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Increasing the energy efficiency of the multi-motor traction electric drive of an electric locomotive for railway quarry transport

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ABSTRACT

The improvement of the energy efficiency of an electric locomotive for railway quarry transport with a multi-motor traction electric drive while disconnection of the traction electric motors has been investigated. Mathematical models of the movement of the train on the track section and during manoeuvring, as well as the model of the energy exchange processes in the traction electric drive, which are used to perform the traction task when the train moves on the track section, have been developed. Through mathematical modelling, the calculation of energy during movement on the track section was performed with all connected and partially disconnected electric motors. When part of the electric motors are disconnected, the energy consumption is reduced by 10% for the cargo half-passage, and by 27% for the empty direct passage. The reduction of energy consumption with disconnected electric motors during manoeuvring has been noticed. The obtained results confirm the expediency and necessity of conducting research aimed to increase the energy efficiency of the multi-motor traction electric drive of an electric locomotive for railway mining transport.

1. Introduction

The need to reduce the impact on the environment and the increase in the cost of energy carriers encourage the research and implementation of energy-saving technologies both in the operation of existing rolling stock and in the creation of new locomotives.

The traction electric drive of the electric rolling stock is a multi-motor electric drive. An effective way to reduce the total energy consumption in such electric drives is to optimize the load between electric motors depending on the operating mode [1,2,3].

Currently, the problem of determining the optimal loads of electric motors in the multi-motor electric drive of vehicles is largely due to the use of energy storage devices as the main energy sources [4,5,6]. In works [7,8], a comparison of energy consumption when using a single- and multi-motor electric drive with different electric motors was performed. The work [7] is devoted to the study of a multi-motor electric drive of an urban electric bus. The use of several traction asynchronous electric motors with a power of 30…45 kW instead of one with a power of 90 kW reduces the total losses in the traction electric motors and, accordingly, energy consumption for movement have been highlighted by authors. Depending on the number and power of electric motors, as well as bus driving modes, the reduction in energy consumption will be 10…45%. In [8], a comparison of the energy consumption of an electric vehicle equipped with a transmission with one and two electric motors has been performed. The use of a two-motor electric drive combinate with a new topology of the transmission ensured an increase of efficiency by more than 5% in established operating modes determined according to the results of the study. In work [9], the traction electric drive with two electric motors has been optimized. The parameters of the gear unit, which provides the best results from the use of a two-motor traction electric drive have been determined by the authors. In [10], the operation of an electric drive with three electric motors was studied. A transmission scheme with three electric motors with a power of 15 kW instead of a transmission with one motor with a power of 45 kW is proposed in the article. The use of a transmission with three electric motors has provided a loss reduction of 1.8% compared to the basic transmission with one electric motor for test task. It should be noted that traction electric drives of wheeled electric transport are investigated in these works. The optimization of load modes and the corresponding structure of the traction electric drive of rail transport have been studied, for example, in [11].

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Domestic studies of the optimization of energy consumption by multi-motor electric drives of rail rolling stock are presented in works [12–14], which theoretically show the expediency of disconnected traction electric motors during moving freight electric locomotives with low-mass trains. The results of experimental studies of the energy consumption of the main line electric locomotive with an asynchronous traction electric drive are given in [15], according to which the reduction of energy consumption when the traction electric motors are disconnected is confirmed: a 15% reduction of energy consumption was achieved during a test passage with 4 electric motors running continuously instead of 8.

Thus, it follows from the above that during using a multi-motor electric drive, it is possible to reduce energy consumption by rationally distributing of the load between electric motors.

In [16], the modes of operation of the traction electric drive of the locomotive for quarry railway transport were analyzed and it was established that in the traction mode the locomotive works with a power of no more than 1500 kW for about 70% of the duration of a half-passage when a loaded train is moving. During movement with empty wagons, the power of the electric locomotive does not exceed 1000 kW on 80% of the duration of the half-passage. At the same time, the nominal power of the locomotive is 6700 kW. In the electrodynamic braking modes (EBD) during movement with empty wagons, the power does not exceed 4500 kW (67% of the nominal), and for more than 60% of the time of operation in this mode, the power does not exceed 2500 kW (37% of the nominal). The traction electric drive works with a load that is 15…40% of the nominal for a significant part of the time. Taking into account the decrease in the efficiency of an asynchronous electric motor when its power is reduced, a decrease in the efficiency of the traction electric drive as a whole is expected. To eliminate this, disconnection of the part of the traction electric motors can be used, which will cause the work of the connected electric motors with a power close to the nominal one. As a result, the efficiency of electric motors will increase and energy consumption for traction will decrease.

