Prospects for the application of electricity storage systems on the ground branch of the Tashkent metro

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Abstract. The purpose of the work is to evaluate the efficiency of promising electricity storage systems in the traction power supply system of the above-ground line of the Tashkent metro. The work uses methods of simulation modeling of the interaction of urban electric rolling stock and the traction power supply system with electricity storage devices. The modeling was carried out taking into account the frequency of changes in operating modes of electric rolling stock, including regenerative braking, which affects the energy performance of electricity storage systems. The characteristics of the operation of electricity storage systems, an assessment of the voltage level on the buses of sectioning posts, the duration of episodes of operation in charge and discharge modes, their number and the corresponding total volumes of electricity per day were obtained. The calculation results make it possible to assess the prospects for using electricity storage systems in the operating conditions of the ground part of the Tashkent metro. Key words: traction power supply system, electrical load schedule, electricity storage systems, post-sectioning, simulation modeling, operating episodes, voltage level, state of charge, depth of discharge, energy intensity.

1 Introduction

The development of electricity storage technologies makes it possible to solve a set of problems to increase the efficiency of power supply systems for various purposes, including in transport. Modern technologies make it possible to use electricity storage systems in the traction power sector of railway transport, taking into account the peculiarities of its operation. Current issues are related to solving problems of coordinating the operation of an electricity storage device with the railway traction power supply system, setting up the device, calculating normal and emergency modes, assessing the potential effectiveness of the application, etc. To solve these problems, it is necessary to consider the operating conditions of electricity storage systems and obtain an assessment their effectiveness in the conditions of the existing section of the railway, in particular the Tashkent Metro (TM), which is being developed through above-ground lines. The compact location, short length and closed nature of the TM traction power supply system in conditions of heavy traffic of electric trains

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characterizes it as a unique testing ground that allows testing new equipment and technologies under operating conditions. Some modern technologies and materials are already successfully used in TM, for example, in the field of organizing train traffic, safety, traction and infrastructure [1-5]. Traction substations use modern power and switching equipment. The TM traction power supply system includes five traction substations and four sectioning posts located on a double-track section of the railway. The graph of the electrical load of traction substations has two areas of maximum values, corresponding to the peaks of passenger traffic. However, analysis shows [6-10] that the expanding network of existing TM land lines, first of all, excessively consumes electricity from the city grid and makes a negative contribution to the global sustainable development program [11-13].

The main goal of the work is to evaluate the efficiency of promising electricity storage systems in the traction power supply system of the ground line of the Tashkent metro.

2 Results of the work and their discussion

The prerequisites for achieving the main goal of the work are the results of search work to ensure transportation safety, reduce emissions into the environment, improve cars, their components, parts [14-20], which are carried out at the Research Center for Railway Transport of the Tashkent State Transport University.

The operation of electric trains shows a high level of energy recovery when using regenerative braking, reaching in some cases up to 50% of traction energy consumption. Recording the currents and voltages of electric trains using motion parameter recorders allows one to determine the operating ranges of traction currents and voltages on the pantographs of electric rolling stock per day.

The graph of the electric traction load of electric rolling stock in current-voltage coordinates (Fig. 1) differs from similar graphs obtained for sections of railways with a predominance of freight traffic. The average slope coefficient of this characteristic for MCC conditions is –0.17, for sections with flat and mountainous profile types – –0.068 and –0.14, respectively, while the ranges of voltage changes on the pantographs of TM electric trains are wider in the traction mode (from 2900 to 3800 V) and regenerative braking (from 3100 to 3900 V). These differences are related to the conditions of traffic organization in the areas considered. The change in traction load and voltage on the current collectors of one of the electric trains during the period of its movement is illustrated in Fig. 2.

The most effective locations for storing electricity storage systems are linear devices of the traction power supply system (sectioning posts or parallel connection points). This circumstance is due to the simultaneous reduction of electricity losses in the traction power supply system and an increase in throughput and carrying capacity in the intersubstation area. Converting passive sectioning posts into active ones by placing electricity storage devices on them allows one to obtain a number of positive effects in the traction power supply system.

The efficiency of using electric energy storage systems for TM conditions was determined based on the results of simulation modeling of the operation of the traction power supply system, obtained using the software package. The operating conditions of electric trains and the parameters of the traction power supply system were taken as the initial data for modeling. Graphs of electrical load of power equipment and voltage changes are built on the basis of instantaneous calculation schemes.

