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Efficiency of Electric Energy Storage Systems on the Moscow Central Circle


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ABSTRACT

The urban railway systems using state-of-the-art technologies for train traffic, safety, traction and rail infrastructure are becoming increasingly widespread in the world. The Moscow Central Circle railroad is an example illustrating their integration into the urban transportation system of a megacity.

Development and continuous modernization of such railroad systems during their operation generate new innovative approaches, particularly in the field of electric power supply.

Electric traction load on the traction electric power supply system of the Moscow Central Circle railroad has several features explained by prevalence of passenger traffic and frequent changes of operating modes of electric trains. Frequently used regenerative braking determines the statement of the problem of developing a complex of measures to increase the efficiency of traction power supply system measured by the criterion of output capacitance reduction and of energy efficiency indicators' growth. The use of electric energy storage systems within the traction power supply system can help to solve the mentioned problem.

The objective of the described research is to assess the efficiency of the implementation of the electric energy storage devices within the system of traction power supply system of the Moscow Central Circle. The research uses the methods of statistical processing of the measurement data and of simulation modelling. Simulation modelling of interaction of electric rolling stock with traction power supply system within the Moscow Central Circle allows to obtain the characteristics of load chart of electric energy storage systems and of bus voltage at sectioning posts, to evaluate the durations of operation cycles in charge and discharge modes, their number and relevant total amount of electric energy per day.

The obtained results allow assessing the technical features of various types of electric energy storage devices regarding operating conditions within traction power supply system of the Moscow Central Circle and to determine the economic efficiency of their implementation.

Keywords: *transport, railway, urban transportation, electrical engineering, electric trains, traction power supply system, the Moscow Central Circle, electric energy storage systems, electrical load chart, simulation modelling, operation cycles, stabilizing voltage, charge level, energy capacity.*

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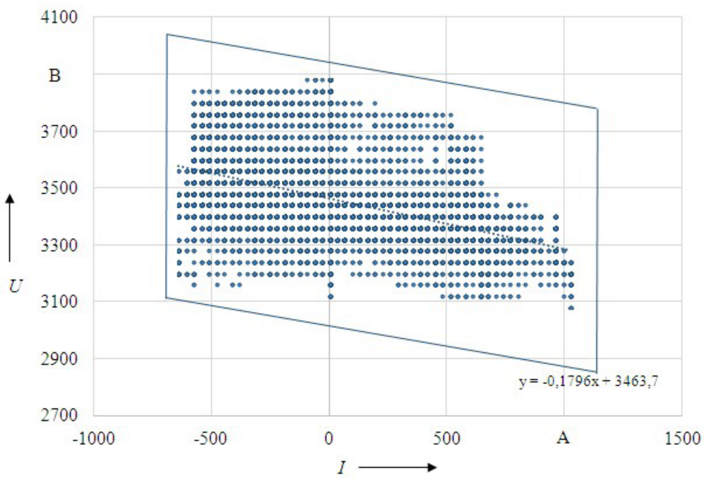


Pic. 1. Chart of current and voltage changes on current collector of electric trains of ES2G series on the MCC (according to DHST data).

Introduction

The Moscow Central Circle (MCC)[1] is a railroad section which applies advanced technologies commonly used in Russia to control train traffic, ensure safety, provide traction and maintain the infrastructure [1; 2]. Traction substations of traction power supply system of the MCC operate modern power and switching equipment comprising dry type converter transformers, high-speed circuit breakers, modular type switchgears, state-of-the-art rectifier converters etc. The traction power supply system comprises five traction substations and four sectioning posts. Electric trains of ES2G Lastochka [Swallow] series are circulating on the Moscow Central Circle to ensure passenger transportation.