The purpose of the work is to study the possibility of increasing the energy efficiency of an electric locomotive for railway quarry transport with a multi-motor traction electric drive with using of disconnection of traction electric motors.

2. Mathematical model

Mathematical modeling was used to determine energy consumption parameters. Determination of train movement indicators was carried out by solving the traction task, which was supplemented by a model of energy exchange in the traction electric drive [8,14,17].

Two modes of operation are distinguished during the train movement, movement on a section of the track, and maneuvering, the mathematical description must be performed separately. This is related to the low accuracy of the description of the maneuvering processes. Therefore, directly solving the traction task for movement on a section of the railway can be executed.

2.1. The model of traffic on the railway section

It is assumed that the train is modeled as a chain of solid bodies that are connected by a rigid connection during the creation of the train movement model on a section of the railway. This increases the accuracy of calculations of the resistance forces to movement [18]. The system of equations of motion has the following form

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

where ξ – the coefficient taking into account the units of measurement; V – train speed; t – time; S – path; ρ – the coefficient that takes into account the rotation of the locomotive underframe parts; f_L – a specific tractive effort of the locomotive in traction mode or electrodynamic braking; w_L – a specific effort of resistance to the motion of an electric locomotive; w_W – a specific effort of moving wagons resistance; b – a specific braking effort of pneumatic brakes.

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

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

where F_L – the tractive effort of the locomotive in traction or electrodynamic braking mode; M_{Lk} – the mass of the locomotive section; s – number of locomotive sections;M_{Wj} – the mass of the wagon, n – number of wagons.

The tractive effort of the locomotive can become a value in the traction area [19]. In the case of a multi-motor electric drive with an individual drive of wheel pairs, under the condition of the same load of the electric motors, the tractive effort was determined by the following expression

$$F_L = F_D N_D \tag{3}$$

where F_D – tractive effort is realized by one driven axle; N_D – the number of working electric motors of the electric locomotive.

The specific resistance to movement of the locomotive and wagons was determined by the expression

$$w = w_o + w_i + w_r + w_p + w_b \tag{4}$$

where w_o– the main specific resistance to movement, w_i– additional specific resistance to movement from the slope; w_r– additional specific resistance to movement from movement along a curve; w_p– additional specific resistance to movement from the forward movement of wagons; w_b – additional specific resistance during the movement of the train.

Related to the possibility of operation of the electric locomotive with the disconnected electric motors, its main specific resistance was determined by the following expression

$$w_o = w'_o \frac{N_{D1}}{N_{M1}} + w'_x \left(1 - \frac{N_{D1}}{N_{M1}}\right) \tag{5}$$

where w'_o– the main specific resistance of the movement of the electric locomotive in traction mode; w'_x– the main specific resistance of the electric locomotive in coasting mode; N_{M1} – the total number of motored axles of the sections; N_{D1} – the number of working traction electric motors of the section.

Calculation expressions for determining the specific resistance and recommendations for use are given in [20,21].

As mentioned above, to clarify the calculation of resistance effort, the train was modeled as a chain of solid bodies. In this case, the specific resistance from the slope and when moving along the curve was determined for each wagon or section of the electric locomotive separately. At the same time, it is assumed that the car is completely on the section of the railway if its center of mass is within the section.

The train motion model is supplemented with a tractive effort regulator in the following form

$$F = \begin{cases} F_L, & V < (V_{\max} - \Delta V) \\ 0, & (V_{\max} - \Delta V) \leqslant V < V_{\max} \\ -F_L, & V > (V_{\max} + \Delta V) \end{cases} \tag{6}$$

where $V_{\max}$ – permissible speed of movement; ΔV – zone of “insensitivity”.

At the same time, the intensity of the tangent change depends on the current speed and was determined by the expression

$$\left(\frac{\Delta F}{\Delta t}\right) = \begin{cases} \left(\frac{\Delta F}{\Delta t}\right)_{\max}, & V < V_{\min} \\ k_F\left(\frac{\Delta F}{\Delta t}\right)_{\max}, & V_{\min} \leqslant V < (V_{\max} - \Delta V) \end{cases} \tag{7}$$

where $V_{\min}$ – minimum adjustment speed; k_F – intensity reduction factor; $\left(\frac{\Delta F}{\Delta t}\right)_{\max}$– the maximum intensity of the change in speed of the tractive effort.

