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Increasing the Efficiency of Recuperation Through the Use of Energy Storage Systems for the Own Needs of Traction Substations

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ABSTRACT

The use of regenerative braking by electric rolling stock on DC railways makes it possible to increase the energy efficiency of the transportation process. The effective use of regenerative braking is associated with creation of conditions for receiving energy obtained through it. For these purposes, rectifier-inverter converters and energy absorbing devices are currently used in the traction power supply system.

A promising technology that provides an increase in the efficiency of the use of regenerative braking is energy storage, which allows this energy to be used in the future to cover the traction load curve. A feature of the use of regenerative braking on single-track sections of DC railways with low traffic intensity is the need to use converters or energy absorbing devices. One of the options for increasing the efficiency of recuperation energy use is the adoption of energy storage systems for the own needs of traction substations. The use of this technical solution is advisable on single-track sections with intensive use of regenerative braking, the effectiveness of which is explained through a decrease in power consumption for own needs of the substation from the external grid.

The international research allows us to identify the widespread trend towards the application of electricity storage technology in various fields: from renewable energy sources to electric power systems, including transport power supply systems. International practices demonstrate successful implementation of pilot projects of adoption of energy storage systems for solving problems of increasing the efficiency of electric urban and suburban transport, as well as of metro systems.

The objective of the work is to assess the energy performance of energy storage systems when using recovered energy for own needs of a traction substation. The study is based on the methods of mathematical and simulation modelling, optimisation, and mathematical statistics.

The discussed issues refer to the use of energy storage systems to provide power supply for own needs of DC traction substations. Main issues of operation of storage systems are considered with the help of a substation case study. The features of the recuperation load curve are described to explain the use of hybrid technologies for developing a storage system. The example of the considered traction substation helps to demonstrate the solution to the problem of determining main parameters of the storage system, considering the specifics of operation of electrochemical and electrical modules.

Keywords: *railways, regenerative braking, direct current, traction substation, own needs, storage system, power, power consumption, hybrid device.*

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Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

The intensive development of energy storage technologies, transformation, and a decrease in the unit cost of storage systems stipulates consideration of the issues of their application to increase the energy efficiency in transportation systems.

As international studies show, at present, the issues of using energy storage systems based on storage devices of various types are relevant, and this technology is used in the electric power industry for renewable energy sources [1; 2], power supply systems of settlements [3; 4], vehicles [5; 6], transport systems [7; 8], and others.

Development of technologies, improvement of specific characteristics and reduction of the cost of various types of electric energy storage devices determine the prospects for the use of storage systems for rolling stock and in railway power supply systems while solving a wide range of problems [9–11].

STATEMENT OF THE PROBLEM

The *objective* of the article is to determine the influence of the power consumption of energy storage systems on the efficiency of use of recuperation energy and power when energy storage systems are located at traction substations for supplying their own needs; to identify the nature of the change in the rate of recuperation energy efficiency in general and with regard to modules of the hybrid storage system depending on their power consumption; to assess the level of parameters of storage systems intended for own substation's needs and based on hybrid technology using the example of a traction substation with a given own needs' load and recuperation capacity. The assessment of the energy performance of the storage system is carried out using the *methods* of mathematical and simulation modelling. The parameters of the hybrid storage system are estimated based on the *methods* of optimisation and mathematical statistics.

RESULTS

Substation Load Characteristic

Electricity storage systems at electrical substations and stations are used as a backup source of electricity, which makes it possible to increase reliability of power supply for own needs up to 1000 V in case of a voltage failure at AC buses. A feature of railway traction substations is the appearance on DC buses of excess recuperation energy transmitted to sections of contact network of adjacent inter-substation sections or to the substation AC network. The specified recuperation energy, depending on the current load level, is distributed over AC connections of traction substations, and is partially returned to the external power supply system [12]. One of the options aimed at increasing the efficiency of the use of recuperation energy is the use of storage systems, which makes it possible to smooth the traction load curve or reduce power consumption for traction needs using recuperation energy.

Reception of excess recuperation energy at traction substations is carried out using reversible converters (rectifier-inverter (inverter) converters) or energy absorbing devices (based on rheostat modules).

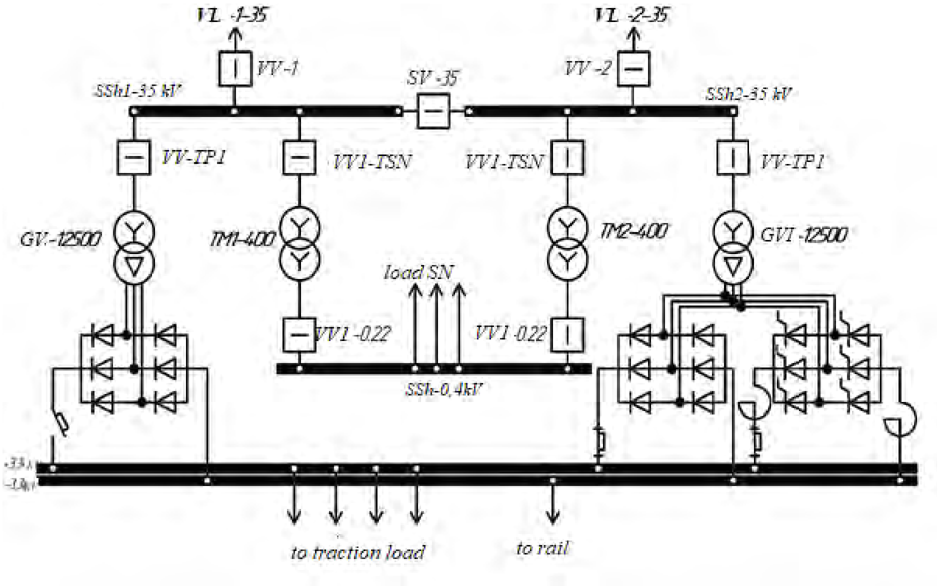
The traction load curve at the input of reversible converters makes it possible to assess the level of traction and recuperation load, and to evaluate the statistical indicators. An example below shows load curves for one of traction substations on a single-track section of the railway with intensive use of regenerative braking. A fragment of the circuit of the main electrical connections of a substation with a reversible converter, considered when solving the problem, is shown in Pic. 1.

Based on the data of the «Energy Alpha 2» software package, the load curves, and curves of recovered energy with a one-minute interval were built for the traction substation. In the case under consideration, the maximum power consumption of the traction load does not exceed 12,5 MW, that of recuperation does not exceed 1,8 MW (Pic. 2). In more than 80 % of measured cases, the traction load at the input of the rectifier during the day does not exceed 1500 kW, and the recuperation load does not exceed 1050 kW.

