

Operating modes of electric energy storage systems on the Moscow Central Ring

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Abstract. Improving the performance of electric traction systems is associated with the use of new technologies, the introduction of which is preceded by an assessment of the technical efficiency of their work. Nowadays, electric energy storage systems in Russia have not found application in electric traction systems, but questions are being actively developed on advisability and possibility of their use. And electric traction load of electric traction system of the Moscow Central Ring is not an exception, which forms in the conditions of domination on the area of passenger traffic and frequent electric tractions stops. Electric energy of high level of return of electric trains was formed on the site. Obtaining the technical result of assessing the use of energy storage systems of electric energy is most expedient to perform on the basis of simulation modeling of the interaction of electric rolling stock and electric traction system in the conditions of the Moscow Central Ring. Modeling results allow receiving the main characteristics of storage units and voltage load graph, determining the duration of work episodes in charge and discharge modes, their number and appropriate total volumes of electric energy per day. The received results allow assessing requirements to the technical characteristics of storage systems in relation to work conditions in the electric traction system of the Moscow Central Ring and performing assessment of economic efficiency of this activity.

1 Introduction

Moscow Central Ring (MCR) is a railway area on which high technologies found application, which are used in Russia in the field of trains traffic organization, safety, traction and infrastructures [1, 2]. In the electric traction system of MCR on traction substations, modern samples of power and switching equipment found application: dry converting transformers, fast acting switches, distributive devices of modular execution, modern rectifier converters etc. The electric traction system includes five traction substations and four posts of sectionalization. On the MCR area, passenger trains of the ES2G «Lastochka» series run in passenger traffic. Organization features of passenger traffic lead to formation of an electric load graph, which has two fields of maximum values, which are appropriate to the spike of passenger traffics. Besides, the features of MCR should include the electric

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trains' traffic conditions, which are characterized with frequent stops, accelerations and braking.

2 Problem statement

In the conditions of MCR, the electric trains of series ES2G (Siemens Desiro Rus) allow efficiently using regenerative braking, creating conditions for energy exchange between adjacent electric rolling stock and contributing increase of transportations efficiency. The date processing results of traffic parameters registers «RPD MPSU and D» of electric trains on MCR per day allow receiving working traction currents and voltages ranges on current collectors of the electric rolling stock (fig. 1).

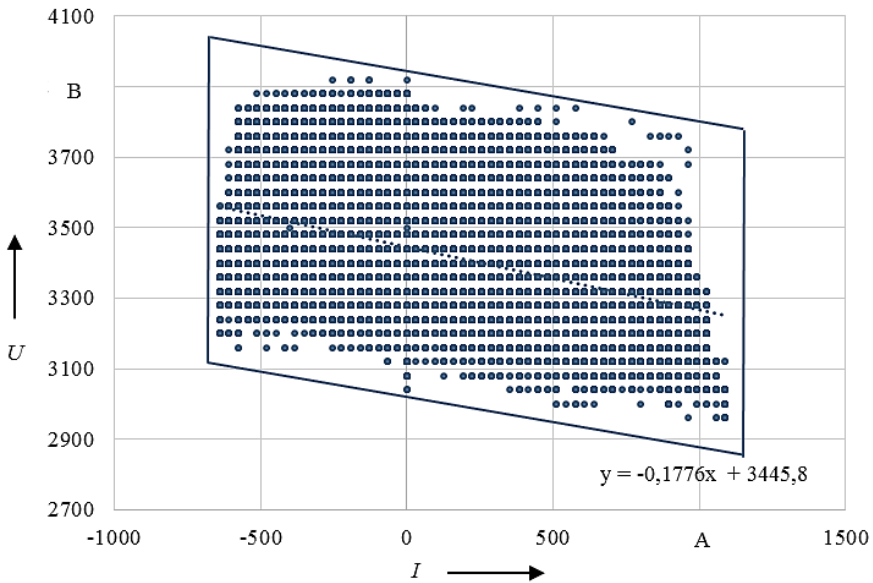


Fig. 1. Currents and voltages changes graph on current collector of electric trains ES2G on MCR.