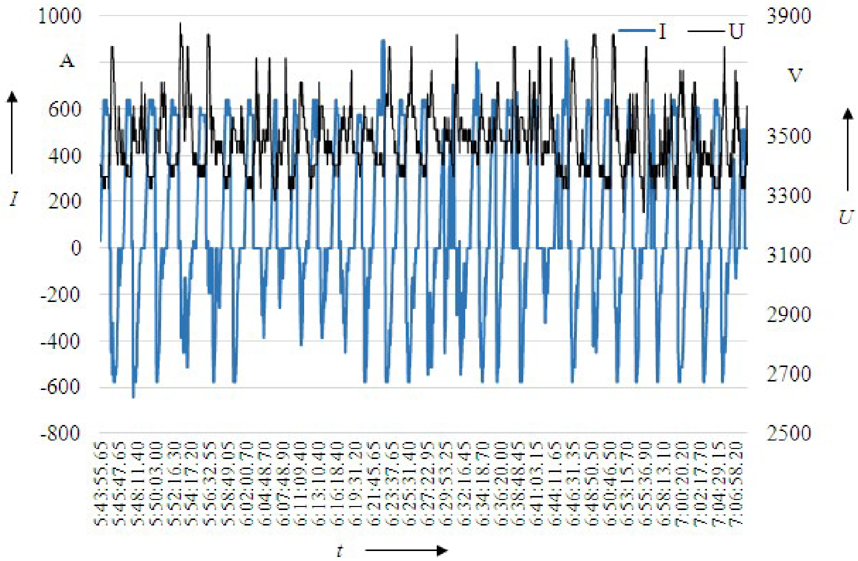
The peculiarities of passenger train traffic result in formation of electrical load chart with two areas of maximum values corresponding to passenger transportation peaks. Besides, train traffic, characterized by frequent stops, accelerations and braking actions shall also be regarded as the peculiarity of the MCC.

The *objective* of the research is to assess the efficiency of the use of electric energy storage devices within the system of electric traction power supply system of the Moscow Central Circle. The study of the issues of the application of the energy storage devices allows to assess the impact of their operation on the energy indicators of the electric traction power supply system. The research used the *method* of statistical processing of the measurements of electrical values of the electric rolling stock and of the electric traction power supply system, as well as *methods* of simulation modelling.

Results.
Analysis of measurement data

Under the conditions that prevail on the MCC the electric trains of ES2G series (Siemens Desiro Rus) enable the efficient regenerative braking creating the basis for energy exchange between neighboring rolling stock and contributing to enhancement of traffic energy efficiency. The results of processing of data on the electric trains circulating on the MCC collected during a day by motion parameter recorders of micro-processor-based control and diagnostic system of the Directorate for high-speed transportation (DHST) of the JSC Russian Railways make it possible to obtain the working ranges of traction currents and voltages at current collectors of electric rolling stock (Pic. 1). The chart shows voltage change range regarding traction and regenerative braking modes. The character of the given chart differs from similar ones for the sections with prevailing freight traffic. Firstly, for the MCC conditions the average characteristic slope coefficient is -0.17 versus -0.068 and -0.14 coefficients, obtained for locomotives of series 2ES6 and 2ES10 on railway sections with plain and mountainous terrains correspondingly [3]. Secondly, the voltage change range at the current collectors of electric trains ES2G is considerably wider. The voltage varies from 2900 V to 3800 V in the traction mode and from 3100 to 3900 V in regenerative braking mode. Considering that railway track profile relates to the type II (plain terrain) [4], the above-mentioned differences

[1] For more information please see [Electronic resource]: https://www.mosmetro.ru/mcc/moscow-central-circle/.



Pic. 2. Electric traction load schedule of an electric train circulating on the MCC (according to DHST data).

shall be associated with traffic organization conditions, which have an impact both on traction energy consumption and on imbalance level [5]. The frequency distributions for the given values show that voltage distribution is close to normal probability law (average value is approximately 3400 V), current distribution is close to uniform distribution in negative and positive ranges (for regenerative braking and traction modes).

