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DEVELOPMENT OF A METHOD FOR DETERMINING THE PARAMETERS OF ENERGY STORAGE DEVICES TO ENSURE UNINTERRUPTED POWER SUPPLY FOR AUXILIARY NEEDS OF AN ELECTRIC TRAIN

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The aim of this article is to conduct experimental research to determine the energy storage parameters for providing uninterrupted power supply to the auxiliary needs of electric trains. Analytical power calculations for the auxiliary equipment of electric trains were performed based on the operating manual data. Additionally, a statistical method of data processing on the energy consumption of electric trains was applied. The operational fleet and service routes of the motor wagon depot TCh-31 Omsk and OAO "Omsk-Prigorod" of the West Siberian Railway were examined. The ED4M series electric trains were selected for analysis, as they are the most common in the TCh-31 Omsk depot. The auxiliary equipment of ED4M electric trains was investigated, and the nominal power values of units and devices providing auxiliary needs for the motor wagon rolling stock were determined. Key performance indicators of the motor wagon rolling stock were obtained on different operating sections under varying ambient temperatures, based on data from the motion and control parameter recording systems (RPDA-E). This allows for the identification of the most optimal parameters for the electric energy storage system. The developed method will enable potential manufacturers of energy storage systems to define their essential parameters, as well as assess the feasibility of their application on specific electric trains and operating sections. In summary, for the example considered in this article, it is noteworthy that the energy storage system operates in brief intervals. The average duration of the charging mode is 60 seconds, and the returned energy volume by the motor wagon rolling stock, determining the energy capacity, averages 28 kWh at a maximum power of 0.8 MW. Based on these values, it can be concluded that the recuperation energy volume and, consequently, the energy capacity of the storage system are insufficient to cover the electric energy consumption of the electric train in traction mode. Therefore, the storage system, including its use for reducing peak loads during traction mode, can be considered. It is important to note that, for providing uninterrupted power supply to the electric train's own needs throughout the entire journey, the returned electrical energy volume during regenerative braking is also insufficient. This necessitates exploring the charging of the energy storage system at the departure station or during motion from the converter of own needs at times of minimal loading.

Keywords: electric train, energy storage, needs of an electric train, heating and air conditioning, lighting systems, auxiliary electric machines, static converters

1 INTRODUCTION

Nowadays, suburban passenger transportation is an important social task of subsidiaries of Russian Railways JSC. However, this type of transportation is unprofitable (even on the verge of breaking), except for those in Moscow and Saint Petersburg. This fact pushes companies to search for and implement various measures and technical solutions to improve the efficiency of suburban communication.

A considerable share of electricity consumed by the company falls on train traction, which is why the priority task of the energy strategy of the Russian Railways holding for the period up to 2020 and for the future up to 2030 is a significant increase in the energy efficiency of train traction [1]. Therefore, this issue is one of the most urgent for suburban transport, where one can reduce costs.

Various energy storage systems may solve this problem [2–5]. According to preliminary estimates, the introduction of such systems will allow using excess recovery energy to power the needs of an electric train (heating, ventilation, etc.), which will reduce electricity consumption and other costs associated with additional training of locomotive crews in rational train driving modes, as well as maintenance and repair of motor-car rolling stock.

There are many different energy storage systems. However, since the motor-car rolling stock accelerates and slows down a significant number of times per trip, the frequency of charge-discharge cycles will significantly reduce the service life of lead-acid batteries. To a large extent, this negative factor is reduced for hybrid energy storage systems, which, for example, include both rechargeable batteries and supercapacitors.

Currently, the cost of storage systems is quite high, so choosing certain parameters of an energy storage device is one of the most important tasks, affecting the final cost, efficiency, and payback of this device.

Motor-car rolling stock is operated in various conditions (track profile, temperature, mass, etc.). Therefore, it is impossible to solve the problem of installing an energy storage device on an electric train to use it for powering their own needs using standard offers from manufacturers of storage systems. One can correctly choose the energy storage parameters only by conducting experimental studies in the operation of electric trains. Based on the assessment of the traction load, the parameters of the auxiliary equipment, and operational factors, it is possible to draw an unambiguous conclusion about the use of certain accumulation systems on motor-car rolling stock.

