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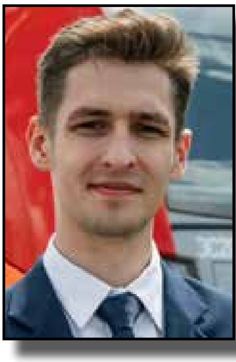
The Use of Electric Energy Storage Devices to Improve Traction Properties of Autonomous Locomotives





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ABSTRACT

The analysis of international experience in development of autonomous locomotives with a hybrid power plant allowed to prove the possibility of increasing the operating efficiency of diesel locomotives using electric energy storage devices.

A proposed circuit diagram of the power system of a diesel locomotive implies as source of energy both a diesel engine and a traction battery with a DC pulse chopper. An algorithm has been developed to control the traction drive of a diesel locomotive with a hybrid power plant, which ensures an increase in the tractive force of the locomotive on sections with difficult track profile. Modernisation of the power system of a diesel locomotive using a hybrid power plant is considered for the diesel locomotive of 2TE116 series. A mathematical model of operation of a diesel locomotive traction drive powered by a hybrid energy source through a controlled voltage breaker has been developed using the energy balance equations of a traction electric motor. Respective traction properties of 2TE116 diesel locomotive with a standard power plant and a hybrid power plant were calculated using numerical modelling methods in MatLab and LabView software environments. It is shown that, over the entire range of operation speed, a diesel locomotive with a hybrid power plant allows obtaining a tractive effort 15 % higher than a diesel locomotive with a standard power plant. Calculations have proved that increasing the traction properties of the modernised 2TE116 diesel locomotive makes it possible to increase the designated weight of the train by 15 %, and, accordingly, the efficiency of using the locomotive as a traction unit on the railway network.

<u>Keywords:</u> railway transport, electric energy storage devices, hybrid power plant, improvement of operation characteristics of a mainline diesel locomotive.

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INTRODUCTION

With the continuous growth in volume of transportation by rail, there is a need for a maximum use of the carrying capacity of rolling stock. It fully refers to development of railway transport in Russia and to Russian Railways JSC[1] [1; 2].

Within technical developments, design departments and engineering centres constantly raise questions about the production of modern, more powerful locomotives with higher tractive force and capable of transporting more cargo.

One of the ways to increase the traction efficiency of locomotives is to improve their design through modernisation, which consists in the use of more modern technical devices.

Currently, traction rolling stock with hybrid energy sources is becoming widespread. In Germany, a Prima H3 hybrid shunting locomotive manufactured by Alstom is in operation. It is equipped with lithium traction batteries, weights 67 tons, its traction force when starting is 225 kN, power is 700 kW [3]. In Russia, the machine-building holding JSC Transmashholding designed and presented at the International Railway Salon of 1520 space PRO Dvizhenie.Expo a hybrid autonomous shunting locomotive with a traction energy storage capacity of 240 kW[2]. In Switzerland, work is currently underway on production of a dual-mode locomotive of the new 93 series using lithium titanate oxide batteries, powered by a 25 kV 50 Hz AC contact network, with a power of the locomotive itself of 1300 kW [4].

[1] Transport strategy of the Russian Federation until 2030 with the forecast for the period until 2035. [Elextronic resource]: https://mintrans.gov.ru/file/473193. Last accessed 17.09.2023.

[2] TEM5Kh Shunting hybrid diesel locomotive. [Electronic resource]: https://sitmag.ru/article/25569 manevroviy gibridniy teplovoz tem5h gibridniy-avtonomniy-lokomotiv-obrel-plot. Last accessed 02.10.2023.