In the mode of electrodynamic braking, the tractive effort increases with maximum intensity. This description of the change in tangential force in a certain sense corresponds to the manual control of an electric locomotive.

The tractive power was determined by the expression

$$P_L = F_L V \tag{8}$$

Thus, expressions (1)-(8) constitute a mathematical model of train movement on a section of the railway.

2.2. The model of train movement during maneuvering

The model of train movement during maneuvering causes difficulties since the mode of movement when loaded or unloaded is jolts for moving cars. The direct solution of the traction task for this regime is associated with difficulties due to inaccuracies in the mathematical description of the effort of motion resistance at speeds close to zero. Therefore, we will evaluate the tractive power based on the following considerations.

The effort of resistance to the motion of the train is determined by the expression

$$F_{Wi} = \sum_{k=1}^{s} M_{Lk}\left(w'_{Lk} + w_b\right) + \sum_{j=1}^{n} \left(M_{Tj} + M_{Ri}\right)\left(w'_{Wj} + w_b\right) \tag{9}$$

where w'_L – specific resistance to the movement of the electric locomotive during maneuvering; w'_W – specific resistance to movement of wagons during maneuvering; M_{Tj} – tare weight of one wagon; M_{Ri} – a mass of ore that is loaded or unloaded.

If necessary, Eq.(10) can take into account other components of the train's specific resistance in case of need. The specific resistance is determined at the speed that the train reaches at the end of the thrust.

If we assume that the speed of the train increases linearly during the thrust, then the duration of the shock can be determined by the expression

$$T_i = \sqrt{\frac{2M_i L_i}{F_{Mi} - F_{Wi}}} \tag{10}$$

where F_{Mi} – a tractive effort of the electric locomotive during maneuvering on the i-th movement. When calculating, it is advisable to accept this effort as constant; M_i – the mass of the train at the i-th shock; L_i – the path traveled by the train at the i-th thrust under traction.

The tractive effort of the electric locomotive during maneuvering must exceed the resistance force of the loaded train

$$F_{Mi} > F_{Wi} \tag{11}$$

and it is expedient to accept it equally a constant amount.

Then the dependence on speed in time is described by the expression

$$V_i(t) = a_i t, \quad 0 < t < T_i \tag{12}$$

where a_i – acceleration of the train during the i-th movement.

Acceleration of the train during the i-th movement, which is determined by the expression

$$a_i = \frac{F_{Mi} - F_{Wi}}{M_{\rho i}} \tag{13}$$

where $M_{\rho i}$ – the mass of the train (including rotating parts) on the i-th movement.

The mass of the train is determined by the expression

$$M_{\rho i} = \sum_{k=1}^{s} \rho_{Lk} M_{Lk} + \sum_{j=1}^{n} \rho_{Tj}\left(M_{Tj} \pm M_{Ri}\right) \tag{14}$$

where ρ_{Lk} – coefficient of rotating masses for wagons, ρ_{Tj} – coefficient of rotating masses for wagons.

The speed of the train at the end of the thrust

$$V_{Ti} = a_i T_i \tag{15}$$

Power "at the wheel" is defined as

$$P_i(t) = V_i(t) F_{Mi}, \quad 0 < t < T_i \tag{16}$$

The maximum tractive power is determined by the expression

$$P_{\max i} = a_i F_M T_i \tag{17}$$

The duration of train movement after the thrust is determined by the expression

$$T_{im} = \frac{L_m}{V_{\max i}} \tag{18}$$

where L_m – the length of the path traveled by the train after the shock; $V_{\max i}$ – velocity at the end of the stroke.

The speed at the end of the thrust is determined by the expression

$$V_{\max i} = a_i T_i \tag{19}$$

Thus, Eq. (9)-(19) makes up the mathematical model of train movement during maneuvering.

2.3. Modeling of energy exchange in traction electric drive

The traction electric drive of an electric locomotive includes part of its traction system, which provides power and control of the traction electric motors. The study of the input links of the traction system [21,22] is not performed in this work.

