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Improving Traction Characteristics of a Diesel Locomotive with a Hybrid Power Plant

Elena Yu. LOGINOVA

Grigory Yu. KUZNETSOV

Elena Yu. Loginova [1], Grigory Yu. Kuznetsov [2]

[1, 2] Russian University of Transport, Moscow, Russia.
✉ [1] ejy-loginova@mail.ru, [2] kuznetsov_gy@mail.ru.

ABSTRACT

The expediency of using a hybrid power system with the use of traction batteries on a diesel locomotive is substantiated since the relevance of the problem being solved lies in the possibility of increasing the weight norm of the train without reducing the performance of the main power equipment of the diesel locomotive, which is of great importance for improving the efficiency of railways.

To predict the effectiveness of introduction of autonomous locomotives with a combined power source, traction properties of a diesel locomotive equipped with a set of traction batteries are estimated by mathematical modelling. The basis of the method is a dynamic model of train movement, in which the locomotive is represented as an electromechanical system with a direct current electric drive, where a diesel power generator and a lithium-ion battery are used as the primary energy source. It is shown that the use of a hybrid power source with a storage device with capacity of 1300 ampere-hours on a diesel locomotive makes it possible to increase the weight rate of a train by 18 % when moving along a typical profile. Particular attention is paid to the requirements for operation of traction electric machines to prevent their premature failure. It was found that during movement of a locomotive with a hybrid power plant with a train of the calculated weight and under normal environmental conditions (20°C and normal barometric pressure), an increase in the load current of traction motors does not lead to overheating of their windings at the calculated upward slope.

The model suggested is universal and allows calculating the efficiency of a diesel locomotive with a hybrid power plant under any driving conditions.

Keywords: railway transport, autonomous locomotive, hybrid power plant, lithium-ion battery, dynamic train movement model, traction electric machines.

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

INTRODUCTION

The issue of developing diesel locomotives capable of moving with trains of increased weight is currently being decided based on the requirements for increasing the power of autonomous locomotives and reducing the cost of their operation (fuel, oil, etc). An increase in the weight rate of a train can be implemented with hybrid diesel locomotives, which use traction batteries (accumulators) as an additional power source to accumulate free energy for its subsequent use for heavy traffic mode. Energy storage devices are widely used in hybrid power sources [1–4].

Accumulators on rolling stock are already applied for the use of additional energy [5–7]. To reduce the operating costs of a diesel locomotive, it is necessary to choose an energy storage device with high specific rates in terms of capacity, stored energy density, and service life [8–9]. At the same time, energy storage devices for traction conditions must have low weight and size and be designed for high currents. Besides traction modes, several works on the use of energy storage devices refer also to the improvement of the efficiency of regenerative braking of locomotives [1; 3; 4].

The amount of energy that can be stored in the storage device directly affects its cost [10].

The use of energy storage devices in railway transport is a comprehensive task, in solving which it is necessary to consider the operation of the entire locomotive equipment [11–15]. In addition to the traction battery, the energy storage circuit contains expensive energy converters based on power electronic switches with complex control algorithms. As a result, the price of the power equipment of a hybrid diesel locomotive grows significantly, and its development requires a justification of economic efficiency. Therefore, the calculation of the increase in the traction properties of a hybrid diesel locomotive compared to a diesel locomotive is an important stage in development and adoption of hybrid energy sources on autonomous locomotives.

One of the main problems in creating hybrid diesel locomotives is the coordinated operation of two power units: a diesel engine and a traction energy storage device (TES). The solution of this problem requires development of a dynamic model of the energy system of a diesel locomotive with a hybrid energy source and performance of numerical experiments to determine its traction properties; and this constitutes the *objective* of the study.