The sites and series of DC electric trains of the TCH-31 Omsk motor car depot of the West Siberian Railway (ZSZHD) and Omsk-Prigorod JSC acted as a testing ground for experimental research.

The parameters of the sections of operation of electric trains are presented in Table 1.

Table 1. Parameters of the operation areas of the TCH-31 Omsk motor car depot and Omsk-Prigorod JSC

Sites	Parameters of the operation site
Irtyshskoe – Omsk	169 km long; flat track profile with slopes of no more than 2%–3‰ steepness; the section is almost straight with a small number of curves of a large radius (one of the longest straight sections on the railway network of Russia)
Nazyvaevskaya – Omsk	149 km long; the entire length of the haul is mainly dominated by the flat track profile of the path with limiting ascents up to 5 ‰
Tatarskaya – Omsk	150 km long; flat track profile with limiting ascents up to 5 ‰
Isilkul – Omsk	138 km long; flat track profile with limiting ascents up to 3%–5‰

The most extensive and flat section is the Irtyskoye–Omsk segment, featuring gradients of up to 3 ‰, while the remaining sections include challenging ascents with slopes reaching up to 5 ‰.

The inventory fleet of the depot and Omskprigorod JSC is shown in Fig. 1 and Fig. 2.

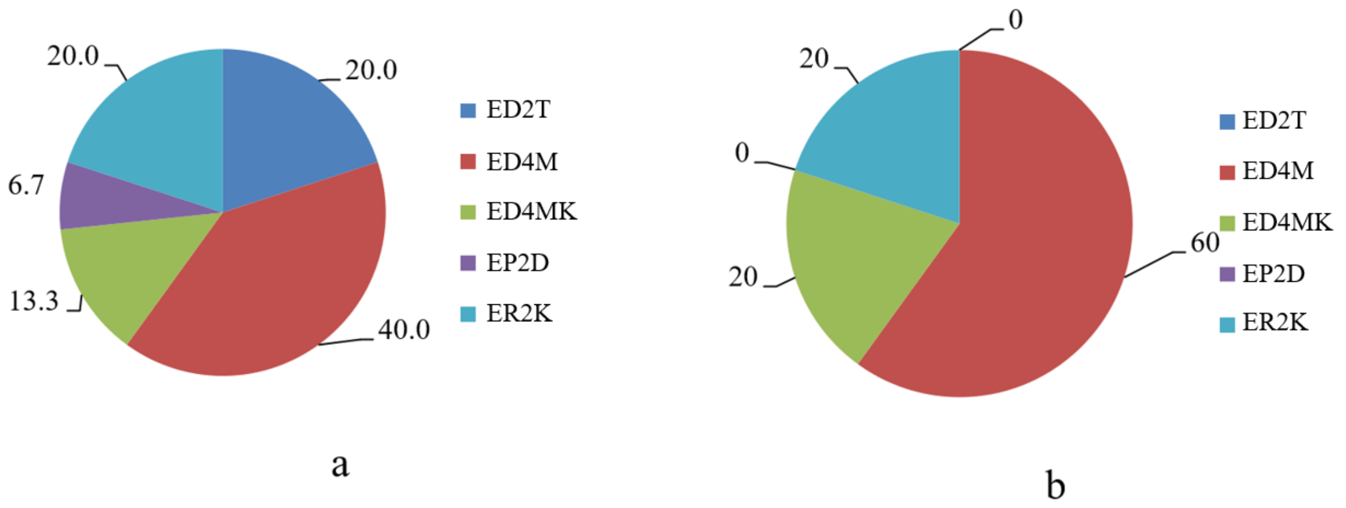

Fig. 1. The share of the electric train series in the TCH-31 Omsk motor car depot (a) and Omsk-Prigorod JSC (b)