The given graph shows the voltages changes ranges in modes of traction and regenerative braking. The given graph character differs from similar graphs for areas with a predominance of heavy traffic that, firstly, for the conditions of MCR an average tilt coefficient is $-0,17$ opposite to coefficients $-0,068$ and $-0,14$, which were received for electric locomotives of series 2ES6 and 2ES10 on the areas with plain and mountain profile types respectively [3], secondly, the voltage changes ranges on current collectors of electric trains ES2G are significantly wider and equal in traction mode from 2900 V up to 3800 V, in regenerative braking mode from 3100 up to 3900 V. Taking into account the area way profile, which refer to the IIInd type (plain) [4], the given differences should connect with conditions of traffic organization, which influence both traction electricity consumption and non-balance level [5]. Frequency distributions for conducted values show that voltage distribution is next to the normal distribution low (average value is about 3400 V), current distribution is next to the even distribution in the negative and positive ranges (for modes of regenerative braking and traction).

The traction load graph of electric trains, express to MCR, is characterized with frequent use of regenerative braking. As an example, there is a graph of traction load and voltage on current collector of one electric train during a period of traffic on MCR from 5:43 till 7:06 hh:mm (fig. 2).

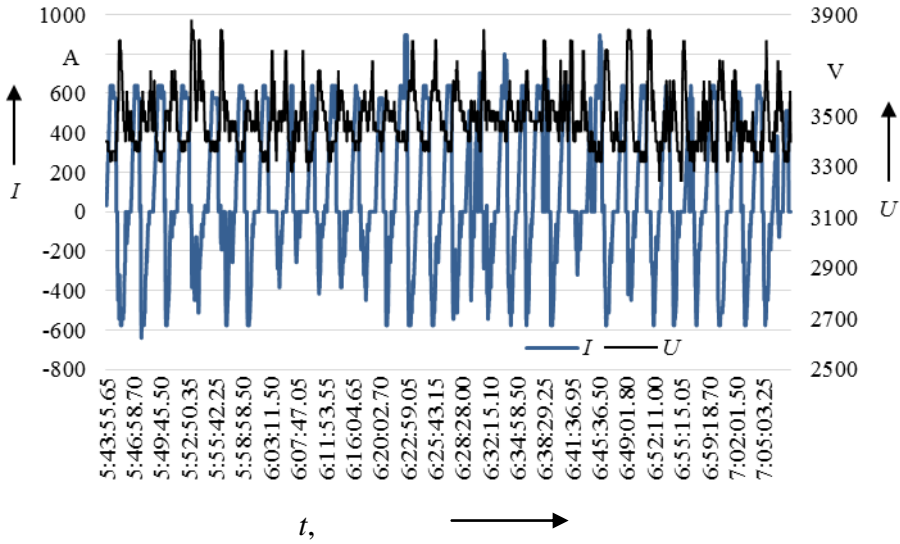


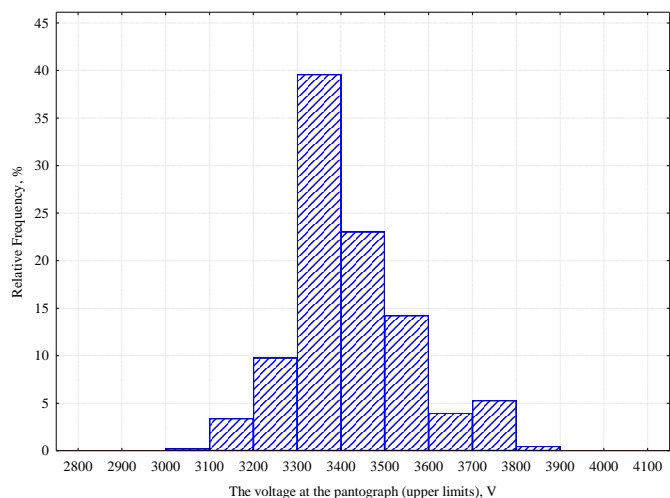
Fig. 2. Electric train traction load graph on MCR.

Herewith the received by traffic results of electric trains ES2G on MCR the frequent distribution of voltage and current on current collector show the sufficiently wide range of observed values (fig. 5a, b).

