ORIGINAL ARTICLE
DOI: https://doi.org/10.30932/1992-3252-2023-21-2-1

World of Transport and Transportation, 2023,
Vol. 21, Iss. 2 (105), pp. 152–163

Simulation of Short-Term Modes of Operation of Traction Power Storage Devices

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ABSTRACT

The concept of building a traction power supply system with power storage devices provides for their operation to solve the following problems: increasing the transit and carrying capacity, energy efficiency of transportation, reliability of power supply and quality of electric energy. The implementation of pilot projects to solve various problems in the field of traction power supply both in Russia and abroad shows their technical effectiveness.

Improving reliability of power supply with the help of storage devices today is considered mainly for options for their use as on-board devices on electric rolling stock or as stationary devices at traction power supply system facilities. Increasing reliability of power supply is achieved through operation of energy storage systems in case of forced or post-emergency modes of operation of traction power supply systems. When solving this problem, it is required to evaluate the voltage level, the change of which is due to the discharge characteristic of the used energy storage device.

The objective of the work is to assess the change in the voltage level and energy intensity of the energy storage device used on-board electric rolling stock or as stationary one at traction power supply facilities.

Based on the proposed models, the paper assesses the change in the voltage of the energy storage device for the conditions of a short-term absence of voltage in the catenary system using the example of three types of batteries and a supercapacitor. The results obtained in the work allow proceeding to assessment of the performance of electric energy storage systems under various conditions of development of traction load and for different operating modes of the traction power supply system.

Keywords: railways, traction power supply system, electric rolling stock, simulation model, Matlab software package, storage battery, supercapacitor, voltage level, energy intensity.

Funding: the study was supported by the Russian Science Foundation grant No. 22–29–00002, https://rscf.ru/project/22-29-00002/.

For citation: Nezevak, V. L., Dmitriev, A. D., Samolinov, S. S. Simulation of Short-Term Modes of Operation of Traction Power Storage Devices. World of Transport and Transportation, 2023, Vol. 21, Iss. 2 (105), pp. 152–163. DOI: https://doi.org/10.30932/1992-3252-2023-21-2-1.

The text of the article originally written in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

INTRODUCTION

Failures in operation of the switching equipment of traction substations and the catenary system cause a change in the normal mode of power supply of inter-substation zones, in which individual sections of the catenary system operate in a single-sided power supply mode. The duration of forced operation modes can be different and vary from several minutes to several hours or days. The concept of using electricity storage devices in the traction power supply system of railways provides for solving the problems of increasing transit and carrying capacity, energy efficiency, reliability of power supply, etc. by regulating energy exchange modes. Among particular tasks of improving reliability of traction power supply through the use of storage systems it is possible to highlight the task to assess the voltage level on the buses of linear devices to which they are connected, considering the characteristics of energy storage devices. Energy storage devices of various types can be used, while electrochemical and electrical ones are among the most operated. The voltage drop on the buses of accumulation systems of these types is most pronounced in the first moments of operation and depends on their total energy consumption, which is associated with nonlinearity of discharge characteristics. The issues of assessing the voltage level and its dependence on the total energy intensity are related to the task of improving reliability in post-emergency and forced modes of operation of traction power supply and are relevant.

FORMULATION OF THE PROBLEM

The objective of the article is to develop a simulation model of a traction power supply system containing an electric energy storage device to assess the effect of its type and energy intensity on the voltage level and, based on the developed simulation model, to determine the voltage level for the selected types of electricity storage devices, to evaluate the effect of energy consumption on the voltage level for stationary and on-board application models. The calculations use the *methods* of simulation modelling and of processing of experimental results.

RESULTS

Studies on various aspects of operation of electric power storage devices are carried out by both foreign and Russian researchers. Approaches to the use of renewable sources without electric energy storage systems have several disadvantages, and projects for their implementation on railways without considering the specifics of traction power consumption are inappropriate since they have a rather long payback period, as shown in [1, 2]. A few studies are devoted to development of a self-regulating power supply system, in which the regulation of operating modes of the devices incorporated into the system, including power storage units, is carried out based on automatic control, as shown, for example, in articles [3, 4]. Several authors consider traction power supply systems with renewable energy sources regarding high-speed railways [5]. The control strategy for hybrid devices based on compensation of the high-frequency component of the variable power with the help of a supercapacitor and of the low-frequency component with the help of a storage battery is considered in the article [6].

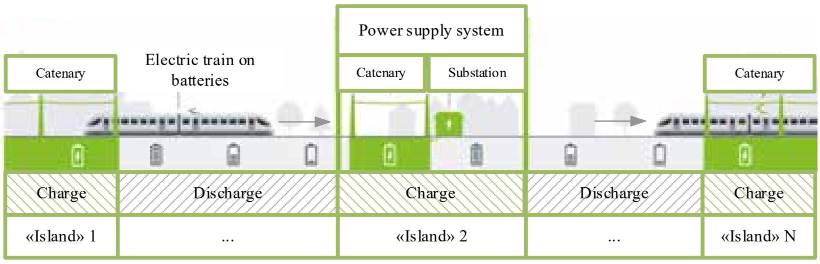
Currently, pilot projects on the use of electricity storage technologies in the transport systems refer to the traction power supply system and passenger electric rolling stock both of railways and the metro, as well as to other areas of transportation where storage systems are used as on-board systems.