Assessing the operating conditions of an electricity storage device in the TM traction power supply system allows one to obtain indicators on the volume and duration of charge and discharge modes. In relation to the operating conditions of the storage device at the sectioning station, frequency histograms for the volume of electricity and the duration of episodes of operation in discharge and charge modes are shown in Fig. 3, I and II, respectively. The average number of episodes of operation in the charging and discharging

mode of electric energy storage devices for operating conditions at sectioning posts for the discharge mode is 542 episodes, for the charging mode – 404 episodes.

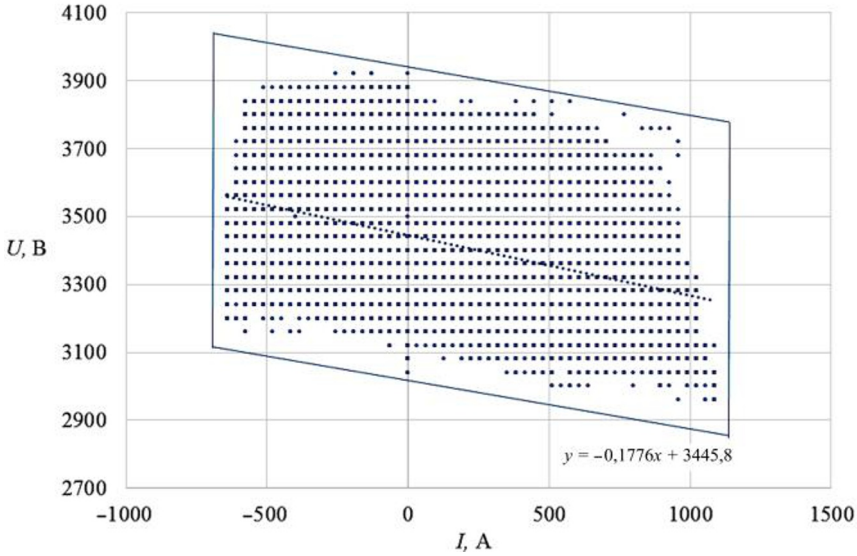


Fig. 1. Changes in currents and voltages on the current collector of electric trains

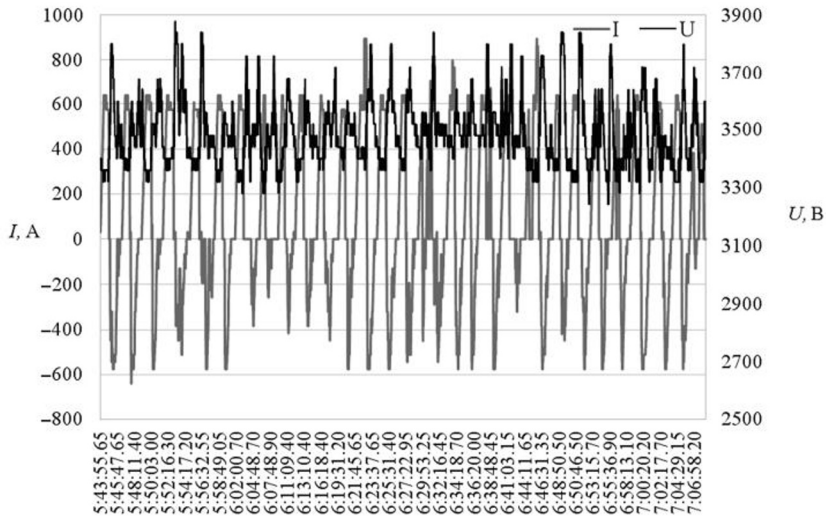


Fig. 2. Graph of traction load of electric train TM

For the given operating conditions of the storage system, it was found that the duration of operating episodes for operating modes does not exceed 5 minutes, and the volume of electricity does not exceed 50 kWh for an episode. In general, the duration of operation of storage systems in charge and discharge modes is characterized by short duration and a large number of repetitions during the day.

Necessary conditions for assessing the operation of storage devices in a traction power supply system include the degree of charge and the depth of discharge of electrical storage devices. The performance of electricity storage systems depends on the initial voltage, internal resistance, charge and discharge currents, amount of electricity and energy intensity.

When determining the degree of charge, the equations of Shepherd, Khaskina–Danilenko, etc. are used.