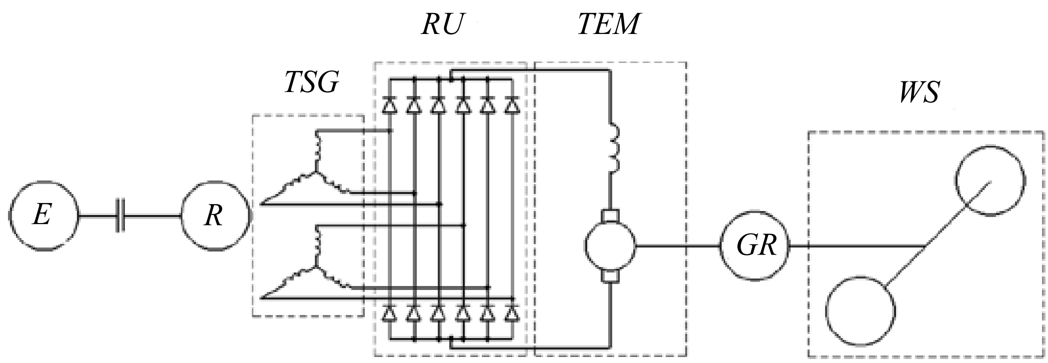
The *objective* of the study was the use of electric energy storage devices on autonomous rolling stock by changing the standard design of conventional 2TE116 AC-DC diesel locomotive.

RESULTS

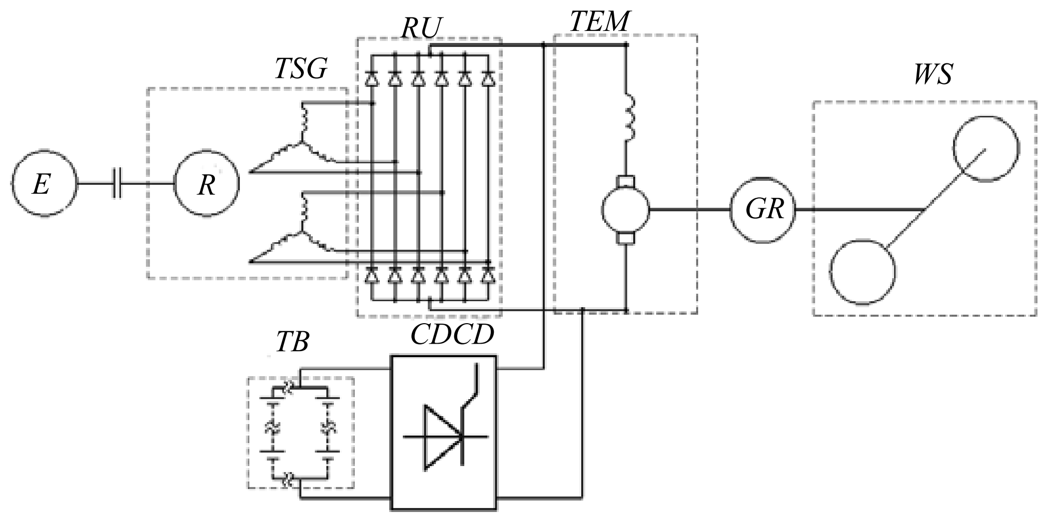
The studied diesel locomotive 2TE116 is a locomotive that uses a diesel internal combustion engine (E) as the primary source of energy. Its functional electromechanical and circuit diagram is shown in Pic. 1. The diesel engine is used in locomotives due to its high reliability and higher effective power [5]. The engine converts the chemical energy of the fuel into the mechanical energy of rotation of the crankshaft. Mechanical energy is converted into electrical energy by rotating the rotor (R) of a synchronous generator (TSG), which converts the rotational mechanical energy into alternating current electrical energy. By using a rectifier unit (RU), alternating current is converted into direct current [6] and supplied to locomotive traction electric motors (TEM). Locomotive traction electric motors constitute an electrical machine that converts electrical energy into mechanical rotational energy. To apply a high starting torque, a traction gear reducer (GR) is used, which increases the torque but reduces the rotation speed. Subsequently, rotation with a large torque is transmitted to the wheelset of the locomotive and sets it in motion.

The functional electromechanical and circuit diagram of the 2TE116 hybrid diesel locomotive is shown in Pic. 2.

Changing the design of a locomotive to turn it into a hybrid one consists of installing an additional electric energy storage device, a special case of which is a traction battery (TB). In the design of the locomotive, the TB is used to implement electrodynamic regenerative braking,



Pic. 1. Functional electromechanical and circuit diagram of the conventional 2TE116 diesel locomotive [performed by the authors].



