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Unification of Onboard Traction Energy Storage Devices for Railway Rolling Stock

Mikhail V. YAROSLAVTSEV

Mikhail V. Yaroslavtsev
Toraighyrov University, Pavlodar, Republic of Kazakhstan.
ORCID 0000-0002-1440-2065; SCOPUS Author ID 56532450300; Russian Science Citation Index SPIN-code 3977-8959.
✉ *myaroslavtsev@yandex.ru.*

ABSTRACT

As the cost of traction lithium batteries decreases, many rolling stock models are being created that use them to receive recovery energy, equalise the load on the energy source, and ensure autonomous operation. The objective of the work is to show the advantages of separate design and production of onboard traction storage devices and the rolling stock using them, which will require standardisation of energy storage devices, as well as to outline the range of requirements that will need to be set when developing a standard, and to illustrate proposals by identifying possible requirements for weight, size and energy characteristics of a unified energy storage device. For this purpose, a review of approaches to the use of energy storage devices and modern designs of rolling stock on which traction batteries are used is followed by main scenarios for the use there-of.

Following identification of main processes of energy conversion by the traction drive of locomotives at various time intervals, the parameters of energy storage devices were assessed for a wide range of possible scenarios for their application using methods of traction theory.

The results obtained allowed calculating main characteristics of unified energy storage modules. A specific analysis was carried out to identify the limitations that determine energy intensity and power, weight, dimensions and method of mounting of storage devices, their rated voltage. Requirements are formulated for design of a standard mechanical, electrical and information interface of the proposed modules.

Keywords: *railways, traction energy storage device, lithium-ion battery, standardisation, interchangeability, energy saving.*

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INTRODUCTION

A rapid introduction of traction energy storage devices (TESD) intended for railway rolling stock has manifested since the beginning of the 2020s [1; 2]. Catenary-battery electric trains with a range of up to 100–200 km have been operated in the UK, Germany, Denmark, Japan and are planned for delivery to the USA, Latvia and other countries [1, 2, 3, 4]. In 2021, first battery electric locomotive with a storage unit of a capacity of 2,4 MWh, designed for coordinated operation together with mainline diesel locomotives, was tested in the USA [5]. EMD Joule offers similar battery electric locomotives with storage capacity from 4 to 14,5 MWh with a power output of 1500–5700 kW [6], which are being tested in the USA and Brazil, and Wabtec offers battery electric locomotives of capacity from 1,1 to 8,5 MWh with power output up to 5000 kW [7]. In China, a battery electric locomotive ordered by Thailand with a range of up to 200 km [8], a mainline electric locomotive with a storage capacity of 0,2 MWh for shunting operations and a catenary-battery shunting locomotive with a capacity of 0,35 MWh ordered by Hungary have been built [9]. Several other electric locomotives with battery-powered last-mile capability are being developed [10]. In Russia, in recent years, hybrid and catenary-battery shunting locomotives of TEM35, TEM5Kh, TEM9N, EMKA2 series have been developed [11].

The active development of new types of locomotives has become possible following improvement of lithium-based batteries, which have a high specific energy and high specific power, as well as of electric double layer capacitors (EDLC). Their typical parameters according to data from [3] and from manufacturers [12] are described in Table 1. The scope of application of traction lithium batteries is regularly expanding as their price decreases. Thus, according to various estimates by Bloomberg, by 2030 the price of batteries will decrease by 1,5–3 times compared to 2023 [13].

Technical and economic calculations carried out by Stadler in 2021 showed that the use of battery electric trains on non-electrified lines can be more profitable than diesel trains, even

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[1] Stadler Flirt Akku. [Electronic resource]: https://www.stadlerrail.com/en/flirt-akku/details/. Last accessed 22.05.2023.

[2] Alstom presents its battery-powered multiple unit train in Saxony [Electronic resource]: https://www.alstom.com/sites/alstom.com/files/2021/09/07/20210907_PR_DACH_Saxony_BEMU_Demo_EN.pdf. Last accessed 22.05.2023.

[3] 新たな「蓄電池電車」を男鹿線に導入します [A new battery train will appear on the Oga line] [Electronic resource]: https://www.jreast.co.jp/akita/press/pdf/20151120–1.pdf. Last accessed 22.05.2023.

[4] Metro class 777 IPEMU. [Electronic resource]: https://www.stadlerrail.com/media/pdf/mmer_ipemu0922e.pdf. Last accessed 22.05.2023.

[5] BNSF Battery Electric Locomotive Report. [Electronic resource]: https://ww2.arb.ca.gov/sites/default/files/2022–11/zanzeff-bnsf-belreport.pdf. Last accessed 22.05.2023.

[6] EMD Joule battery-electric locomotive. [Electronic resource]: https://s7d2.scene7.com/is/content/Caterpillar/CM20220627–26f7e-6007b. Last accessed 22.05.2023.

[7] Battery electric locomotive technology FLXdrive. [Electronic resource]: https://www.wabteccorp.com/FLXdrive-Battery-Electric-Locomotive?inline. Last accessed 22.05.2023.

[8] CRRC Dalian delivers battery locomotive to Thailand. [Electronic resource]: https://www.railjournal.com/technology/crrc-dalian-delivers-battery-locomotive-to-thailand/. . Last accessed 22.05.2023.

[9] CRRC Locomotives in Europe. [Electronic resource]: https://crrczelc-europe.com/locomotives-in-europe/#norebro-custom-646cada43b9861. Last accessed 22.05.2023.

[10] Traction: Going the last mile. [Electronic resource]: https://www.railwaygazette.com/in-depth/traction-going-the-last-mile/59444.article. Last accessed 22.05.2023.
Traxx locomotive with zero-emission last mile operational in 2025. [Electronic resource]: https://www.railtech.com/rolling-stock/2022/09/20/traxx-locomotive-with-zero-emission-last-mile-operational-in-2025/. Last accessed 22.05.2023.