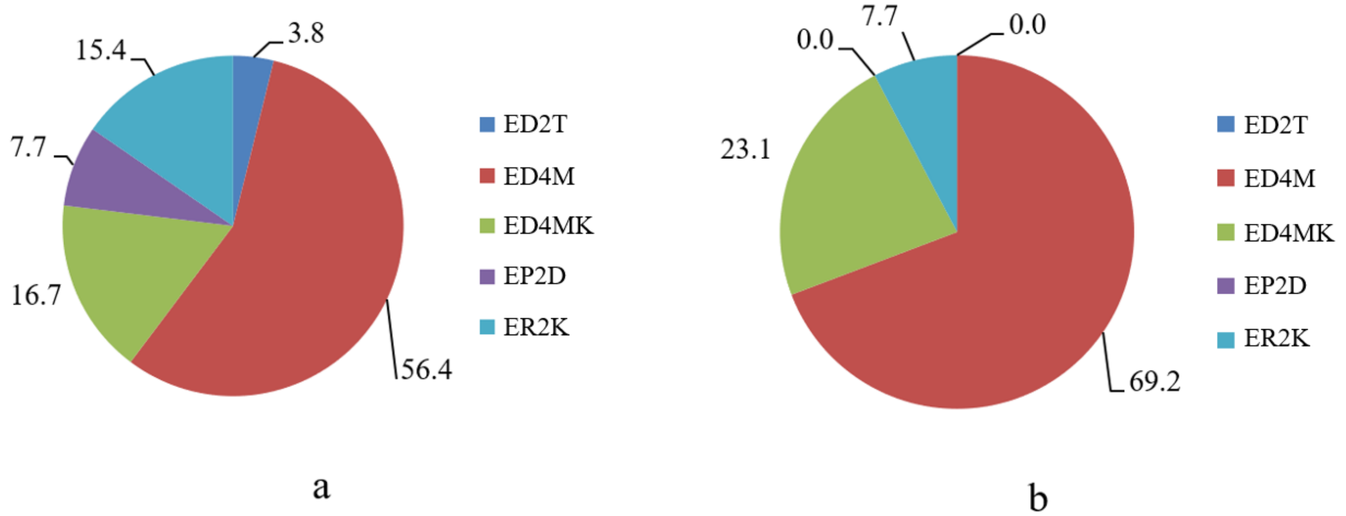

Fig. 2. The share of cars of the electric train series in the TCH-31 Omsk motor car depot (a) and Omsk-Prigorod JSC (b)

The analysis of Fig. 1 and Fig. 2 shows that the most common series of electric trains in the TCH-31 Omsk motor car depot and Omsk-Prigorod JSC is the ED4M series and its modification ED4MK (differ from ED4M by a more comfortable layout of cars). In this regard, this series of electric trains should be considered in more detail during experimental studies.

2 MATERIALS AND METHODS

The objective of this study is to determine the parameters of an electric energy storage system to potentially ensure uninterrupted power supply for the proprietary needs of electric trains.

To achieve this goal, it is necessary to conduct experimental trips of electric trains to determine energy consumption during journeys on operational sections at different ambient temperatures. Subsequently, statistical processing of these results should be performed.

For evaluating the electricity consumption indicators for the proprietary needs of ED4M series electric trains, three methods can be employed: conducting simulation modeling (as demonstrated in works [6 – 12]), performing analytical power calculations for the auxiliary equipment of electric trains based on the operating manuals, and conducting statistical processing of data on the energy consumption of electric trains.

Within the scope of this publication, the second and third methods will be utilized, as the depot possesses operating manuals for electric trains and data on energy consumption, energy recuperation, and proprietary needs during journeys.

Information obtained from a series of trips of ED4M series electric trains from the depot allows the presentation of measurements of energy consumption for traction (heating, auxiliary needs, and recuperation) in the coordinates of section – temperature (month, speed) and the assessment of their changing patterns.