In railways' traction power supply systems, electric energy storage systems as mobile devices can also be used to solve temporary problems, the duration of which can reach several dozens of days. An example is overhaul of infrastructure devices, the duration of which can reach one to two months, during that period one or more sections of the catenary system are taken out of operation for a quite long time.

Lithium-ion batteries are widely used as on-board electric power storage systems on electric trains, their charging time is reduced to 10 minutes, and the mileage during discharge reaches 100 km. Lithium-ion batteries have been used in Bombardier Talent 3 electric trains operated on sections with 15 kV AC power supply systems[1] and in several other series of electric rolling stock of European manufacturers.

The expediency of using electric power storage devices on passenger electric rolling stock increases as the intensity of traffic decreases and is justified, as a rule, on low-traffic sections of

[1] Realize your vision with Bombardier TALENT 3 BEMU. Bombardier. APTA 2019 Rail Conference, 2019. [Electronic resource]: https://www.apta.com/wp-content/uploads/Realize-your-vision-with-Bombardier-TALENT-3-BEMU_Yves_Lappierre.pdf. Last accessed 14.01.2023.



Pic. 1. Structural diagram of the «island» system of traction power supply[2].

railways. To reduce capital investments in infrastructure in these areas, the so-called «island» traction power supply system is considered (Pic. 1). Its feature is the absence of a catenary system in a few sections of electric rolling stock traffic. The charge of the onboard storage systems is carried out when the electric train is on the «islands» 1…N equipped with the catenary. The effectiveness of development of these systems is associated with renouncement to diesel traction.[2] With an increase in the masses, speeds and traffic intensity of trains, the economic feasibility of introducing electric power storage systems decreases, due to the need for a corresponding increase in energy intensity [7].

Operational control in traction power supply systems is implemented considering operating conditions of power and switching equipment of traction substations and linear devices of the catenary system [8]. Operation in forced operating modes of the traction power supply system is characterised by an increase in the load of traction substations and a corresponding drop in the voltage level in the catenary system [9], which makes it necessary to monitor energy indicators and develop measures to strengthen the traction power supply system [10, 11].

The length of the disconnected sections of the catenary system on hauls and stations determines the requirements for the range of autonomous movement of the electric rolling stock to the nearest serviceable section of catenary system as illustrated by the example of a power mode of the inter-substation zone (Pic. 2).

The energy parameters for an electric train within the inter-substation zone of the length l with two traction substations *TS1* and *TS2* depend on various conditions (track profile, direction of movement, speed, and range of autonomous movement l_i). The energy indicators were evaluated based on the simulation of *Velaro RUS* operation when driving along St. Petersburg – Moscow section (Pic. 3). On the graph, the abscissa l_d indicates the direction of movement of the electric train with the minimum power consumption.

The results of calculations performed for *Velaro RUS* electric train during its travelling along one of the inter-substation zones of Tver–Moscow section show the change in power consumption and average power consumption depending on the maximum speed (Pic. 4).

Work in post-emergency modes of operation of electric power storage systems must be coordinated with automation in the traction power supply system [12].

The energy intensity of the onboard electric power storage system for driving at speeds not exceeding 100 km/h is about 1000 kWh, depending on the conditions for generating the traction load. Similar energy intensity estimates are given in other studies for on-board electric energy storage systems[3] for which the maximum power does not exceed 2 MW. The ratio of maximum power and energy intensity of electric energy storage systems allows the use of batteries that admit discharge with currents of $2C_n$.

When carrying out overhaul works, modernisation or reconstruction of infrastructure devices, one of the sections of the catenary system is turned off. The movement of trains is carried out according to the alternative traffic schedule (Pic. 5). In these modes of operation, there is a risk that the voltage level on the

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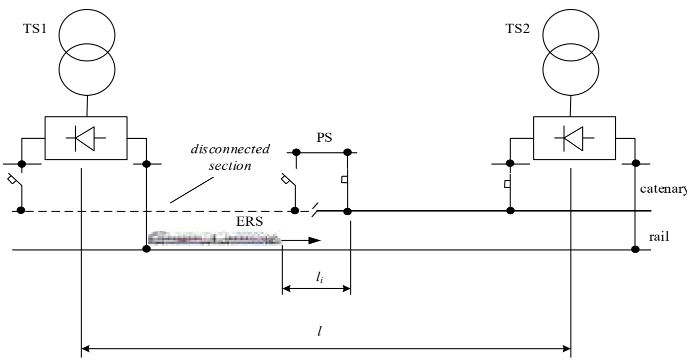
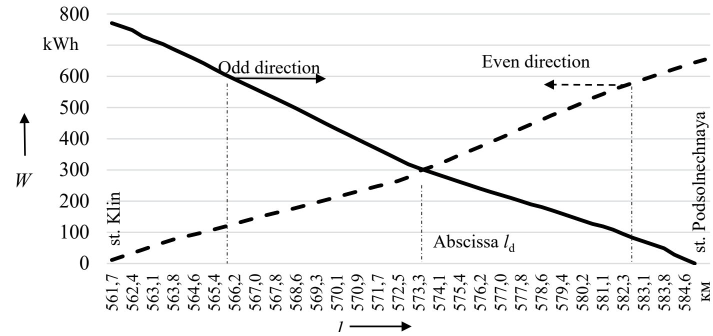
[2] Deutsche Bahn baut erstmals Oberleitungsinseln für Regionalverkehr mit Akku-Zügen / Deutsche Bahn. [Electronic resource]: https://www.deutschebahn.com/de/presse/pressestart_zentrales_uebersicht/Deutsche-Bahn-baut-erstmals-Oberleitungsinseln-fuer-Regionalver kehr-mit-Akku-Zuegen-7343070. Last accessed 14.01.2023.