RESULTS

Energy Circuit of a Hybrid Diesel Locomotive

The energy circuit of a hybrid diesel locomotive provides for operation of two energy sources for traction motors (Pic. 1). Regarding a diesel locomotive with an AC/DC power system, the main energy source consists of a diesel engine D, a traction synchronous generator (TSG) with a combined control system, a rectifier unit (RU), and traction electric motors (TEM) 1–6. For the possibility of shifting electric motors to the braking mode, the power system is equipped with a brake switch (BS).

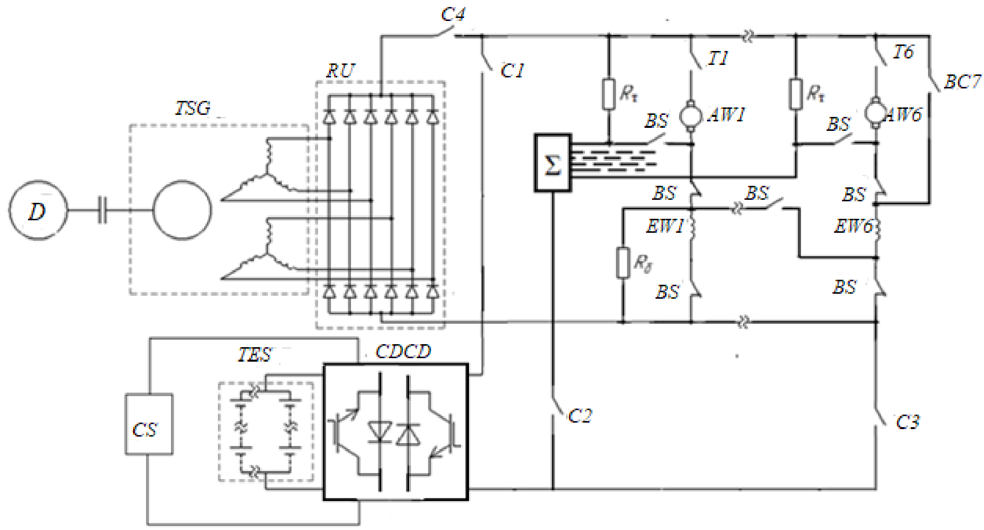
The additional energy source includes a traction energy storage device (TES) and a charge and discharge control device (CDCD) with a control system (CS). The process of TES charging is carried out in the braking modes of the diesel locomotive by turning on the TES to the voltage of the TEM using contactor C2.

On a hybrid diesel locomotive in the traction mode, the TEM windings can be powered both from the TSG together with the TES storage, and only from the TSG. The TES discharge current is regulated by the CDCD control device, which is a module based on IGBT transistors and CS. The CDCD device connects the TES to the traction drive of the locomotive by contactor C3 (with closed contactor C1). In conditions of low resistance to movement, the contactor C3 disconnects the TES from the traction electric drive and the latter is powered from the TSG through the RU.

If necessary, the TES can be disconnected from the power circuit by opening contactors C1, C2 and C3.

If it is necessary to use the electrical energy of only traction energy storage devices, for example, to work on station tracks, it is enough to open the contactor C4 and close the contactors C1 and C3. At the same time, as in the braking mode, the diesel engine must operate under load so that the TSG voltage is sufficient for operation of the TEM cooling fan motors.

When operating a TEM from a hybrid energy source, there is a danger of overheating of its windings since the increase in traction torque is implemented by increasing the current. This requires equipping the TEM with a winding temperature control system. At present, the



Pic. 1. Traction electrical circuit of a hybrid diesel locomotive with AC-DC transmission,
T1 – train contactor switch of TEM 1; T6 – train contactor switch of TEM 6; BC7- braking contactor; EW1 – excitation winding of TEM1; EW6 – excitation winding of TEM6; AW1 – armature winding of TEM1; AW6 – armature winding of TEM 6 [performed by the authors].

problem of controlling the current temperature of the windings of electrical machines has been solved and there is no difficulty in controlling the voltage of the TSG and the CDCD unit to limit the current of traction motors.