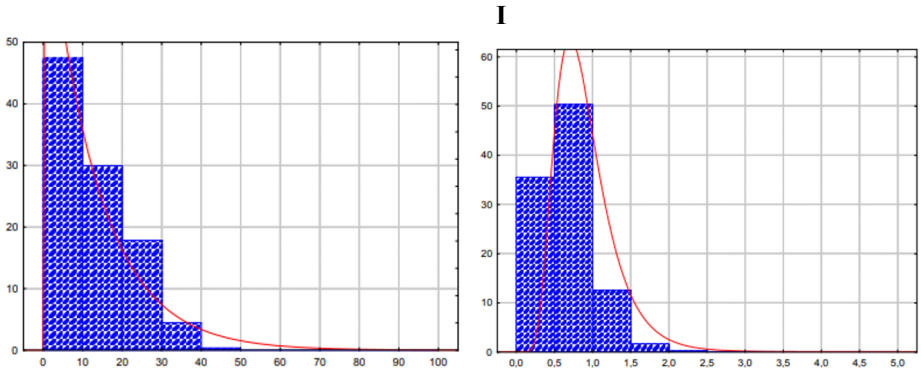
One simple way to assess the state of charge is based on the Ah meter, the amount of electricity or the Wh meter for charge and discharge modes.

Plotting a graph of changes in the cumulative volume of energy makes it possible to obtain the required level of useful energy intensity W_{UEI} as the difference between the maximum W_{max} and the minimum cumulative value W_{min} per day. The indicated volume of W_{UEI}, assuming that the efficiency of the storage system is equal to unity, allows us to estimate the degree of charge of the storage device at the kth step of calculations using the following formula:

$$S_oC_k = \frac{\sum_{t_0}^{t_k} u_k \cdot i_k \cdot \Delta t_k}{W_{UEI}} \cdot 100$$

where: u_k, i_k – voltage and current values for the k-th time interval; k Δt_k – time step.

According to the results of simulation modeling for the most severe operating conditions of the storage system - the switching voltage per discharge is equal to the open circuit voltage, the external characteristic is “hard” - the maximum energy intensity for operating conditions at sectioning posts is in the range of 950–1300 kWh. For the considered sectioning station, the maximum useful energy intensity of the W_{UEI} is 1185 kWh. A graph of changes in the degree of charge of the storage system, constructed under the condition that the initial degree of charge is equal to SoC0 = 50% (discharge depth 95%), is shown in Fig. 4, a. When restrictions are introduced on the useful energy intensity of 500 kWh, the state of charge of the S_oC does not change the cyclicity during the day under consideration (Fig. 5, b). The total volume of electricity per day in discharge mode with limited energy intensity drops from 7054 to 5920 kWh, i.e. by 16.1%, in charge mode - from 7166 to 6168 kWh, i.e. by 13.9%. With further limitation of energy intensity, for example, to 300 and 200 kWh, there is a decrease in the volume of electricity for the discharge mode, for the options under consideration - by 22.2 and 24.9%, respectively, for the charge mode - by 21.6 and 24.7%, respectively.



(a) Energy volume in discharge mode, kWh

(b) Duration of discharge episode, min

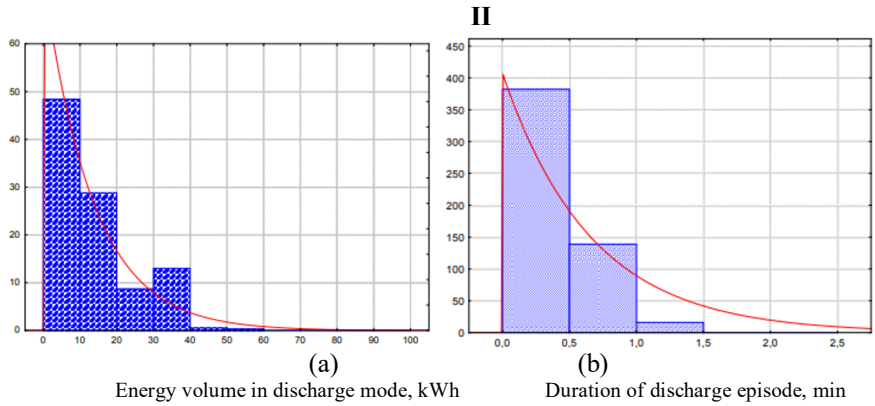


Fig. 3. Frequency histogram of the distribution of the volume of electricity (I, a; II, a) and the duration of the episode (I, b; II, b) in the discharge and charge modes, respectively (the ordinate shows the relative frequency of oscillations in%)