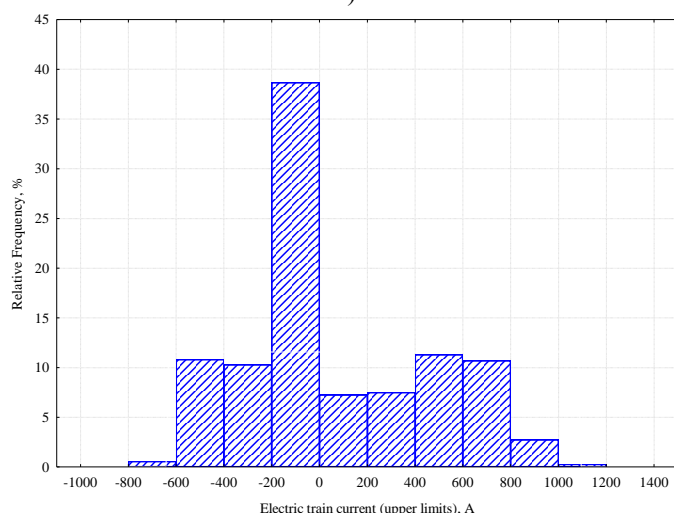
3 The simulation modeling

The feature of the electric traction load of MCR is the cyclicity of traction and regenerative braking modes, comparability of currents levels in modes, characteristic voltage level change, which appropriates to the electric train work modes. The specified features of electric traction load lead to the high level of specific recovery, which is observed in borders of MCR, and determine the questions relevance of energy exchange processes regulation in the electric traction system.

Global trends in management of energy exchange flows in the electric networks, devices creation, which provide the work in the buffer mode, voltage stabilization and work efficiency of renewable energy sources, led to appearance and development of the electric energy storage systems [6 – 10, 20]. The given questions problematic is typical and for the electric traction, specifically, for the conditions of MCR.



a)



b)

Fig. 3. Voltages (a) and current (b) changes graph on current collector of electric trains ES2G on MCR.

One of the directions of the energy efficiency increase on MCR is the inverters setting, which allow providing the energy recovery receiving and its transfer to the AC bus bars. Location places of inverters in borders of MCR are determined by traction and electric calculations, by which the return energy volume is, determined [11]. The electric energy storage systems implementation in the electric traction system is an alternative option, having a range of advantages for inverters setting on traction substations, which reveal in a possibility of storage units setting on the linear units and improvement of load capacity parameters of the electric traction system [12].

The researches implementation in the study of electric energy storage units' efficiency in the electric traction system should be performed for equipments work conditions, accepted on MCR. In particular, on traction substations as a work mode a scheme of alternate and parallel work of converter units was accepted. For example, on traction substation st. Andronovka there was accepted a parallel work mode of converter units. This

fact should consider in calculations, assuming that the external units' characteristics are not identical [13]. Tilt coefficients of the external units' characteristics of substation recovery units (PVA-1, PVA-2) for the given example are -0.03 and -0.06 (fig. 6).

Different characteristics for modeling purposes of energy exchange processes in the storage systems don't have essential value. In this case it is acceptably to take an average tilt coefficient of external characteristic.

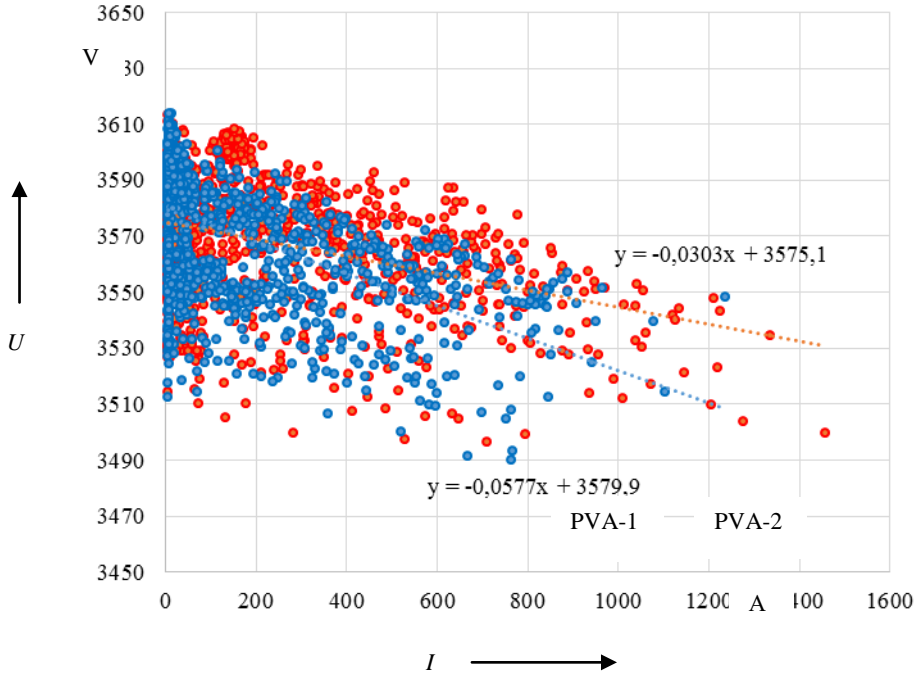


Fig. 6. External characteristics PVA-1 and PVA-2 of substation st. Andronovka.