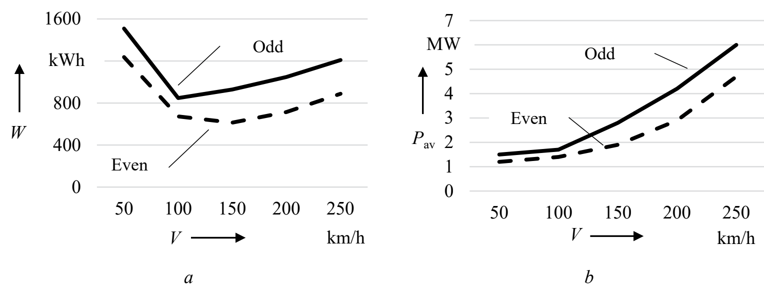
[3] Hybrid train. How the Russian battery-powered locomotive will work [Russian title: Gibridnyi poezd. Kak budet rabotat' rossiyskiy Lokomotiv na akkumuliatorakh]. [Electronic resource]: https://gudok.ru/content/science_education/1598983/?ysclid=ll4z3bgyba487665577. Last accessed 14.01.2023.



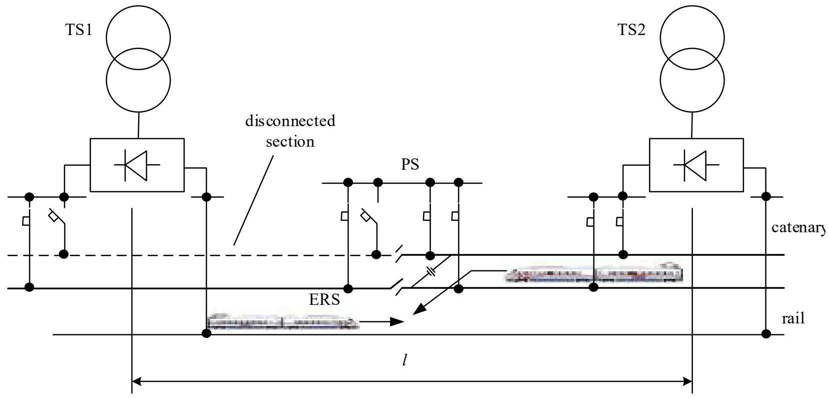
Pic. 2. Inter-substation zone power mode [compiled by the authors].



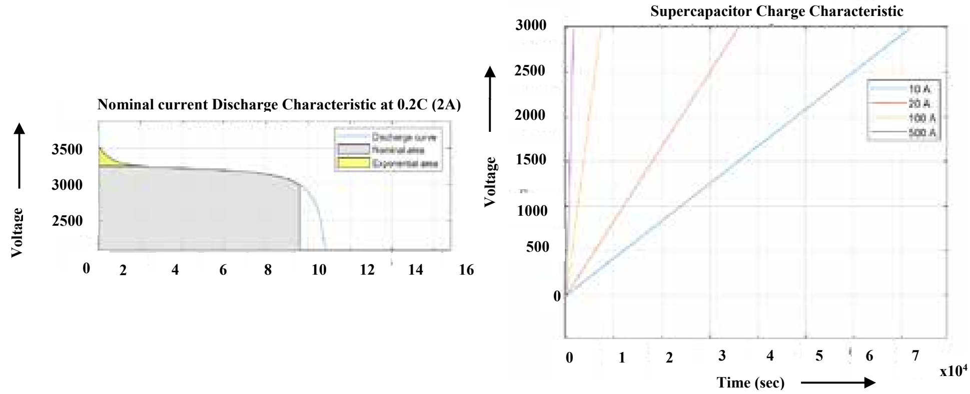
Pic. 3. Electricity consumed by the electric train [compiled by the authors].



Pic. 4. Graphs of changes in power consumption (a) and the average power of an electric train (b) depending on the speed [compiled by the authors].



Pic. 5. Scheme of the electric train movement when the section of the catenary system is disconnected [compiled by the authors].



a *б*

Pic. 6. Nominal discharge NiMh (a) and charge EDCL supercapacitor (b) characteristics [created by the authors in Matlab environment].

pantographs will go beyond the lower limit of the permissible range.

The simulation of the traction power supply system is carried out for electric power storage devices based on batteries and an electric double layer supercapacitor (EDLC). Storage devices are considered based on four types of batteries: nickel-metal hydride; nickel-cadmium; lithium-ion; lead acid ones. When modelling the energy storage device, a capacitor with a double electric layer was used [13]. The discharge characteristics of the above batteries (for a nominal capacity of 10 Ah) and of a supercapacitor, implemented in the corresponding Matlab models, are shown in Pic. 6.

When considering the charging and discharging characteristics of batteries, it is necessary to account for the exponential zone of voltage change, which characteristics, in contrast to supercapacitors, can be considered as linear over the entire range (Pic. 6).

To describe the processes of voltage measurement depending on the load in the charge and discharge modes, analytical expressions are used based on Peikert, Shepherd equations, Thévenin, Zimmermann – Peterson models, etc. [14, 15].

For a lead-acid battery, the Matlab model uses the following equations to determine voltage in discharge and charge modes.

