1(E) > E_m, E_1(E, 0) + \\
\text{if } \left( \frac{L_0}{2} < L \leq L_0 \right) \land E_1(E) < E, E, E_1(E, 0)
\end{align*}
\]  

\[ (12) \]

**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                                                                 | 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, $I_{dAV}$, A   | 1885                  | 1810        | 1810           | 1810           |
| Mean power of the electric train within the driving distance, $P_{AV}$, kW | 5506                  | 5506        | 5506           | 5506           |
| Mean power of the traction network within the driving distance, $P_{dAV}$, kW | 6304                  | 6220        | 6232           | 6228           |
| Mean power loss within the driving distance, $\Delta P_{AV}$, kW       | 789                   | 714         | 726            | 722            |
| Mean efficiency within the driving distance, $\eta_{AV}$               | 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, $\Delta W$, kW-h            | 328                   | 293         | 298            | 297            |

\[
I_{AV} = \frac{1}{L_0} \int_0^{L_0} \left( \frac{P_d}{U} \right) dL;  
\]

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

\[
P_{dAV} = \frac{1}{L_0} \int_0^{L_0} P_d dL = \frac{1}{L_0} \int_0^{L_0} \left( \frac{E_2 - E_1 - E_2 R_d S}{\rho_e L} \right) dL;  
\]

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

\[
P_{AV} = \frac{2}{L_0} \int_0^{L_0} \left( \frac{U (L) \frac{E}{\rho_e L_0} \left( 1 - \frac{L}{L_0} \right) + R_d L_0}{L} \right) dL;  
\]

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

\[
P_{AV} = \frac{2}{L_0} \int_0^{L_0} \left( \frac{E_2 - E_1 - E_2 R_d S}{\rho_e L} \right) dL;  
\]

- the mean power of the traction network within the driving distance (with asynchronous stabilization (mode 2)):
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., & Plakhhtii, 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., Plakhhtii, 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/matecconf/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

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/en14144156

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., & Kotelevec, 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 (SIEMEN), (pp. 483–488). IEEE. https://doi.org/10.1109/SIEMEN.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. Pluhin, 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
ронній (однаковий 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 випрямлювач – 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 електродвигуннах 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 Shkurpela
oleksandr.shkurpela@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