For the numerical solution of the problem of estimating the traction properties of a diesel locomotive under operating conditions, its dynamic model was developed. The energy circuit in the model was represented by a hybrid energy source based on the diesel locomotive 2TE116 (Table 1). TES in the model is represented by blocks of LT-LFP70M traction batteries (Table 2).

Diesel locomotive 2TE116 with a capacity of 2200 kW has an AC-DC electric transmission with ED-118 traction motors and is one of the most common freight diesel locomotives in Russia and the post-Soviet countries.

In general, batteries in the transport industry are used to start gas turbine and piston engines, in industrial transport, electric vehicles, and also as emergency, backup or auxiliary power sources [16–23]. Lithium-ion batteries are modern energy storage devices. The LT-LFP70M traction battery packs for the diesel locomotive hybrid power source were selected based on their effective use to power the electric motors of machines and on-board rail transport systems. Besides, this type of batteries is already used on the experimental TEM5X hybrid diesel locomotive.

The characteristics of train movement resistance were assumed based on [25].

Modelling of train movement was carried out according to the generalised track profile of class III in accordance with the classification of VNIIZhT (Research Institute of Railway Transport), for which the calculated upward slope is i_c = 9 ‰ [25]. At the same time, the calculation of the current temperature of the TEM armature windings was carried out in accordance with the methodology given in [24].

At the first stage of calculations, the normal weight of the train was estimated for the locomotive operating with a standard energy system (without energy storage), and it was taken as the base value.

The calculated weight of the cargo train Q_c was determined based on the fact that the power of the locomotive is fully used during uniform movement at the calculated speed v_c along the calculated upward slope i_c. The calculated weight of a cargo train Q_c was determined by the formula, kN:

$$Q_c = \frac{F_{cr} - P_{adh}\left(w_m^{'}\left(v_c\right) + i_c\right)}{w_m^{''}\left(v_c\right) + i_c}, \qquad (1)$$

where $w_m^{'}(v_c)$ – main specific resistance to locomotive movement in traction mode at design speed, N/kN;

$w_m^{''}(v_c)$ – main specific resistance to movement of a cargo train (cars) at calculated speed, N/kN;

Table 1

The main parameters of the 2TE116 diesel locomotive [24]

Locomotive weight, t	276
Calculated speed v_c, km/h	24,2
Calculated traction force F_{cr}•10^3, N	506
Adhesive weight P_{coupl}, kN	2760
Design speed V_d, km/h	100

Table 2

Rated parameters of LT-LFP70M battery cells [8]

Cell capacity, ampere-hour	73
Energy density, W•h/kg	130
Rated voltage, V	3
Permissible long-term discharge current, A	146
Maximum short-term discharge current, A	219
Maximum charge current, A	73
Internal resistance, m•Ohm	0,5
Battery life in the charge-discharge interval, cycles	5000
External dimensions, H x W x T, mm	222 x 135 x 30
Weight, kg	1,8
Operating temperature range during discharge, C°	-30–+50

F_{cr} – calculated traction force of the locomotive at the calculated speed, N;

P_{adh} – adhesive weight of the locomotive, kN;

i_c – steepness of the calculated upward slope, ‰.

The main specific resistance to movement of the locomotive in the traction mode w_m' was calculated based on [24], N/kN:

$$w_m'(v_c) = 1,9 + 0,01 \cdot v + 0,0003 \cdot v^2, \quad (2)$$

the main specific resistance to movement of four-axle cars on roller bearings in accordance with [24], N/kN was calculated as:

$$w_m''(v_c) = 0,7 + \frac{3 + 0,09 \cdot v + 0,002 \cdot v^2}{q_m}. \quad (3)$$

As a result, it was found that the calculated weight of the cargo train Q_c for the track profile with a calculated gradient of upward slope of 9 ‰ was 43280 kN or 4413 tons.

In the MathCad software package, the motion mode of the 2TE116 locomotive with a train was simulated with and without a traction battery.