During the research you should take into account the voltage level on traction substations, which can substantially differ because of number of reasons. The voltage change graph on bus bars 3.3 kV, the values for which were recalculated by one minute intervals of averaging for measurements on the side of higher voltage, is given on fig. 7. For the specified cases voltage of idle speed should determine at absence of traction load with following averaging for modeling purposes.

The most effective placements of electric energy storage units are placements of linear devices in the electric traction system (posts of posts sectionalization or points of parallel connection). This circumstance is conditioned by simultaneous electric energy losses reduction in the electric traction system and increasing of bandwidth transportation capacity on the inter substation area. Passive posts of sectionalization transformation into active by means of placement on which the electric energy storage units allows receiving a row of positive in the electric traction system [14].

Use efficiency researches of electric energy storage units were performed with the help of simulation modeling in the software complex CORTES on the basis of traction calculation and performed traffic graph of MCR. By modeling there was taken into account voltage difference on traction substations bus bars. Subject to the work conditions of storage systems are like work conditions of rectifier-inverter converters, modeling of energy exchange processes was performed for inverters by following setpoints values by voltage 3600 V and 3550 V for charge and discharge modes respectively. For specified conditions with the help of instant schemes there were received the electric load graphs and voltage

changes on post of sectionalization bus bars (as an example on fig. 8 there is given a graph of voltage change on post of sectionalization bus bars PSK 270).

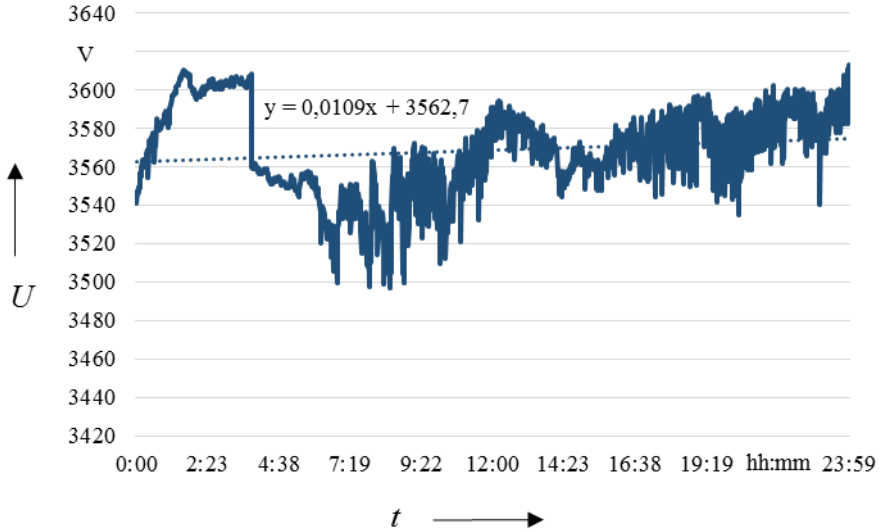


Fig. 7. Voltage change graph on bus bars 3.3 kV of st. Andronovka.

The received according the modeling results frequency voltage distribution on post of sectionalization bus bars shows fairly narrow range of observed values (as an example on fig. 9 there is given distribution for PSK 270).

Modeling results allow assessing change ranges of electric energy storage units' currents on posts of sectionalization. Current ranges assessment for conditions of devices placement устройств on posts of sectionalization of MCR for received average values (mean) and mean-square deviation (SD) are given on fig. 10.

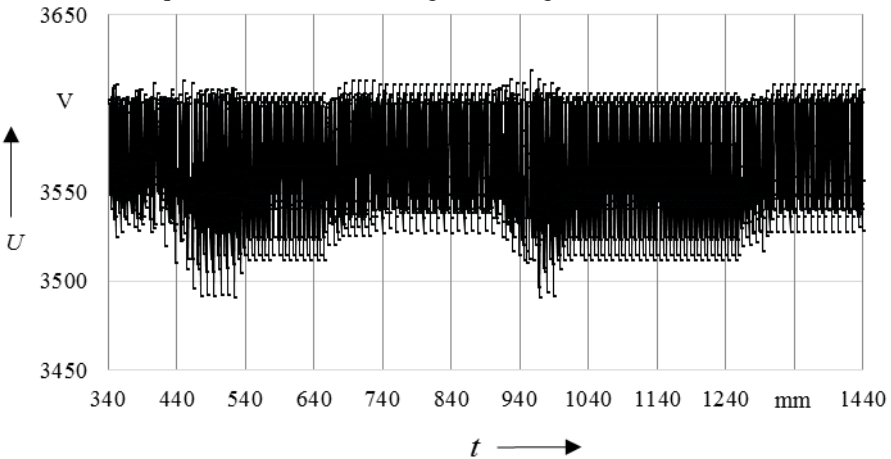


Fig. 4. Graph of voltage change on post of sectionalization bus bars PSK 270.