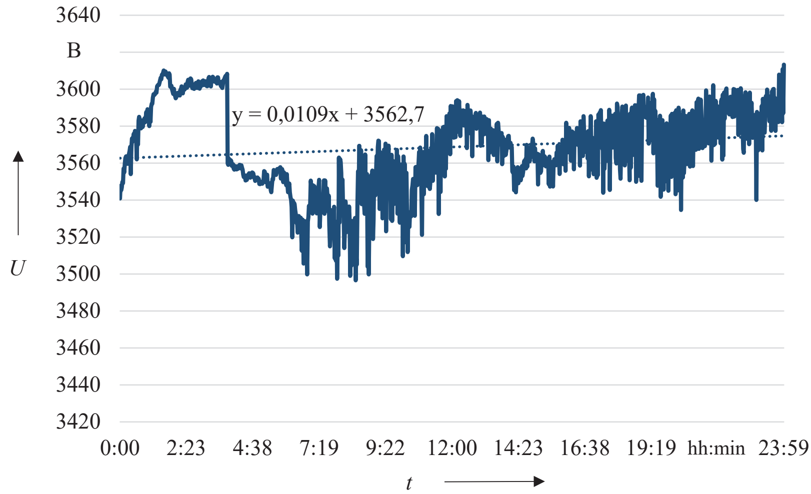
Traction load schedule of electric trains circulating on the MCC is characterized by frequent regenerative braking actions. The Pic. 2 illustrates that fact by traction load and current collector voltage schedule of an electric train circulating on the MCC within the period 5:43 to 7:06 hh:mm. Specific features of the MCC trains' electric traction load are: the cyclic recurrence of traction and regenerative braking modes, the comparability of current levels in both modes, a specific change of voltage level corresponding to the operating modes of the electric train. The above-mentioned features of electric traction load result in the high level of specific recovery observed within the MCC and determine the relevance of the issues of the control of energy exchange processes within the traction power supply system.

The global trends in the fields of energy exchange flows control in electric networks, of development of devices providing float operation, of voltage stabilization and of growth in efficiency of renewable energy sources' operation have resulted in the emergence and development of electric energy storage systems [6–13]. The range of the above-mentioned issues is also peculiar for electric traction load, namely, for the MCC conditions.

Results of data processing

Installation of inverters receiving the regenerated energy and transferring it to AC buses is one of the methods to increase energy efficiency of the MCC. The inverter locations within the MCC are determined by traction and electrical calculations which figure out regenerated energy amount [11]. The introduction of energy storage systems into traction power supply system is an alternative option which has advantages compared with inverters installed at electric traction substations. The advantages lie in possibility to install the energy storage devices on devices located in-between traction substations and in improved load capacitance rates of traction power supply system [12].

The research on energy storage devices' efficiency within the traction electric power supply system should be conducted considering equipment operating conditions approved for the MCC. Particularly, traction substations use alternating and parallel operation of the converter units as an operation mode. For



Pic. 3. Chart of 3,3 kV bus voltage variation, station Andronovka (according to TE data).

instance, the traction substation Andronovka (belonging to Moscow Directorate of power supply of TransEnergo (TE) – a subsidiary to JSC Russian Railways) applies the parallel operation of the converter units. This circumstance shall be considered in calculations, assuming that the external characteristics of the converter units are not identical [13]. Slope coefficients of external characteristics of substation converter units are -0,03 and -0,06 for the example under consideration. The difference in characteristics does not have an essential significance for the purpose of modelling energy-exchange process in electric energy storage systems. In that case it is acceptable to assume that external characteristic slope coefficient has an average value.

