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Simulation of the operation of the on-board energy storage in the tractional system of a quarry locomotive

The ways of updating the rolling stock of open-pit railways have been considered and the main methods of using the energy storage on the locomotive for open-pit railways have been determined. A mathematical model has been developed, which includes a model of train movement along the railway section and during maneuvering and a model of energy processes in the traction system with onboard energy storage. Simulations were performed in a cycle that included movement from the crushing plant to the transshipment point with empty dump trucks, maneuvering during loading, movement from the crushing plant to the transshipment point with loaded dump trucks, and maneuvering during unloading. The simulation took into account the limitation of power consumption at the level of 4000 kW. The parameters of the energy storage device were determined, for which Toshiba SCiB 20Ah-HP cells were selected. The power of the energy storage is 3600 kW, and the energy capacity is 414 kWh. The use of modules for the formation of an energy storage device is proposed. It was determined that the energy consumption per work cycle with the selected energy exchange algorithm taking into account electrodynamic braking is about 200 kWh, and the charge reduction per drive cycle is 36%. The service life of the energy storage with the selected cells is estimated at 8 years.

***Keywords**: locomotive, rolling stock, modeling, energy storage*

Introduction . According to explored iron ore reserves, 18% of the world's reserves are located in Ukraine, and in terms of iron content, Ukraine's share is 10.5-11% of the world's reserves [1]. The transition to "green" steel requires the use of technologies that minimize CO2 emissions at all stages of extraction and processing of iron ore raw materials. In this context, the use of electrified railway transport at mining and beneficiation plants for the transportation of raw materials corresponds to the general direction of the "green course". Taking into account the fact that the cost of transportation with electric traction is lower compared to diesel traction, electric transportation also reduces the cost of final products. In addition, the introduction of powering the electric traction system of open-pit railways from renewable energy sources will make it possible to approach transportation with zero CO_2 emissions.

For the effective use of electric traction, a fundamental renewal of the rolling stock of electrified quarry railways is necessary. At present, domestic quarries mainly operate traction units produced by JSC "Dnipro Electric Locomotive Plant" (Dnipro). The long period of operation of the traction rolling stock and its traction-energy indicators, which do not correspond to the conditions of operation, determine the urgency of the task of creating a modern locomotive for open-pit railways.

Analysis of recent research and problem statement. Rail transport in quarries is widely used in the CIS countries. Renewal of rolling stock is carried out both by purchasing new traction units and by modernizing old models.

At present, the renewal of electric vehicles in Ukrainian enterprises is carried out by modernizing existing traction units [2-4]. The most progressive can be considered the modernization of the traction unit OPE1A(M), which involves the replacement of the outdated traction-controlled rectifier and part of the contact apparatus, the compressor unit, and the use of a microprocessor control system. This contributes to increasing the reliability of the traction unit and improving the working conditions of the locomotive crew. However, the preservation of traction commutator motors does not allow improvement of traction-energy characteristics, and the use of zone-phase control of the input converter makes it impossible to improve energy consumption from the traction network. In addition, the uncontrolled electric drives of motor fans for cooling traction electrical equipment lead to inefficient energy consumption by auxiliary systems. Another drawback is the too low traction properties of the traction unit in an autonomous mode of operation in the case of powering by the diesel section (if it is available). In the absence of a diesel section, movement in non-electrified parts of the route is impossible. It is worth noting that such technical solutions are also used on new traction units. At the same time, a traction unit NPM2 equipped with a traction electric drive based on asynchronous electric motors was developed and manufactured. This corresponds to modern approaches to the creation of locomotives. This traction unit has increased traction and energy properties.

Domestic developers worked out a project of a traction unit with an asynchronous electric drive [5,6]. It is indicated that their use will allow for a change in the structure of the locomotive fleet. As a result, a significant decrease in energy consumption during the operation of new traction units is predicted. The life cycle cost of such traction units is significantly lower compared to the life cycle cost of advanced traction units equipped with a traction electric drive with commutator motors.