To determine energy efficiency indicators, it is necessary to develop a mathematical model of energy exchange. We assume that the traction electric drive can work both in the traction mode and electrodynamic braking mode when moving on a section of the railway. During maneuvering, the traction electric drive works only in the traction mode. Fig. 1 shows a generalized scheme of energy flows in the traction electric drive in the traction mode (Fig. 1a) and the electrodynamic braking mode (Fig. 1b).

Model of energy exchange in traction mode. The power consumed from the intermediate circuit by one traction inverter is determined by the expression

$$P_{DC1} = r(P_T + \Delta P_{GB} + \Delta P_{TM}) + \Delta P_{TI} \tag{20}$$

where r – the number of traction electric motors powered by one inverter; P_T – tractive power, which is determined by Eq.(9) or Eq.(17); ΔP_{GB} – losses in the traction gear-box; ΔP_{TM} – losses in the traction electric motor; ΔP_{TI} – losses in the traction inverter.

Taking into account the provisions of [23], losses in the traction reducer can be determined in the simplest form by the expression

$$\Delta P_{GB} \approx \Delta P_{GBnom} \frac{P_T}{P_{TMnom}} \tag{21}$$

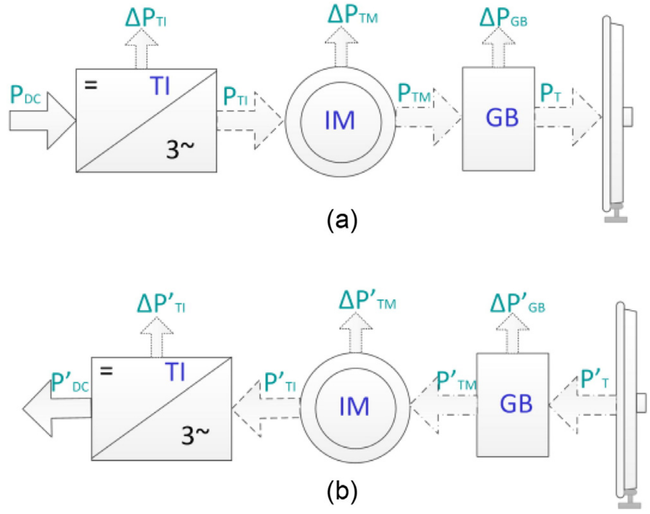


Fig. 1. Generalized scheme of energy flows in the traction electric drive: TI – traction invertor, IM – induction motor, GB – gear-box.

where ΔP_{GBnom} – losses in the traction gear-box at the nominal power of the traction electric motor; P_{TMnom} – nominal power of the traction electric motor.

Losses in a traction electric motor depend significantly on its mode of operation. To simplify the calculations, it is advisable to calculate the losses in the electric motor in advance as a function of the torque on the shaft and the rotation speed $\Delta P_{TMo} = f(M_{TM}, n_{TM})$.

The torque of the electric motor is calculated by the expression

$$M_{TM} = \frac{F_{KP} D_{KP}}{2\mu_{GB}} + \frac{30}{\pi}\frac{\Delta P_{GB}}{n_{TM}} \tag{22}$$

where F_{KP} – the tractive effort realized by one axis; D_{KP} – the diameter of the driving wheel of the electric locomotive; μ_{GB} – transmission ratio of the traction gear-box; n_{TM} – the frequency of rotation of the electric motor, which is determined by the expression

$$n_{TM} = \frac{1000\mu_{GB} V}{60\pi D_{KP}} \tag{23}$$

When starting (V = 0), the second term in Eq. (22) is not taken into account.

Losses in the traction electric motor can be calculated according to [24]. It should be noted that when powering the traction electric motor from the voltage inverter, losses from higher harmonic current and voltage occur in it. To calculate it, it is necessary to know the spectral composition of the inverter voltage and the dependence of the electric motor resistance on the frequency [25]. Determining rational inverter voltage modulation algorithms is the task of a separate study [26]. Therefore, evaluation of the loss from a non-sinusoidal power supply providing using the following expression

$$\Delta P_{TMh} = P_{TMnom}\left(\frac{1}{\eta_1 - \Delta\eta} - \frac{1}{\eta_1}\right) \tag{24}$$

where η_1 – the efficiency of the electric motor with a sinusoidal power supply; $\Delta\eta$ – decrease in the efficiency of the electric motor with a non-sinusoidal power supply.