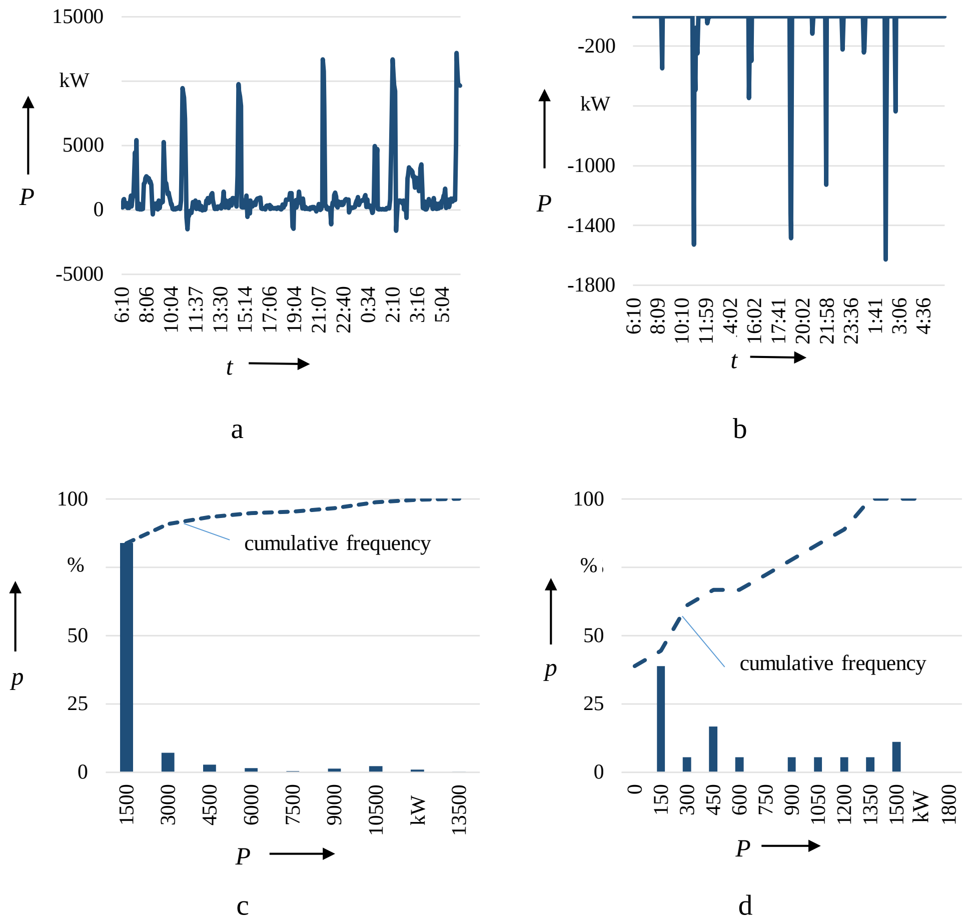
Designed or statistical measurement data make it possible to estimate, for the current level of traction load, the maximum values of recuperation power $P_{\max\ rec}$ on the buses of the substation and to determine the charge power of the storage system P_{ESS} considering the prospect of increasing the load $k_{prosp.}$:

$$P_{ch\,ESS} \geq k_{prosp} P_{\max\ rec}. \quad (1)$$

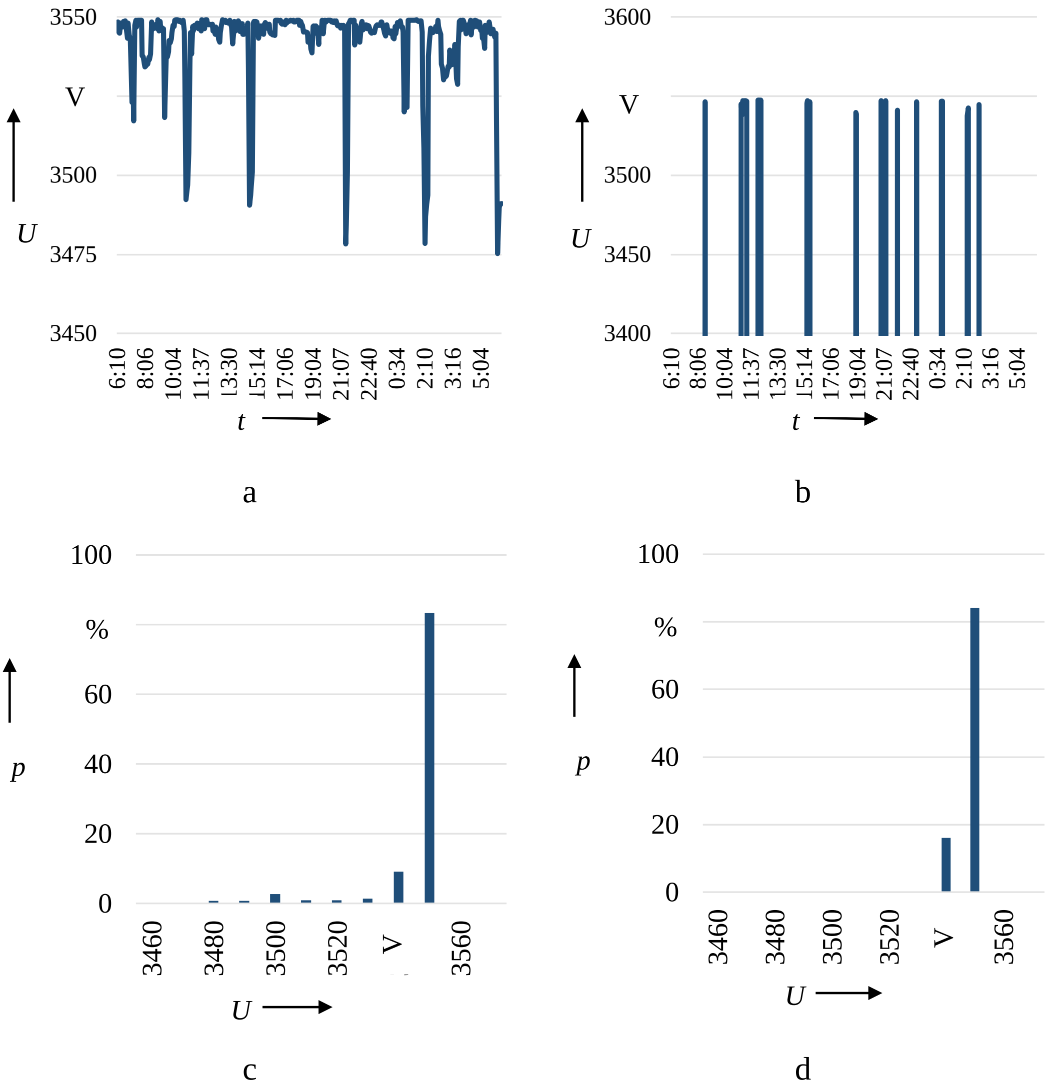
The choice of settings for operating modes of the energy storage system is based on the rate of traction load and voltage on the buses [14; 15]. The voltage level on the substation buses in the



Pic. 1. Fragment of a typical circuit of a DC traction substation with a reversible converter [13].