In [7], the authors proposed an electric locomotive with an asynchronous traction electric drive and an on-board energy storage device. Based on observations of the operation of traction units at domestic mining and beneficiation plants, the use of an on-board storage device is proposed not only for the accumulation of energy during electrodynamic braking but also for powering its traction system when the power of the traction network is limited [8]. In [9], the energy required to maneuver the traction unit during loading at the overload point and unloading at the crushing plant has been estimated. The use of energy storage devices to ensure maneuvering of mainline locomotives ("last mile" function) is becoming widespread on modern locomotives [10, 11]. Another way of using onboard energy storage devices is powering the traction system of electric rolling stock while moving through non-electrified areas [12-14]. In practice, this concept is applied to rolling stock [15-17]. This approach can also be applied to the rolling stock of quarry railway transport. This will allow, firstly, to move through areas where the deployment of a catenary network is impractical or impossible. Secondly, it will allow the movement with traction during passing through neutral inserts and car crossing roads, over which there is no contact wire. The last-mentioned are arranged for the movement of quarry dump trucks. The train follows such sections with the pantograph lowered, in virtue of inertia. As a result, the speed of movement decreases. At the end of the section without a contact wire, traction mode is established. And since the speed of the train has decreased, the train accelerates to the permissible speed. This leads to additional energy consumption. As we can see, the energy storage can be used for various purposes. It is necessary to carry out modeling, which allows evaluation of the traction systems and energy storage parameters for taking into account all before mentioned aspects.

The purpose and tasks of the research. The purpose of the work is to study the operation of the traction system and on-board energy storage of the locomotive for mining railways. The tasks of the article consist of modeling and researching the processes of energy exchange in the traction system of a mining locomotive equipped with onboard energy storage.

Research materials and methods. The locomotive data given in [7] has been used for the research. The research will be conducted by solving the traction task for the section of the road, as well as determining the movement indicators during maneuvering [9].

The mathematical model of train movement on the section of the track was developed based on the provisions of the theory of locomotive traction [18]. The motion is described by a system of equations in the following form

$$\begin{cases} \dfrac{dV}{dt} = \dfrac{\xi}{\rho}\left(f_L - (w_L + w_W) - b \right); \\ \dfrac{dS}{dt} = V, \end{cases} , \qquad (1)$$

where ξ – the coefficient that takes into account the units of measurement;
V – train speed;
t – time;
S – distance;
ρ – the coefficient that takes into account the rotation of the parts of the crew part;
f_L – the specific tangential force of the locomotive in the mode of traction or electrodynamic braking;
w_L – the specific force of resistance to the movement of an electric locomotive;
w_W – the specific force of resistance of moving wagons;
b– specific braking force of pneumatic brakes.

The specific tangential force of the locomotive in the mode of traction or electrodynamic braking was determined by the expression

$$f_L = \frac{F_L}{\sum_{k=1}^{s} M_{Lk} + \sum_{j=1}^{n} M_{Wj}}, \qquad (2)$$

where F_L– the tangential force of the electric locomotive in traction mode or electrodynamic braking mode;
M_{Lk} – mass of the locomotive section;
s – number of locomotive sections;
M_{Wj} – dump truck mass;
n – the number of dump trucks.

Specific resistance to movement was calculated as

$$w = w_0 + w_a, w = w_0 + w_a, \qquad (3)$$

where w_0 – the main specific resistance of the train;
w_a – additional specific resistance of the train.

The main specific resistance of the train is determined by the expression

$$w_0 = \frac{w_L \sum_{k=1}^{s} M_{Lk} + w_w \sum_{j=1}^{n} M_{Wj}}{\sum_{k=1}^{s} M_{Lk} + \sum_{j=1}^{n} M_{Wj}}, \tag{4}$$

where w_L – the main specific resistance of the locomotive movement;
w_w – the main specific resistance to the movement of thoughts.

The main specific resistance during the movement of the locomotive for the link track is determined by the following expression [18]

$$w_L = \begin{cases} \left(2.6 + 0.07V + 0.0025V^2\right)g, F_L > 0 \\ \left(2.8 + 0.023V + 0.00075V^2\right)g, F_L \le 0 \end{cases}, \tag{5}$$

where V – speed of movement, expressed in km/h;
g – acceleration of free fall, which is 9.81 m/s^2.

The main specific resistance to the movement of loaded dump trucks of type 2VC105 is determined by the expression

$$w_w = \left(3.6 + 0.04 \cdot V\right) \cdot g,. \tag{6}$$

The main specific resistance to the movement of empty dump trucks type 2VC105 is determined by the expression

$$w_w = \left(4.8 + 0.05 \cdot V\right) \cdot g. \tag{7}$$

The additional specific resistance to the movement of the train was determined by the expression

$$w_a = w_i + w_r + w_s + w_e + w_t, \tag{8}$$

where w_i – additional specific resistance of the movement caused by the slope;
w_r – additional specific resistance of the movement in curved areas;
w_s – additional specific resistance while the start of the moving;
w_e – additional specific resistance of the forward movement of wagons;
w_t – additional specific resistance caused by conditions of the railway track.