Discharge mode ($i_* > 0$):

$$f_{\text{disch}}\left(it,i_*,i\right)=E_0-K_1\cdot\frac{Q}{Q-it}\cdot i_*-\\-K_2\cdot\frac{Q}{Q-it}\cdot it+\overline{LF}^{-1}\left(e^s,sel\left(s\right)\right),\qquad(1)$$

where E_0 – constant initial voltage, V;

K_1, K_2 – constants, respectively V/A and V;

Q – rated battery capacity, Ah;

i_* – low-frequency current, A;

i – battery current, A;

t – operation time in charge or discharge modes, h;

– implemented capacity, in Ah;

$LF(x)$ – rated Laplace function,

$$\overline{LF}\left(x\right)=\frac{1}{\sqrt{2\pi}}\int_0^x e^{\frac{-t^2}{2}}dt\ ,\qquad(2)$$

where e^s – function of voltage change in the zone close to voltage of battery open circuit;

sel*(s)* – function, the value of which corresponds to battery operation mode: for discharge mode sel*(s)* = 0, for charge mode sel*(s)* = 1.

Charge mode ($i_* < 0$):

$$f_{\text{ch}}\left(it,i_*,i\right)=E_0-K_1\cdot\frac{Q}{0{,}1Q+it}\cdot i_*-\\-K_2\cdot\frac{Q}{Q-it}\cdot it+\overline{LF}^{-1}\left(\frac{e^s}{s},sel\left(s\right)\right).\qquad(3)$$

For a lithium-ion battery, the following voltage equations are used in the model to determine the voltage in discharge and charge modes.

Discharge mode ($i_* > 0$):

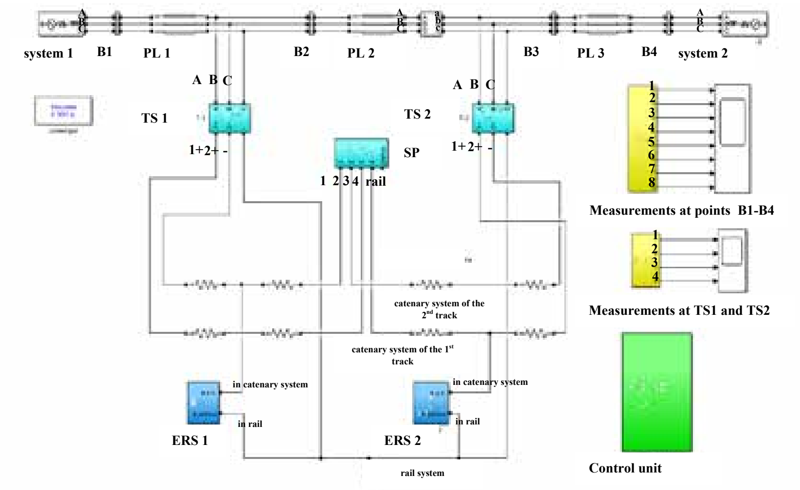
$$f_{\text{disch}}(it,i_*,i)=E_0-K_1\cdot\frac{Q}{Q-it}\cdot i_*-\\-K_2\cdot\frac{Q}{Q-it}\cdot it+Ae^{-B\cdot it},\qquad(4)$$

where A – voltage of the exponential part of the characteristic, V;

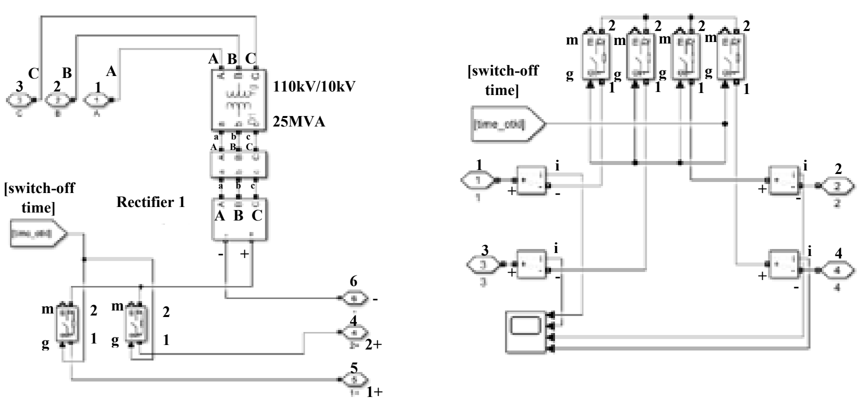
B – coefficient, corresponding to the respective capacity of the exponential part of the characteristic, $(\text{A}\cdot\text{h})^{-1}$.

Charge mode ($i_* < 0$):

$$f_{\text{ch}}(it,i_*,i)=E_0-K_1\cdot\frac{Q}{0{,}1Q+it}\cdot i_*-\\-K_2\cdot\frac{Q}{Q-it}\cdot it+Ae^{-B\cdot it},\qquad(5)$$



Pic. 7. Model of traction power supply system in Matlab [compiled by the authors].



a *b*

Pic. 8. Model of a traction substation (a) and sectioning post (b) [compiled by the authors].

For nickel-cadmium and nickel-metal hydride batteries, the following equations are used in the model to determine the voltage in discharge and charge modes.

Discharge mode ($i_* > 0$) is described by the equation (1).