Pic. 2. Traction load power on the buses of the substation (a), recuperation power (b), distribution of traction power load (c) and of recuperation load (d) (developed by the author).



Pic. 3. Voltages on the buses in the traction mode (a), recuperation mode (b) and voltage distribution in the traction mode (c), and in recuperation mode (d) (developed by the author).

traction mode and in the recuperation energy return mode does not differ significantly, more than 80 % of the measurements record the voltage in the range from 3500 to 3550 V for both modes (Pic. 3).

When setting the operating modes, the conditions for switching on the storage system for charging will be defined as the absence of a load current at the 3,3 kV input and a voltage level exceeding the no-load voltage, considering the voltage change on the high-voltage buses:

$$I_{\text{inp}\,3,3} \approx 0;$$
$$U_{\text{bus}\,3,3} \ge U_{\text{no-load}}. \qquad (2)$$

The operating conditions of the storage system in the discharge mode are based on the rate of load due to substation's own needs and on the required voltage minimum maintenance mode (curves and graphs of power and voltage are shown in Pic. 4). The rate of the existing load is assessed according to the measurement data and is specified considering the development prospects.

The power of the storage system in the discharge mode will be determined based on the full satisfaction of the own needs' power considering the margin (k_m):

$$P_{disch\,\text{ESS}} \ge k_m P_{\max\,\text{ON}};$$
$$U_{\min\,\text{ON}} \le U_{\text{bus ON}} \le U_{\max\,\text{ON}}. \qquad (3)$$

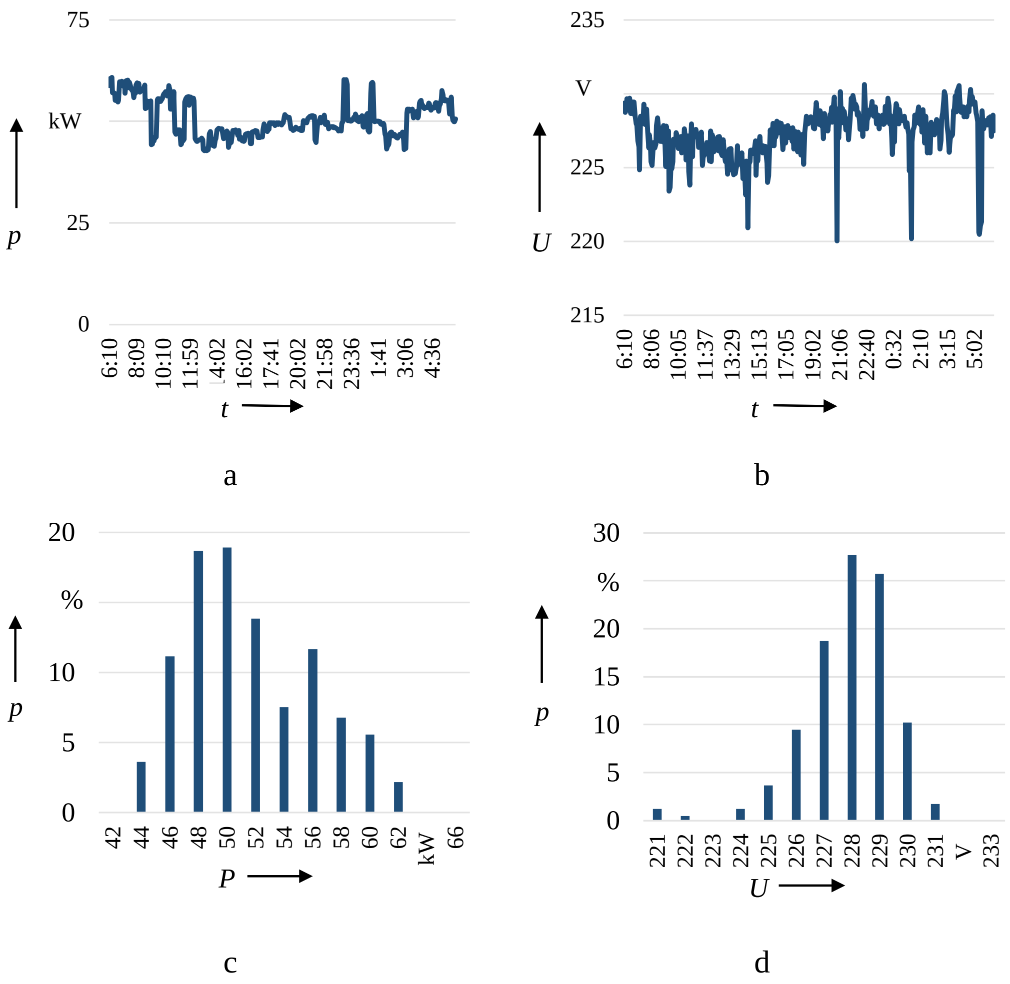
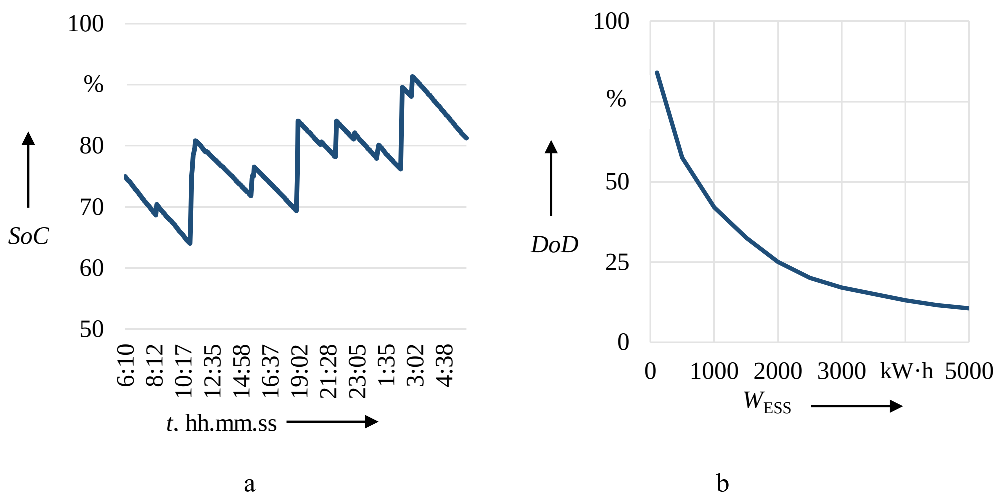


Рис. 4. Power (a) and voltage (b) of the system of own needs of the substation; power distribution (c) and voltage (d) on 0,4 kV buses (developed by the author).