Changes in the value of additional resistance caused by changes in climatic conditions were not taken into account in the calculations.

Additional resistance during moving on a slope was determined as

$$w_i = i \cdot g,, \tag{9}$$

where i – slope of the site, expressed in thousandth.

Specific additional resistance from movement along a curved section of the track was determined by the expression

$$w_r = \frac{700}{R} \cdot g, \tag{10}$$

where R – the radius of the curve.

Additional resistance during movement was determined by the expression

$$w_s = \frac{\left(\frac{20}{q_l}\right)\sum_{k=1}^{s} M_{Lk} + \left(\frac{20}{q_w}\right)\sum_{j=1}^{n} M_{Wj}}{\sum_{k=1}^{s} M_{Lk} + \sum_{j=1}^{n} M_{Wj}} g, \tag{11}$$

where q – axle load of a rolling stock unit, expressed in tons.

Additional resistance during moving was taken into account at a speed of less than 10 km/h.

The additional specific resistance from the forward movement of the wagons is determined by the expression

$$w_e = \left(0.15 + \frac{|i|}{1000}\right) \cdot w_0. \tag{12}$$

Additional resistivity due to track condition

$$w_t = \left(k_{tr} - 1\right) \cdot w_0, \tag{13}$$

where k_{tr} – coefficient that takes into account the technical condition of the track. In calculations, it is taken equal to 1.1.

Control of traction force or electrodynamic braking is carried out so, that the permissible speed is maintained. There are no limits on the intensity of changes in traction and braking. Expressions (1)-(13) make up a mathematical model of train movement along a section of the track.

The mathematical description of the processes in the traction system of a mining electric locomotive equipped with an onboard energy storage system has been developed taking into account [8, 9, 19].

In traction modes, the power consumed from the energy storage is determined by the expression

$$P_{ES} = \begin{cases} 0, & \left(P_{TD} + P_{AUX}\right) \le P_{IN}; \\ \left(P_{TD} + P_{AUX}\right) - P_{IN}, & \left(P_{TD} + P_{AUX}\right) > P_{IN}, \end{cases} \tag{14}$$

where P_{TD} – the power consumed by the traction electric drive from the intermediate circuit;
P_{AUX} – the power consumed by auxiliary systems of the electric locomotive;
P_{IN} – the maximum power that can be drawn from the input converter.

In expression (14), it is assumed that the storage capacity is sufficient to power the traction system of the locomotive ($P_{ESN} \ge P_{TD} + P_{AUX} - P_{IN}$)().

The power consumed by the traction electric drive can be simply determined by the expression

$$P_{TD} = \frac{P_L}{\eta_{TD}}, \tag{15}$$

where P_L – tangent power of the electric locomotive;
η_{TD} – the efficiency of the traction electric drive is 0.9.

For refined calculations, it is necessary to use the efficiency dependence calculated for the entire traction area.

Due to the significant power and capacity of the onboard energy storage system, it will have a modular composition. Assuming that the models have an identical design and operating modes, we will consider the operation of one module in the future.

The power that is consumed from the storage system module is defined as

$$P = \frac{P_{E\Sigma}}{m \cdot \eta_{B}},\ P = \frac{P_{ES}}{m\eta_{B}}, \tag{16}$$

where m – the number of modules that are connected in parallel;
η_B – the efficiency of the matching converter, which for simplicity is taken as a constant value equal to 0.97.

The voltage of the energy storage is determined by the expression

$$U = E - R \cdot I, \tag{17}$$

where E – EMF of the module;
R – equivalent electrical resistance of the cells of one module;
I – current of one energy storage module.

The EMF of the module is determined by the expression

$$E = N_s \cdot E_{cell}, \tag{18}$$

where N_s – the number of cells connected in series;
E_{cell} – EMF of one cell.

Equivalent electrical resistance of elements of one module

$$R = R_{cell} \cdot \frac{N_s}{N_p}, \tag{19}$$

where R_{cell} – electrical resistance of one cell;
N_p – the number of parallel branches in the module.