The total losses in the traction electric motor are determined by the expression

$$\Delta P_{TM} = \Delta P_{TMo} + \Delta P_{TMh} \tag{25}$$

Losses in the inverter are determined by the expression

$$\Delta P_{TI} \approx (1 - \eta_{TI}) P_{TMnom} \tag{26}$$

where η_{TI} – efficiency of traction inverter.

The total power that is consumed from the power source is determined by the expression

$$P_{DC} = P_{DC1}\frac{N_D}{r} \tag{27}$$

Eq. (20)-(27) constitute a mathematical model of energy exchange in the traction electric drive in traction mode. Eq. (21)-(28) are used both moving on a section of the railway and maneuvering.

The energy consumed from the intermediate circuit was determined by the expression

$$E_{DC} = \int_0^T p_{DC}(t)dt \tag{28}$$

where $p_{DC}(t)$– dependence of the power consumed from the intermediate power circuit; T – duration of the movement.

Model of energy exchange in the mode of electrodynamic braking. The power supplied to the intermediate circuit from one inverter is determined by the expression

$$P'_{DC1} = r(P'_T - \Delta P'_{GB} - \Delta P'_{TM}) - \Delta P'_{TI} \tag{29}$$

where P'_T – tractive power, which is determined by (Eq. 8); $\Delta P'_{GB}$ – losses in the traction gear-box; $\Delta P'_{TM}$ – losses in the traction electric motor; $\Delta P'_{TI}$ – losses in the traction inverter.

Losses in traction electric drive components during electrodynamic braking are determined similarly to losses in traction mode. Exceptions are losses in the traction electric motor $\Delta P'_{TMo} = f(M_{TM}, n_{TM})$, in the calculation of which it is necessary to use the dependence of losses for the electrodynamic braking mode.

The total power supplied to the intermediate circuit is determined by the expression

$$P'_{DC} = P'_{DC1}\frac{N_D}{r} \tag{30}$$

The energy supplied to the intermediate circuit during electrodynamic braking was determined by the expression

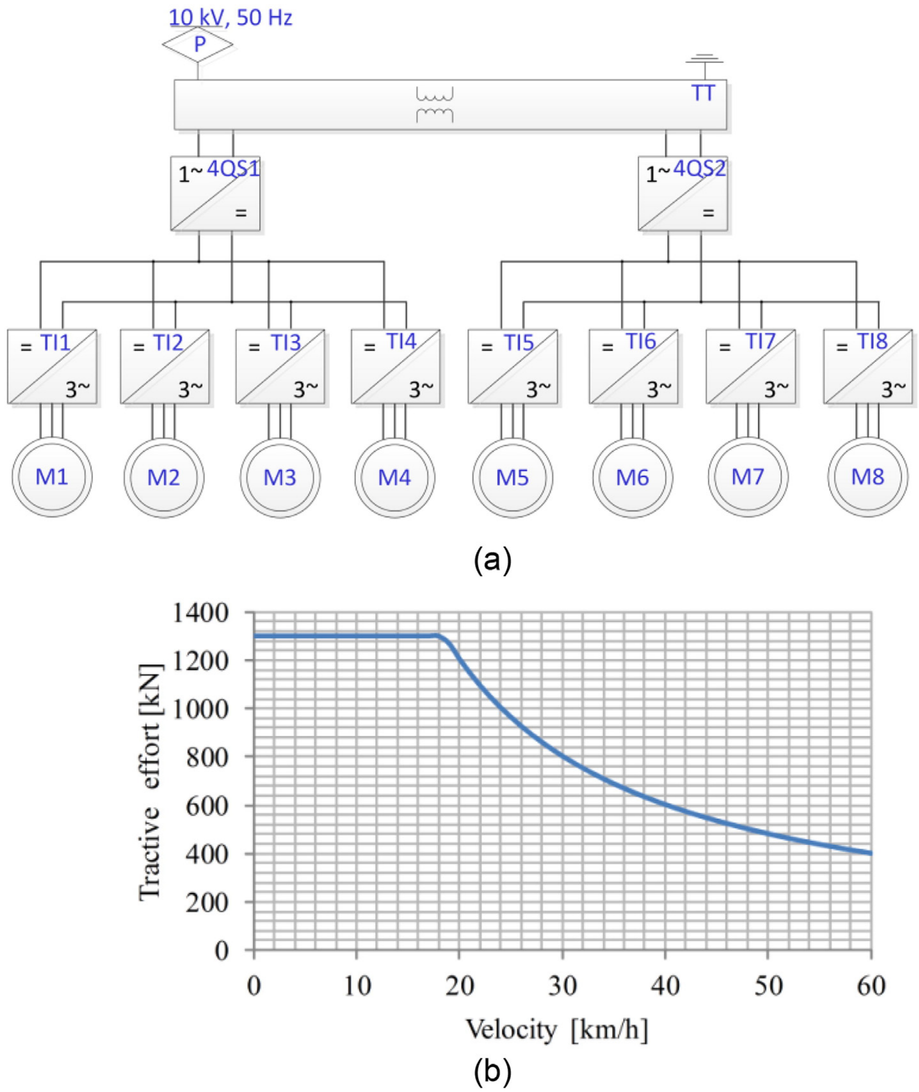
$$E'_{DC} = \int_0^T p'_{DC}(t)dt \tag{31}$$