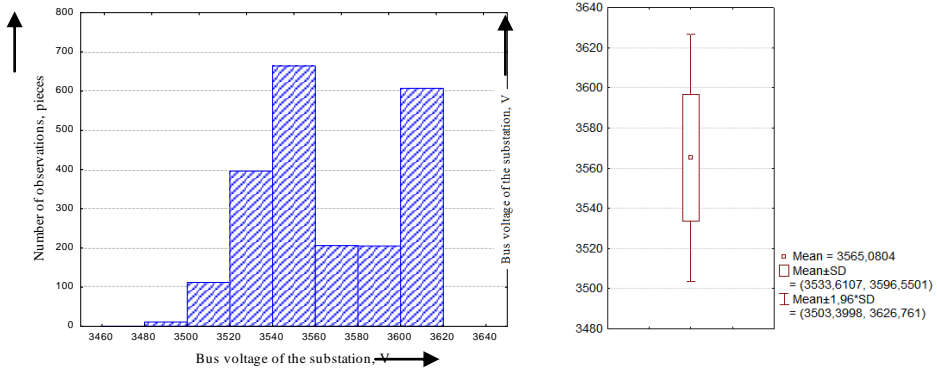


Fig. 9. Frequency histograms of voltage distribution on post of sectionalization bus bars PSK 270.

Work mode of load energy storage unit is characterized by electric energy volumes in charge and discharge modes, the work episodes duration in the given modes. Calculated characteristics for charge and discharge modes in relation to the storage unit work conditions on post of sectionalization PSK 270 are given on fig. 11 and 12, respectively.

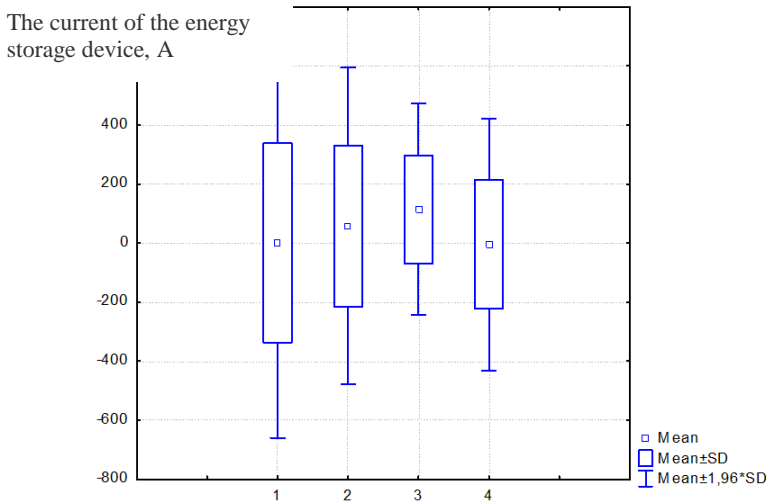


Fig. 10. Change range of electric energy storage units' currents on posts of sectionalization: 1 – PSK 270, 2 – PSK 445, 3 – PSK-1, 4 – PSK Cherkizovo.

Average number of work episodes in charge and discharge modes of the electric energy storage units for work conditions on posts of sectionalization for charge mode is 542 episodes, for discharge mode is 404 episodes.

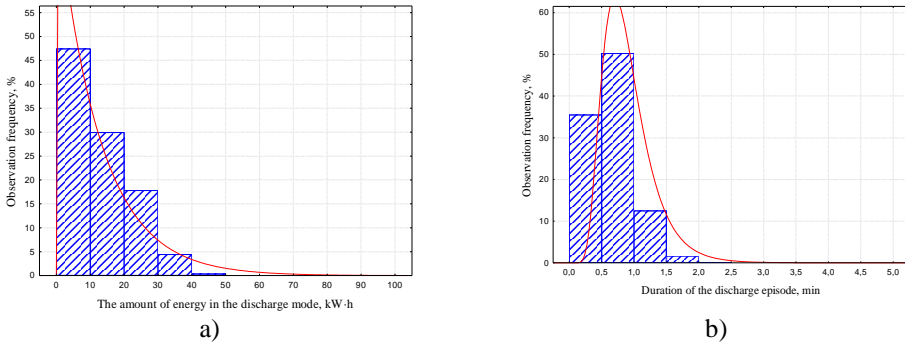


Fig. 11. Frequency histogram of electric energy volume distribution and episode duration in discharge mode for PSK 270.