Pic. 5. The state of charge (a) and depth of discharge of the storage system (developed by the author).

Table 1

Characteristics of episodes of charging for the considered substation (developed by the author)

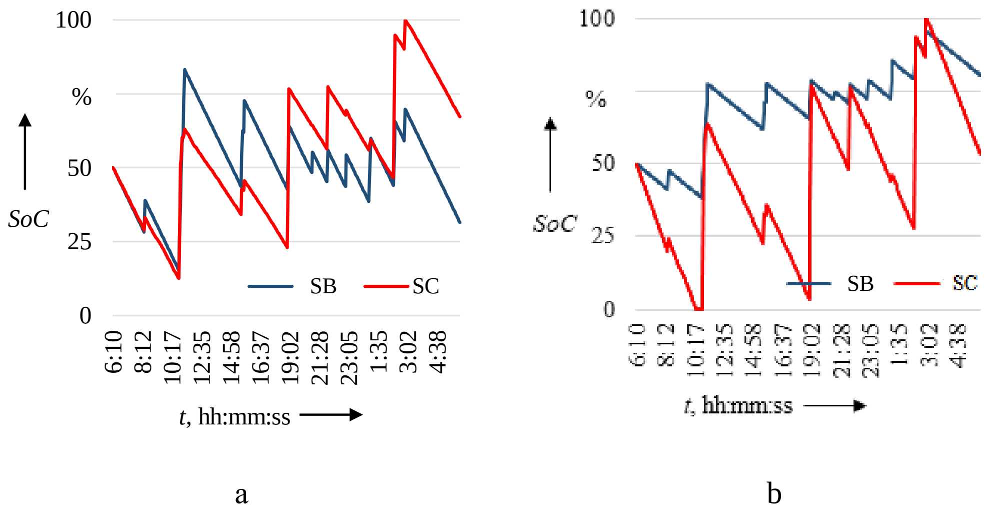
$N_{episode}$	I_{max}, A	I_{min}, A	U_{max}, B	U_{min}, B	*t*, min
1	98,7	98,7	3546,5	3546,5	3,4
2	22,1	431,8	3547,3	3538,3	23,8
3	4,2	12,8	3547,7	3547,6	6,8
4	1,4	1,4	3547,6	3547,6	3,4
5	34,9	153,9	3547,2	3545,3	6,8
6	84,5	84,5	3546,6	3546,6	3,4
7	372,5	419,6	3539,9	3538,7	6,8
8	32,7	32,7	3547,2	3547,2	3,4
9	0,4	0,4	3547,3	3547,3	3,4
10	318,3	318,3	3541,1	3541,1	3,4
11	62,9	62,9	3546,6	3546,6	3,4
12	61,5	67,9	3546,8	3546,8	6,8
13	257,1	459,8	3542,6	3537,7	6,8
14	179,8	179,8	3544,6	3544,6	3,4
Average	109,4	166,0	3545,6	3544,4	6,1

Charge and Discharge Conditions of the Storage System at the Substation

The state of charge of the storage system and the dependence of the depth of discharge on the nominal energy capacity are estimated based on the load curves on 3,3 kV buses and own needs' curves. For the considered traction substation, the curves of the state of charge and the dependence of the depth of discharge on the nominal energy capacity are shown in Pic. 5. Evaluation of the storage system operation for the existing and design conditions makes it possible to evaluate the nature of the change in the state of charge and the required power intensity. The peculiarity of operation of storage systems intended for the own needs of traction substations is the multiple excess of the charge power over the discharge power and the need for a significant increase in power consumption to limit the depth of discharge. In the case under consideration, charge prevails in the curve of the state of charge and limiting the depth of discharge to 30 % determines the power consumption at the level of 2000 kW•h (7200 MJ). The assessment of the power consumption of the storage system for traction substations, given in [16], needs to be adjusted due to the relatively low value indicated at the level of 200 MJ.

Besides these features, it is necessary to note a short duration of the episodes of charging. The duration of the episodes of charging is in the range from 1 to 24 minutes, and the total number of episodes for the case under consideration is 14 per day (Table 1). Similar values were obtained when studying the traction load for various objects of the traction power supply system [17–19].

The described features of the storage systems operation should be considered when choosing the type of storage device or using hybrid technology. Currently, the industry produces network storage systems based on lithium-ion batteries of various modifications. Manufacturing using container or cabinet design allows changing their power in a wide range from 100 to 1000 kV•A with the possibility of increasing



Pic. 6. The state of charge of the storage modules of the storage system for the first (a) and second (b) options (compiled by the author).

it by connecting several systems in parallel to obtain a total power of up to 20 MV•A and above. The fast-charging time for lithium-ion batteries is about 0,5 hours, which is significantly less than the average duration of an episode of charging for a traction substation. At the same time, the charge time of other types of storage devices, for example, of supercapacitors, does not exceed 10 minutes.

The number of elements in storage modules, regardless of the type, is determined by the required rates of voltage of the storage system and of load by calculating the elements connected in series and in parallel:

$$m = \frac{U_1}{U_{2\,nom}}; \quad n = \frac{I_1}{I_{2\,nom}}. \qquad (4)$$

According to the conditions for limiting the depth of discharge, the use of lithium-ion batteries in the storage system requires a higher energy consumption compared to other types of energy storage devices that are not sensitive to the depth of discharge, for example, to supercapacitors. In this regard, to reduce the total power consumption of the storage system, options for using hybrid technology are being considered. Depending on the combination of the power consumption of the storage elements in the system, their state of charge and the depth of discharge change. As an example, for the substation under consideration, curves of the state of charge are presented for two combinations of the power capacity of a storage battery (SB) and a supercapacitor (SC) with equal total energy consumption for the following values (Pic. 6):

1) 100/1700 (charge) and 10/1700 (discharge) kW and 100/500 kW•h, respectively, with a depth of discharge of 68 and 88 % for battery and SC, respectively (Pic. 6a).

2) 150/1700 (charge) and 10/1700 (discharge) kW and 250/350 kW•h, respectively, with a depth of discharge of 58 and 100 % for battery and SC, respectively (Pic. 6b).