The EMF of the cell E_{cell} and the resistance of the cell R_{cell} depend on the degree of discharge, temperature, number of spent cycles, etc. [20-22]. For estimated calculations, it is sufficient to take into account the dependence of EMF on the degree of discharge. The resistance of the cell can be assumed as constant. For modeling, the R-int cell model is adopted [23-25].
The dependence of EMF on the degree of discharge can be described analytically [26,27]. It is possible to use tabular data and interpolation procedures when performing numerical calculations. This approach will be used in the simulation.

The current of the storage module is determined by the expression [28, 29]

$$I = \frac{E - \sqrt{E^2 - 4P \cdot R}}{2 \cdot R}. \tag{20}$$

In the simplest case, the estimation of the degree of charge of the battery can be performed by determining the degree of charge of one cell [30]. The calculated ratio looks like this

$$SOC_t = SOC_0 - k\frac{1}{Q_{cell}}\int_0^{\tau} \eta_C \left(\frac{I}{N_p}\right) dt, \tag{21}$$

where SOC_0 – degree of charge before discharge;
τ – duration of the discharge stage;
Q_{cell} – nominal capacity of one cell;
η_C – Coulomb efficiency is assumed equal to 1 according to [30];
k – coefficient, which takes into account the units of measurement.

Let`s neglect Discharge losses. Charging of the energy storage device while driving is carried out in the mode of electrodynamic braking.

The power supplied to the on-board energy storage system is determined by the expression

$$P'_{ES} = \begin{cases} 0, \quad P'_{TD} \le P'_{AUX}; \\ P'_{TD} - P'_{AUX}, \quad 0 < \left(P'_{TD} - P'_{AUX}\right) \le P_{ESN}; \\ P_{ESN}, \quad \left(P'_{TD} - P'_{AUX}\right) > P_{ESN}, \end{cases} \tag{22}$$

where P'_{TD} – the power supplied to the intermediate circuit from the traction electric drive;
P'_{AUX} – the power consumed by the auxiliary systems of the electric locomotive in the mode of electrodynamic braking.

The power supplied to the intermediate circuit from the traction electric drive is determined by the expression

$$P'_{TD} = \eta'_{TD} P_L, \tag{23}$$

where η'_{TD} – the efficiency of the traction electric drive in the electrodynamic braking mode is 0.9.

The power that is transferred to one module of the energy storage system is determined by the expression

$$P' = \frac{\eta'_B \cdot P'_{ES}}{m}, \tag{24}$$

where η'_B – The efficiency of the matching converter, which for simplicity is taken as a constant value equal to 0.97.

The storage voltage is determined by the expression

$$U = E + R \cdot I', \tag{25}$$

where I' – current of the module during charging.

The current of the storage module is determined by the expression [28, 29]

$$I' = \frac{E - \sqrt{E^2 - 4P \cdot R}}{2 \cdot R}, \; . \tag{26}$$

The degree of charge is determined by the expression

$$SOC_t = SOC_0 + k \frac{1}{Q_{cell}} \int_0^{\tau} \eta_C \left(\frac{|I'|}{N_p} \right) dt. \tag{27}$$

Expressions (14)-(27) make up a mathematical model of energy exchange processes in a traction system with onboard energy storage.

Motion simulation during maneuvering is carried out according to the method given in [9]. During maneuvering, energy is only consumed from the accumulator, therefore energy processes are described by expressions (14)-(21).

The developed mathematical model will provide a study of the operation of the traction system and the energy storage during the movement cycle, which consists of movement from the crushing plant to the overloading point, maneuvering at the overloading point during ore loading, movement from the overloading point to the crushing plant, and maneuvering during unloading.

Research results. *Input data.* The study was carried out for traffic conditions at PrJSC "Poltava Ferrexpo Mining" [7]. The movement of a train with a locomotive equipped with an asynchronous traction electric drive and an on-board energy storage device is studied.