[11] Seleznev, I. L., Shafrygin, A. V., Chekmarev, A. E., Khokhryakov, V. A., Vanin, I. V. Meet: TEM5Kh – the concept of a new hybrid locomotive [*Znakomtes: TEM5Kh – kontsept novogo gibridnogo lokomotiva*]. *Lokomotiv*, 2019, Iss. 12, pp. 30–32.
Kuznetsov, L. V. Sinara locomotives follow the course of the Environmental Strategy [*Lokomotivy «Sinary» sleduyut kursom Ekologicheskoi strategii*]. *Lokomotiv*, 2021. – № 11. – С. 2–3.
Electric locomotive EMKA2. [Electronic resource]: https://eec.eaeunion.org/comission/department/dotp/klimaticheskaya-povestka/bank/118091/. Last accessed 22.05.2023.

[12] Winston battery. [Electronic resource]: http://en.winston-battery.com/index.php/products/power-battery. Last accessed 22.05.2023.
SCiB rechargeable battery – Toshiba. [Electronic resource]: https://www.global.toshiba/ww/products-solutions/battery/scib/product/cell.html. Last accessed 22.05.2023.
Ultracapacitor overview – Maxwell Technologies. [Electronic resource]: https://maxwell.com/products/ultracapacitors/. Last accessed 22.05.2023.

[13] Goldie-Scot, L. A Behind the Scenes Take on Lithium-ion Battery Prices – Bloomberg NEF. [Electronic resource]: https://about.bnef.com/blog/ behind-scenes-take-lithium-ion-battery-prices/. Last accessed 22.05.2023.
Bullard N. Even High Battery Prices Can't Chill the Hot Energy Storage Sector – Bloomberg NEF. [Electronic resource]: https://www.bloomberg.com/news/articles/2023–01–12/even-high-battery-prices-can-t-chill-the-hot-energy-storage-sector. Last accessed 22.05.2023.

Table 1

Technical and economic characteristics of energy storage devices [performed by the author based on data [3][9,12]]

Type of ESD	$LiFePO_4$	$Li_4Ti_5O_{12}$	EDLC
Specific energy, Wh/kg	125	90	6
Specific discharge power, W/kg	250–350	1800	not limited for traction storage devices
Specific charge power, W/kg	120	1800	
Density of elements, t/m ^{3}	1,6	2,0	1,0
Specific cost, $/kWh	120–150	200–250	5000–10 000
The number of charge-discharge cycles	3000	up to 20 000	$1\cdot10^6$–$10\cdot10^6$

without considering energy savings from regenerative braking[14].

In the coming years, we can expect development of new series of locomotives equipped with traction energy storage devices for the 1520 mm gauge network. There are many possible scenarios for using TESD on rolling stock [4–11]. A description of the tasks they solve is given below when assessing energy density and power.

Although areas of application differ in the requirements for power and energy density of storage devices, which determines their weight and dimensions, as well as for the service life of the TESD, the operating conditions of traction lithium batteries are similar regardless of their purpose. Currently, energy storage devices, as a rule, are designed individually for each series of rolling stock. But as the scope of their application expands, the unification of energy storage devices becomes relevant.

The development and production of a number of standard sizes of unified modular storage devices for traction rolling stock (TRS) will create the prerequisites for a more dynamic and efficient development of new types of traction. This solution will allow:

1. To increase the reproducibility and repeatability of technical solutions used in production of series of energy storage devices, which will stabilise their quality and reduce costs.
2. To separate the tasks of designing a locomotive and an energy storage device, which will speed up their development and allow expanding the range of production.
3. To create the opportunity to choose between different types of storage devices on one type of rolling stock.
4. To increase the dependability of operation of rolling stock with energy storage devices due to the ease of their replacement.
5. To obtain a possibility of stationary charging of modules with their exchange at turnover points, if this is justified by operating conditions.
6. To be able to exchange storage devices with different degrees of battery degradation between locomotives operating within the sections of different lengths of battery-powered running and ruling gradient. This will make it possible to extend the service life of energy storage modules beyond the nominal number of charge-discharge cycles under conditions that do not require the implementation of their full capacity.

Standardisation of energy storage devices corresponds to the modern trend towards increasing the modularity of locomotive designs, implemented, for example, in TEM9, TEM23, TEM33 series of diesel locomotives and by some manufacturers of vehicles for modes of transport other than rail[15].

The data presented allow us to conclude on the relevance of the further task of developing new series of TRS using traction energy storage devices. Therefore, *the objective* of the work is to analyse the characteristics and conditions of operation of energy storage devices, to show the feasibility of standardising traction energy storage devices for different types of TRS and for different purposes of their use, and to propose criteria for normalising the parameters of energy storage modules.

To show possible features of energy storage modules for various series of TRS and different

[14] Stadler manifests market leadership in alternative drive technologies: DB Regio orders more battery-operated trains. [Electronic resource]: https://www.stadlerrail.com/en/media/article/stadler-manifests-market-leadership-in-alternative-drive-technologies-db-regio-orders-more-battery-operated-trains/1080/. Last accessed 22.05.2023.

[15] NIO's battery swap network open to other brands. [Electronic resource]: https://cnevpost.com/2023/04/02/nio-battery-swap-network-open-to-other-brands-like-cloud-service-william-li/. Last accessed 22.05.2023.

areas of application, the study has assessed their specific characteristics and considered the limitations of their design according to the conditions of their operation. The *methodology* of the study is described together with the results obtained.