One of the most important parameters, which influence the storage unit energy characteristics, there are voltage setpoints, which determine its work in different modes. For given conditions by storage unit work episodes [15 – 16] there was received that storage unit work episodes in different modes don't exceed 5 min, in particular, for PSK 270 it is no more than 2 min, and electric energy volume doesn't exceed 50 kWh for an episode, that means the energy exchange processes are short-time and with plenty of repetitions during the day.

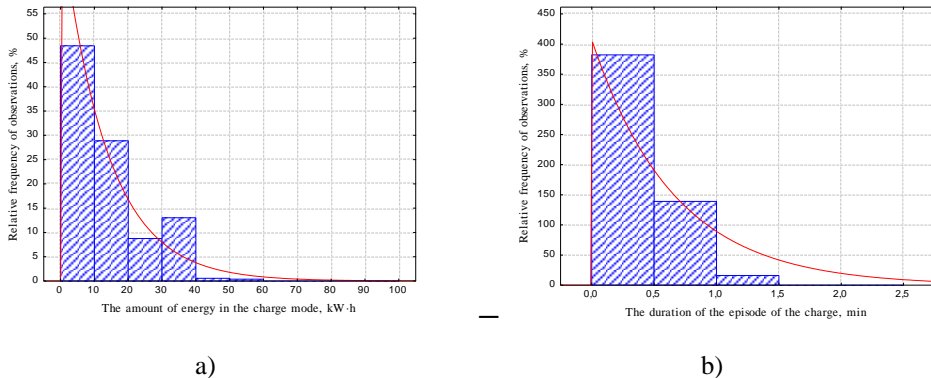


Fig. 12. Frequency histogram of electric energy volume distribution and episode duration in charge mode for PSK 270.

4 The received results

The electric energy storage units charge degree is determined by row of factors: initial voltage, internal resistance, discharge current, electricity number, capacity, discharge current (charge). In calculations of charge degree we use equations of Shepherd, Haskina-Danilenko, Romanov [17 – 19], the other empirical dependences, equations, which were received with the help of regression analysis instrument or artificial neuronal networks model. One of the simple assessment ways of charge level is a way based on a counter $A \cdot h$ or electricity number. Modification of this method is a method based on a counter $W \cdot h$ for charge and discharge modes, which is suitable for assessment of storage unit work in general form. This method we use further for energy exchange processes assessment in the electric traction system.

Change graph building of energy cumulative volume allows receiving required level of useful energy intensity W_{EESU} as a difference between the maximum W_{max} and the minimum cumulative value W_{min} per day. Specified volume W_{EESU} allows assessing the level of storage unit charge on the k -th step of calculations by following formula:

$$SoC_k = \frac{\sum_{t_0}^{t_k} u_k \cdot i_k \cdot \Delta t_k}{W_{H\text{ЭЭ}}} \cdot 100, \quad (1)$$

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

Simulation modeling results of the electric rolling stock and the electric traction system interaction show that in the absence of restrictions on the value of electric energy storage unit energy intensity for the conditions of PSK 270 required useful energy intensity $W_{H\text{ЭЭ}}$ reaches the level 1185 kWh. In relation to useful energy intensity the change graph of charge level by admitting that the initial charge level $SoC_0 = 50\%$, is given on fig. 12, a. At introduction of restrictions for useful energy intensity in the amount of 500 kWh the change graph shows that SoC doesn't change the cyclicity during the considered day and doesn't substantially change its own character (fig. 12, b).

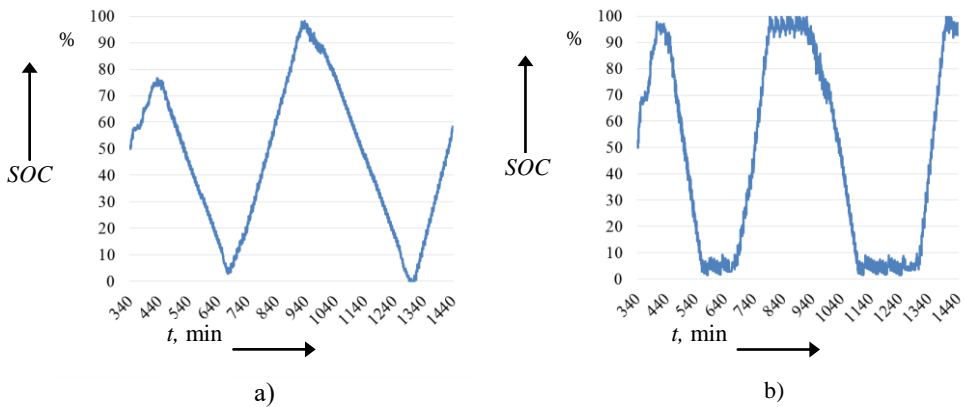


Fig. 12. Change graph of SOC for storage units on PSK 270: a – without restrictions for energy intensity, b – with restriction of 500 kWh.