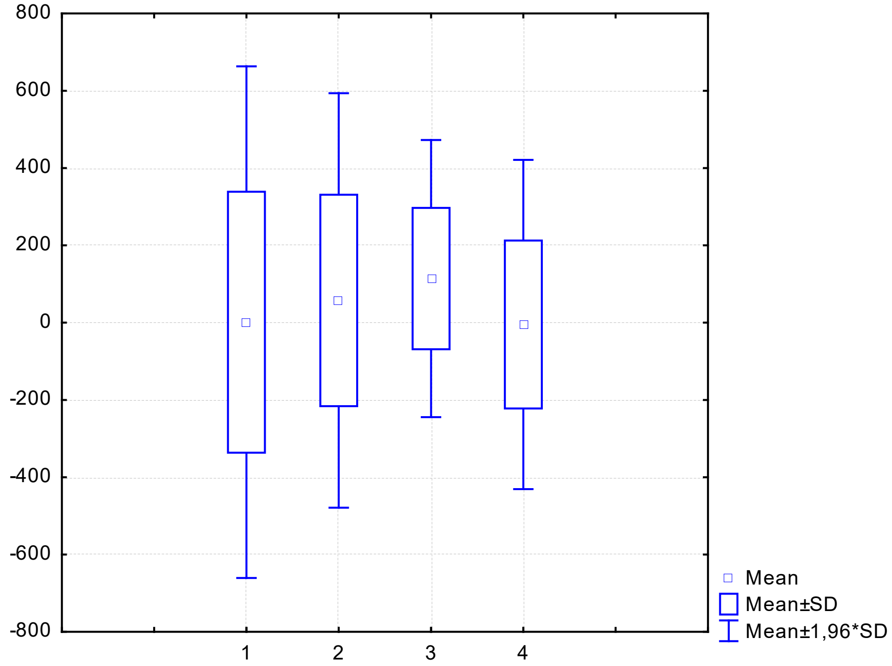
When performing the studies, we should consider the existing voltage level at traction substations, which may essentially differ due to a set of reasons. Time chart of voltage variation at 3,3 kV buses, which values have been recalculated for one-minute averaging intervals for the measurements at the highest voltage side, is shown in Pic. 3. For considered cases the no-load (float) voltage shall be determined in the absence of traction load followed by averaging for the purpose of modelling.

Electric energy storage devices can be most efficiently located at the sites of location of devices of traction power supply system in-between substations (sectioning posts or parallel connection posts). The above-mentioned consideration is explained by simultaneous reduction of electrical power losses in traction power supply system and increase in transit and traffic capacity at the inter-substation area. The transformation of the passive sectioning posts into the active ones by placing energy storage devices at them allows to obtain some positive effects for the traction power supply system [14].

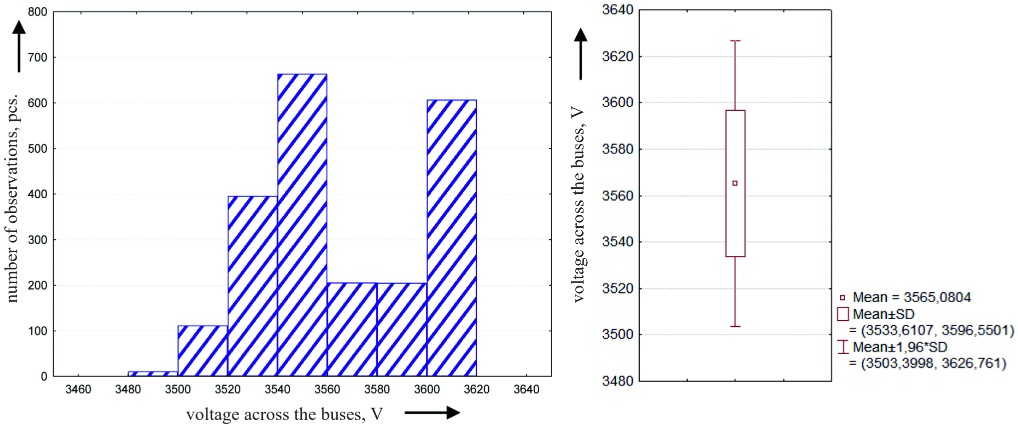
The efficiency of electrical energy storage system application was studied by means of simulation modelling in KORTES [complex calculation of traction power supply] software package based on traction calculations and records on the execution of train traffic schedule of the MCC. The modelling accounted for difference of voltages across traction substation buses. Considering that the conditions of storage systems operation are similar to the conditions of reversive converters operation, the energy exchange processes were simulated for inverters using the voltage settings of respectively 3600 V and 3550 V for charge and discharge modes. For the given conditions the electrical load charts and charts of voltage variation across sectioning posts were obtained by means of instantaneous schemes.

The frequency distribution of voltage across sectioning post buses obtained during simulation reveals quite narrow range of observed values (for instance, the distribution for PSK 270 [AC sectioning post 270] is shown in Pic. 4.

The simulation results allow us to evaluate the current variation ranges of energy storage devices at sectioning posts. The evaluation of



Pic. 4. Frequency bar chart showing voltage distribution across the buses of sectioning post PSK 270 (authors' calculations).