RESULTS

Estimation of Power and Capacity of Onboard Traction Energy Storage Devices

Determining the mass and dimensions of a battery-type energy storage device requires finding its two main parameters which are capacity and power. Their exact calculation for given conditions is a complex task that requires development of parameters for promising locomotives and analysis of their operating modes. Installing powerful energy storage devices on existing series of locomotives is, as a rule, impossible, since this would require significant changes in the equipment layout, traction converter circuits, control systems, body ventilation systems, etc.

It is important to note that to find the values of power and capacity of the energy storage device, it is not enough to know the time distribution of the power consumed by the traction drive. It is necessary to predict the largest and smallest energy reserves of the energy storage device during the voyage, for which it is necessary to establish the dependence of the power of the traction electric drive on time using traction calculations or from records of motion parameter recorders. Although a complete solution of such a problem for a wide range of situations within the framework of a single study is impossible, for the purposes of the article an approximate calculation is offered that allows us to estimate the capacity of onboard energy storage devices under the typical scenarios of their use described below.

In case of *reuse of regenerated braking energy* when stopping at a station, the capacity of the energy storage device is determined primarily by the kinetic energy of train movement. In this situation, the losses to overcome resistance to movement are small in relation to the kinetic energy (1)[16]:

$$E = k\frac{mV^2}{2}\,. \qquad (1)$$

[16] The designations used in expressions (1)–(5) are explained after the expression (5).

It is accepted that the power of the energy storage device must ensure implementation of the full power of traction motors.

When *levelling out the unevenness of the traction load* caused by the alternation of modes due to the characteristics of the track profile as well as to the imposed speed limitations, the capacity is estimated by the power of the locomotive and duration of maintaining a given mode (2):

$$E = kPt\,. \qquad (2)$$

As an analysis of the graphs of modes used shows, for locomotives it is typical to alternate positions of control unit at least every 30 minutes. It is typical that electric and diesel trains (motor driven rolling stock (MDRS)) periodically change power consumption which is caused by stops for boarding passengers. In the calculation, it is assumed that the time they travel from station to station does not exceed, as a rule, 15 minutes.

When travelling for *longer distances* power consumption depends primarily on average values of main and additional resistance to movement.

Requirements for TESD *during shunting movements, as well as when overcoming the «last mile»* while approaching the loading site, capacity was evaluated for a travel range of 10 km with an equivalent slope of 5 ‰ according to the expression (3):

$$E = kmL(w + ig)\,. \qquad (3)$$

Movement using only energy storage device along a section of 100 km and 300 km. Capacity of TESD is also determined according to the expression (3). In both cases, it is assumed that the elevation difference on the site is 500 m, which is considered when setting the equivalent slope. For the latter tasks, during the evaluation calculation it is permissible to neglect energy losses caused by speed fluctuations and by braking.

Since TESD can be installed on various types of TRS, the calculation of their characteristics is carried out in specific form, per 1000 kW of locomotive hourly power. To move from specific values to absolute ones, it is necessary to increase them in proportion to the power of the locomotive when determining capacity according to (2) or in proportion to the mass of the train for expressions (1) and (3). However, since at equal coefficient of adhesion and running speed the traction force of a locomotive is proportional to its power, the mass of the train can also be approximately considered proportional to power.

The calculated values of travel speed, slope and length of sections were chosen to ensure the possibility of operating the energy storage devices over the most part of the network. The mass of the train per 1 MW hourly power of the locomotive with an axle load of 25 tons is accepted as corresponding to the critical norm for sections with a ruling gradient of 5 ‰.

When choosing the type of energy storage devices, it is important to consider their service life. As studies of battery durability show [12; 13], the amount of energy that a lithium battery can absorb during its service life weakly (within 20 %) depends on the depth of discharge. When receiving electrical energy from the circuit, the only type of battery for which the cost of received energy exceeds the cost of receiving it from the circuit are lithium titanate batteries [14]. Another advantage is their high power, which in some cases makes it possible to significantly reduce the mass of the energy storage device and make it expedient to use it on rolling stock, despite the higher specific cost compared to lithium iron phosphate (lithium ferrophosphate) batteries. It was for this type that the calculations included an assessment of the mass and dimensions of energy storage devices.

The mass and volume of energy storage devices are determined by their specific characteristics given in Table 1 in accordance with (4, 5):

$$m_{ES} = k_m \max\left(\frac{E}{E_S}, \frac{P}{P_S}\right), \quad (4)$$

$$V_{ES} = \frac{k_V}{\rho} \max\left(\frac{E}{E_S}, \frac{P}{P_S}\right), \quad (5)$$

In expressions (1)–(5):

E – capacity of an energy storage device, kJ;

$k = 1,2$ – coefficient taking into account losses during energy conversion;

m – mass of the train moved by one section of TRS, t;

V – running speed of the train, m/s;

P – a TRS section's power, kW;

t – duration of TESD being in discharge mode, s;

w – specific resistance to train movement at speed V, N/t;

i –normalised slope at the section where locomotive is battery-driven, ‰;

g – free fall acceleration, m/s^2;

L – travel range using battery power, km.

m_{ES} – TESD mass, kg,

V_{ES} – TESD volume, m^3,

E_S – specific energy of TESD, kJ/kg,

P_S – specific power of SD, kW/kg,

$k_m = 1,5$ – ratio of the total mass of the module to the mass of the batteries,

$k_V = 2$ – ratio of the total volume of the module to the volume of the batteries,

ρ – battery density, kg/m^3.

When calculating, it was assumed that the volume of the module, taking into account the housing and battery control system, is 2 times more than the volume of the battery cells, and the mass of the module is 1,5 times greater. In all cases, the reserve for losses during electrical and electrochemical energy conversions is additionally considered, taken equal to 20 % of the capacity of the energy storage device. Resistance to motion *w* is determined according to the requirements of the Rules for Traction Calculations [17].

The calculation results are given in Table 2.