To numerically determine the traction characteristics of a diesel locomotive with a hybrid and standard power source, comparative calculations of the driving modes were performed:

1. Calculation of traction force and kinematic characteristics of movement with the train of the basic normal weight of 4413 tons.
2. Calculation of the traction force and kinematic characteristics of movement of a diesel locomotive with a hybrid energy source with a train, the weight of which exceeds the base one.
3. Calculation of TES currents for powering the TEM during movement of a diesel locomotive with a hybrid energy source and trains, the weight of which exceeds the base one.
4. Calculation of temperatures of TEM windings during movement of a diesel locomotive with a hybrid energy source and trains, the weight of which exceeds the base one.

Calculation of Traction Force and Kinematic Characteristics of the Locomotive

The calculation of the traction force and the kinematic characteristics of the train with the base normal weight was carried out based on the operating conditions of the TSG working with the TEM.

Based on the value of the locomotive speed and the current characteristics of the EDU-133 traction motors, taking into account the values of the excitation attenuation coefficients, the load current of the TEM was determined.

Electromagnetic moment of the traction motor M_{tem}, Nm:

$$M_{tem} = c_m \cdot I_a \cdot F, \quad (4)$$

where c_m – constant of the traction motor, determined by the dependence:

$$c_m = \frac{N \cdot p}{a} \cdot \frac{1}{2\pi} = c_e \cdot \frac{1}{2\pi}. \quad (5)$$

The tangential moment on the wheel of the entire diesel locomotive M_t, taking into account the number of axles, Nm:

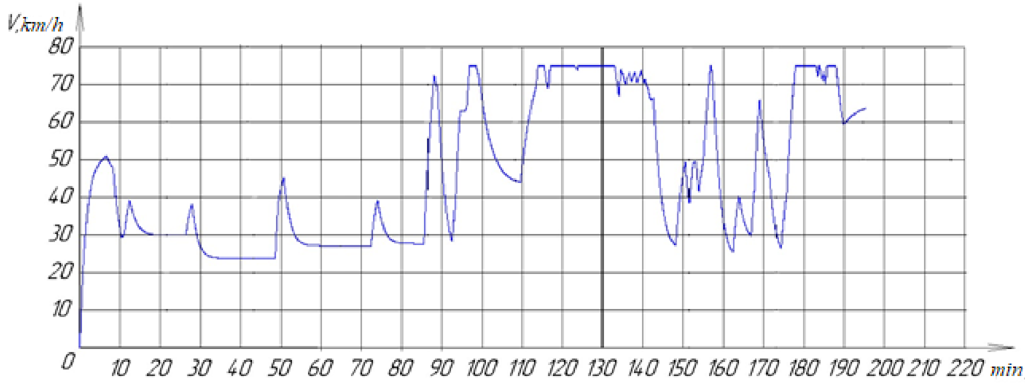
$$M_t = n_{ax} \cdot M_{tem} \cdot \mu_{tr} \cdot \eta_{tr}, \quad (6)$$

where n_{ax} – the number of diesel locomotive axles;

η_{tr} – the efficiency of the traction reducer;

μ_{tr} – gear ratio of the traction reducer.

Tangential traction force of a diesel locomotive F_t, N:



Pic. 2. Change in the speed of a diesel locomotive with a standard power plant and the train of the calculated weight when moving along a class III track profile depending on the travel time V = f(t) [performed by the authors].

$$F_t = M_t / R_w, \tag{7}$$

where R_w – radius of the locomotive wheel.

Acceleration of the train, m/s:

$$a(v,s) = \frac{F_t(v) - w''_m(v) - w'_m(v) - i(s)}{Q_c + P_{coupl}}. \tag{8}$$

The locomotive speed curve obtained based on mathematical calculation in the MathCad program is shown in Pic. 2.