Pic. 2. Functional electromechanical and circuit diagram of the hybrid 2TE116 diesel locomotive [performed by the authors].

as well as to allocate additional power to the locomotive on difficult sections of the track to pass track grades. Also, the traction battery can replace the standard traction battery and provide starting of a diesel internal combustion engine, powering the on-board circuit and the auxiliary needs of the locomotive. To regulate the charge-discharge currents of a traction battery, it is necessary to install a charge-discharge control device (CDCD), which is a two-way pulse constant voltage chopper. Thus, this device will control the maximum charge-discharge currents allowed for the traction battery.

The functional application of a traction electric battery is to implement it on difficult sections of the track by connecting it in parallel with traction synchronous generators to traction electric motors.

The traction force of a locomotive with an electric transmission depends on the mechanical torque on the traction electric motor, the radius of the wheels of the locomotive wheelset and the gear ratio of the traction gear reducer, N:

$$F_k = \frac{n_{ax} \cdot M_k \cdot i}{R_k}, \quad (1)$$

where n_{ax} is the number of motorised axles of the locomotive, pcs;

M_k – torque (moment) created by the traction motor, Nm;

i – gear ratio of traction gear reducer;

$R_к$ – radius of the locomotive wheelset, m.

The number of axles, the radius of the locomotive's wheelsets and the gear ratio of the traction gear reducer are design parameters of the locomotive that cannot change during its operation. Thus, the value of the locomotive's traction force can be increased by increasing the torque on the traction electric motors.

It is known[3], that the torque of a series excitation DC electric motor is determined by the dependence, Nm:

$$M_к = c_m \bullet I_{ar} \bullet F_{ex} = c_m \bullet I_{ar} \bullet I_{ex} = c_m \bullet I_{ar}^{\,2}, \quad (2)$$

where c_m – motor design constant;

I_{ar} – current flowing through the armature winding, A;

I_{ex} – current flowing through the excitation winding, A;

F_{ex} – magnetic flux of the excitation winding, Wb.

Thus, we can conclude that the torque of the traction electric motor is directly proportional to the square of the value of the current of the armature winding of the traction motor.

Modern traction batteries, such as the LT-LFP770P battery manufactured by Liotech LLC, allow a nominal discharge equal to the value of the nominal battery capacity c_n equal to 770 A[4].

Thus, in relation to 2TE116 diesel locomotive, it is possible to sequentially install an n-number

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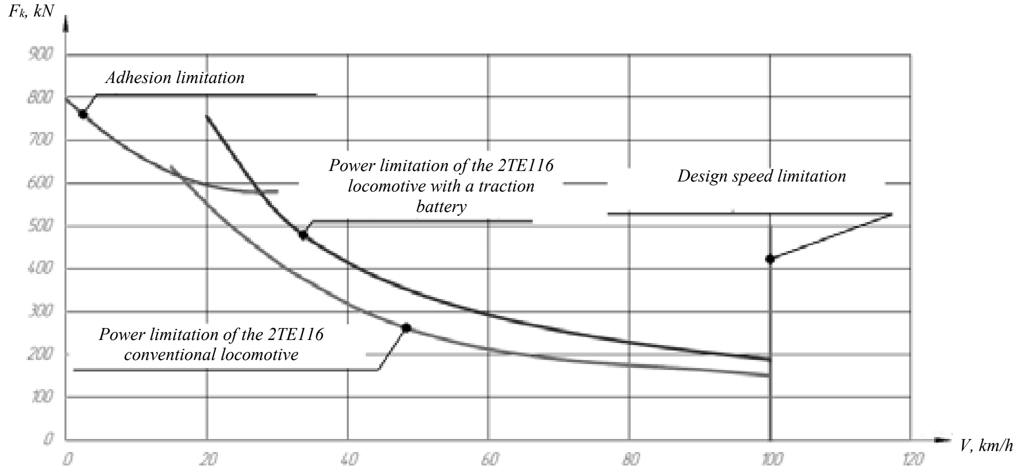
[3] Proskuryakov, V. S., Sobolev, S. V. Calculation of electrical machines: Study guide. National Research Tomsk Polytechnic University. Tomsk, Publishing house of Tomsk Polytechnic University, 2011, 112 p. [Electronic resource]: https://portal.tpu.ru/SHARED/v/VOV/uchebnaya_rabota/Tab1/Tab/UP1.pdf. Last accessed 02.10.2023.