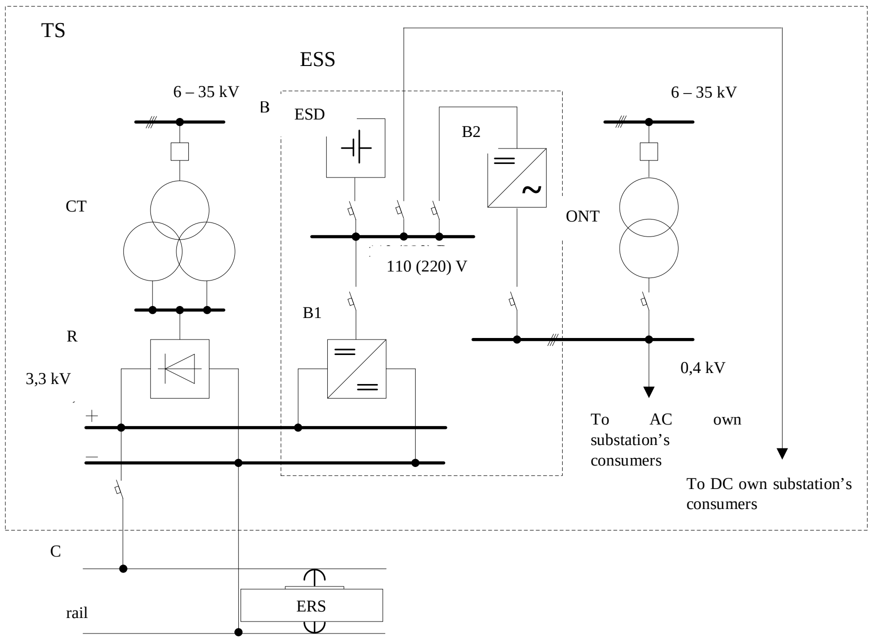
These examples show the possibility of changing the operating conditions of storage modules while maintaining the total power consumption of the system.

Circuit Implementation

Depending on the connection of the storage system to the substation' DC buses, two variants of the circuit implementation can be distinguished. The first option is transmission of power to the system through a DC-to-DC voltage converter (B1), then to the own needs' AC buses through a DC-to-AC voltage converter B2 (Pic. 7).

In the second version, power transmission is carried out by three-phase current using the B1 converter, and the substation DC buses are supplied from the storage device through the B2 converter.

In both versions, B1 converters are produced considering the maximum charging power. Converter B2 for the first version is performed intended for maximum power of own substation's consumers, for the second version the power of the converters B2 and B1, respectively, is equal (Pic. 8). The power of the B2 converter for the



Pic. 7. Connection circuit of the storage system (first version) (developed by the author).
Symbols used for Pics. 7–8: TS – traction substation; ESS – energy storage system; ESD – energy storage device; ONT – own needs' transformer; R – rectifier; CT – converter transformer; B1, B2 – Bilateral AC-DC converters; C – catenary; ERS – electric rolling stock.

second variant is higher by the value of the substation DC busbar load. The advantage of the system implementation circuit according to the second option is the use of a voltage of 0,4 kV, which makes it possible to reduce the level of the rated (nominal) current in the main circuits and reduce losses in them, the disadvantage is the need to use a second converter B2 with a power equal to that of B1. To provide galvanic isolation of circuits for own power supply, the converter circuit includes an isolation transformer.

Model for Determining the Parameters of the Storage System

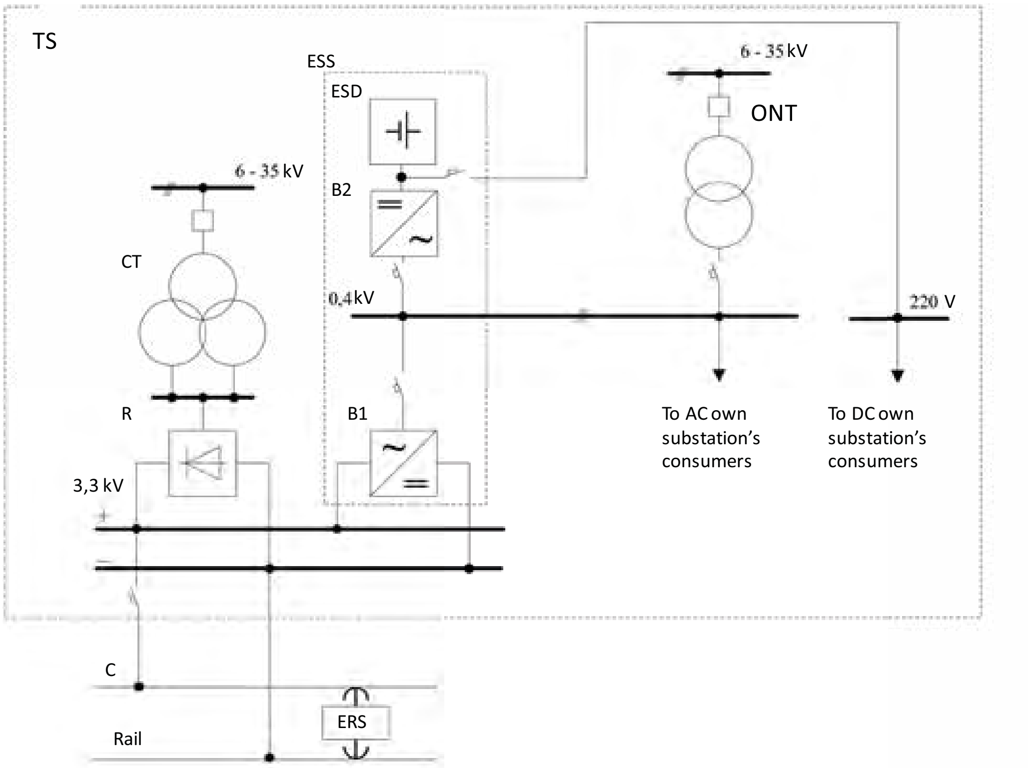
Various options for distribution of the energy capacity of the storage units of the hybrid system differ in their energy performance and cost, which is an integral indicator. In general case, when evaluating investment projects, the effect will be determined, on the one hand, by inflows based on savings in electricity consumed for own needs, on the other hand, by the cost of maintenance, construction, and installation work, replacement of storage elements, etc. Since the indicated costs are assumed to be equal for all options, then when choosing the power consumption of the storage modules of the hybrid system, the objective function of the problem will consider the values of the parameters and their unit cost (power and power consumption). In this case, solving the problem of determining the power and power consumption makes it possible to determine the optimal values of these quantities based on the following mathematical model:

$$\begin{cases} C = aP^{SB}_{nom} + bW^{SB}_{nom} + cP^{SC}_{nom} + dW^{SC}_{nom} \to \min; \\ P^{SB}_{nom\ char} + P^{SC}_{nom\ char} \geq \max\left(P^{rec} - P^{ON}\right); \\ P^{SB}_{nom\ disch} + P^{SC}_{nom\ disch} \geq \max\left(P^{ON} - P^{rec}\right); \\ P^{SB(SC)}_{nom} = \max\left(k^{SB(SC)}_{char} P^{SB(SC)}_{nom\ char}; k^{SB(SC)}_{dischar} P^{SB(SC)}_{nom\ disch}\right); \\ \forall t_i \in [0;\ T]: 0 \leq \sum_{0}^{t_i} W^{SB(SC)}_{t_i} \leq W^{SB(SC)}_{nom}; \\ P^{SB}_{nom\ char(disch)} \leq k^{SB}_{char(disch)} \dfrac{W^{SB}_{nom}}{t};\ P^{SC}_{nom} \geq P^{rec}_{max}; \\ d^{SB}_{char} + d^{SC}_{char} \geq d_{char\ min}; \\ d^{SB}_{disch} + d^{SC}_{disch} \geq d_{disch\ min}; \\ d^{ON}_{oper} \geq d^{ON}_{oper\ min}; \\ d^{rec}_{oper} \geq d^{rec}_{oper\ min}; \\ DoD^{SB(SC)}_{min} \leq DoD^{SB(SC)} \leq DoD^{SB(SC)}_{max}; \\ SoC^{SB(SC)}_{start} - SoC^{SB(SC)}_{end} \geq 0; \end{cases} \quad (5)$$

where C – target function;

a, b, c, d – specific cost of power and power capacity of the storage battery and supercapacitor, respectively;

P^{SB}_{nom}, W^{SB}_{nom}, P^{SC}_{nom}, W^{SC}_{nom} – nominal (rated) power and nominal power capacity of the storage battery and supercapacitor, respectively;



Pic. 8. Connection circuit of the storage system (second version) (developed by the author).

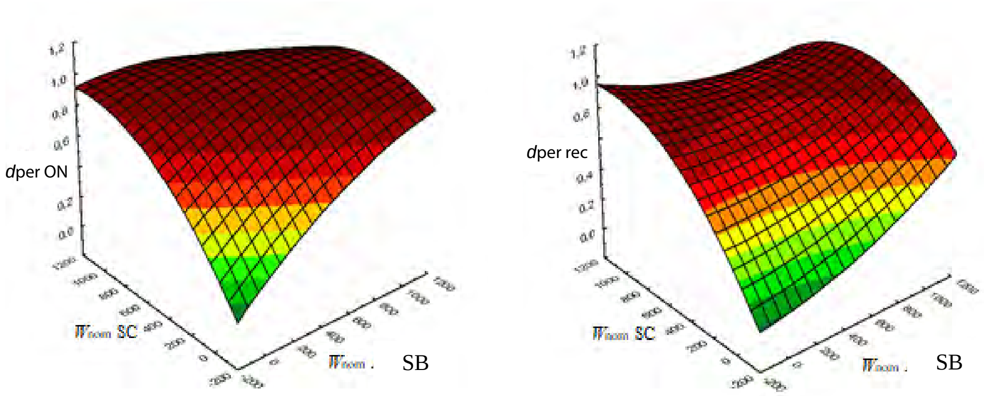
$P^{SB}_{\text{nom char}}$, $P^{SC}_{\text{nom char}}$ – nominal power of charging the storage battery and supercapacitor, respectively;

P^{rec}, P^{ON} – power of recuperation and of own substation's needs, respectively;

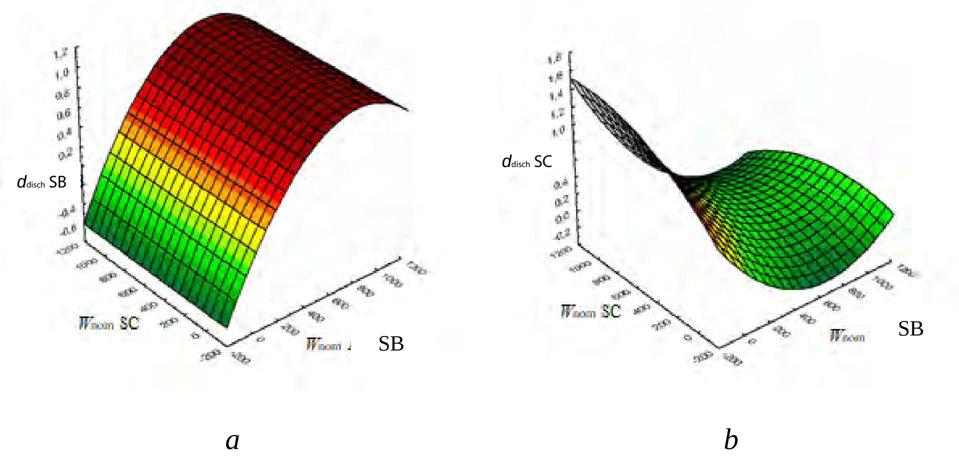
$P^{SB}_{\text{nom disch}}$, $P^{SC}_{\text{nom disch}}$ – nominal discharge power of the storage battery and supercapacitor, respectively;

$k^{SB(SC)}_{char}$, $k^{SB(SC)}_{disch}$ – coefficients of increase in nominal charge and discharge power for the storage battery and the supercapacitor, respectively;

$W^{SB(SC)}_{t_i}$, $W^{SB(SC)}_{nom}$ – amount of energy within the interval of the episode t_i and the nominal power capacity of the storage battery and supercapacitor, respectively;



Pic. 9. Rates of the use of substation's own needs energy (a) and recuperation energy (b) (developed by the author).



Pic. 10. Rates of the use of discharge energy of the storage battery (a) and supercapacitor (b) (developed by the author).

t – estimated duration of charge and discharge modes;

$d_{\text{oper.}}^{\text{ON}}$ – coefficient of use of electricity for own needs during discharge:

$$d_{\text{oper}}^{\text{ON}} = \frac{W_{\text{disch}}}{W^{\text{ON}}}; \quad (6)$$

$d_{\text{oper}}^{\text{rec}}$ – coefficient of use of recuperation energy during charging:

$$d_{\text{pper}}^{\text{rec}} = \frac{W_{\text{char}}}{W^{\text{rec}}}; \quad (7)$$

$d_{\text{char(disch)}}^{\text{SB(SC)}}$ – coefficient of energy use in charge and discharge modes for a storage battery and a supercapacitor, respectively:

$$d_{\text{char(disch)}}^{\text{SB(SC)}} = \frac{W_{\text{char(disch)}}^{\text{SB(SC)}}}{W_{\text{char(disch)}}}; \quad (8)$$

W_{disch}, W_{char} – volumes of energy of the storage system in discharge and charge modes, respectively;

W^{ON}, W^{rec} – volume of electricity for auxiliaries and recuperation for the billing period;