As the calculation results show, in case of using lithium-titanate batteries, for most areas of TESD application, except for receiving regenerated braking energy (requiring the least energy reserve), their parameters are determined by capacity. At the same time, for lithium iron phosphate batteries, in most cases the limiting parameter is the battery power. Based on the totality of their characteristics, it is currently advisable to use lithium titanate batteries for most applications, except for ensuring movement over long distances [14].

Since at the design stage of a new series of TRS the designer has the freedom to choose measures to increase the strength of the body and change the electrical equipment circuit, the task of incorporating TESD into the design of the locomotive seems completely solvable. The most important fundamental problem on this path seems to be ensuring the ability to maintain the power of the locomotive without exceeding the restrictions on dimensions and axle load. At the concept level, before development of the design, it can be noted that the existing series of TRS, having a common type of traction and purpose, may have a difference in power per unit mass exceeding 20 %. This supposes a possibility of reducing the weight and dimensions of equipment for installing onboard TESD of relatively small capacity with a total weight of up to 10–15 tons and a volume of up to 10 m^3. For tasks that

[17] Rules for Traction Calculations of Train Operation [Pravila tyagovykh raschetov dlya poezdnoi raboty]. Moscow, JSC Russian Railways, 2016, 515 p.

Table 2

Parameters of energy storage devices depending on the function they perform [performed by the author]

Estimation of the volume of an energy storage module with $Li_4Ti_5O_{12}$ (LTO) batteries, m^3/MW	1,3	0,6	0,5	6,2	6,2	3,1	3,1	0,7	0,5	33,7	11,2	3,1	51,9	25,3	5,9
Estimation of the mass of the LTO battery, considering the housing and support systems, t/MW	2,1	0,9	0,8	10,2	10,2	5,1	5,1	1,2	0,8	55,6	18,5	5,1	85,6	41,7	9,7
Volume of LTO batteries, m^3	0,6	0,3	0,3	3,1	3,1	1,5	1,5	0,4	0,3	16,8	5,6	1,5	26,0	12,6	2,9
Weight of LTO batteries according to power, t	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6
Weight of LTO batteries according to capacity, t	1,4	0,6	0,1	6,8	6,8	3,4	3,4	0,8	0,2	37,0	12,3	3,4	57,1	27,8	6,5
Volume of $LiFePO_4$ batteries, m^3	5,2	5,2	5,2	5,2	5,2	5,2	5,2	5,2	5,2	16,7	5,6	5,2	25,7	12,5	5,2
Weight of $LiFePO_4$ batteries according to power, t	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3	8,3
Weight of $LiFePO_4$ batteries according to capacity, t	1,0	0,4	0,1	4,9	4,9	2,4	2,4	0,6	0,2	26,7	8,9	2,4	41,1	20,0	4,7
Capacity of TESD, MJ	450	200	40	2200	2200	1100	1100	250	75	12000	4000	1100	18500	9000	2100
TESD power, kW	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Running speed, km/h	80	120	100	80	120	100	20	40	40	80	120	100	80	120	100
Weight, t	1500	300	90	1500	300	90	1500	300	90	1500	300	90	1500	300	90
Type of rolling stock	Cargo train	Passenger train	MDRS	Cargo train	Passenger train	MDRS	Cargo train	Passenger train	MDRS	Cargo train	Passenger train	MDRS	Cargo train	Passenger train	MDRS
Main function of a storage device	Receiving braking energy before stopping			Buffering of load irregularities on the energy source			Autonomous travel over a 10 km area or shunting work			Autonomous travel over a 100 km area, elevation difference up to 500 m			Autonomous travel over a 300 km area, elevation difference up to 500 m		

require the highest capacity of TESD (battery-powered travelling over long distances, overcoming climbs in mountainous areas), it is possible to propose their placement into a specialised section of locomotive, if the current rate of specific energy and cost of TESD allows such a solution.

Basic Requirements for Energy Storage Devices

Operating conditions impose several constraints on the TESD design, which must be determined when drawing up technical specifications. These include:

1. Determining the total mass and dimensions of TESD, based on the requirements for power and capacity, as well as on ensuring operating modes and ease of use. This will allow assignment of an easy-to-use basic module size, which will be a multiple of possible storage device's types.

2. Selecting the rated voltage (range of voltages) of the module and the number of series-connected elements in it. The rated voltage of TESD is determined primarily by the convenience of their interface with the power circuits of the locomotive.

3. Selecting a charge equalisation system, since lithium batteries are damaged when overcharged. Many circuit solutions for such systems are known [15; 16], differing in the amount of energy loss and cost. There is no need to standardise them, but it may be important to consider the requirement for the ability to turn off some of the cells to control the battery voltage and improve its dependability.

4. Ensuring temperature conditions. Although modern traction batteries have a relatively wide range of operating temperatures (from –40 to +65 °C for $Li_4Ti_5O_{12}$, from –45 to +85 °C for $LiFePO_4$) [15–17], the experience of their

operation indicates the need to narrow the range to maintain high energy and power characteristics of elements. Depending on the amount of current flowing and temperature, both cooling and heating of the batteries may be required [17].

To heat the module in winter, it is necessary to introduce heating elements into its design, as well as external thermal insulation. Cooling can be provided using various coolants. The simplest solution is to use ambient air. In this case, it is advisable to provide an external system for its centralised supply.

5. Design of the TESD interface, which is further understood as a set of technical requirements that ensure mechanical, electrical and logical interfacing of replaceable modules with locomotive systems, being mentioned below.

5.1. Mechanical fastening that ensures reliable fixation of the module and the ability to quickly dismantle it.

5.2. Connection to ventilation ducts for supply and exhaust of cooling air with the possibility of closing the ducts when operating at low temperatures.