Calculation of Traction Force and Kinematic Characteristics of a Hybrid Locomotive

The calculation of the traction force of a diesel locomotive with an energy storage device is carried out similarly, except for the calculation of the current on the traction motors.

Current on each motor of a hybrid diesel locomotive in the traction mode $I_{m(acb)}$, A:

$$I_{m(acb)} = I_m + \frac{I_{discharge}}{n_{ax}}, \tag{9}$$

where I_m – current, supplied to the TEM from the TSG, A;

$I_{discharge}$ – discharge current of the traction battery, A.

The calculation of the kinematic characteristics of a hybrid diesel locomotive in the MathCad program is shown in Pic. 3.

The current of the energy storage device was determined based on the voltage on the TES elements.

Calculation of Currents of the Traction Power Storage

Voltage in the zone of exponential discharge $U_{bat.exp}$ is described by a nonlinear equation [26], V:

$$U_{bat.\,exp} = BattA \bullet e^{-BattB \bullet \Delta q}, \tag{10}$$

where Δq – the decrease in battery capacity at the integration step.

Empirical coefficients were used to determine the parameters of the TES battery in accordance with [26]:

$$BattA = 0{,}084 \bullet U + 0{,}00004, \tag{11}$$

$$BattB = 60{,}693 \bullet Q_{battery}^{-0{,}999}, \tag{12}$$

where U – current value of the battery cell voltage, V.

$Q_{battery}$ – current value of the battery capacity, ampere-hour.

As a result, the voltage U on the battery at the current time during discharge, V:

$$U = BattE0 + U_{bat.\,exp} + U_{bat.\,nom} + U_{bat.\,nom.\,discharge}, \tag{13}$$

when charging, V:

$$U = BattE0 + U_{bat.\,exp} + U_{bat.\,nom} + U_{bat.\,nom.\,charge}, \tag{14}$$

where

$$BattE0 = 1{,}0843 \bullet U - 0{,}00002, \tag{15}$$

$U_{bat.\,nom}$ – voltage component in the zone of the nominal operating mode, V;

$U_{bat.\,nom.\,discharge}$, $U_{bat.\,nom.\,charge}$ – voltage components in the charge or discharge zone, V.

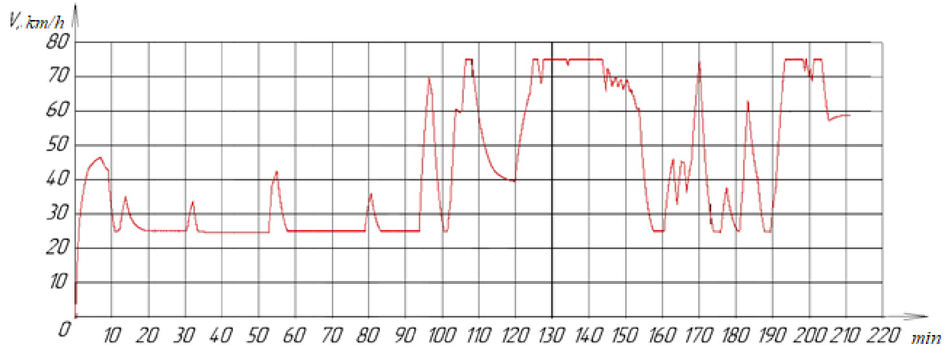
Voltage in the zone of the nominal operating mode of the battery $U_{bat.\,nom}$ is described by the equation, V:

$$U_{bat.nom.} = \frac{-BattK \bullet BattQc}{BattQc - \Delta q}, \tag{16}$$

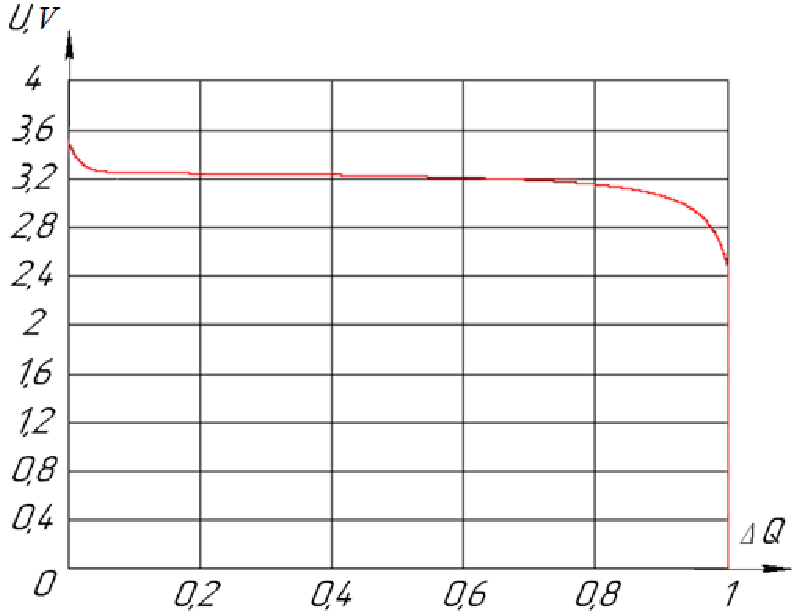
where *BattK, BattQc* – empirical coefficients:

$$BattK = 0{,}006196 \bullet \frac{U}{Q_{battery}}; \tag{17}$$

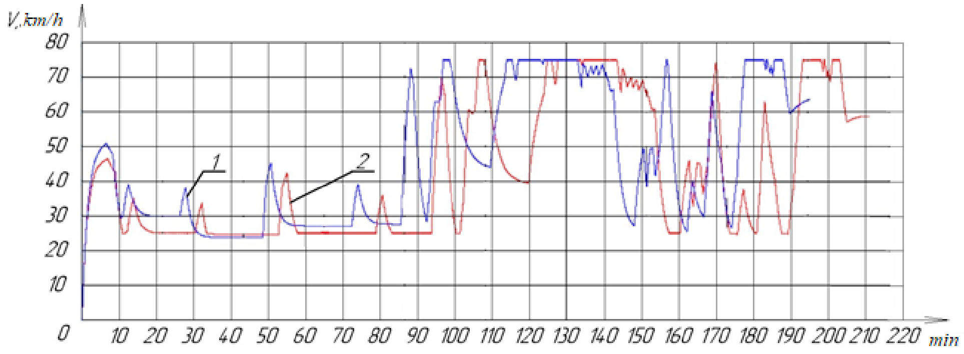
$$BattQc = 1{,}0341 \bullet Q_{battery} - 0{,}0013. \tag{18}$$



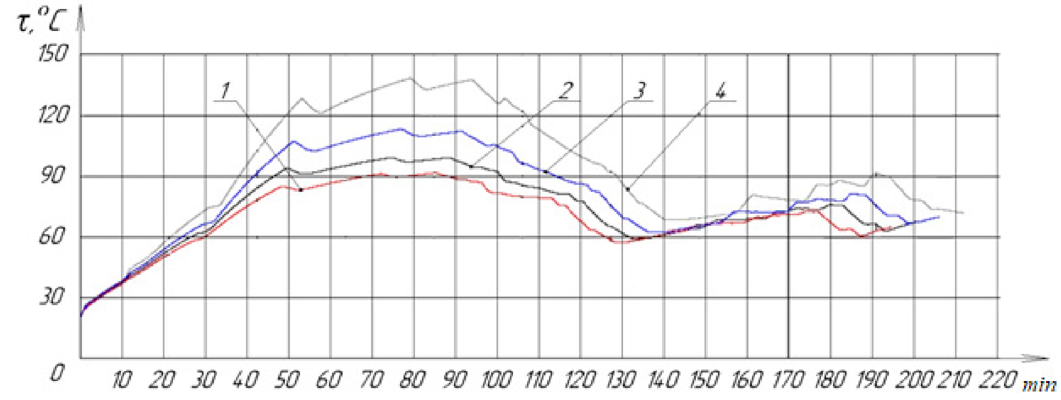
Pic. 3. Change in the speed of a diesel locomotive with a hybrid power plant when moving with a train of 5750 tons of weight along a III class track profile depending on the travel time V = f(t) [performed by the authors].