[4] Operation instructions for LFP-P batteries of lithium-ion series with a nominal capacity of 200 A·h, 240 A·h, 300 A·h, 380 A·h, 700 A·h, 770 A·h LT.38294932.3482.003–2016RE, 2016, 25 p.



Pic. 3. Comparison of traction properties of 2TE116conventional and hybrid diesel locomotives [performed by the authors].

of traction battery cells with a nominal capacity of 770 Ah, which will operate on six parallel-connected traction electric motors of the diesel locomotive. Thus, the maximum permissible value of current from the traction battery on each electric motor will be, A:

$$I_{TEM}^{TB} = \frac{I_{TB}}{n_{TEM}} = \frac{770}{6} = 128{,}3, \qquad (3)$$

where I_{TB} – value of the discharge current of the traction battery, A;

n_{TEM} – number of traction electric motors per locomotive section, pcs.

The amperage on each traction electric motor is calculated based on the characteristics of the traction synchronous generator, which can be obtained from the Rules for Traction Calculations for Train Operation (RTC)[5].

Accordingly, the amperage of the traction synchronous generator will be determined as, A:

$$I_{TEM}^{TSG} = \frac{I_{TSG}}{n_{TEM}}, \qquad (4)$$

where I_{TSG} – value of the current of traction synchronous generator, A.

Thus, the final value on the locomotive traction electric motor is determined by the dependence, A:

$$I_{TEM} = I_{TEM}^{TSG} + I_{TEM}^{TB}. \qquad (5)$$

Using equations (1–5), knowing the design parameters of the 2TE116 diesel locomotive, of the GS-501A traction synchronous generator and of the ED-118A traction electric motor, it is possible to calculate the traction properties of the 2TE116 diesel locomotive with a traction battery.

The comparison of traction characteristics of 2TE116 conventional and hybrid diesel locomotives is shown in Pic. 3. The limiting adhesion value for a diesel locomotive cannot be expanded by increasing the torque of the traction electric motors, since this will lead to slipping of wheelsets and will not bring useful work [7]. The limiting conditions regarding design speed is determined based on the conditions of the permissible impact of the locomotive on the track, the running properties of the locomotive, the possibility of it derailing and the strength of its components and assemblies. For reasons of traffic safety, this restriction cannot be changed. From the calculations performed, it is clear that the use of a traction battery makes it possible to increase the traction force of a diesel locomotive by 25–35 % in continuous running mode.

From Rules for Traction Calculations[5] it follows that the choice of the estimated mass of the train is made based on the following relationship, t:

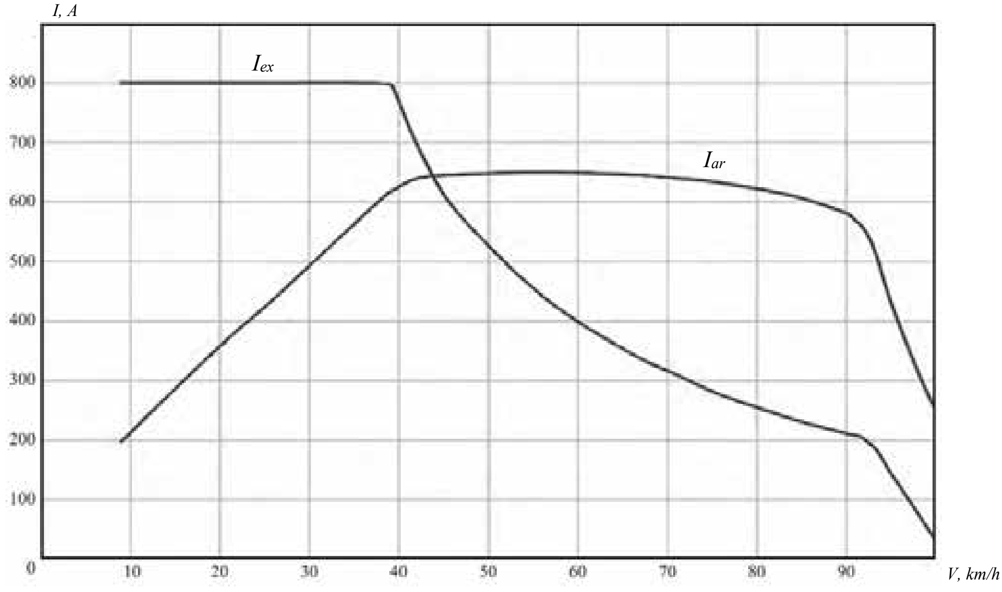
$$Q = \frac{F_{kd} - (w_0^{'} + i_d) \cdot P}{w_0^{''} + i_d}, \qquad (6)$$