where $p'_{DC}(t)$ – power dependence in the intermediate circuit in the electrodynamic braking mode.

Thus, mathematical models of energy exchange processes for traction and electrodynamic braking modes are described respectively by expressions (20)-(28) and (29)-(31).

3. Research results and discussion

The study of the possibility of increasing the energy efficiency of an electric locomotive for railway mining transport with a multi-motor traction electric drive when applying the disconnection of traction electric motors will be carried out using the example of a 16-axle electric locomotive [16].The axial formula of the electric locomotive is 2(B_0-B_0 + B_0-B_0), the mass is 2x200 tons, and the length is 20 m is assumed. The structural diagram of the traction electric drive of one section is shown in Fig. 2a. The limit traction characteristic of the electric locomotive under study is defined in [16] and shown in Fig. 2b. To simplify the calculations, the ultimate braking characteristic is assumed symmetrical about the horizontal axis. According to [27], we take the transmission ratio of the traction gearbox as large as possible. Calculations showed that with a drive wheel diameter of 1.05 m, it is possible to use a traction reducer with a gear ratio equal to 5.33.



(a)

(b)

Fig. 2. Scheme of traction electric drive with individual power supply of electric motors: P – pantograph; TT – traction transformer; 4QS1, 4QS2 – input converters; TI1…TI8 – traction invertor; M1…M8 – traction induction motors.

The profile of the path from the crushing plant to the quarry (for an empty half-passage) is shown in Fig. 3. The loaded half-passage is carried out in the reverse direction. Model 33–7141 dumpcars with a carrying capacity of 115 tons are used to transport the ore. Dumpcar's tare weight is 50 tons, length is 15 m. There are 14 dumpcars on the train.

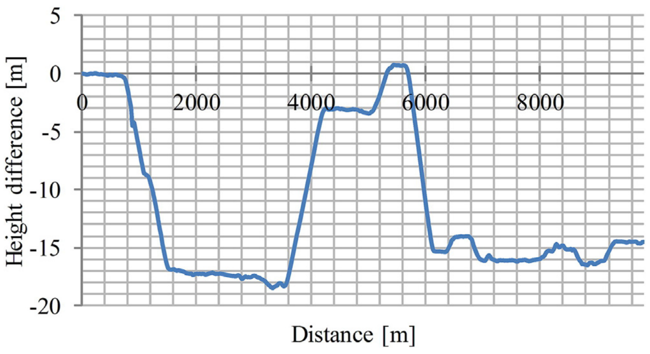


Fig. 3. Profile of the section of the railway.

The authors performed the calculations of the traction asynchronous electric motor in accordance following [28]. The main parameters of the electric motor and the data necessary for calculating the dependence of losses on torque and rotation frequency are given in the appendix.

According to [24,28], the dependence of the losses in the traction electric motors depending on the rotation frequency and the torque on the shaft was calculated for the traction mode. The dependence is shown in Fig. 4. Calculations for EBD mode were performed according to [26].

The type of dependence is similar to the dependence in Fig. 4 In both cases, the calculations were carried out in the range of rotation frequency 0…1000 rpm and the torque range 0…10000 Nm. When calculating, it was assumed that the law was being followed $U/f = const$ until the voltage is less than the nominal value, after which the law was adopted $U = const$ in the calculation. The temperature of the windings was assumed to be equal to 150 °C by the requirements of the standards.