The suitability of the approximations can be evaluated based on the following main criteria [13–15]:

Sum of squared errors (SSE), determined by Formula 1:

$$SSE = \sum_{k=1}^{n}(y_k - \hat{y}_k)^2 \qquad (1)$$

where y_k represents the observed value in x_k;

$\hat{y}_k$ represents the predicted value in x_k.

denotes the squared mixed correlation (*R^2*) Formula 2:

$$R^2 = 1 - \frac{SSE}{SST} \qquad (2)$$

where SST is the total sum of squares, determined by Formula 3:

$$SST = \sum_{k=1}^{n}(y_k - \bar{y})^2 \qquad (3)$$

where $\bar{y}$ represents the mean value of variable y;

denotes the adjusted value of the squared mixed correlation (*Adj R^2*) Formula 4:

$$AdjR^2 = 1 - \frac{SSE(n-1)}{SST(n-m)} \qquad (4)$$

where n is the number of data points;

m is the number of model parameters x_k.

represents the root-mean-square error of estimation (*RSME*) Formula 5:

$$RSME = \sqrt{\frac{SSE}{n-m}} \qquad (5)$$

As an approximation method, we will employ the locally weighted regression method, which is utilized for approximating non-linear relationships between variables [16,17]. This method is non-parametric and well-suited for fitting a smooth surface among the results.

3 RESULTS

We will assess the nominal power of the auxiliary equipment of the ED4M electric train based on the operating manuals of electric trains, aiming to determine the maximum energy capacity of the energy storage system.

According to scholars [18], the main consumers of electricity for the needs of electric trains are heating and air conditioning systems (Table 2), lighting systems (Table 3), as well as auxiliary electrical machines and control circuits (Table 4).

Table 2. Information on the climatic equipment of cars of electric trains of the TCH-31 Omsk motor car depot and Omsk-Prigorod JSC

Series	Number	Driver's cab			Interior of the car		
		Type of microclimate system	Nominal power, kW	Quantity, pcs	Type of microclimate system	Nominal power, kW	Quantity, pcs
ER2K	1171, 1193, 1194	-	-	-	Furnace and calorifer heating	Calorifer (24.8); furnaces G (9.8) M (16) P (12.8)	14
ED4M	0049, 0079, 0132	Furnace and calorifer heating	-	6	Furnace and calorifer heating	Calorifer (24.8); furnaces G (9.8) M (16) P (12.8)	25
	0195, 0196	UKV-4,5-ED	4.5	4	VVEK-3000/628-30	26	14
	0244, 0309	UKV-4,5-ED	4.5	4	AMVO VE	24	14
	0342	UKV-4,5-ED	4.5	2	OVPU-2500-3000	13.6-37.8	6
	0494	SOK VE-10-01	11.4	2	SOK VE-10-01		8
ED4MK	0072, 0152	Furnace and calorifer heating		4	Furnace and calorifer heating	Calorifer (24.8); furnaces G (9.8) M (16) P (12.8)	12
EP2D	0188	SOK VE-10-01	11.4	2	SOM	24	6

Table 2 shows that the most common variant of the climate control system for electric trains of the ED4M series and their ED4MK modifications is the heating-ventilation supply unit OVPU 2500-3000/628-25, which includes a high-voltage EQ 3000/628-25 electrocalorifer with a capacity of 13.6–37.8 kW, and an AMVO VE monoblock ventilation-heating unit, which includes a VVNBE-3000/628 or EQV 3000/628 high-voltage electrocalorifier with a capacity of 24 kW [11].

Table 3. Lighting systems of electric trains of the TCH-31 Omsk motor car depot and Omsk-Prigorod JSC

Purpose of lamps	Type of lamps	Voltage, V	Power, W	Quantity, pcs
ED4M (0049, 0079, 0132, 0195, 0196, 0244, 0309, 0342) and ED4MK (0072, 0152)				
General interior lighting	SLV 20/32-735	220	20	G-11 M-16 P-16
General lighting of the driver's cabin	B230-240-60-1	230–240	60	4
General lighting, lighting of vestibules and toilets	B220-230-100-5	220–230	100	G-5 M-4 P-4
After-hours lighting; lighting of attics, cupboards, and wagon boxes; signal lamps in cabinets; lighting designed	PH110-15	110	15	G-11 M-11 P-11

Purpose of lamps	Type of lamps	Voltage, V	Power, W	Quantity, pcs
ED4M (0049, 0079, 0132, 0195, 0196, 0244, 0309, 0342) and ED4MK (0072, 0152)				
to control the boarding and - departure of passengers				
Headlight	KGM 110-600	110	600	2
Green light fixtures	PH604,8 (TS 60-10)	60 (60)	4.8 (10)	2
Signal lights, signal buffer lights	S110-60 (S110-60-01)	110	60	4
Lighting of the service vestibule	S110-60	110	60	4
ED4M (0494) and EP2D (0188)				
General interior lighting	Light line SL-072	220	880	2
After-hours interior lighting	Light line SL-072	110	60	2

According to Table 2, the main electricity consumption for lighting on most electric trains of the ED4M series and its ED4MK modifications is accounted for by fluorescent lamps of the SLV 20/32-735 type in the interior of cars of later releases and SL-072 light lines in the interior of cars of earlier releases with a total capacity of no more than 2 kW.