Charge mode ($i_* < 0$):

$$f_{ch}\left(it, i_*, i\right) = E_0 - K_1 \cdot \frac{Q}{0{,}1Q + |it|} \cdot i_* - K_2 \cdot \frac{Q}{Q - it} \cdot it + LF^{-1}\left(\frac{e^s}{s}, sel(s)\right). \quad (6)$$

The supercapacitor voltage is determined in the model based on the Stern equation [16] by the formula:

$$V_{sc} = \frac{N_s Q_T d}{N_p N_e \varepsilon \varepsilon_0 A_i} + \frac{2 N_e N_s RT}{F} \sinh^{-1} \bullet \left(\frac{Q_{TR}}{N_p N_e^2 A_i \sqrt{8RT\varepsilon\varepsilon_0 c}}\right) - R_{sc} i_{sc}, \quad (7)$$

where A_i – interface area between electrodes and electrolyte, m^2;

c – molar concentration of a substance, mole/m^3;

r – molecular radius, m;

F – Faraday constant, C/mole;

i_{sc} – supercapacitor current, A;

V_{sc} – supercapacitor voltage, V;

T – operating temperature, K;

R_{sc} – total resistance, Ohm;

N_e – number of electrode layers, pcs.;

N_p, N_s – number of supercapacitors connected in parallel and in series, respectively, pcs.;

Q_T – electric charge, C;

R – universal gas constant, J/(mole K);

d – effective molecular diameter, m;

ε – dielectric constant of the material, F/m;

ε_0 – permittivity of free space, F/m.

Table 1

Results of determining SoC of an ERS on-board storage device [compiled by the authors]

Indicator	NiMh	NiCd	LiIon		LeAc(Pb)	EDLC
Average value	98,77	98,86	98,70		98,96	97,74
Maximum value	100,00	100,00	100,00		100,00	100,00
Minimum value	96,73	96,99	96,55		97,27	93,97

The operation of on-board and stationary devices for storing electricity is considered using the example of an inter-substation zone, which is a fragment of a traction power supply system (see Pics. 2 and 5). The model contains two power sources (system 1 and system 2), simulating electric power systems, two traction substations (TS1 and TS2), a sectioning post (SP) and traction network of the 1st and the 2nd tracks. The electric rolling stock is represented in the model by two units (ERS1 and ERS2), the load of which for modelling is assumed to be constant in the range of up to 20 s.

To measure electrical quantities in the model, oscilloscopes are used, which make it possible to fix processes in power lines (PL 1 – PL 3) at the corresponding points (B1 – B4). The regulation of the accumulation devices is carried out using the control unit. A general view of the model of the traction power system created in Matlab environment is shown in Pic. 7.

Models of traction substations TS1, TS2 and sectioning post are shown in Pic. 8. The traction substation contains a power step-down transformer with primary voltage of 110 kV, secondary voltage of 10 kV and rated power of 25 MV·A. The rectifier is represented by "Rectifier" block, which is connected to the catenary system of two tracks using appropriate switches, which are ideal switches

The sectioning post (see Pic.8) is represented by a common bus to which four switches are connected, they are similar to those used in substations. The outputs of the switches are connected to the corresponding sections of the catenary system (1–4) of two tracks. Current sensors and an oscilloscope are connected also at the sectioning post, allowing registration of the load on the connections.

The model of the rectifier converter implements a circuit of a twelve-pulse series-type rectifier, at the output of which a single-link resonant-aperiodic filter is connected (Pic. 9).

Simulation of operation of the on-board electric power storage device is performed using an ERS model, in which an electric power storage device is connected in parallel with the load (Pic. 10). To control the power storage device, the ERS model contains switches that allow turning off the main circuits of ERS and turning on the on-board power storage device.

Four types of batteries and a supercapacitor are considered as a storage device. The analytical descriptions of voltage changes for the different modes of their operation are given above in formulas (1)–(6).

To assess the influence of operating modes of the traction power supply system on the external power supply system, a measurement scheme was implemented that allows recording oscillograms and determining the root-mean-square values of electrical quantities (Pic. 11).

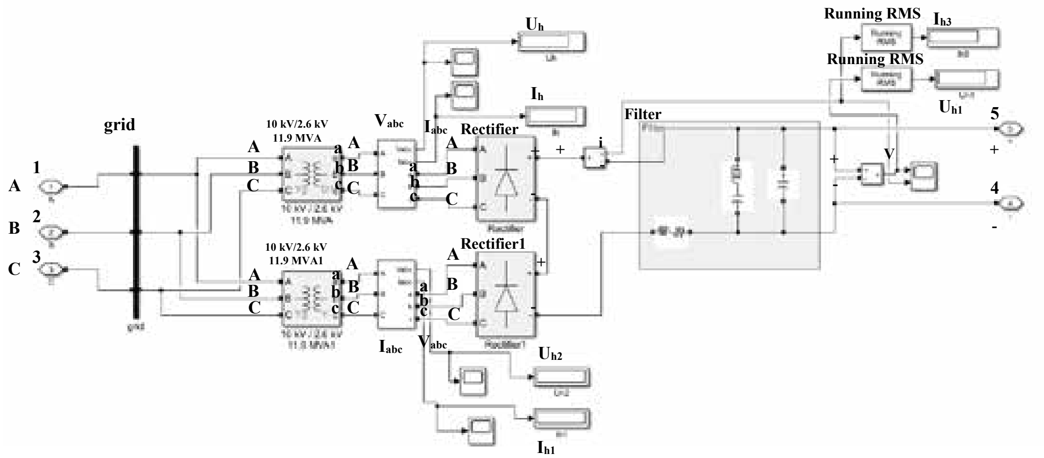
Similarly, the measurement scheme at the traction substation was made, which makes it possible to record the changes in electrical quantities on the DC side (Pic. 12).