The total electric energy volume per day in discharge mode in the second case falls in relation to the first from 7054 kWh up to 5920 kWh, that is 16.1 %, in charge mode it falls from 7166 kWh up to 6168 kWh, that is 13.9 %. At introduction of restrictions for energy intensity up to 300 kWh and 200 kWh we can see the volumes reduction for discharge mode for 22.2 % and 24.9 % respectively, for charge mode for 21.6 % and 24.7 % respectively. Change graphs of charge level show that charge/ discharge episodes on some parts of the day don't alternate, but follow in a row, that determines the characteristic daily schedule type, which is conditioned by transportation cyclicity.

The electric energy storage units' placement on posts of sectionalization allows improving parameters of the electric traction system load capacity and increasing the transportation process energy efficiency.

Let's consider calculation results of load capacity for a base variant, in the quality of which there is accepted the existing variant, in which there are no electric energy storage systems or other regenerative braking energy receivers of electric rolling stock.

As indicators of load capacity let's consider two: the load coefficient of traction substations rectifiers and the minimum voltage level on the electric rolling stock current collector.

Rectifiers load coefficient, r.u. (relative units), is determined by formula:

$$k_{n, \delta t} = \frac{I_{d t}}{\sum I_{\delta n o m} \cdot k_{\delta o n \delta t}}, \quad (2)$$

where I_d – the most average current value for a period t , A; $I_{in nom}$ – nominal current of rectifier units, which is defined by number of included under load units, A; $k_{per in t}$ – coefficient of permissible load (for averaging intervals 0.25 min. – 1.9, 2 min. – 1.5, 15 min. – 1.25, 30 min. and more – 1.0).

Load coefficient change of traction substations rectifiers, %, is determined by formula:

$$\Delta k_{n, \delta t} = \frac{k_{n, \delta t}^{\delta a 3} - k_{n, \delta t}^{\delta a p}}{k_{n, \delta t}^{\delta a 3}} \cdot 100, \quad (3)$$

where $k_{n, \delta t}^{\delta a 3}$, $k_{n, \delta t}^{\delta a p}$ – load coefficients of traction substations rectifiers by averaging period t for base and considered variant respectively.

The greatest reduction of rectifiers load coefficient was noted on the substation of st. Pokrovsko-Streshnevo and st. Andronovka, the coefficient level reduction of rectifiers is more than 25 % and 35 % respectively.

Assessment of total electric energy volumes in charge and discharge modes is performed for placement conditions of electric energy storage units on the posts of sectionalization of MCR. Comparison of storage unit electric energy volumes W_{EESU} by posts of sectionalization shows a need of electric energy volumes balancing (fig. 13) by means of charging implementation in standby mode by voltages on bus bars of post of sectionalization, which are close to idling voltage of traction substations for storage units, which are placed on the posts of sectionalization PSK 445 and PSK 170.

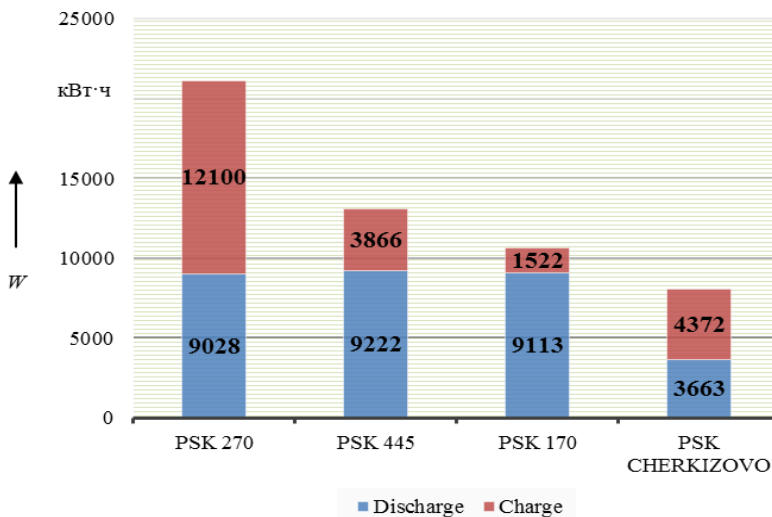


Fig. 13. Electric energy volumes histogram of electric energy storage units by work modes.