Table 4. Auxiliary electrical machines and converters

Purpose of the electric machine and converter	Type of electric machine	Voltage, V	Power, kW	Quantity, pcs
ED4M (0049, 0079, 0132, 0195, 0196, 0244, 0309, 0342, 0494) and ED4MK (0072, 0152)				
Providing power for the needs of an electric train	NVP-44/38 electric machine converter	3,000	44	G-1 P-1
Drive of the main EC 7V M6 electric air compressor	Asynchronous motor with a MAK 160 short-circuited rotor	220/380	5	G-1 P-1
Compressor drive for lifting the collector bow	P-31M DC motor	110	0.75	G-1 M-1
Cleaning the front windows of the driver’s cab	Motoreductor	24	0.011	G-2
EP2D (0188)				
Providing power to the control circuits, lighting, battery charge, excitation winding circuits of traction motors during braking	PSN 110 U1 static converter	220	40	G-1 P-1
Providing power to climate installations	PSN 110 U1 static converter	380	70	G-1 P-1

Based on Table 4, one can conclude that electric machine converters NVP-44/38 with a power of 44 kW are used on electric trains of the ED4M series and its ED4MK modifications. Static converters PSN 110 U1 with an output power of 110 kW are used on more modern EP2D series to supply all components of their own needs. In electric trains of the ED4M series, the electric machine converter does not provide power to microclimate systems since these systems are directly powered by the contact network with a voltage of 3,000 V.

Based on the analysis of Tables 2–4, it can be concluded that the maximum hourly power for heating systems, auxiliary electrical machines, and control circuits is 83.8 kW per carriage.

For a more precise determination of the energy storage system parameters to potentially ensure uninterrupted power supply for the proprietary needs of the electric train, we will utilize the data from experimental trips conducted by crews on operational sections of the TCh-31 depot in both forward and reverse directions, considering various outside temperatures.

The average ambient air temperature during trips on four operational sections is presented in Figure 3. The experimental trips were conducted throughout the year, reflecting temperature variations from +30°C to -30°C characteristic of the geographical location of the TCh-31 Omsk depot. The figure clearly illustrates the temperature differences in the ambient air during the experimental trips, allowing us to account for this crucial influencing factor.