To simulate an emergency shutdown, time constants are entered into the control unit (Pic. 13), corresponding to the following marks: 0 – beginning of the period of time under consideration; 5 s – emergency shutdown of switches at the traction substation and the sectioning post; 10 s – turning on the power storage device; 15 s – voltage recovery in the catenary system and turning off the power storage device. Simulation time – 20 s.

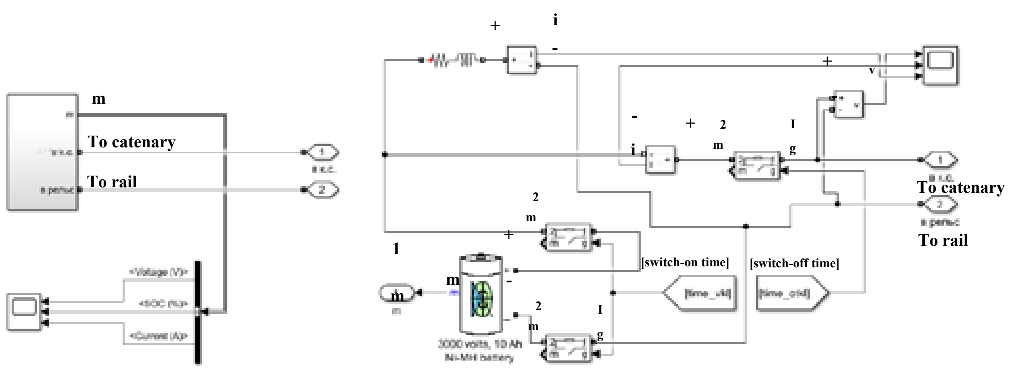
The control unit corresponds to the situational model regarding removing voltage in the catenary system, lack of voltage, turning on the on-board storage device, re-applying voltage and turning off the device.

The results of modelling the processes of emergency power supply from a power storage device, consisting of various batteries or a supercapacitor, make it possible to evaluate the nature of the change in voltage, degree of charge and load current and other electrical quantities. An example of an assessment of the degree of state of charge (SoC) of the power storage device for the considered modelling period is shown in Table 1.

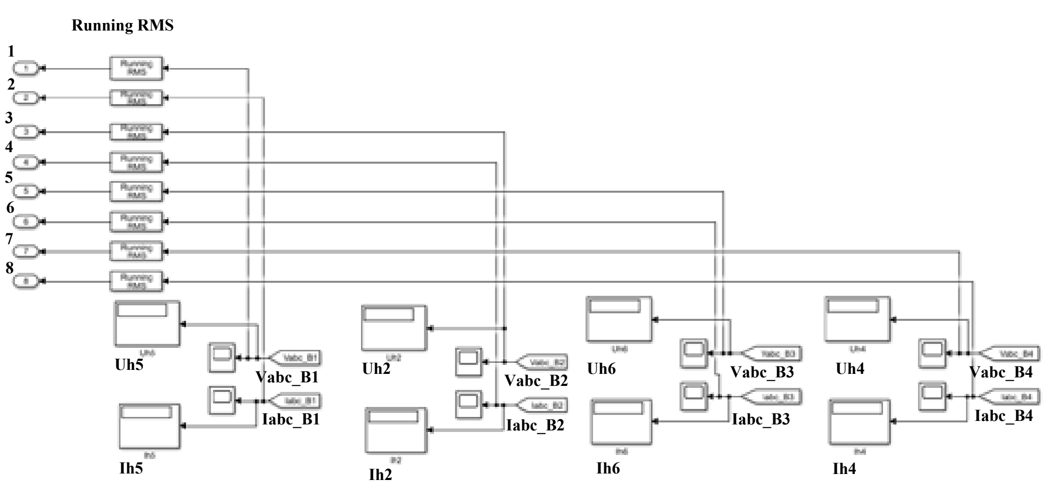
The minimum values of SoC are observed for the supercapacitor (EDLC), the maximum – for the lead-acid battery (LeAc(Pb)). For nickel-



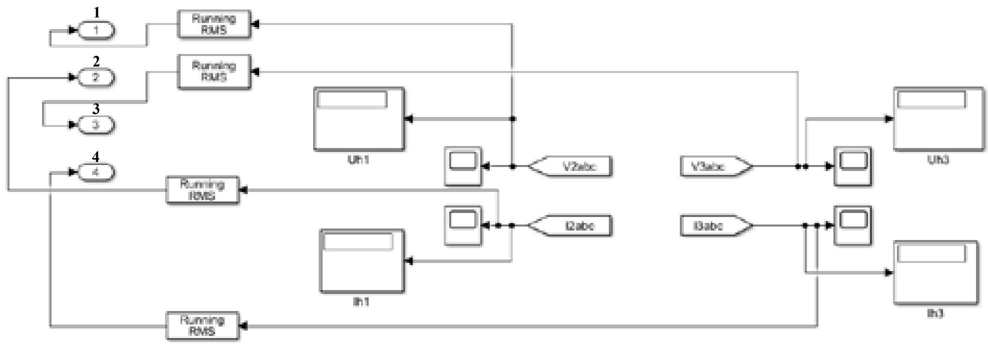
Pic. 9. Model of converting units [compiled by the authors].