Pic. 5. Range of load variation of energy storage devices on sectioning posts' buses: 1 – PSK 270, 2 – PSK 445, 3 – PSK-1, 4 – PSK Cherkizovo (authors' calculations).

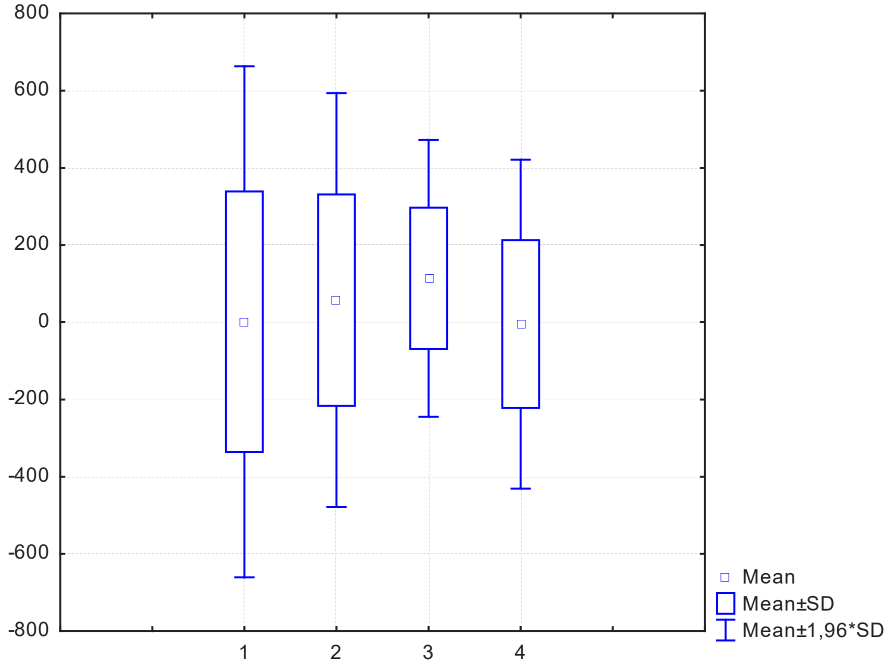
current ranges for the conditions of energy storage devices at sectioning posts within the MCC for the obtained mean values and root-mean-square deviation (SD) is shown in Pic. 5.

Mode of energy storage device operation is characterized by the amount of electrical energy in charge and discharge modes, by duration of operation in each of those modes. Design characteristics for discharge and charge modes as applied to the operating conditions of energy storage device at PSK 270 are presented respectively in Pic. 6 and Pic. 7.

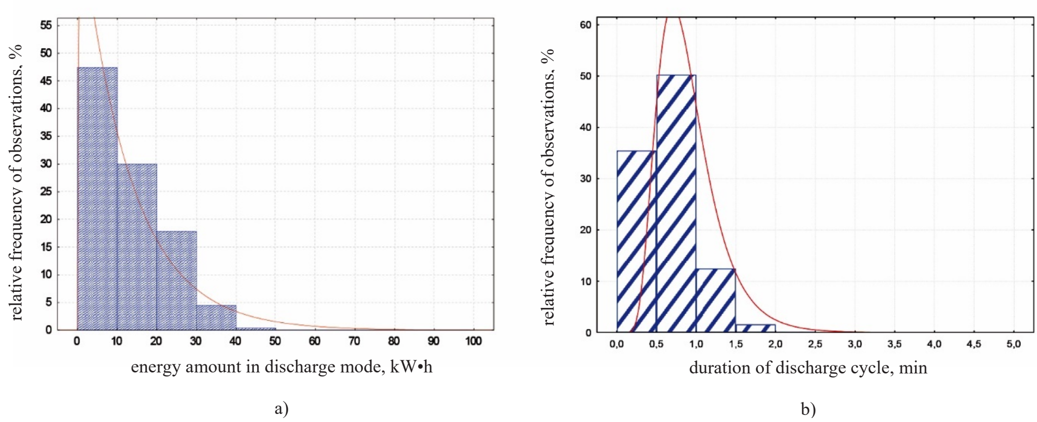
The average number of cycles of operation of energy storage devices for the operating conditions at the sectioning posts is 542 for the discharge mode and 404 for the charge mode.