The losses in the traction reducer were calculated according to [23]. For the nominal mode, losses amount to 1.73 kW.

The calculation of losses in the electric motor with a non-sinusoidal power supply requires the determination of the rational

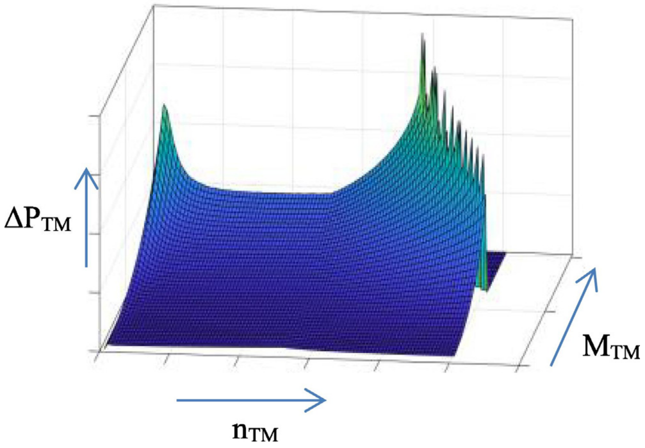


Fig. 4. Losses in traction motor for traction mode.

parameters of the PWM of the inverter, which is not included in this study. According to estimates [26,29], the efficiency of the traction electric motor due to power supply from the voltage inverter can decrease by 1.2…1.7%. Therefore, let's assume that the reduction in efficiency of the electric motor is 1.5% for all operating modes.

The calculation of losses in the traction inverter requires, as in the case of the traction electric motor, the determination of the parameters of the PWM of the inverter depending on the operating mode. However, the analysis of the efficiency characteristics of traction inverters shows that their efficiency exceeds 98% in a wide range of loads [30]. Therefore, we consider it permissible to assume that the losses in the inverter will be a constant value that corresponds to the losses in the nominal mode. According to expression (26), with an inverter efficiency of 98% and a power of 430 kW, the losses in the inverter will be 8.6 kW with individual power supply of electric motors.

Results of the research. Let's consider several scenarios of traction electric drive control during movement on a section of the railway.

Scenario №1. The simplest way to control the traction electric drive is to evenly load the traction electric motors. At the same time, in coasting mode, movement is possible both with magnetized electric motors [31] and movement with complete de-energization of electric motors.

Fig. 5a shows the dependence of the tangential power during the movement of a loaded train from the quarry to the crushing plant, and Fig. 5b shows the dependence of the tangential power during the movement of an empty train from the crushing plant to the quarry. The specified dependencies are obtained when solving the traction problem according to expressions (1)-(8).

Scenario №2. Let's consider a possible option for controlling the traction electric drive with de-energization of part of the traction electric motors. At the same time, we believe that the load will be distributed evenly between the electric motors.

The number of working electric motors is determined by the condition

$$N_{TM} = \max(N_1, N_2) \tag{32}$$

where N_1 – the number of driving axles required to ensure a given tractive effort; N_2 – the number of driving axes necessary to realize the provision of the given tractive power.

The number of driving axles required to ensure a given traction force is determined by the expression

$$N_1 = \frac{F_c}{F_s/N_{M1}} \tag{33}$$

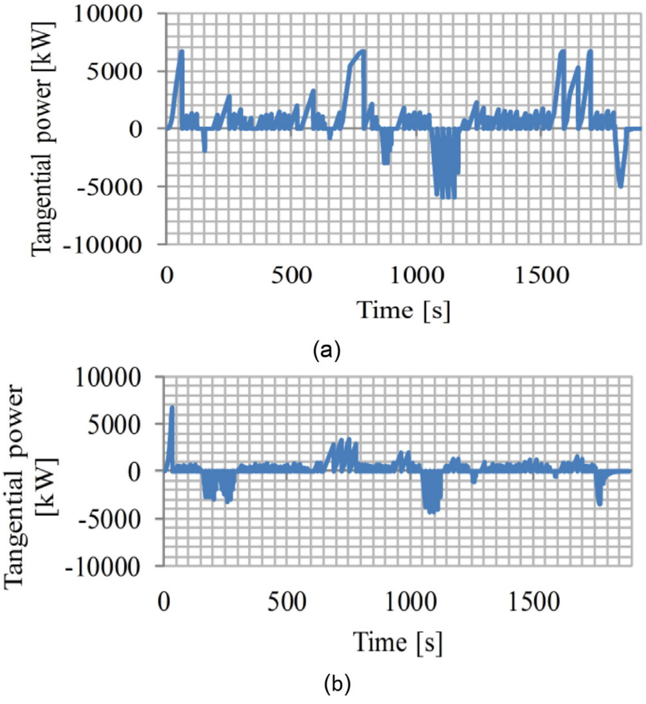


Fig. 5. Tractive power during movement on a section of the railway.

where F_c – the current value of the tractive effort; F_s – tractive effort at the ultimate characteristic at the current speed of movement.