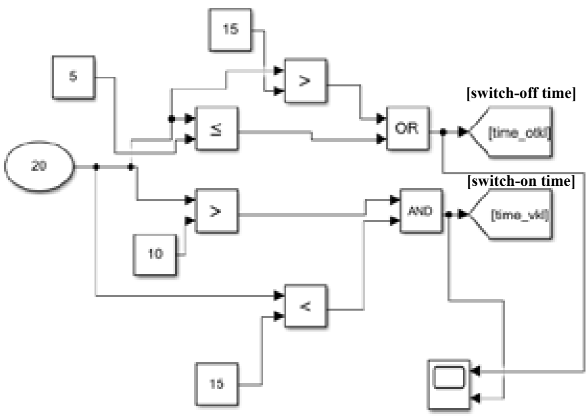
Pic. 10. Model of electric rolling stock with on-board power storage system [compiled by the authors].



Pic. 11. Scheme of measurements in power lines [compiled by the authors].



Pic. 12. Scheme of measurements at the traction substation [compiled by the authors].



Pic. 13. Control unit of the power storage device [compiled by the authors].

metal hydride (NiMh), nickel-cadmium (NiCd) and lithium-ion (LiIon) batteries intermediate values are observed. In this regard, according to the level of the minimum value of the degree of charge for the ERS it is advisable to use the LeAc(Pb) battery.

Graphs of voltage, SoC and load current for application of a lead-acid battery storage device are shown as an example in Pic. 14.

Modelling of processes was executed for a stationary storage device at a traction substation and a sectioning post, as well as for a situational model, corresponding to removing voltage in the catenary system by turning off the switches of the catenary system connections, following by automatic restart (ART) time delay, then by turning on the sectioning post and power storage device, and finally by returning to the normal power supply. The control unit implements time delay similarly to the first considered model (see Pic. 13).

For simulation, the models of the traction substation and the sectioning post, shown in Pic. 15, are used. Simulation results for a given interval (a lead-acid battery is used as an example) are shown in Pic. 16.

Based on the results of the calculation regarding a power storage system with similar characteristics placed at the sectioning post, the values of SoC were determined for four types of batteries and a supercapacitor (Table 2).

The minimum values of SoC are observed for the supercapacitor (EDLC), the maximum values are characteristic of the lead-acid (LeAc(Pb)) battery. When using power storage systems at sectioning posts, it is advisable to use LeAc(Pb) batteries.

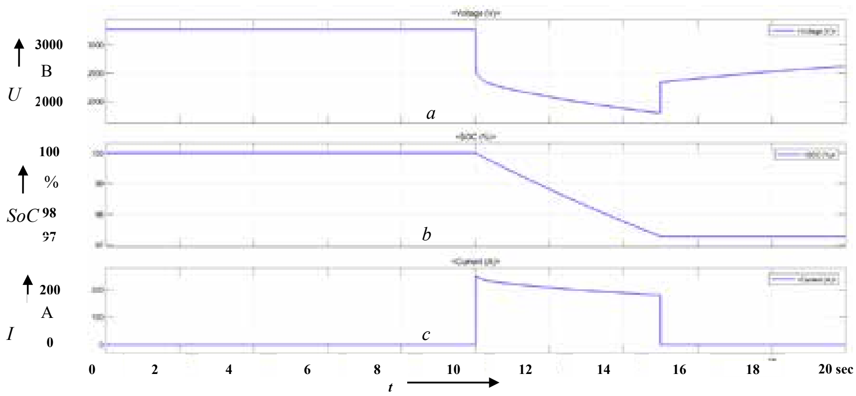
The voltage drop at the output of the power storage device when turned on is determined by the discharge characteristic of batteries or/and supercapacitors. During the initial period, the voltage at batteries of various types is determined by the exponential zone of the characteristic. The drop in the voltage level can be significant and critical for ensuring operation of the electric rolling stock.

To avoid voltage drop while maintaining the traction load at a given level, the energy intensity

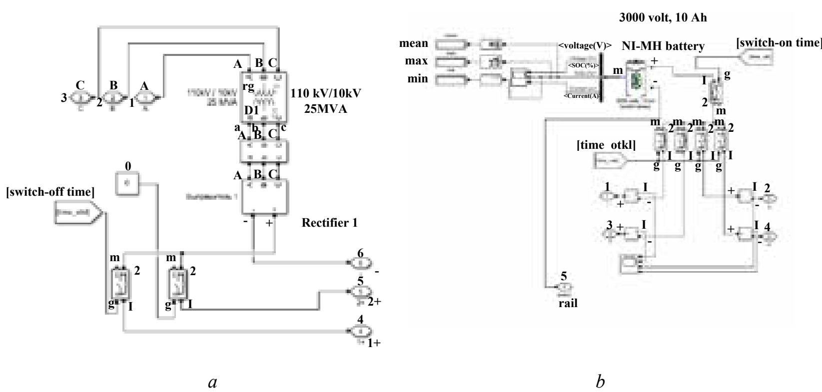
Table 2

Results of determining SoC for the power storage device with energy capacity of 10 kVh, placed on the SP [compiled by the authors]

Indicator	NiMh	NiCd	LiIon	LeAc(Pb)	EDLC
Average value	98,17	98,32	98,06	98.52	95,97
Maximum value	100,00	100,00	100,00	100,00	100,00
Minimum value	95,17	95,56	94,87	96.13	89,30



Pic. 14. Results of modelling the operation of the on-board power storage system of electric rolling stock [compiled by the authors].



Pic. 15. Models of a traction substation (a)0 and a sectioning post (b) [compiled by the authors].