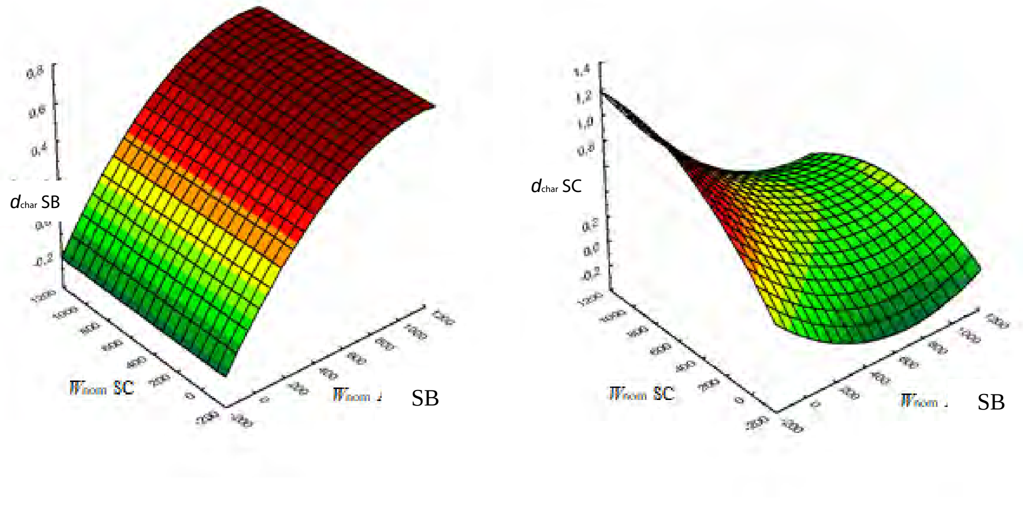
$W_{\text{char(disch)}}^{\text{SB(SC)}}$ – volume of electricity in charge and discharge mode for a storage battery and a supercapacitor, respectively.

The problem is solved in two stages. At the first stage, the load curve of own substation's needs and power of excess recuperation on buses of the substation is taken as initial data. For the given load profiles, simulation modelling is performed for different power consumption and capacity of storage devices of the system, and coefficients of energy use in charge and discharge modes are determined.

This stage serves to determine restraints on maximum charging and discharging power of the battery and supercapacitor, as well as features of operation, which should include the priority of charging for the battery and limitation of its discharge power. For a supercapacitor, conditions are specified under which the maximum power of this module is used as an additional one to ensure reception of recovered power.

Simulation of the storage system operation for various options of combining energy capacities allows one to obtain functions that describe the change in energy efficiency rates in charge and discharge modes for battery and supercapacitor modules with different combinations of power consumption and power. The obtained values are used to approximate the obtained values for each coefficient.

The second stage serves to solve the problem of finding optimal parameters of the storage system. The specified problem belongs to the problems of conditional nonlinear optimisation, the solution of which is carried out by direct and indirect methods. To solve the problem under consideration, descent method with penalty functions is used. In descent methods, the choice of the direction of descent considers the constraints of the problem in an explicit form; in the methods of penalty functions, the problem is reduced to a sequence of unconstrained optimisation problems by adding auxiliary functions to the objective function and passing to considering constraints in an implicit form.



a *b*

Pic. 11. Rates of the use of charge energy of the battery (a) and supercapacitor (b) (developed by the author).

Simulation Results

The results of simulation modelling for a given load curve of the substation under consideration make it possible to determine the change in design coefficients depending on energy consumption of the storage system modules. For a given load curve of own consumers and recuperation, the shares of power and energy use are determined by the parameters of storage modules.

The load curve of substation's own needs and the curve of return of the recuperation energy to the buses of the substation under consideration makes it possible to determine the nature of the change in the coefficients of energy use of the modules in charging and discharging modes. The curves of the change in the use rates obtained in the Statistica program are shown in Pic. 9.

The results obtained for the coefficients of the use of the load of substation' own needs and recuperation energy can be presented in an analytical form:

$$d_{oper}^{ON} = 0{,}5007+0{,}0007 \bullet x+0{,}001 \bullet y-2{,}6219E\text{-}7 \bullet x^2 - -5{,}9361E\text{-}7 \bullet x \bullet y-5{,}1047E\text{-}7 \bullet y^2; \quad (9)$$

$$d_{oper}^{rec} = 0{,}3439+0{,}0001 \bullet x+0{,}0011 \bullet y+1{,}9312E\text{-}7 \bullet x^2 - -4{,}2204E\text{-}7 \bullet x \bullet y-5{,}4906E\text{-}7 \bullet y^2. \quad (10)$$

where x – nominal energy capacity of the storage battery W_{nom}^{SB}.;

y – nominal power capacity of the supercapacitor W_{nom}^{SC}.

Changes in the coefficients of the use of discharge energy of the storage battery and supercapacitor are shown in Pic. 10 and can be presented in an analytical form:

$$d_{disch}^{SB} = -0{,}0323+0{,}0025 \bullet x-1{,}4095E\text{-}17 \bullet y - -1{,}5934E\text{-}6 \bullet x^2+5{,}6831E\text{-}21 \bullet x \bullet y+8{,}0468E\text{-}21 \bullet y^2; \quad (11)$$

$$d_{disch}^{SC} = 0{,}5329-0{,}0019 \bullet x+0{,}001 \bullet y+1{,}3312E\text{-}6 \bullet x^2-5{,}9361E\text{-}7 \bullet x \bullet y-5{,}1047E\text{-}7 \bullet y^2. \quad (12)$$

The curves of the coefficients of the use of charge energy of the battery and supercapacitor are shown in Pic. 11 and can be presented in the following analytical form:

$$d_{char}^{SB} = 0{,}0225+0{,}0012 \bullet x-3{,}2526E\text{-}18 \bullet y-5{,}1582E\text{-}7 \bullet x^2+9{,}7887E\text{-}21 \bullet x \bullet y-2{,}1176E\text{-}21 \bullet y^2; \quad (13)$$

$$d_{char}^{SC} = 0{,}3214-0{,}0011 \bullet x+0{,}0011 \bullet y+7{,}0893E\text{-}7 \bullet x^2-4{,}2204E\text{-}7 \bullet x \bullet y-5{,}4906E\text{-}7 \bullet y^2. \quad (14)$$

The depth of discharge according to the results of calculations in an analytical form is described as follows:

$$DoD^{SB} = 29{,}6301+0{,}1349 \bullet x-2{,}4425E\text{-}15 \bullet y-0{,}0001 \bullet x^2+9{,}385E\text{-}19 \bullet x \bullet y+1{,}7483E\text{-}18 \bullet y^2; \quad (15)$$

$$DoD^{SC} = 59{,}2418-0{,}0526 \bullet x+0{,}1388 \bullet y+1{,}14E\text{-}7 \bullet x^2+1{,}8425E\text{-}5 \bullet x \bullet y-0{,}0002 \bullet y^2. \quad (16)$$