5.3. Connection to DC buses for receiving and transmitting electrical energy from the traction converter.

5.4. Providing power supply for the module's own needs when using an external power source, considering the power required to ensure its thermostating.

5.5. Connection to the information bus to provide communication with the locomotive control system.

6. Microprocessor control and diagnostic system. The control system must perform a number of functions, listed below.

6.1. Determining the charge level of the energy storage device.

6.2. Collection of diagnostic information to monitor the degree of wear of battery cells. Assessment of the energy stored within each group of elements based on the voltage across it and the amount of current passed.

6.3. Module temperature and charge equalisation control.

6.4. Module shutdown in case of overvoltage, short circuits, overheating, fire.

6.5. Communications with the locomotive control system, as well as indication of the charge level and emergency conditions on the module body. To ensure versatility and preserve the capacity of communication lines, it is advisable to select a specialised bus that uses one of the frequently used data transfer protocols, for example CAN. At the same time, the head controller of the communication line ensures interaction of the energy storage devices with the locomotive control system and must be developed considering the features of a specific series.

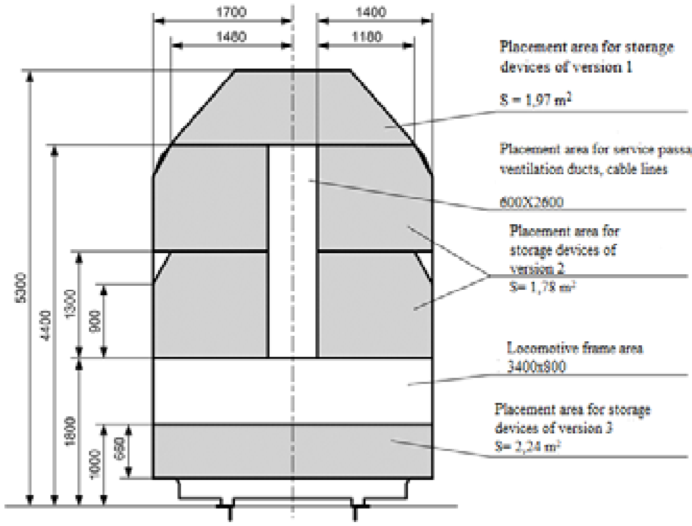
7. The influence of cost and dependability requirements for modules on their design. Despite the long-term downward trend in costs of energy storage devices, battery cells will continue to account for the largest share of energy storage module costs. This justifies increasing the complexity of the design of storage modules for the sake of increasing battery life. The effectiveness of charge equalisation and temperature control solutions should be determined taking into account the effect of increasing the service life of energy storage devices and reducing energy losses in them.

The Rationale of the Main Parameters of Battery Modules

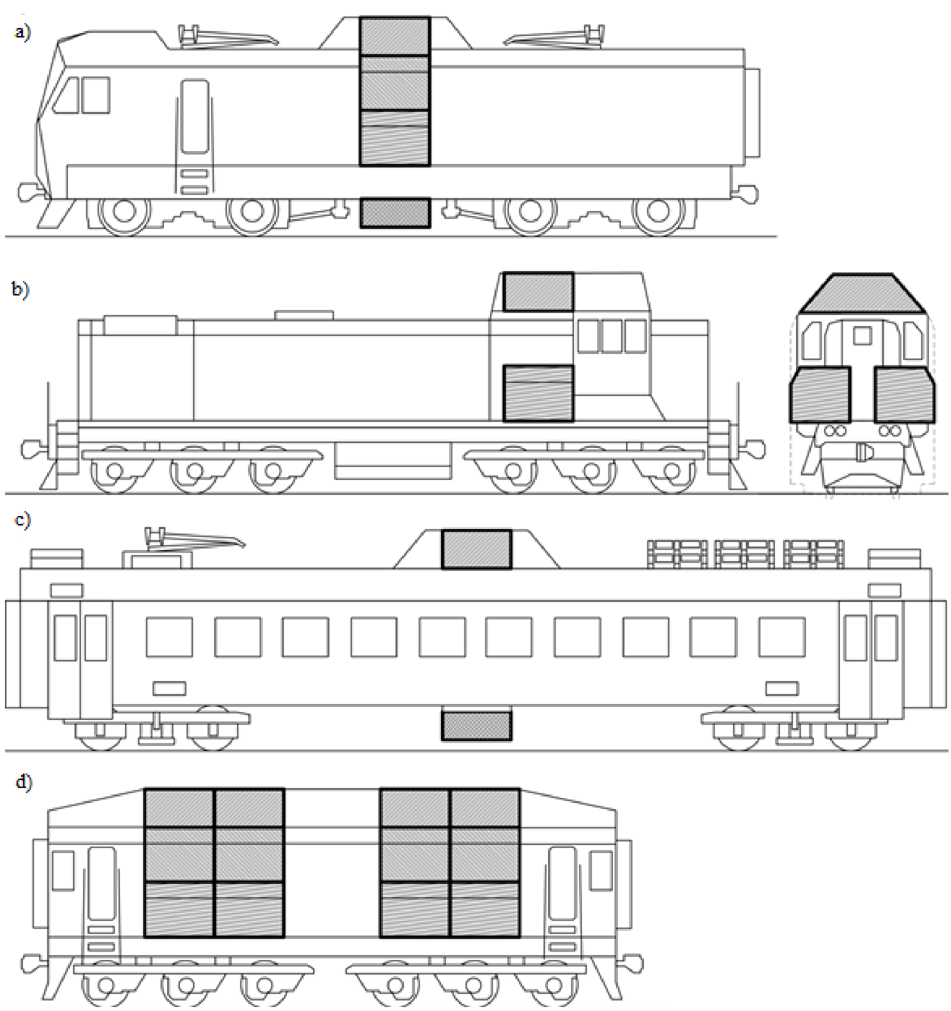
Next, the analysis was carried out of the conditions that most influence the number of elements and system connection diagram in the module.