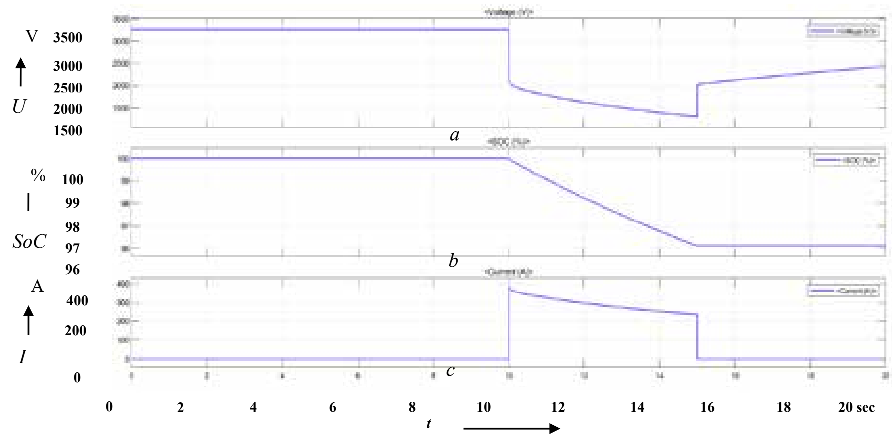
of power storage devices should be chosen with a margin.

Based on the results of simulation of operation of the power storage device in the traction power supply system, the dependences of the voltage change on the rated energy intensity were obtained (Pic. 17).

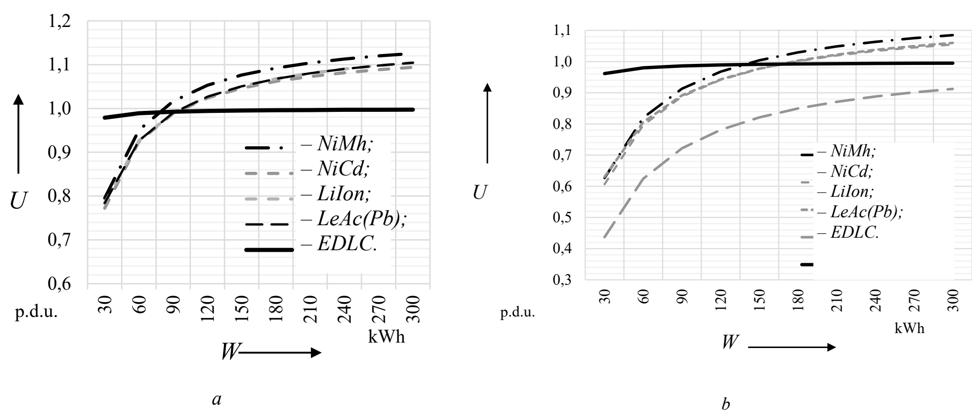
The assessment of the change in voltage for batteries has been performed relative to the open circuit voltage, taken as a base value. For the NiMh battery, the specified voltage was 3533,9 V, NiCd – 3432,5 V, LiIon and LeAc(Pb) – 3491,9 V, EDLC – 3000 V.

The difference in the discharge characteristics of the on-board and stationary storage systems causes a voltage drop to the level of 0,8 p. d. u. (procedure defined units) as compared to the nominal level for a given load when using on-board systems and up to a level of 0,4–0.6 p. d. u. for the option of stationary placement of the power storage system. Unlike storage batteries, the use of a supercapacitor does not require a significant increase in energy intensity for the short-term operating conditions under consideration.

The results of the calculations make it possible to estimate the required energy intensity based on the conditions necessary for providing voltage on the busbars of the device. For the electric train traction load under consideration, the energy intensity of the on-board storage system is estimated at 90 kWh (when using batteries) and 30 kWh (when using supercapacitors). For the stationary use



Pic. 16. Results of modelling the operation of the power storage system at the sectioning post [compiled by the authors].



Pic. 17. Minimum voltages for on-board (a) and stationary (b) systems [compiled by the authors].

of the energy storage system (when used at the sectioning post of the catenary system), the smallest increase in energy intensity is observed when a rechargeable battery based on NiMh batteries is used. A larger energy capacity is required for storage devices based on NiCd and LiIon batteries, and a maximum (by three times) increase is needed for storage devices based on LeAc (Pb) batteries. The increase in energy intensity for supercapacitors is comparable to that of lead-acid batteries (by a factor of two).

When solving the problems of increasing the transit and carrying capacity with the help of electric power storage devices, the criteria are the indicators of the load capacity of the traction power supply system. To achieve the targets, an increase in the energy intensity and power of the electricity storage is required, as illustrated for DC and AC traction power supply systems in [17–19], where the energy intensity of electricity storage reaches the level of 1,5 and 12,0 MWh, respectively.

CONCLUSION

The energy intensity selected according to the conditions necessary for ensuring the transit and carrying capacity is checked based on simulation relative to a given load under conditions of operation in post-emergency and forced modes of operation of the traction power supply system.

The results of simulation modelling were obtained for the case of placing power storage devices both on the electric rolling stock and in the traction power supply system. For each variant, simulation was performed for electric energy storage devices built with the considered batteries and/or a supercapacitor.

The developed models can be used to determine the energy performance of the traction power supply system in solving various problems with the help of electric power storage devices built with various types of electric power storage devices.

Prospects for further research are associated with development of algorithms for regulating electric power storage systems in terms of voltage and traction load, considering the specifics of direct and alternating current traction power supply.

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Article received 30.12.2022, approved 18.04.2023, accepted 25.04.2023.