Evaluation of operating conditions of energy storage systems

Stabilizing voltage is one of the most important parameters of an energy storage device, influencing its energy characteristics and determining its operation in charge, discharge and quiescent modes. For the given



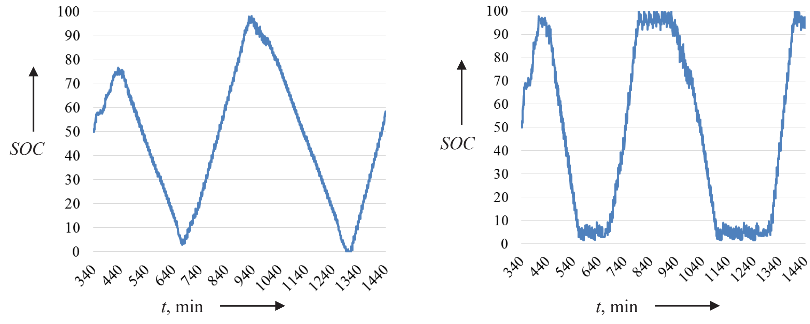
Pic. 6. Frequency bar chart showing distribution of electrical energy amount and duration of operation in discharge mode for PSK 270 (authors' calculations).



Pic. 7. Frequency bar chart showing distribution of electrical energy amount and duration of operation in charge mode for PSK 270 (authors' calculations).

conditions of the different episodes of operation of energy storage device [18–20] it was found that a cycle of operation of the energy storage device in any mode does not exceed five minutes, namely, for PSK 270 it does not last more than two minutes, and energy amount does not exceed 50 kW•h per episode, i.e. energy exchange processes are short-term, and repeatedly iterated during the day.

The state of charge level of energy storage devices is determined by several factor comprising initial voltage, internal resistance, quantity of electricity, capacity, discharge (charge) current. The equations of Shepherd, Haskina-Danilenko, Romanov [21–23], other empirical dependences, equations obtained by means of regression analysis or artificial neural networks are applied for calculations of the charge level. A simple method to evaluate the state of charge level is an A•h meter-based method or a method based on the quantity of electricity. The method based on W•h meter for the charge and discharge modes is a modification of the above-mentioned method, and it is applicable to evaluate energy storage device operation in general. This method is



a) b)

Pic. 8. Chart of SOC variation for energy storage device at PSK 270: a – with unlimited energy capacity, b – with energy capacity limited to 500 kW•h (authors' calculations).

used for further evaluation of energy exchange processes in traction power supply system.

Constructing a chart of cumulative electric energy amount variation makes it possible to obtain the required level of net energy capacity W_{rec} as difference between the maximum W_{max} and the minimum cumulative value W_{min} per day. This W_{rec} amount allows us to evaluate the state of charge level of energy storage device at k-th step of calculation using the formula below:

$$SoC_k = \frac{\sum_{t_0}^{t_k} u_k \bullet i_k \bullet \Delta t_k}{W_{rec}} \bullet 100, \qquad (1)$$

where u_k , i_k are voltage and current values for k-th time interval;

Δt_k – time increment.

The results of simulation modelling of interaction of the rolling stock with traction power supply system show that if the value of power capacity of energy storage device is not limited for the conditions of PSK 270, then the required net energy capacity W_{rec} reaches the level of 1185 kW•h. If applied to net energy capacity, the chart of state of charge level variation, under the assumption that the initial level of state of charge SOC_0 = 50 %, is shown in Pic. 8a. If the net energy capacity is limited to 500 kW•h, then the variation chart shows that SOC does not change cyclic recurrence during the day and does not significantly change its character (Pic. 8b). In the second case the total amount of electrical power per day in the discharge mode decreases compared to the first case from 7054 kW•h to 5920 kW•h, i.e. decreases by 16,1 %, in the charge mode it decreases from 7166 kW•h to 6168 kW•h, i.e. decreases by 13,9 %. If the energy capacity is limited to 300 kW•h and 200 kW•h we observe decreases for the discharge mode by respectively 22,2 % and 24,9 %, for the charge mode by respectively 21,6 % and 24,7 %. The charts of state of charge level variation show that charge/discharge cycles at some time intervals of the day do not alternate, but succeed, thus determining the appearance of the daily chart, explained by the cyclical nature of traffic.

