FEATURES OF THE TRACTION LOAD FOR DETERMINING THE PARAMETERS OF THE ELECTRIC ENERGY STORAGE DEVICE

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ABSTRACT

Based on the data regarding operation of locomotives of the series 2ES6 and 2ES10, the averaged parameters of the electric power storage in the DC traction system on lines with heavy and long-distance trains have been identified. The modes of the storage devices are characterized by a short-term nature. The average duration of their operation in the charging mode is approximately 100 s, and the volume of the returned energy by the electric rolling stock, which determines the energy capacity, averages 100 kW•h, with a maximum power of 7,1 MW. The processing of measurement results shows that the observed distributions of stresses and traction load of the substation are not subject to Gauss's laws.

Keywords: *railway, traction power supply system, heavy traffic, traction load, energy efficiency, sectioning post, power storage, electric rolling stock, experiment.*

Background. *The emergence of heavy traffic on the world's railways is associated with the need to achieve a more economical mode of transportation. The organization of routes with high loads led to the emergence of trains weighing up to 20 000 tons in China [1], 14 000–16 000 tons in the USA [2], up to 48 000 tons in Australia [3] and other countries [4].*

The development of heavy traffic on the Russian road network stipulates other requirements for the traction power supply system (TPS) to provide throughput and carrying capacity than those envisaged by the design indicators of electrification of the 1960–1980s, which meant the handling of freight trains weighing up to 5000 tons at intervals of passing movement up to 20 minutes. The increase in the weighted norms of trains and the reduction of the minimum intervals revealed a number of sections that limit the capacity and carrying capacity.

Since 2006, in order to provide the main direction for development of the network – handling of trains with a mass of 6000 tons and more with an interval of about 10 minutes – the departments of the power supply of the holding Russian Railways have carried systematic work to strengthen TPS, including direct current lines, application of buffer TPS, increasing the voltage in the contact network to 12 or 24 kV, or switching to alternating current [5].

Objective. *The objective of the authors is to consider characteristic of the traction load to determine the parameters of the electric energy storage device.*

Methods. *The authors use general scientific and engineering methods, comparative analysis, evaluation approach, graph construction.*

Results. *One of the alternatives for strengthening the TPS of direct current in areas with organization of heavy and long train traffic are power storage systems. They are used in advanced world practices in passenger urban transport, for example, when operating 24-meter buses [6], or on hybrid cars and locomotives with lithium-ion batteries and fuel cells [7, 8]. Taking into account the features of TPS of direct current, you can expect a tangible effect from the use of power storage on the railways as well.*

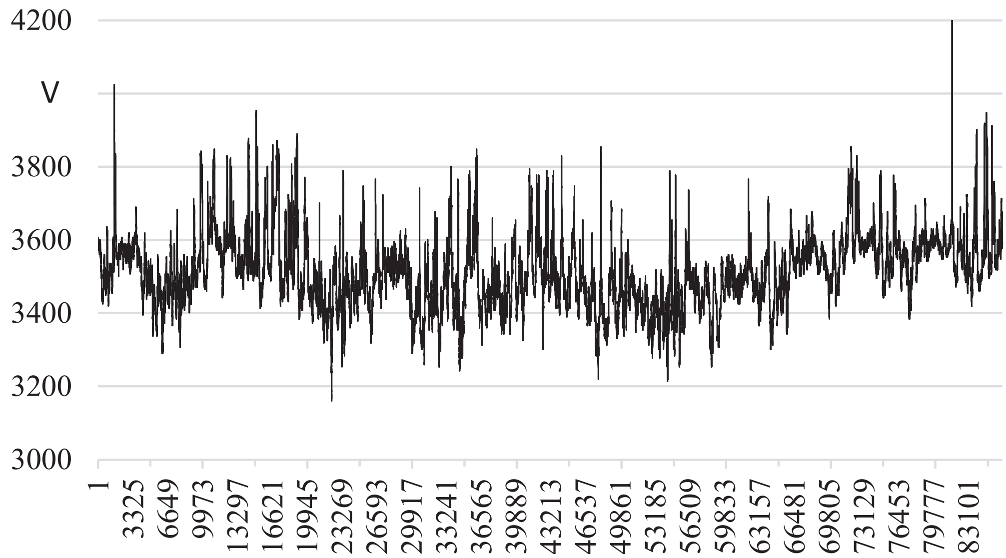
The main factor associated with the emergence of «limiting» inter-substation zones is the low voltage on the current collector, caused by the operating modes of the electric rolling stock (ERS) and the voltage losses in the traction network. And here it is very important to choose the location of the energy storage as close as possible to the source of generation and consumption of energy. In the traction power supply system, the linear device – the sectioning post of the contact network or the point of parallel connection is the most effective from a technical point of view [9–11].