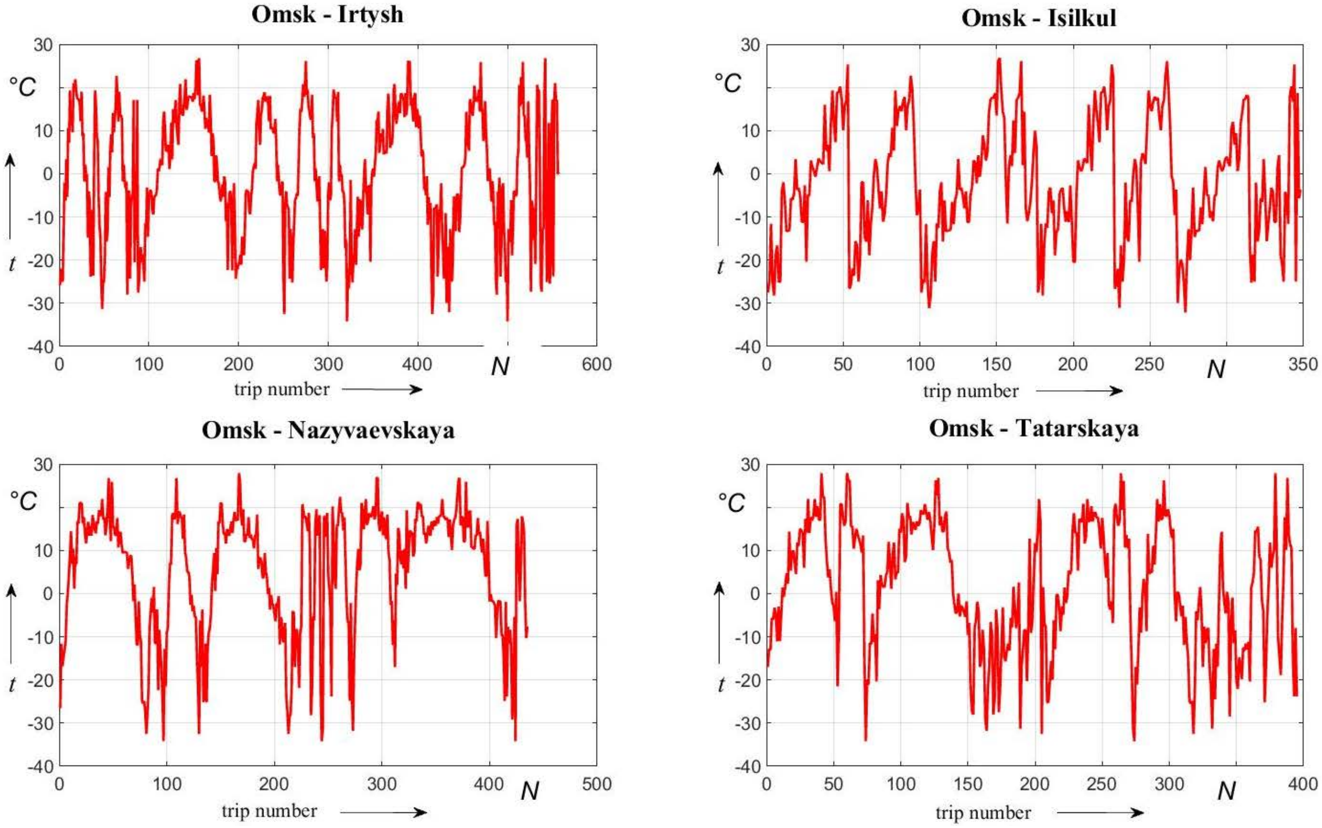

Fig. 3. Average ambient temperature during experimental trips

To conduct the statistical analysis and visually present the trip results, we will use the Matlab program, specifically the Curve Fitting Toolbox. This toolbox allows for curve and surface fitting to the data, considering the regression analysis conducted.

The results of the analysis of electricity consumption for heating and auxiliary machines with control circuits on operational sections with different numbers of motor cars are depicted in Figures 4–6. On the X-axis, the direction of the electric train's movement on the selected operational sections is represented, while the Y-axis displays the recorded ambient temperature during the trip. The Z-axis illustrates the electricity consumption based on the trip results.

Thus, one can see that the electricity consumption for heating in winter can exceed the consumption for auxiliary machines and control circuits by 4–6 times; it varies from 0 to 150 kWh in summer and from 150 to 1,000 kWh in winter.