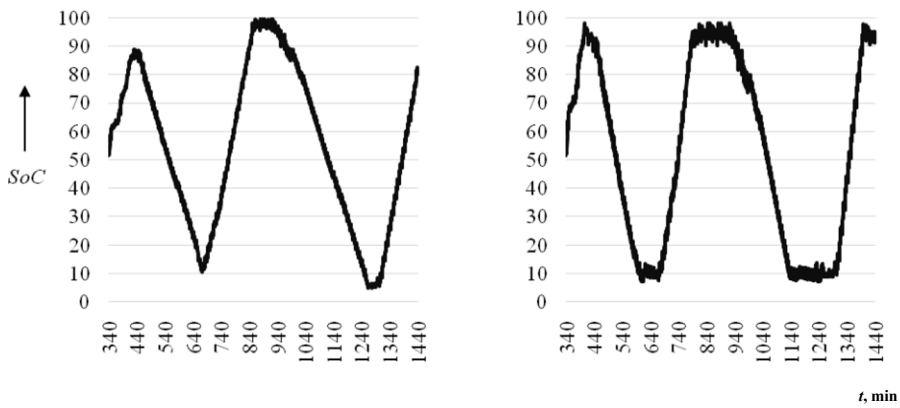


Fig. 4. SoC changes for the drive: a – without restrictions on energy intensity, b – with a limitation of 500 kWh

Placing electricity storage devices at sectioning posts allows one to improve the load capacity of the traction power supply system and increase the energy efficiency of the transportation process. Let's consider the results of calculating load capacity indicators for two options - with or without an electricity storage system (basic). The main indicators of load capacity include the load factor of rectifiers of traction substations and the minimum voltage level at the pantograph of electric rolling stock. The load factor of the rectifiers (pu) is calculated as follows:

$$k_{t.rl} = \frac{I_d}{\sum I_{nom} \cdot k_{add.t}}$$

where: I_d – the highest average current value for period t, A; I_{nom} – rated current of rectifier units, determined by the number of units connected to the load, A; k_{add} in t – permissible load coefficient (for averaging intervals of 0.25 min – 1.9; 2 min – 1.5; 15 min – 1.25; 30 min and more – 1.0).

The change in the load factor of rectifiers of traction substations (%) is determined by the formula:

$$\Delta k_{n.vt} = \frac{k_{n.vt}^{baz} - k_{n.vt}^{\text{var}}}{k_{n.vt}^{baz}} \cdot 100$$

where: k^{base}_{nvt}, k^{var}_{nvt} – load factors of rectifiers of traction substations during the averaging period t for the base and considered options, respectively.

According to the calculation results for the application options for electricity storage systems, the greatest reduction in the load factor of rectifiers is observed at the traction substations of the Pokrovsko-Streshnevo and Andronovka MCC stations - by 25 and 35%, respectively.

A characteristic condition for the operation of electricity storage systems is the insufficiency of recovery volumes - the discharge mode predominates in the graph of the degree of charge. For these cases, it is necessary to charge electricity storage systems from the contact network in a voltage range close to the open-circuit voltage of traction substations.

A comparison of the options in terms of the minimum and one-minute voltage shows that for the option of using electricity storage devices, the minimum voltage on the pantograph of electric rolling stock is observed to be higher on average by 1.5% relative to the base option.

It is possible to implement several options for placing electricity storage systems in the TM system. With regard to the criterion of energy efficiency, the best option is the one that corresponds to the placement of systems at the traction substation and sectioning posts that border the substation on both sides. In this case, the potential energy savings per day for passenger traffic is about 24.6 thousand kWh, the level of electricity losses is 3.4%. An alternative option is to place electricity storage devices at the specified sectioning posts - the potential for energy savings for this option is 24.6 thousand kWh per day, the level of electricity losses is 3.6%.

3 Conclusions

Thus, based on the results of simulation modeling and calculations for the TM traction power supply system, the following conclusions can be drawn about the potential efficiency of using electricity storage devices.