Work on the storage of electricity and the determination of its parameters has been conducted for relatively long time, but the use of these devices is limited primarily by their high cost and a long payback period. At the same time, the technical effect of power storage is undoubted. Currently, there is a fairly wide choice of types and sizes, including inductive storage devices for superconductors, supercapacitors (ionistors), accumulators [12], and so on. It should be noted that such tools and various circuit solutions for charging and subsequent discharge of energy into the network are also considered in the organization of Smart Grid networks [13–15], which allow improving the quality of their modes management.

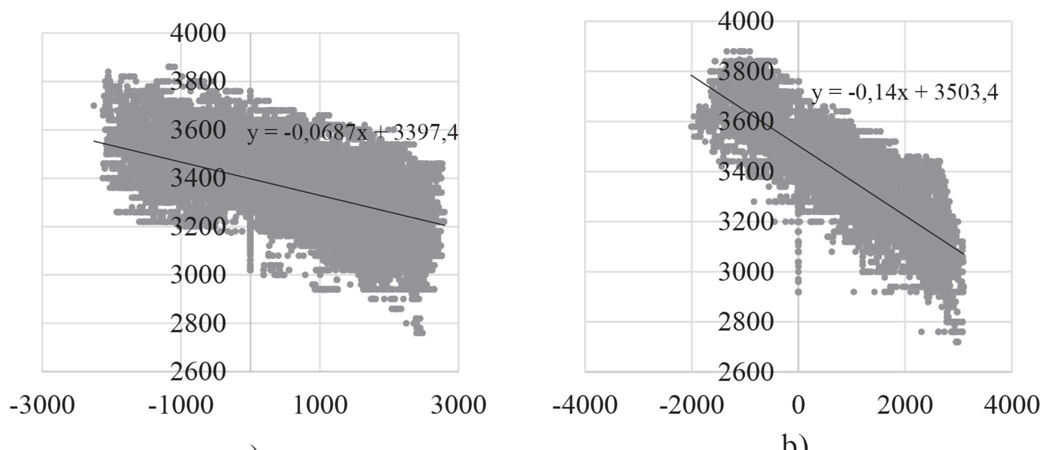
The use of energy storage devices at the post of sectioning allows reducing the level of power consumption by traction substations by increasing the efficiency of regenerative braking, increasing the average level of voltage on the current collector of electric rolling stock and reducing the average current of the traction load, which contributes to increasing the throughput and carrying capacity of the railway section [11].

The main parameters that determine the mode of operation of the power storage device are the following: nominal power, energy capacity, overload capacity, charge and self-discharge time, discharge depth, service life and capital costs. All of them concern TPS, the feature of which is the sharply uneven character of the indicators, caused by the unevenness of the train schedule. In addition, in the conditions of increasing of the mass of the train and switching to heavy traffic, peak loads on TPS increase, which leads to an even greater unevenness in the daily schedule of the load of the traction substations. With the purpose of revealing the limiting modes of operation, we consider daily diagrams of load and voltage on 3,3 kV tires of one of the traction substations at the section for handling heavy trains Taiga–Mariinsk of the West Siberian Railway, whose track profile is of type III (Pic. 1).

The substation has uncontrolled rectifiers with a 12-pulse serial-type circuit (converter



Pic. 1. Graph of voltage changes on the tires of the traction substation within 24 hours.