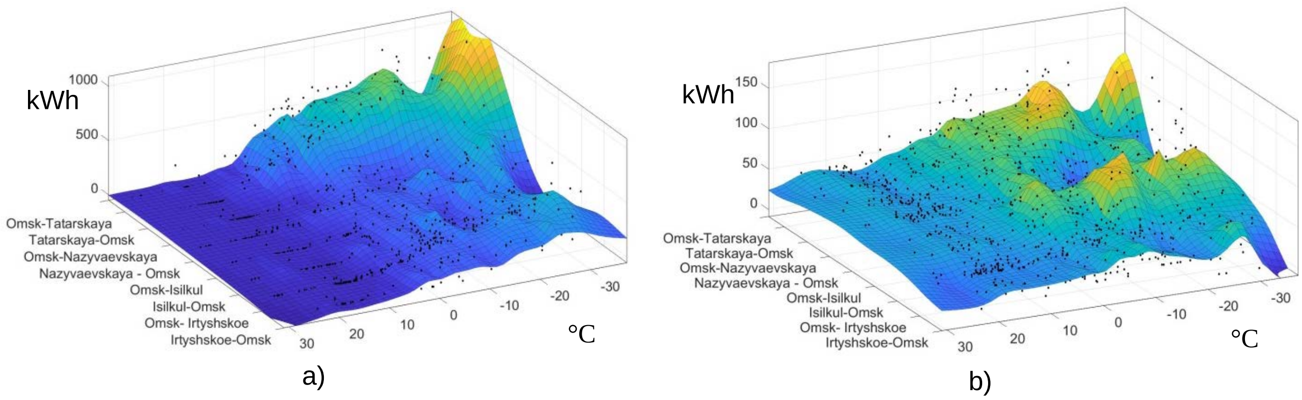

Fig. 4. Dependency of the electricity consumption of the ED4M electric train for heating (a) and auxiliary machines and control circuits (b) in a three-car configuration based on the operational section and the ambient temperature.

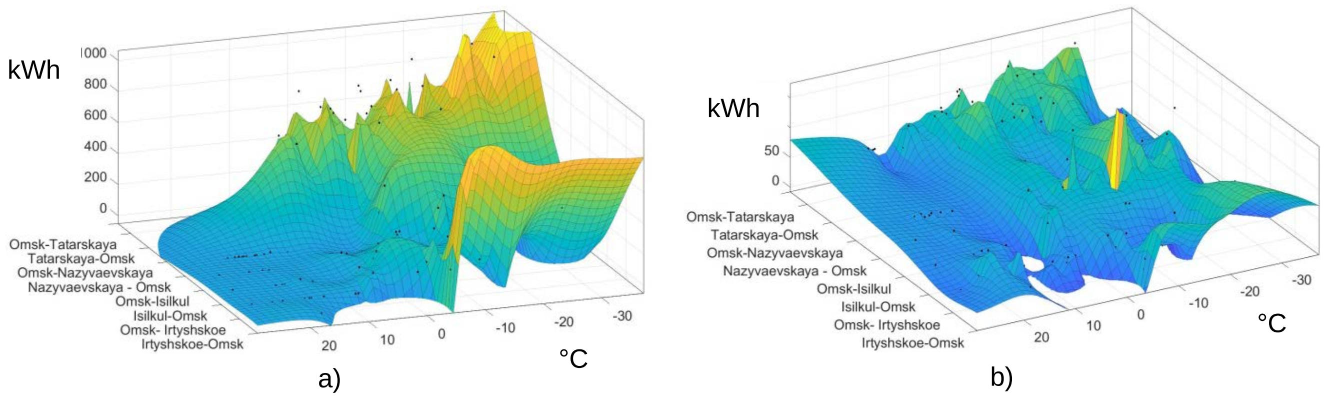

Fig. 5. Dependency of the electricity consumption of the ED4M electric train for heating (a) and auxiliary machines and control circuits (b) in a four-car configuration based on the operational section and the ambient temperature.