To solve the optimisation problem in the MatLab environment, the mathematical model takes the following form of representation (17):

As an example, the results of solving the problem obtain for the following initial data are

$$
\begin{cases}
f = ax_1 + bx_2 + cx_3 + dx_4 \to min \ : \text{ target function;} \\
-x_1 - x_3 + 1700 \le 0 : \text{ power limitation;} \\
-x_1 \le 0 : \text{ positive values} \\
-x_2 \le 0 \\
-x_3 \le 0 \\
-x_4 \le 0 \\
x_1 \le 2000 : \text{ positive values range limitation;} \\
x_2 \le 10000 \\
x_3 \le 2000 \\
x_4 \le 10000 \\
-0{,}2x_2 + x_1 \le 0 : \text{ ratio of SB power and energy capacity;} \\
-5x_4 + x_3 \le 0 : \text{ ratio of SC power and energy capacity;} \\
x_2 + x_4 - 10000 \le 0 : \text{ total energy capacity;} \\
-x_2 - x_4 + 500 \le 0 : \text{minimal energy capacity} \\
0{,}3994 - 0{,}0006 \bullet x_2 - 0{,}001 \bullet x_4 + 2{,}1\text{E} - 7 \bullet {x_2}^2 + \\
+5{,}9\text{E} - 07 \bullet x_2 \bullet x_4 + 5{,}1\text{E} - 07 \bullet {x_4}^2 \le 0 : \text{ share of load energy} \\
\text{ use regarding substation's own needs;} \\
0{,}5561 - 1{,}0\text{e} - 4 \bullet x_2 - 0{,}0011 \bullet x_4 - 1{,}9\text{E-}7 \bullet {x_2}^2 + \\
+0{,}00422\text{E} \bullet x_2 \bullet x_4 + 5{,}5\text{E-}7 \bullet {x_4}^2 \le 0 : \text{ share of} \\
\text{ recuperation energy use;} \\
29{,}6301 + 0{,}1349 \bullet x_2 - 2{,}4425\text{E} - 15 \bullet x_4 - 0{,}0001 \bullet x_2^2 + \\
+9{,}385\text{E} - 19 \bullet x_2 \bullet x_4 + \ 1{,}7483\text{E} - 18 \bullet x_4^2 : \text{ SB depth of discharge;} \\
59{,}2418 - 0{,}0526 \bullet x_2 + \ 0{,}1388 \bullet x_4 + \ 1{,}14\text{E} - 7 \bullet {x_2}^2 + \\
+1{,}8425\text{E} - 5 \bullet x_2 \bullet x_4 - 0{,}0002 \bullet {x_4}^2 : \text{ SC depth of discharge.}
\end{cases}
\quad (17)
$$

presented below: a = 30 rel.un./kW; b = 40 reel. un./kW•h;
C = 60 rel.un./kW; d = 80 rel.un./kW•h; P_{rec} = 1700 kW; P_{ON} = 60 kW, P_{SC} = 1700 kW; $DoD_{min}^{SB(SC)}. = 0\,\%$; $DoD_{max}^{SB} = 30\,\%$. $DoD_{max}^{SC} = 100\,\%$.

Presentation of the Problem in Matlab Environment (18)

The value of the objective function for the given conditions was 170,7 thousand relative units (rel.un.) of the cost with the following parameters of the storage system: power and energy capacity of the storage battery were 269,3 kW and 1346 kW•h, respectively, of supercapacitor – 1430,1 kW and 286,1 kW•h, respectively.

The proposed mathematical model makes it possible to obtain the main parameters of a hybrid storage system with a minimum cost based on the initial data on the load and recuperation at the traction substation, given constraints and accepted assumptions. The cost of the life cycle, considering changes in the service life of storage elements, self-discharge rate, degradation, environmental impact, etc., can be taken as a target (objective) function in the model. The solution of this problem makes it possible to determine the parameters of storage systems for other objects of the traction power supply system [20–23].

CONCLUSIONS

The proposed application of the energy storage system allows to reduce power consumption for auxiliary (non-traction) own needs of a substation due to the use of recuperation energy and to ensure reception of excess recuperation energy on buses of the DC traction substation.

The peculiarities of storage systems for auxiliary needs of traction substations are the excess of the charge power over the discharge

```
>> A=[-1,0,-1,0;0,0,1,-5;0,1,0,1;0,-1,0,-1];
b=[-1700;0;10000;-500];
Aeq=[1,-0.2,0,0];
beq=0;
lb = [0,0,0,0];
ub = [2000,10000,2000,10000];
a1=30;b2=40;c3=60;d4=80;
x0=[100;1000;100;1000];
fun= @(x)a1*x(1)+b2*x(2)+c3*x(3)+d4*x(4);
nonlcon = @unitdisk;
x=fmincon(fun,x0,A,b,Aeq,beq);
[x,fval,exitflag,output,lambda,grad,hessian] =
fmincon(fun,x0,A,b,Aeq,beq,lb,ub,nonlcon)
```

(18)

Results of solving the problem:

```
x(1) = 0.2693·10³
x(2) = 1.3463·10³
x(3) = 1.4307·10³
x(4) = 0.2861·10³
fval = 1.7066e+05
 iterations: 12
 funcCount: 65
 constrviolation: 5.6843e-14
 stepsize: 7.2468e-06
 algorithm: 'interior-point'
 firstorderopt: 2.0000e-06
 cgiterations: 0
```

power, the need for a significant increase in energy consumption to limit the depth of discharge when using electrochemical storage devices, short duration of episodes of charging, the average duration of which is about five minutes. These features determine the use of types of storage devices other than electrochemical ones, and the use of hybrid systems capable of fast charging, the depth of discharge of which does not affect the service life.

Two options are proposed for connecting the electric energy storage system to auxiliary needs' consumers of a traction substation, differing in the power of converters.

Based on simulation modelling of operation of storage units of the hybrid storage system, the results of changes in the coefficients of the use of recuperation energy, auxiliary (own) needs of the substation, incl. separately for the storage elements of the system, are obtained.

A mathematical model is proposed that allows, based on the change in the coefficients of the use of recuperation energy and of the energy of auxiliaries at storage elements, to determine capacity and energy consumption of the storage system by the criterion of the cost of the system.

The obtained results of the solution make it possible to evaluate the parameters of a hybrid system for accumulating electricity for auxiliary needs of traction substations on the railway network of Russia and abroad.

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