The influence on the indicators of load capacitance

Placing of energy storage devices at sectioning posts allows to improve the load capacitance of the electric power supply system and to increase energy efficiency of transportation process.

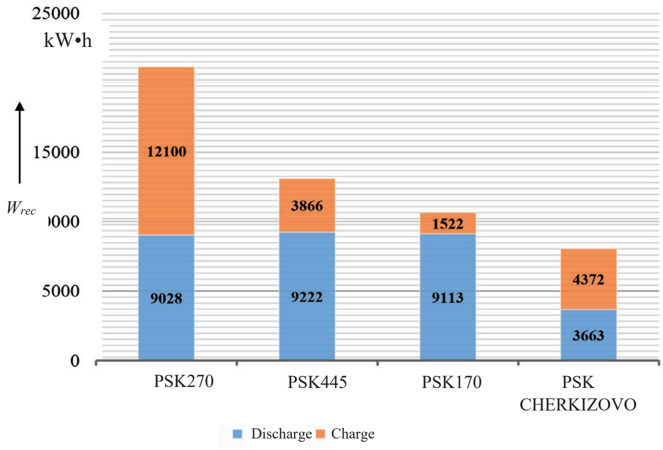
Let us consider the results of calculations regarding load capacitance for the basic variant. The basic variant is assumed to be an existing variant of power supply system but without energy storage devices or any other receivers of power pf regenerative braking of the rolling stock.

We'll consider two indicators of the load capacitance: load factor of traction substation rectifiers and minimum voltage level on current collector of the rolling stock.

Load factor of rectifiers is determined using the formula below:

$$k_{l.r.t} = \frac{I_{d\,t}}{\sum I_{r\,nom} \bullet k_{acc.r.l.\,t}}, \qquad (2)$$

where I_d is a largest mean value of current for the period t, A;



Pic. 9. Bar chart of electrical energy amounts of energy storage devices divided by operating modes (authors' calculations).

$I_{r\ nom}$ is a nominal current of rectifier units, determined by the number of rectifiers under load, A;

$K_{all.r.l.\ t}$ – acceptable load coefficient (for averaged time intervals 0.25 min – 1,9; 2 min – 1,5; 15 min – 1,25; 30 min and more – 1,0).

Variation of load coefficient of traction substation rectifiers, %, is determined by the formula below:

$$\Delta k_{l.r.t} = \frac{k^{bas}_{l.r.\ t} - k^{cons.}_{l.r.\ t}}{k^{bas}_{l.r.\ t}} \bullet 100, \qquad (3)$$

where $k^{bas}_{l.r.\ t}$, $k^{cons.}_{l.r.\ t}$ are load coefficients for traction substations rectifiers at average period t for basic variant and variant under consideration.

The largest reduction in rectifiers' load coefficient was observed at substations of Pokrovskoye-Streshnevo station and of Andronovka station, the load coefficients of rectifiers were respectively lower by over 25 % and 35 %.

The total amounts of electrical energy in discharge and charge modes are evaluated considering the location of energy storage devices at the sectioning posts of the MCC. Comparison of electrical energy amounts of storage devices W_{rec} at each sectioning post has shown that they should be balanced (Pic. 9) by means of recharge in standby mode when sectioning post bus voltage is close to no-load voltage of the traction substations for storage devices located at sectioning posts PSK 445 and PSK 170.

Comparison of variants by minimum and one-minute voltage, made to evaluate voltage stabilizing effect at sectioning post buses exerted by energy storage devices, has shown that for the variant of energy storage device arrangement according to the basic variant the minimum voltage on current collector of electric rolling stock is higher by 1,5 % or by 50 V on an average.