The volumes of energy realized by electricity storage devices at TM sectioning posts by operating episodes for charge and discharge modes do not exceed 50 kWh. The duration of episodes of operation in charge and discharge modes is no more than 3.0 minutes, the number of episodes is 600 cases per day. These conditions make it possible to maintain the degree of charge by alternating short discharge-charge cycles. The graph of the degree of charge of electricity storage devices at TM sectioning posts is characterized by cyclical operation - it has two cycles per day. The useful energy capacity for electricity storage devices is estimated to be in the range of 950–1300 kWh. For two sectioning posts, the charge graph is dominated by discharge. Reducing the useful energy intensity of storage devices to 200–300 kWh leads to a loss of energy volume during regenerative braking of about 30%.

The effect of using electricity storage devices at MCC sectioning posts is to reduce the load factor of rectifiers at traction substations by an average of 28.6% and increase the minimum voltage by 1.5%. According to the energy efficiency criterion, the use of electricity storage systems allows increasing the level of energy efficiency by 13.3%.

References

1. R.V. Rahimov, et.al., AIP Conference Proceedings **2432**, 030066, 030066-1–030066-6 (2022). DOI:10.1063/5.0089484
2. B. Abdullaev, et.al., E3S Web of Conf. **402**, 01013, 1–9 (2023) DOI: 10.1051/e3sconf/202340201013
3. B.P. Rashidov, et.al., *Corrosion of Aluminum and Aluminum Alloys Used for Rolling Stock.* Metal Science and Heat Treatment (2023). DOI 10.1007/s11041-023-00910-5
4. B. Abdullayev, R. Rahimov, F. Khikmatov, Kh. Otajonov, D. Sultonaliev and P. Abdurahmonov, AIP Conference Proceedings **2612**, 060034, 060034-1 – 060034-12 (2023). https://doi.org/10.1063/5.0113108
5. Sh.B. Djabbarov, et.al., E3S Web of Conf. **371**, 04035, 1–9 (2023) DOI:10.1051/e3sconf/202337104035
6. Ya.A. Khurmatov, et.al., E3S Web of Conf. **402**, 04009, 1–8 (2023) DOI: 10.1051/e3sconf/202340204009
7. Y. Boronenko, R. Rahimov, Transport Problems **16(3),** 199–211 (2021). DOI: 10.21307/TP-2021-053
8. Y. Boronenko, A. Gayipov, et.al., E3S Web of Conf. **402**, 06011, 1–10 (2023) DOI:10.1051/e3sconf/202340206011
9. Y. Boronenko, et.al., Lecture Notes in Mechanical Engineering, pp. 450–460 (2022). DOI: 10.1007/978-3-031-07305-2_45
10. R. Rahimov, et.al., E3S Web of Conf. **264**, 05049 (2021). DOI: 10.1051/e3sconf/202126405049
11. D.V. Miklushevskiy, et.al., Tsvetnye Metally **2015(9),** 6–12 (2015) DOI: 10.17580/tsm.2015.09.01
12. Y.N. Mansurov, et.al., Metallurgist **62(1-2),** 169–175 (2018) DOI: 10.1007/s11015-018-0640-z
13. A.A. Aksenov, et.al., Tsvetnye Metally **(4),** 81–85 (2017). DOI: 10.17580/tsm.2017.04.12
14. A.I. Bezrukikh, et.al., Int. J. of Adv. Manuf. Technology **120(1-2),** 761–780 (2022). DOI: 10.1007/s00170-022-08817-w
15. Y.N. Mansurov, J.U. Rakhmonov, Non-ferrous Metals **45(2),** 37–42 (2018). DOI: 10.17580/nfm.2018.02.07
16. Yu.N. Mansurov, A.A. Aksenov, V.P. Reva, Tsvetnye Metally **(5),** 77–81 (2018). DOI: 10.17580/tsm.2018.05.11
17. A.A. Aksenov, et.al., Metallurgist **61(5-6),** 475–484 (2017). DOI: 10.1007/s11015-017-0520-y
18. V.S. Rudnev, et.al., Tsvetnye Metally **(1),** 59–64 (2017). DOI: 10.17580/tsm.2017.01.10
19. S. Djabbarov, et.al., E3S Web of Conf. **402**, 04010, 1–14 (2023) DOI 10.1051/e3sconf/202340204010
20. S. Saidivaliev, et.al., E3S Web of Conf. **389**, 05023, 1–10 (2023) DOI:10.1051/e3sconf/202338905023