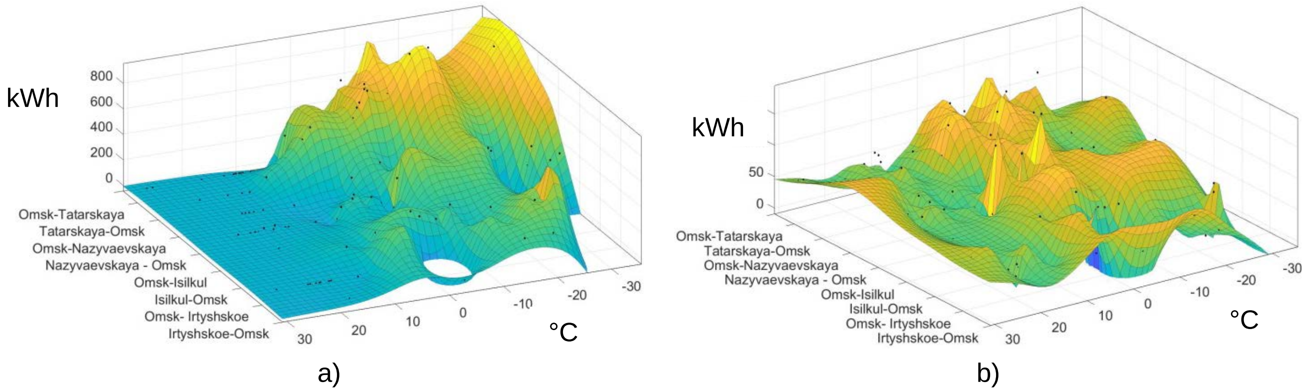

Fig. 6. Dependency of the electricity consumption of the ED4M electric train for heating (a) and auxiliary machines and control circuits (b) in a five-car configuration based on the operational section and the ambient temperature.

This approach enables the evaluation of a key parameter of the energy storage system - energy capacity (maximum, average, and minimum values), contingent on the operational section and ambient temperature. This parameter is critical for ensuring uninterrupted power supply for the proprietary needs of the electric train.

However, the optimal value for energy capacity and other parameters (nominal power, overload capacity, charging and discharging time, depth of discharge, operational lifespan, and capital costs) of energy storage systems, vital for their further production, can only be determined through a detailed analysis of each trip. The consumption pattern and magnitude of electricity for the electric train's proprietary needs significantly depend on factors such as the track profile (flat or hilly), operational behavior of the electric train, and so forth.

To obtain more detailed characteristics of the energy storage system, it is necessary to utilize information stored in the "black boxes" manufactured by the AVP "Technology" company, which are installed on the ED4M electric trains. Let's examine a fragment of the recording from the "black boxes" of the ED4M electric train, using one trip as an example (see Fig. 7).

In Zone 1 of Figure 7, the values of the current consumed by the motor cars of the electric train are indicated, providing more detailed insights into the characteristics of the traction mode, regenerative braking, or minimal load (coasting, waiting for operation, or pneumatic braking).

During 11 minutes of the electric train's operation (Figure 7, Zone 1), the highest current value in traction mode reaches 360 A, while the lowest occurs in regenerative braking at -240 A. The voltage level at the pantograph of the electric train does not exceed 3750 V, with the minimum voltage level being 3200 V. Three instances of traction mode were recorded with energy consumption of 29.1 kWh, 58.2 kWh, and 116.4 kWh. The regenerative braking was applied twice, returning 28.6 kWh and 28.2 kWh of electrical energy.

Fig. 7. The window of the RPDA-E cartridge

Overall, for this segment, it is noteworthy that the operation modes of the energy storage system are of a short-term nature. The average duration of operation in charging mode is 60 seconds, and the volume of energy returned by the motor wagon rolling stock, determining the energy capacity, averages 28 kWh at a maximum power of 0.8 MW.

Based on the provided values, it can be concluded that the volume of recuperation energy, and consequently, the energy capacity of the storage system, is insufficient to cover the electric train's energy consumption in traction mode. Therefore, the storage system, including its use to reduce peak loads during traction mode, can be considered.

In the mode of minimum load (heating, auxiliary machines, and control circuits), the electric train operated five times with an energy consumption volume of 5 kWh. The highest current value for proprietary needs reached 40 A, and the voltage level at the pantograph of the electric train did not exceed 3750 V, with the minimum voltage level being 3613 V.

Decoding the "black boxes" reveals that the currents consumed by the heaters for heating have varying values and an uneven pattern. This variation may indicate differing thermal insulation properties of the electric train cars.

It is worth noting that, even for ensuring uninterrupted power supply for the proprietary needs of the electric train throughout the entire trip, the volume of electrical energy returned during regenerative braking is insufficient. This necessitates consideration of the issue of charging the energy storage system at the departure station or during motion from the converter for proprietary needs at a time when it is least loaded.

4 CONCLUSIONS

Thus, the method for determining the main parameters of an energy storage device to ensure uninterrupted power supply for auxiliary needs of an electric train based on data from cartridges of motion and auto-driving parameter registration systems (RPDA-E) manufactured by AVP Tekhnologiya can be used for further research. Based on the assessment of the traction load, the parameters of the auxiliary equipment, and operational factors, one can draw an unambiguous conclusion about the use of certain accumulation systems on motor-car rolling stock.

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