The operation of energy storage devices results in decrease in rectifiers' load coefficient at the MCC traction substations by 12,5 % to 28,6 % per day on an average. The largest amounts of electrical energy in charge and discharge modes of the energy storage devices are observed at the sectioning post PSK 270, where the ratio of discharge and charge electrical energy is 1/1,3.

The comparison of load capacitance indicators of traction power supply system for the variants with energy storage devices and with inverters, has shown that in the case of the use of energy storage devices there is a decrease in load coefficient of substation rectifier transformers by 22,5 % per day on an average and an increase in average minimum voltage on current collectors of electrical trains by 4,1 % or by 150 V approximately.

The comparison of the variants using respectively reversible converters and energy storage devices by energy efficiency has shown only an insignificant discrepancy of the obtained values. The variant applying reversible converters at traction substations might show 11,97 % increase in transportation energy efficiency, while the variant applying energy storage devices at sectioning posts might allow to attain 11,94 %

Table 1

Electric power consumption for traction for different variants (authors' calculations)

Variant	Balanced electric power consumption for traction, kW • h	Traction network losses, kW • h	Amount of charge regeneration, kW • h
Basic variant	181116	6011	0
Variant with reversible converter	159424	5874	16717
Variant with energy storage devices	159490	5014	21862

increase. Losses in traction network for the variant with inverter are of 3,68 % versus 3,14 % losses for the variant applying energy storage devices at sectioning posts (Table 1). Amount of electric energy for regenerative and charge modes for the above-mentioned variants is of 10,5 % and 13,7 % respectively.

According to energy efficiency criterion, the best variant is to apply an inverter at the traction substation of Andronovka station and power storage devices at sectioning posts PSK 270 and PSK Cherkizovo, limiting the substations from both sides. In this case the potential saving of electric power for passenger transportation will be approximately of 24,6 thous. kW • h per day, electric power losses will be of 3,4 %. As an alternative option, the energy storage devices may be located at sectioning posts PSK 270 and PSK Cherkizovo. In that case electric power saving will potentially attain 24,6 thous. kW • h per day, electric power losses will be of 3,4 %.

Conclusions

Thus, according to the results of the research, the following conclusions can be drawn:

1. The amounts of electrical energy processed by energy storage devices at sectioning posts of the Moscow Central Circle in charge and discharge modes, during separate time intervals of operation, do not exceed 50kW • h. In most cases the time duration of operation in each of different modes does not exceed three minutes. The number of operations in discharge and charge modes reaches 600 cases per day.

2. The chart of state of charge level of storage devices at the MCC sectioning posts shows a pronounced cyclical nature of operation (two cycles per day are observed in the chart), explained by peculiarities of traffic schedule of electric trains, namely, by the morning and the evening peaks of transportation. The net energy capacity of energy storage devices is evaluated to be within the range of 950–1300 kW • h. For two sectioning posts (PSK 445 and PSK 1) the state of charge chart is not balanced and requires implementation of recharge in standby mode (within the voltage range of 3550–3600 V). The reduction of net energy capacity to 200–300 kW • h results in the loss of energy amount during regenerative braking by approximately 30 %.

3. The operation of energy storage devices at sectioning posts, unlike reversible converters, allows to reduce rectifiers' load factor at the MCC traction substations by 28,6 % per day on an average, and to increase minimum voltage by 1,5 % on an average. The optimal option by energy efficiency criterion is to place inverters at the traction substation of Andronovka station and energy storage devices at sectioning posts PSK 270 and PSK Cherkizovo. This variant makes it possible to increase energy efficiency by 13,3 %. In that case possible electric power saving per day will be approximately of 24,6 thous. kW • h, electric power losses in the traction system will be of 3,4 %. The alternative option is to place energy storage devices at the sectioning posts PSK 270 and PSK Cherkizovo. In that case the potential electric power saving will be equal to the previous one and electric power losses will be of 3,6 %.

The use of energy storage devices in the electric power supply system of the Moscow Central Circle could allow to balance the load, to stabilize voltage at the buses of the sectioning posts and to increase the efficiency of regenerative braking.

The proposed approaches and methods of the research, once adapted to operation conditions, can be applied for analysis of opportunity to increase traction power supply system efficiency on the urban railroads of other cities and countries and for the railroad transport in general.

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