The energy storage parameters are determined according to [31]. Previous studies [8,9] show that energy storage must be optimized for high power and relatively small capacity. Therefore, it is accepted that the SCiB 20Ah-HP cell manufactured by Toshiba will be used in the energy storage system [32]. The technical parameters of the cell are listed in Table 1

Table 1. **Technical parameters of the cell SCiB 20Ah-HP cell [32]**

Parameter	Value
Capacity, Ah	20
Capacity, kWh	46
Nominal voltage, V	2.3
The highest charging voltage, V	2.9
The lowest discharge voltage, V	1.5
C-rate for long modes	5
C-rate for short-term modes	10
Power (SOC50%, 10 s, 25 ºC), W	1900
The electrical resistance of the cell, Om	$0.6 \cdot 10^{-3}$
WxLxH, m	0.116x0.022x0.106
Weight, kg	0.545

The dependence of the no-load voltage on the degree of discharge is shown in Fig. 1

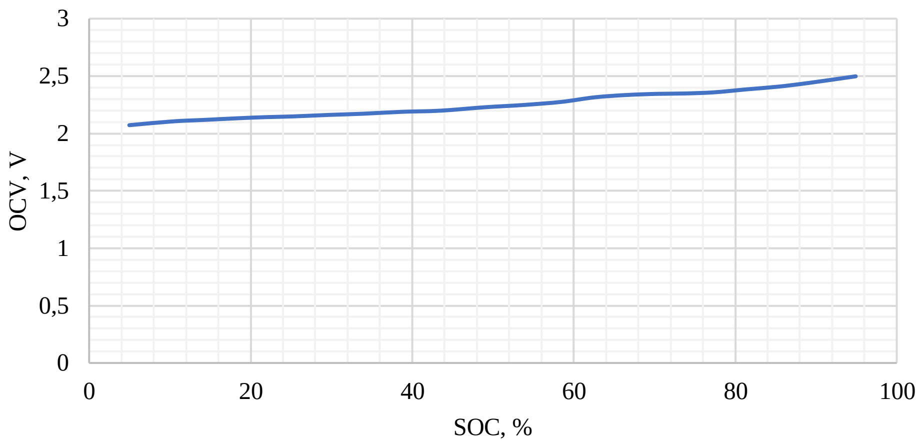


Fig.1. **Dependence of open-circuit voltage (OCV) on the degree of SOC discharge [32]**

Calculations of energy storage parameters [31] are given below. Preliminary calculations show that the energy change in the accumulator is 192 kW*h. We will assume that the voltage of the constant voltage circuit is 900 V. Authors will take into account that when the SOC changes in the range of 5...95%, the cell voltage changes from 2.1 V to 2.5 V in the calculations. We will take these values as the lowest and highest voltage.

The number of serially connected elements is determined by the expression

$$N_s = \frac{U_{dc}}{U_{ch}}, \tag{28}$$

where U_{dc} – intermediate circuit voltage;
U_{ch} – the voltage at which the charging of the element ends, equal to 2.5 V.

Then the number of serially connected elements will add up N_s=360.

In [9] it was determined that the power of the energy storage should be 3540 kW, but accepted equal to 3600 kW.

The number of parallel branches, determined from the condition "by power", is determined by the expression

$$N_2 = \frac{P_{OESS}}{N_S U_{dis} I_{cell}}, \tag{29}$$

where P_{OESS} – nominal power of the energy storage;
U_{diss} – cell discharge voltage;
I_{cell} – permissible charge/discharge current, accepted as 200 A.

After performing the calculation, the number of parallel branches is 24.

The capacity of the on-board SNE is determined by the formula

$$E_{OESS} = \frac{\Delta E}{(SOC_1 - SOC_2)k_1 k_2}, \tag{30}$$

where ΔE – storage capacity;
SOC_1 – the highest degree of charge in the operating mode, accepted as 90%;
SOC_2 – the smallest degree of discharge in working mode, accepted as 10%;
k_1 – the coefficient that takes into account the decrease in the capacity of the OESS during the period of operation, we will take 0.9;
k_2 – the coefficient that takes into account the decrease in the capacity of the OESS with a change in temperature, self-discharge, etc., we will take 0.95.

After performing the calculations, it was determined that the capacity of the onboard energy storage system is 285 kWh.

The number of parallel branches, determined from the "by energy" condition, is determined by the expression

$$N_1 = \frac{E_{OESS}}{N_S E_{cell} k_{ch}}, \tag{31}$$

where k_{ch} – a coefficient that takes into account the decrease in energy, which the energy storage element can store during charging with a current that exceeds the optimal value, accepted equal to 0.9.

After the calculation, it was found that the number of branches is 20.

Finally, it has been assumed that, taking into account the reserve, the number of parallel branches of the drive will be N_p=25 [31].

It is advisable to form the energy storage from separate modules because the power of the energy storage is 3600 kW. Let's assume that there will be 5 such modules (N_m=5). Each module will then have five parallel-connected branches, each of which will have 360 series-connected cells.