Capacity, dimensions and weight. The power of locomotive series built over the last decade varies from 880 kW (TEM18DM) to 6600 kW (EP20), changing between mass series in steps of 600–1000 kW, i. e., by 10–15 % of the maximum. To ensure applicability over a wide range of TRS power, it is necessary to limit the capacity of the module to 1000–2000 MJ. To ensure shunting movements, modules with a capacity of 100–200 MJ can be used. In addition to the requirement for multiplicity of TESD capacity and for different modules for various TESD applications and locomotive power, the dimensions of the modules are also limited by design and operational requirements.

To reduce heat loss in winter, reduce the weight of the body and thermal insulation, it is advisable to reduce the outer surface of the module, taking similar overall dimensions along all axes, and also to increase the size and energy storage capacity of the modules. To ensure freedom of arrangement of promising locomotive series and simplify their design, it is desirable, on the contrary, to reduce the size of the modules. The possibility of using mass lifting equipment and transporting modules by road requires that the mass of the module be limited to 5 tons or 10



Pic. 1. Zones of possible placement of energy storage devices in 1-T dimension [performed by the author].



Pic. 2. Possible options for placing modular energy storage devices: a – on mainline locomotives, b – on shunting locomotives, c – on motor driven rolling stock, d – on a specialised section. The number of modules may vary depending on the purpose of installing the TESD [performed by the author].

tons[18]. Clarification of their parameters requires considering the design requirements that determine the possibility of placing and servicing modules on rolling stock.

When developing the proposals, the task was set to divide the volume that allows the placement of storage devices within the rolling stock's dimensions into parts of equal cross-section to equalise the length and capacity of modules. As shown in Pic. 1, in the section of size 1-T[19] it is possible to distinguish six zones with a cross-section of about 2 m^2 each. This allows to assume the mass of a single module to be 5 tons and the length to be 1,7–1,8 m. Possible layout solutions for different storage applications are presented in Pic. 2.

For storage devices placed in the locomotive body, a symmetrical arrangement is proposed while maintaining a 600 mm wide passage between the modules. It is proposed to set the lower boundary of the area of placement of TESD at a height of 1800 mm from the level of the rail head (RHL), which is determined by the frame dimensions of most locomotive series. The upper boundary is set in accordance with the outline of the 1-T dimension. This scheme allows installing modules both vertically, using a crane, and horizontally, using loaders.

The height of the top point of the roof (excluding equipment) of modern single-story electric trains and passenger cars does not exceed 4400 mm from the RHL. Therefore, it is proposed to place modules within the 1-T dimension above this level. The storage devices placed under the car are proposed to be placed within the clearance up to a height of 1000 mm, which is determined by the smallest standard wheel diameter.

Rated voltage. The value of the rated voltage of the traction energy storage device is also one of the factors most closely related to the main design solutions for locomotives. The energy storage device is a source of energy for traction electrical equipment in the same way as the catenary for an electric locomotive or the traction generator for a diesel locomotive (hereinafter referred to as the primary source of energy).

Considering that the TESD charge requires the ability to smoothly regulate the voltage on it, it can be assumed that the storage devices will find application primarily on rolling stock with four-quadrant traction converters. Only in this case the possibility of receiving regenerated braking energy is implemented and all the benefits of energy storage are achieved. As an exception, a less energy-efficient, but simpler option of installing a charging converter on catenary-battery rolling stock can be used while keeping contactor speed control.

Since the storage device is connected to the traction converter, its operating voltage range should approximately correspond to the voltage range of the primary energy source. This solution will simplify the circuit and increase the efficiency of energy conversion. To justify the voltage level, a review of the characteristics of a modern TRS with an asynchronous traction drive was performed[20, 21, 22, 23, 24, 25, 26, 27]. On a TRS with the ability to be powered from a 3 kV catenary, the DC link voltage, as a rule, corresponds to the catenary's voltage. In other cases, the voltage, as a rule, is assumed to be in the range of 1400–2800 V. Its minimum level

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[18] GOST [State standard] 1575–87 Lifting cranes. Rows of basic parameters [GOST 1575–87 Krany gruzopodemnie. Ryady osnovnykh parametrov].Moscow, IPK izd-vo standarov, 2002, 9 p.

[19] GOST [State standard] 9238-2013 Dimensions of railway rolling stock and proximity to buildings [GOST 9238–2013 Gabarity zheleznodorozhnogo podvizhnogo sostava i priblizheniya stroenii]. Moscow, IPK izd-vo standartov, 2014, 178 p.

[20] Zaitsev, G. K. Construction, operation and repair of diesel locomotives of 2TE25A (2TE25K) series [Ustroistvo, ekspluatatsiya i remont teplovozov serii 2TE25A (2TE25K)]. Moscow, JSC Russian Railways, 2014, 400 p. ISBN 978-5-89035-733-5..

[21] Conversion technology [Preobrazovatelnaya tekhnika]. [Electronic resource]: https://dals.spb.ru/index.php/ru/preobrazovatelnaya-tekhnika. Last accessed 22.05.2023.

[22] Electric train with asynchronous traction drive type EGE series ES2G: Operating manual ES2G.0.00.000.000–01 RE3 [Elektropoezd s asinkhronnym tyagovym privodom tipa EGE serii ES2G: Rukovodstvo po ekspluatatsii ES2G.0.00.000.000–01 RE3]. – Book 4. – Yekaterinburg, JSC Ural locomotives, 2016, 106 p.