Pic. 2. Results of measurements for locomotives 2ES6 (a) and 2ES10 (b).

transformers of TRDP-12500/10 type and rectifiers of TPDE-Zh-3,15k-3,3 and PVE-5AU1). Voltage measurements on 3,3 kV tires of the DC Taiga–Mariinsk traction substation are performed using the BRTN-3,3 registration units with one-second detailisation.

A test of the hypotheses that the observed voltage distribution and load current of the substation correspond to the theoretical law shows that according to the Pearson criterion [16]

$$\chi^2 = \sum_{i=1}^{k} \frac{\left(n_i - n_{i\,theor}\right)^2}{n_{i\,theor}}, \qquad (1)$$

where n_i, $n_{i\,theor}$ – observable and theoretical frequencies; k – number of ranges of observed values determined by the Sturges' formula, in this case the correspondence with the Gaussian distribution laws is not detected. Thus, the voltage on the 3,3 kV tires exceeds the tabulated value by several times (over 1000 against χ^2 5,89 for the confidence probability of 0,95 and the number of degrees of freedom 13).

The resulting distribution (Pic. 3) does not change significantly over the day. The homogeneity of the 24-hour voltage samples on the 3,3 kV tires of the traction substation under consideration was confirmed with the help of the non-parametric Kolmogorov test [17–18]:

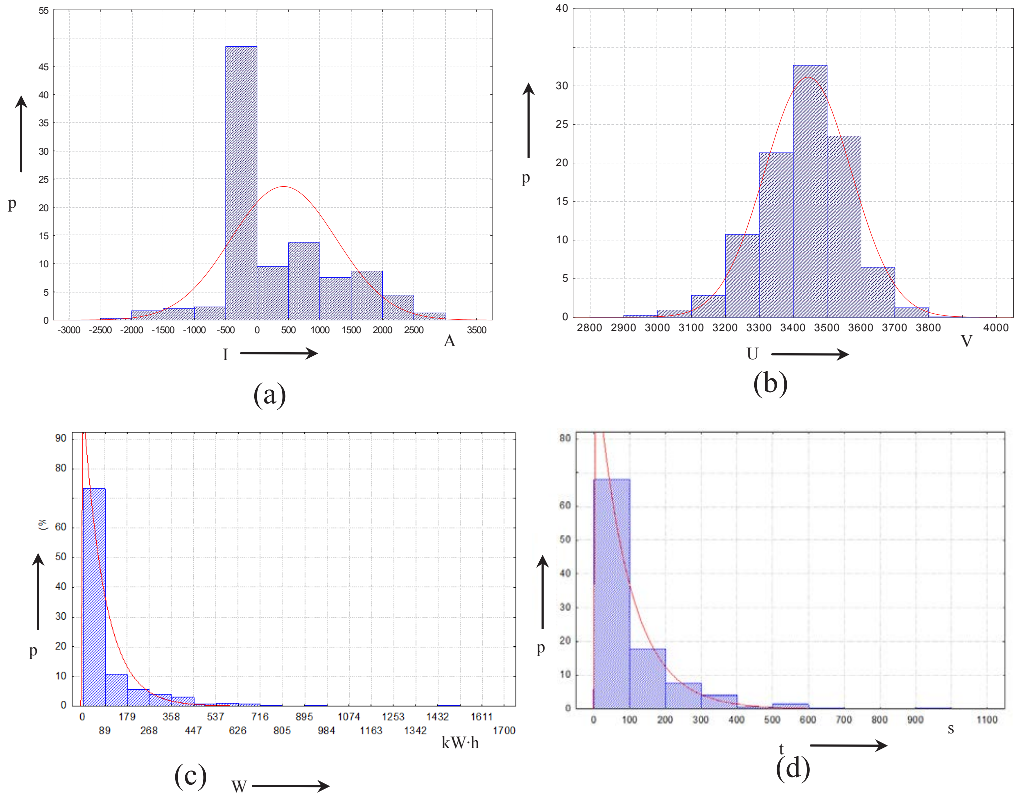
$$D_n = \max_{-\infty<x<\infty} \left| P_i^*(x) - P_j^*(x) \right|, \qquad (2)$$

where $P_i^*(x)$, $P_j^*(x)$ – frequencies of distribution of the experimental data and the theoretical distribution, respectively.