Pic. 4. Discharge characteristic of the simulated battery U = f(ΔQ) [performed by the authors].



Pic. 5. Change in train speed when moving along a III class track profile depending on the travel time V = f(t):
1 – 2TE116 locomotive with a standard power plant and with a calculated train weight of 4413 tons;
2 – locomotive 2TE116 with a hybrid power plant and with a train weighing 5750 tons [performed by the authors].



Pic. 6. Curves of the temperature rise of the armature winding of the traction electric motors of a hybrid diesel locomotive when moving with trains of increased weight:
1 – a train with a weight of 4600 tons and TES with 1 cell of a traction battery; 2 – a train with a weight of 4900 tons and TES with 6 cells of a traction battery; 3 – a train with a weight of 5250 tons and TES with 11 cells of a traction battery; 4 – a train with a weight of 5750 tons and TES with 18 cells of a traction battery [performed by the authors].

In accordance with [26], the voltage rates were calculated in the nominal mode during the discharge $U_{bat.\ nom.\ discharge}$, V:

$$U_{bat.\ nom.\ discharge} = \frac{-BattK \cdot I_{discharge} \cdot BattQc}{BattQc - \Delta q}, \qquad (19)$$

and when charging $U_{bat.\ nom.\ charge}$, V:

$$U_{bat.\ nom.\ charge} = \frac{BattK \cdot I_{discharge} \cdot BattQc}{\Delta q + BattQc \cdot Battkc}, \qquad (20)$$

where $Battkc = 0{,}1$ – battery constant.

The discharge current with the active load $I_{discharge}$ is calculated according to Ohm's law for a section of the circuit, A:

$$I_{discharge} = U/R, \qquad (21)$$

where R – active resistance of the load, to which the battery is connected, Ohm.

The resulting discharge characteristic of the battery is shown in Pic. 4.

Calculation of Heating of Traction Electric Motors

Calculation of heating of traction electric motors was carried out in accordance with [24] when driving in traction mode, ºC:

$$\tau = \tau_{\infty} \cdot \frac{\Delta t}{T} + \tau_0 \cdot \left(1 - \frac{\Delta t}{T}\right), \qquad (22)$$

when driving in idle mode and pneumatic braking, ºC:

$$\tau = \tau_0 \cdot \left(1 - \frac{\Delta t}{T}\right), \qquad (23)$$

where Δt – the considered time interval, min;

τ_0 – initial temperature at the time of calculation;

τ_{∞}, τ_0 – thermal constants for the traction motor.

Thermal constants τ_{∞}, τ_0 for TEM as a function of motor armature current are given in [24].

Analysis of the Results

A comparison of the kinematic characteristics of movement of trains driven by locomotives with standard and hybrid power plants is shown in Pic. 5.

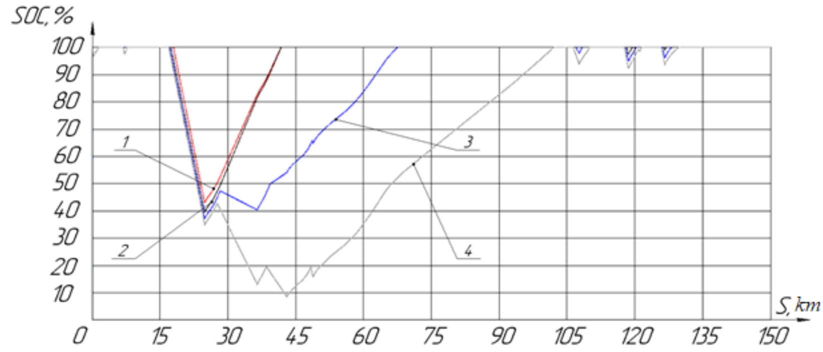
An analysis of operation of the traction electric drive of a locomotive with a hybrid power plant made it possible to calculate the rational parameters of the traction battery to improve the performance of the locomotive.