The total energy capacity of the accumulator is determined by the expression

$$E_{ES} = \frac{E_{cell} N_m N_s N_p U_{cell}}{1000}. \tag{32}$$

After calculations, we will get a result 414 kWh.

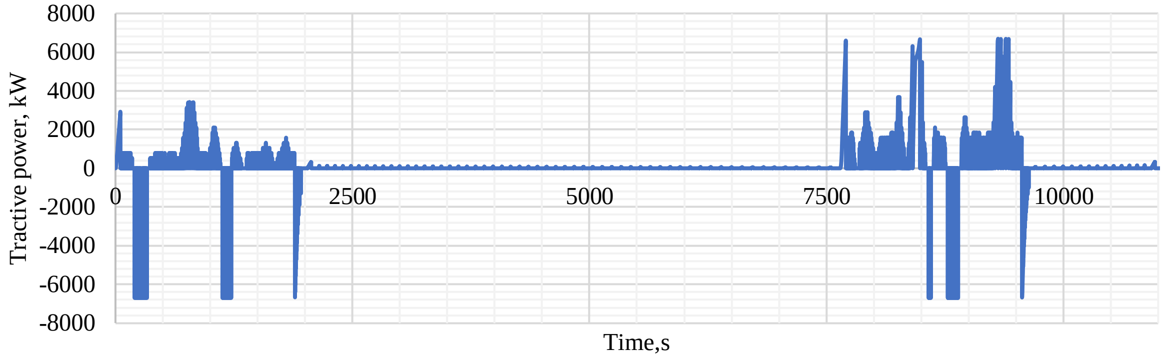
Table 2 shows the dependence of the idling voltage on the degree of discharge for one module.

The equivalent resistance of the module, calculated according to (19), is 0.0432 Ohm.

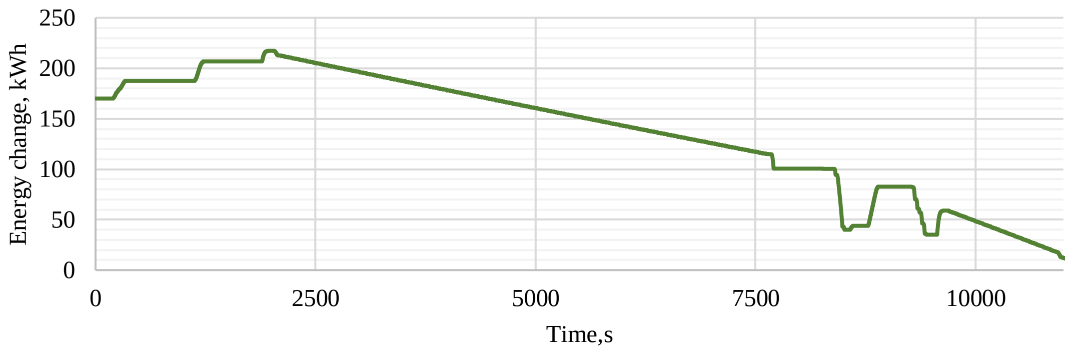
Table 2. **Dependence of OCV open-circuit voltage on SOC for one module**

Parameter	Value										
SOC, %	5	10	14	18	22	25	30	34	39	43	49
OCV, V	746	758	763	767	771	773	778	782	788	791	802
SOC, %	54	58	63	66	70	74	77	81	85	89	95
OCV, V	809	819	833	841	844	845	849	858	867	879	899

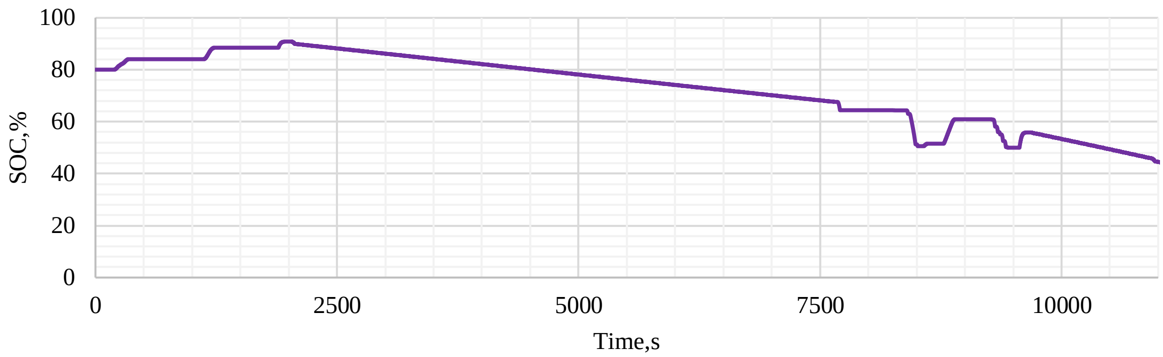
Simulation results. Fig. 2, a shows the time dependence of the tangential power, Fig. 2, b shows the time dependence of the energy change in the accumulator, Fig. 2, c – the time dependence of the change in the degree of charge at the initial charge value of 80%.