where F_{kd} – value of locomotive traction force at design speed, N;

$w_o^{'}$ – locomotive resistance to motion in traction mode, N;

$w_o^{''}$ – train (wagons') resistance to motion in traction mode, N;

[5] Grebenyuk, P. T., Dolganov, A. N., Nekrasov, O. A., Lisitsyn, A. L., Stromsky, P. P., Borovikov, A. P., Chukova, T. S. Rules for Traction Calculation for Train Operation. Moscow, Transport publ., 1985, 287 p. [Electronic resource]: https://djvu.online/file/syjaetzWQPjhN. Last accessed 02.10.2023.



Pic. 4. Dependences of the armature current and excitation current of the ED-118A traction electric motor of the 2TE116 diesel locomotive [performed by the authors].

P – locomotive adhesion weight, t;

i_d – design track grade, ‰.

The dependence (6) makes it clear that the main factor positively influencing the transported mass of the train is the estimated traction force of the locomotive. In accordance with RTC, the calculated traction force of the 2TE116 locomotive at a design speed v_d = 24,2 km/h is 50600 kgf (496 kN). Once the dependence of the traction force on the speed of movement of the 2TE116 hybrid diesel locomotive is used, it becomes clear that the design speed is now observed for the adhesion limitation. Thus, the calculated value of the traction force for the adhesion limitation is 58200 kgf (571 kN). Based on this calculation, we can conclude that the actual transported mass of the train, when using a traction battery on a diesel locomotive, can be increased by approximately 15 %.

One of the advantages of using a traction battery is the ability to recover electrical energy into an electric energy storage device. Currently, diesel locomotives have implemented the possibility of electrodynamic, rheostatic braking, which implies the conversion of the electrical energy received during braking into heat.

Regeneration currents can be preliminarily estimated based on the effective dependence of the armature current of the traction electric motor ED-118A of the 2TE116 diesel locomotive, which is shown in Pic. 4.

The graph shows that the peak value of armature currents is observed at speeds of 40–80 km/h and amounts to 650 A. Thus, the traction battery must be designed to receive peak currents from six traction motors in the amount of 3900 A. However, under the manual for operation, the charging current is limited to 2310 A. In this case, a technical solution can be implemented to partially switch the three traction electric motors of the first bogie to the regenerative braking mode, and the remaining three electric motors of the second bogie can be switched to the rheostatic braking mode with connection to a braking resistor. In any case, the effectiveness of regenerative braking with energy transmission to the traction energy storage device will be determined by the current track profile and the number of activations of the rheostatic braking mode to stop the train or maintain a certain speed.

CONCLUSIONS

The analysis of the possibility of using a traction battery on mainline locomotives showed that the use of a traction battery will make it possible:

1) to increase the tangential traction force on the locomotive by increasing the torque on the traction electric motors, which will increase the possible transported weight of the train by approximately 15 %;

2) to implement the recovery of electrical energy on autonomous rolling stock, which will

increase energy efficiency and ultimately increase the volume of transported goods.

Proposed circuit diagram and mathematical model of the electric drive of a diesel locomotive with a hybrid power plant consisting of a diesel engine and traction batteries allowed numerical studies of a diesel locomotive with a hybrid power plant that have shown that its efficiency as a traction unit increases by 15 %.

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