Equipment of a locomotive with traction battery imposes certain restrictions on operation of power equipment:

1. Current from the electrical storage device causes additional heating of the traction electric motors.

2. In the operating modes of the TES, the modes of deep discharge and increased charge should not be allowed.

3. Weight rate of a train with a hybrid locomotive will be higher than for a serial locomotive; at the same time, it is required to ensure the specified kinematic characteristics of train movement based on the conditions of



Pic. 7. Discharge curves of the traction battery TES of locomotives with a hybrid power plant: 1 – a train with a weight of 4600 tons and TES with 1 cell of the traction battery; 2 – a train with a weight of 4900 tons and TES with 6 cells of a traction battery; 3 – a train with a weight of 5250 tons and TES with 11 cells of a traction battery; 4 – a train with a weight of 5750 tons and TES with 18 cells of a traction battery [performed by the authors].

the map of driving modes and to exclude overheating of the windings of the traction electric motors.

The rational number of electric energy storage cells is calculated from the conditions of normal operation of the locomotive.

Pic. 5 shows that the choice of the right number of battery cells makes it possible to ensure movement of the locomotive through a given section at a calculated speed (V_c = 24,2 km/h), even with the weight of the train, exceeding the calculated one by 30 %.

Pic. 6 shows the change in the temperature of the TEM armature winding during movement of a locomotive with a hybrid power plant (with different numbers of traction battery cells). The results obtained make it possible to establish a functional relationship between the weight of the train and the maximum (or average) temperature of the armature winding for a given mode of motion.

The process of discharge-charge of TES during movement of the locomotive has a pronounced dip in the residual capacity (state of charge, SOC) at the calculated upward slope (Pic. 7). The degree of discharge of the TES is determined by the number of cells and the mode of operation of the power equipment of the diesel locomotive.

CONCLUSIONS

Thus, using the developed model, quantitative indicators of the efficiency of using a hybrid diesel locomotive as a traction unit are determined. Using the example of modelling the operating modes of a diesel locomotive 2TE116 with a hybrid power plant with traction batteries of LT-LFP70M type, the following conclusions have been drawn.

1. As a result of using a traction battery on a diesel locomotive, the weight of the train can be reliably increased by 1000 tons (18 %).

2. Due to the increase in the normal weight of the train, the travel time of the train increases by 8 % while maintaining the set value of the design speed of the diesel locomotive.

3. Due to the increase in the normal weight of the train, the total fuel consumption of the diesel locomotive increases by 9 %.

4. Specific fuel consumption per unit of transportation work, kg/10^4 tkm gr, decreases by 10 % due to a significant increase in the weight of the train.

5. The temperature rise of the TEM armature winding varies within the limits established by GOST-2581 state standard (the maximum temperature of the armature winding of traction motors was τ_{max} = 130ºC).

Based on the results presented above, it can be concluded that the use of a hybrid power plant on a locomotive can significantly improve the traction properties of a diesel locomotive.

The conclusions drawn are inherently universal, e.g., can be applied to any locomotives by substituting the numerical values of their characteristics.

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Information about the authors:

Loginova, Elena Yu., *D.Sc. (Eng), Professor at the Department of Electric Trains and Locomotives of Russian University of Transport, Moscow, Russia, ejy-loginova@mail.ru.*

Kuznetsov, Grigory Yu., *Ph.D. student at the Department of Electric Trains and Locomotives of Russian University of Transport, Moscow, Russia, kuznetsov_gy@mail.ru.*

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