[23] Suburban electric train of urban type EG2TV model 62–4496: Operating manual 4496.00.00.000 RE [Elektropoezd prigorodnogo sledovaniya gorodskogo tipa EG2Tv model 62-4496: Rukovodstvo po ekspluatatsii 4496.00.00.000 RE]. – Tver, JSC TVZ, 2016, 536 p.

[24] Osintsev, I. A., Loginov, A. A. Arrangement and operation of electric locomotive 2ES10 [Ustroistvo i ekspluatatsiya elektrovoza 2ES10]. Moscow, JSC Russian Railways, 2014, 334 p. ISBN 978-5-89035-786-1.

[25] Smaglyukov, D. A. Arrangement and operation of electric locomotive EP20 [Ustroistvo i ekspluatatsiya elektrovoza EP20]. Moscow, JSC Russian Railways, 2015, 361 p. ISBN 978-5-89035-787-8.

[26] TsT-453/08 Operating rules for electric locomotives of the KZ4A series [TsT-453/08 Pravila ekspluatatsii elektrovozov serii KZ4A]. – Astana, 2008. – 446 p.

[27] Zagortsev, V. A. et al. Cargo electric locomotive BKG-1 [Gruzovoi elektrovoz BKG-1]. Gomel, BelSUT, 2021, 271 p. ISBN 978-985-554-958-2

Table 3

Main characteristics of modular traction energy storage devices for installation on rolling stock [performed by the author]

Type of TESD	$LiFePO_4$	$Li_4Ti_5O_{12}$	EDLC
Weight, t	5		
Volume, m^3	from 3,0, depending on the placement area		
Capacity, kWh	625	300	15
Discharge power, kW	1200	6000	not limited for TESD
Charge power, kW	600	6000	
Rated voltage, V	3000		
Rated current, A	400	2000	> 5000

should be sufficient for the inverter to generate voltage on the traction motor. Since asynchronous traction motors have no restrictions on commutation, to optimise the characteristics of the stator windings, their rated line voltage is chosen in the range of 1,4–2,5 kV [18; 19].

It can be expected that several types of TRS will retain the ability to directly connect the traction converter to the 3 kV network. Therefore, it is advisable to take the rated voltage of the drive corresponding to the voltage of the DC catenary. The standard catenary voltage range is 2000–3600 V[28], which is almost the same as the operating voltage of a 1330 cells' lithium titanate battery with a nominal voltage of 3070 V.

Installing individual voltage converters in energy storage modules seems impractical. Modern semiconductor devices have high unit power. The use of a single traction-charging converter will reduce the weight, volume and total cost of the equipment, and simplify the control system. Renouncing to voltage converters as part of storage modules will also increase the overall dependability of the system. The high power of the modules will provide the possibility of their direct parallel connection.

Capacity and power. The main parameters of the proposed modules within given dimensions are presented in Table 3. The capacity of a module based on lithium titanate batteries will be 300 kWh, and the rated power 6000 kW, which makes it possible to install even a single module on a locomotive.

CONCLUSION

The work highlights the prospects for creating new series of railway rolling stock with onboard energy storage devices and lists the problems that can be solved by using them while substantiating feasibility of separating the tasks of designing locomotives and storage modules. A list of requirements is provided, the fulfilment of which will ensure the interchangeability of energy storage modules. An assessment was made of the specific power and energy of the modules for various options for their application.

It is proposed to use standardised modules weighing 5 tons. For example, installing 2–3 modules on a section of a 3000 kW freight locomotive will ensure a constant supply to its primary energy source. Installing one module on a section of an electric train with a power of 1200 kW will not only solve this task, but also provide catenary-free operation within a range of about 100 km. In the future, these recommendations can be clarified, but solving this problem will require an analysis of the operating conditions of rolling stock with energy storage devices,

[28] GOST [State standard] 29322–92 (IEC 38–83) Standard voltages [*GOST 29322–92 (IEC 38–83) Standartnie napryazheniya*].Moscow, Izd-vo standartov, 1992, 7 p.

considering the characteristics of the planned areas of its circulation.

In the future, the scope of application of energy storage devices will increase with the decrease in costs of batteries decreases, development of alternative materials with lower cost, and of new types of storage devices with higher capacity. Standardising and ensuring the interchangeability of energy storage devices will not only simplify and speed up the emergence of new technologies but will also create many new opportunities for their use. This makes it advisable to consider the requirements for electrical energy already at the stage of setting the parameters of promising types of rolling stock.

REFERENCES

1. Prospects for traction batteries in railway transport [*Perspektivy tyagovykh akkumulyatornykh batarei na zheleznodorozhnom transporte*]. *Zheleznie dorogi mira*, 2023, Iss. 1, pp. 43–48. [Electronic resource]: https://zdmira.com/articles/perspektivy-tyagovykh-akkumulyatornykh-batarej-na-zheleznodorozhnom-transporte. Last accessed 22.05.2023.

2. Battery traction recharges decarbonisation fight. [Electronic resource]: https://www.railjournal.com/in_depth/battery-traction-recharges-decarbonisation-fight/. Last accessed 22.05.2023.

3. Yu Miao, Hynan P., von Jouanne, A., Yokochi, A. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. *Energies*, 2019, Vol. 12, Iss. 6, Atricle ID 1074. DOI: 10.3390/en12061074.

4. Nezevak, V. L., Shatokhin, A. P. Features of the Traction Load for Determining the Parameters of the Electric Energy Storage Device. *World of Transport and Transportation*, 2018, Vol. 16, Iss. 2 (75), pp. 84–94. DOI: 10.30932/1992-3252-2018-16-2-8.

5. Loginova, E. Yu., Kuznetsov, G. Yu. Improving Traction Characteristics of a Diesel Locomotive with a Hybrid Power Plant. *World of Transport and Transportation*, 2022, Vol. 20, Iss. 3 (100), pp. 21–29. DOI: 10.30932/1992-3252-2022-20-3-3.