Variants comparison in size of minimum and one minute voltage with the purpose of storage unit effect assessment by voltage no stabilization on bus bars of post of sectionalization shows that for arrangement variant of electric energy storage units regarding base variant minimum voltage on current collector of electric rolling stock provides higher on average by 1.5 % or by 50 V.

The electric energy storage units work leads to load coefficient reduction of rectifiers on traction substations of MCR on average per day from 12.5 % up to 28.6 %. The largest energy volumes in charge and discharge modes of storage unit are observed for post of sectionalization PSK 270 conditions, for which discharge and charge energy volumes refer to each other as 1/1.3.

The load capacity parameters comparison of the electric traction system for use variants of electric energy storage units and inverters shows that in the first case we can see the load coefficient reduction of rectifier substations converters on average per day by 22.5 %, increase of average minimum voltage on electric trains current collectors by 4.1 % or about 150 V.

Placement variants comparison of rectifier-inverter converters and electric energy storage units by energy efficiency level shows minor values deviation. For the variant with rectifier-inverter converters use on traction substations increase of transportation energy efficiency is 11.97 %, for the variant with electric energy storage units use on posts of sectionalization it is 11.94 %. The losses level in traction network for the variant with inverter is 3.68 % contrary to 3.14 % for the variant with storage units' placement on posts of sectionalization (tabl. 1). Electric energy volume for return and charge modes for considered variants is 10.5 % and 13.7 %, respectively.

Table 1. Electricity consumption on traction for different variants.

Variant	Balanced Electricity consumption On traction, kWh	Losses in traction network, kWh	Return volume (charge), kWh
Basic variant	181 116	6 011	0
Variant with RIC	159 424	5 874	16 717
Variant with storage units	159 490	5 014	21 862

By the criterion of energy efficiency the best variant is the variant, which corresponds to inverter placement on traction substation of st. Andronovka and electric energy storage units on posts of sectionalization PSK 270 and PSK Cherkizovo, which restrict substations on both sides. In this case potential saving of electric energy per day for passenger traffic will be about 24.6 th. kWh, electric energy losses level will be 3.4 %. Alternative variant is placement of electric energy storage units on posts of sectionalization PSK 270 and PSK Cherkizovo, in this case the electric energy potential of saving is 24.6 th. kWh per day, electric energy losses level is 3.6 %.

5 Conclusion

Using research results, we can make the following conclusions:

1) energy volumes, which are realized by electric energy storage units on posts of sectionalization of MCR for charge and discharge modes, by work episodes, don't exceed 50 kWh. Herewith in most cases the work episodes duration in different modes doesn't exceed 3.0 min. Work episodes number in discharge and charge modes reaches 600 cases per day;

2) graph of electric energy storage units charge level on posts of sectionalization of MCR shows strongly pronounced work cyclicality (on the graph of charge level we can see two cycles per day), which is bond with features of the electric trains traffic schedule formation, in particular by morning and evening traffic peak. Useful energy intensity for electric energy storage units is estimated in the range of 950 – 1300 kWh. For two posts of sectionalization (PSK 445 and PSK-1) the charge graph isn't balanced and requires charging implementation in standby mode (voltage range 3550 – 3600 V). Reduction of useful energy intensity up to 200 – 300 kWh leads to energy volume loss by regenerative braking by the value about 30 %;

3) electric energy storage units work on posts of sectionalization unlike rectifier-inverter converters use allows reducing load coefficient of rectifiers on traction substations of MCR on average per day up to 28.6 %, increasing minimum voltage on average by 1.5 %. By the criterion of energy efficiency, the best variant is the variant, which corresponds to inverter placement on traction substation of st. Andronovka and electric energy storage units on posts of sectionalization PSK 270 and PSK Cherkizovo which allows increasing energy efficiency level by 13.3 %. In this case, the electric energy potential saving per day for passenger traffic will be 24.6 th. kWh, electric energy losses level in traction network will be 3.4 %. Alternative variant is placement of electric energy storage units on posts of sectionalization PSK 270 and PSK Cherkizovo, in this case the electric energy potential of saving equal to the previous, electric energy losses level is 3.6 %.

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