a)



b)



c)

Fig.2. **Time dependences of traction system parameters**

Depending on the tangential power (Fig. 2, a), four characteristic stages can be distinguished. From the beginning of movement to 2000 s, movement is carried out along the section of the path. The presence of negative values in the power curve is characteristic, which indicates electrodynamic braking. Accordingly, on the time dependence of the change in energy of the accumulator (Fig. 2, b) and the dependence of the discharge degree (Fig. 2, c), an increase in the corresponding values is observed. From 2000 s to 7600 s, the stage of maneuvering under load continues. During this stage, the power source is energy storage, so the energy and the degree of charge of the energy storage are reduced. From 7600 s to 9600 s, traffic continues from the transshipment point to the crushing plant. During this interval, stages of intensive reduction of energy and the degree of charge of the accumulator are observed. This is caused by the consumption of energy from the storage to compensate for the power limitation of the input converter. At the same time, electrodynamic braking is carried out at this stage, which leads to an increase in energy in the storage device. From 9600 s to 11000 s, there is unloading at the crushing plant, where energy is only consumed from the accumulator.

In general, energy storage is discharged from 80% to 44% because the capacity of the battery exceeds the energy required for movement. This is related to the characteristics of the cells selected for the storage device. On the other hand, with this type of discharge, one charge will be enough to carry out two cycles of movement.

The duration of one movement cycle is about 3 hours. Assuming that 6 cycles of movement are carried out during the day, the authors got that there should be three charging of the energy storage. Let the locomotive work for 350 days during the year. Then there will be about 1000 cycles per year. According to the information of the cell manufacturer [32], after 8000 discharge/charge cycles, the initial capacity of the cell practically does not change. Therefore, the duration of use of the storage device can be estimated at 8 years.

Conclusions. A mathematical model was developed and the simulation of energy exchange processes in the traction system of a mining locomotive equipped with on-board energy storage was carried out. The mathematical model combines the model of train movement along the railway section and during maneuvering and the model of energy exchange with an onboard energy storage device. The parameters of the Toshiba SCiB 20Ah-HP cell-based energy storage device have been defined. It has been determined that the energy consumption during the work cycle is about 200 kWh, and the storage battery charge is reduced by 36%. The storage life is estimated at 8 years.

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Моделювання роботи бортового накопичувача енергії у тяговій системі кар'єрного локомотиву

Розглянуто шляхи оновлення рухомого складу кар'єрних залізниць та визначені основні способи застосування накопичувача енергії на локомотиві для кар'єрних залізниць. Розроблено математичну модель, яка включає модель руху поїзда по ділянці залізниці та упродовж маневрування і модель енергетичних процесів у тяговій системі з бортовим накопичувачем енергії. Виконано моделювання у циклі, який включає рух від дробарної фабрики до пункту перевантаження з порожніми думкарами, маневрування при навантаженні, рух від дробарної фабрики до пункту перевантаження з навантаженими думпкарами та маневрування при розвантаженні. При моделюванні враховано обмеження споживаної потужності на рівні 4000 кВт. Визначено параметри накопичувача енергії, для якого обрані комірки Toshiba SCiB 20Ah-HP cell. Потужність накопичувача енергії складає 3600 кВт, енергоємність – 414 кВт·год. Запропоновано застосування модулів для формування накопичувача енергії. Визначено, що споживання енергії за цикл роботи при обраному алгоритмі енергетичного обміну з урахуванням електродинамічного гальмування складає близько 200 кВт·год, а зменшення заряду за цикл руху становить 36%. Термін служби накопичувача енергії з вибраними комірками оцінюється у 8 років.

Ключові слова: *локомотив, рухомий склад, моделювання, накопичувач енергії*