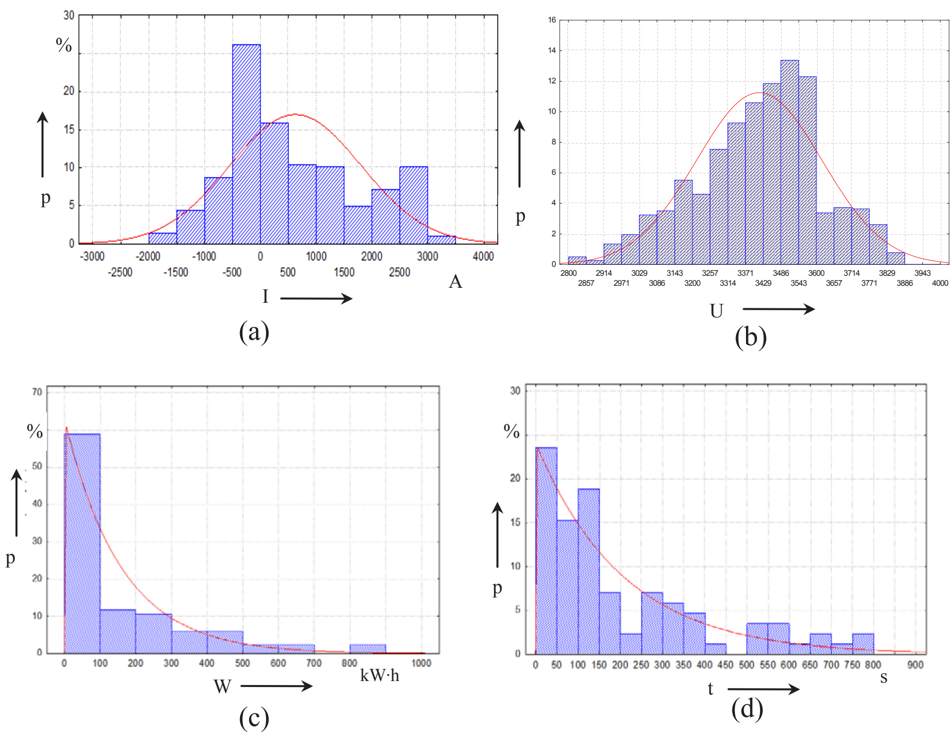
The critical value of the Kolmogorov criterion for two samples is determined from expression

$$D_{cr} = 1,36 \bullet \sqrt{\frac{n+m}{n \bullet m}}, \qquad (3)$$

where n and m – volumes of the samples being compared.



Pic. 3. Distribution of currents (a), voltage at the current collector (b), energy recovery (c), the duration of episodes of regenerative braking (d) of electric locomotives of 2ES6 series.



Pic. 4. Distribution of currents (a), voltage at the current collector (b), energy recovery (c), the duration of episodes of regenerative braking (d) of the electric locomotive of series 2ES10.

Table 1

The most observable values of electrical parameters in the regenerative braking mode

Parameters	2ES6		2ES10	
Current	0–600 A	(90 %)	0–500 A	(70 %)
Voltage	3400–3600 V	(30 %)	3400–3600 V	(35 %)
	> 3600	(10 %)	> 3600	(15 %)
Amount of electric power	0–90 kW•h	(70 %)	0–100 kW•h	(55 %)
Duration of episodes	0–100 s	(70 %)	0–100 s	(40 %)

It is calculated with a confidence probability of 0,95 and the number of intervals of grouping 16 and is equal to 0,48. As a result of calculations for three cases (three days of observation), the voltage samples on 3,3 kV tires for cumulative frequencies differ slightly. The maximum value of the Kolmogorov test for pairs of different days is 0,13, which is much less than the critical one. Taking samples homogeneous, the obtained distributions can be used when characterizing the voltage regime for averaged days.

The results of processing a series of trips for locomotives of 2ES6 and 2ES10 series with trains of various masses, including heavy and long ones, allow to obtain an external characteristic of the locomotive, observed at the sections of its operation. Data on movement ranges in the West Siberian, South Ural and Sverdlovsk railways are shown in Pic. 2.