6. Valinsky, O. S., Evstafiev, A. M., Nikitin, V. V. On the issue of determining the energy storage capacity for traction rolling stock of railways [*K voprosu opredeleniya emkosti nakopitelya energii dlya tyagovogo podvizhnogo sostava zheleznykh dorog*]. *Elektronika i elektrooborudovanie transporta*, 2021, Iss. 2, pp. 8–11. [Electronic resource]: http://eet-journal.ru/upload/iblock/93a/l6167j3bpgez0e4eg5atib9ea6wqk2ei.pdf. Last accessed 22.05.2023.

7. Sychugov, A. N. Program for calculating the parameters of electrical energy storage devices for autonomous traction rolling stock: certificate of registration of the computer program. Reg. № 2022619798 dated 26.05.2022. Application № 2022618257 dated 05.05.2022.

8. Shevlyugin, M. V., Zhetov, K. S., Pletnev, D. S., Glushchenko, M. D. Experimental study of the autonomous operation of electric rolling stock in the metro [*Eksperimentalnoe issledovanie avtonomnogoo khoda elektropodvizhnogo sostava metropolitena*]. *Elektrotekhnika*, 2021, Iss. 9, pp. 19–21. – [Electronic resource]: http://www.znack93.ru/images/archive/2021/09–2021.pdf. Last accessed 22.05.2023.

9. Shtang, A. A., Yaroslavtsev, M. V. Catenary-battery shunting electric locomotive with energy storage based on lithium-ion batteries [*Kontaktno-akkumulyatorniy manevroviy elektrovoz s nakopoitelem energii na osnove litii-ionnykh akkumulyatorov*]. *Elektronika i elektrooborudovanie transporta,* 2016, Iss. 1, pp. 13–16. [Electronic resource]: http://eet-journal.ru/upload/iblock/1f2/9t3gxgjb6vx070j9idtu2n7tp9k8gfv6.pdf. Last accessed 22.05.2023.

10. Yaroslavtsev, M. V., Shchurov, N. I., Anosov, V. N. Energy-efficient traction drive for urban trackless transport [*Energoeffektivniy tyagoviy privod gorodskogo bezrelsovogo transporta*]. Novosibirsk, NGTU publ., 2017, 135 p. ISBN 978-5-7782-3274-7.

11. Kuznetsov, G. Yu., Loginova, E. Yu. Improving the technical characteristics of autonomous locomotives with a lithium-ion traction battery [*Povyshenie tekhniheskikh kharakteristik avtonomnykh lokomotivov s litii-ionnoi tyagovoi batareei*]. *Izvestiya Transsiba*, 2022, Iss. 4 (52), pp. 57–65. [Electronic resource]: http://izvestia-transsiba.ru/images/journal_pdf/2022–4(52).pdf. Last accessed 22.05.2023.

12. Zhou Chengke, Qian Kejun, Allan, M., Zhou Wenjun. Modeling of the Cost of EV Battery Wear Due to V2G Application in Power Systems. *IEEE Transactions on Energy Conversion*, 2011, Vol. 26, pp. 1041–1050. DOI: 10.1109/TEC.2011.2159977.

13. Rosenkranz, C., Kohler, U., Liska, J. L. Modern battery systems for plug-in hybrid electric vehicles. *Power*, 2007, Vol. 1, 100. [Electronic resource]: https://dspace.tul.cz/server/api/core/bitstreams/b7580d40-7453-449d-9200-7601400c6569/content. Last accessed 22.05.2023.

14. Spiridonov, E. A., Yaroslavtsev, M. V. Assessing the efficiency of using energy storage devices in quarry railway transport [*Otsenka effektivnosti primeneniya nakopoitelei energii na kariernom zheleznodorozhnom transporte*]. *Gorniy infomatsionno-analiticheskiy byulleten*, 2022, Iss. 12/2, pp. 241–256. DOI: 10.25018/0236_1493_2022_122_0_241.

15. Gallardo-Lozano, J., Romero-Cadaval, E., Milanes-Montero, M. I., Guerrero-Martinez, M. A. Battery equalization active methods. *Journal of power sources*, 2021, Vol. 246, pp. 934–949. DOI: 10.1016/j.jpowsour.2013.08.026.

16. Xing Yinjiao, Ma Eden, W. M., Tsui Kwok, L., Pecht, M. Battery management systems in electric and hybrid vehicles. *Energies*, 2011, Vol. 4, Iss. 11, pp. 1840–1857. DOI: 10.3390/en4111840.

17. Nema, P., Muthukumar, P., Thangavel, R. Review on Thermal Management System of Li-Ion Battery for Electric Vehicle. In: Sustainable Energy Generation and Storage: Proceedings of NERC 2022, Springer Nature, 2023. pp. 165–184. DOI: 10.1007/978-981-99-2088-4_14.

18. Andryushchenko, A. A., Babkov, Yu. V., Zarifyan, A. A. [*et al*]. Asynchronous traction drive of locomotives [*Asinkhronniy tyagoviy privod lokomotivov*]. Moscow, TMC for education on railway transport, 2013, 413 p. ISBN 978-5-89035-631-4.

19. Shcherbakov, V. G., Petrushin, A. D., Khomenko, B. I., Sedov, V. I. Traction electric machines [*Tyagovie elektricheskie mashiny*]. Moscow, TMS for education on railway transport, 2016, 641 p. ISBN 978–5–89035–926–1. ●

Information about the author:

Yaroslavtsev, M. V., *Ph.D. (Eng), Associate Professor at the Department of Electrical Engineering and Automation of Non-profit joint-stock company «Toraighyrov University» (NJSC « Toraighyrov University»), Pavlodar, Republic of Kazakhstan, myaroslavtsev@yandex.ru.*

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