For locomotives of both series, the load level is within the range 0–2000 A, and the voltage at the current collector is within the range 3200–3900 V, but the observed slope of the external characteristic is different. With linear approximation of data, the slope coefficient for 2ES6 series is «-0,0687», for 2ES10 – «-0,14». The steeper nature of the total load characteristic for 2ES10 series is due to operating conditions – it is carried out in the presence of a mountain profile of the track (4th type), and hence the voltage level on the current collector of the locomotive.

The measurements carried out make it possible to determine the operating voltage range for the power storage device when it operates in charge mode. Considering the voltage level of the idling, the lower voltage limit when the drive is switched to the charge mode should be taken to be no lower than 3600–3650 V. When placing the power storage unit in the sectioning post to provide charging with low currents, the voltage should be reduced by 50–100 V.

Pic. 3 shows the distribution of current values in different operating modes of the locomotive series 2ES6 (a), the voltage on the current collector (b), the energy recovery (c), the duration of episodes of regenerative inhibition (d).

The number of observed values for the period under study was 65 536, the average current value was 423 A, the maximum in the traction mode was 2799 A, the maximum in the recovery mode was 2121 A, and the standard deviation was 842,0. The most observed value of the energy return is in the range from 0 to 89 kW•h. The most observed duration of episodes of recuperative braking is within the range from 0 to 100 s.

Pic. 4 shows the distribution of current values in various operating modes of the electric locomotive of series 2ES10 (a), the voltage at the current collector (b), the energy of recovery (c), the duration of episodes of regenerative braking (d).

The number of observations was 27307, the average current value was 626,2 A, the maximum in the traction mode was 3096 A, the maximum in the recovery mode was 2008 A, the standard deviation was 1174,6. The most observed value of energy recovery lies within the range from 0 to 100 kW•h. The most likely duration of the episode of regenerative braking is in the range from 0 to 100 s.

Among other things, it becomes possible to identify the most observable electrical quantities that characterize the regenerative braking mode for locomotives 2ES6 and 2ES10 (Table 1).

The results of the processing of locomotive travel data with heavy and long trains show that the averaged values of the duration of traction episodes for the 2ES6 series are about 545 s, the recovery mode is about 109 s. For the series 2ES10 – respectively, 335 s and 216 s. Average values of power consumption for each episode in the traction mode for the 2ES6 series are 534 kW•h, in the recovery mode the return volume is 107 kW•h, for the 2ES10 series, the analogous values are 416 kW•h and 161 kW•h.

The maximum power returned to the contact network in the recuperation mode is 7,2 MW for 2ES6 series, 7,1 MW for 2ES10. The averaged values of the maximum current and voltage levels for the use of recovery for locomotives 2ES6 – 891 A and 3505 V, for 2ES10 – 890 A and 3670 V. The average values of the recuperation energy returned to the contact network vary in the range 73–126 kW•h, for 2ES6 series, in almost 75 % of cases, the recovery volume reaches 90 kW•h, for 2ES10 series in 60 % – up to 100 kW•h. In more than 85 % of observed cases, the duration of recovery episodes for 2ES6 series is up to 200 s, for 2ES10 in more than 70 % – up to 400 s.

At the highest level, the average values of the maximum current for each application of regenerative braking are achieved in sections with 4th type of the profile – up to 1030 A. The average of the observed maximum values of voltages on the current collector in the regime of regenerative braking in sections of this profile is 3600 V.

Conclusions. *The results of the processing of travel data for locomotives of 2ES6 and 2ES10 series on sections with different weights and track profile in the conditions of organizing heavy and long traffic allow us to determine the voltage ranges on the power storage device in various modes, the maximum and most probable load, the duration of episodes in charge and discharge modes.*

The estimated operating mode of the power storage device in the traction power supply system is of a short-term nature. The expected average duration of episodes in the discharge mode is within the range of 300–550 s, in the charging mode – 100–250 s. The average useful energy capacity of the storage for the conditions of a *single train following the results of the application of regenerative braking is within the range of 100–170 kW•h.*

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