The number of driving axles obtained from Eq. (33) is required to ensure the given traction force is rounded up to an integer.

The number of driving axes necessary to realize the provision of the given tangential power is determined by the expression

$$N_2 = \frac{P_c}{P_{TMnom}} \tag{34}$$

where P_c – the current value of the tractive power.

The number of drive axles obtained from Eq. (34) required to provide the given power is rounded up to an integer. According to the results of calculations for scenario №2, the dependence of the tangential power is almost identical to that shown in Fig. 5.

Thus, when moving with partially disconnected traction electric motors, the same mode of movement is ensured, as in the case of operation of all traction electric motors of the electric locomotive.

Consider the dependence of losses in the traction electric drive. Fig. 6 shows the dependence of losses in the traction electric drive. Equations (20)-(31) were used in the calculations. The analysis of Fig. 6 shows that the level of losses during movement under scenario No. 1 – with all working electric motors – is higher than in scenario No. 2, where the number of working electric motors is determined from expressions (32)-(34). This is explained by the fact that in the first scenario, the electric locomotive in traction and braking modes moves with all magnetized electric motors, which causes increased energy consumption. The total energy consumption from the intermediate circuit for half-passage is 746 kWh when driving with magnetized electric motors and 725 kWh with de-energized electric motors in coasting mode.

For scenario №2, An alternative scenario is the disconnection of part of the traction electric motors.

During movement according to scenario No. 2, magnetization losses of electric motors are proportional to their number. This ensures a reduction in energy consumption. During work with disconnected electric motors, energy consumption from the intermediate circuit will be 677 kWh. That means, that during movement

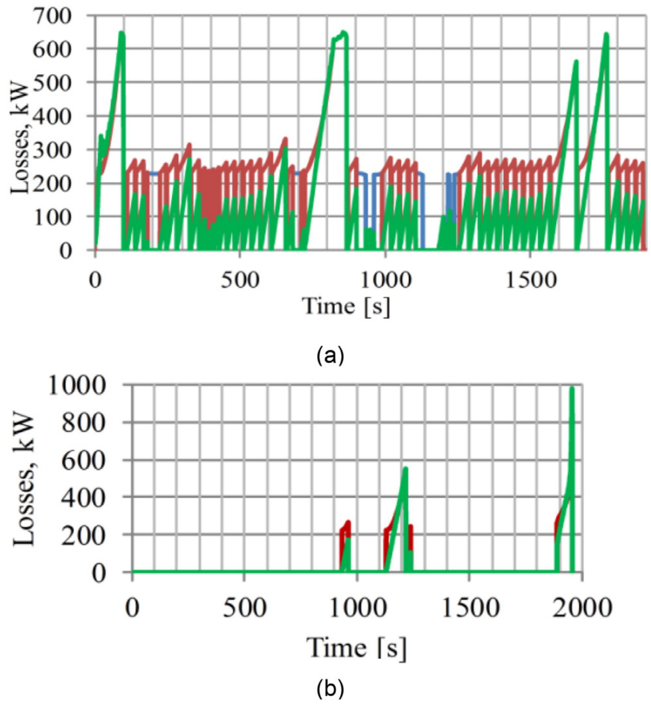


Fig. 6. Losses in the traction electric drive during cargo half-passage: blue line – losses during operation of all electric motors and coasting movement with magnetized electric motors; red line – losses during operation of all electric motors and coasting movement with de-energized electric motors; green line – losses with partial disconnection of traction electric motors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

with partially disconnected electric motors, energy consumption is reduced by approximately 10%. When the traction electric drive is operating in EDB mode, 98 kWh of energy is returned to the intermediate circuit by all electric motors. During work with the partially disconnected electric motors, the same value is equals 102 kWh.

Fig. 7a shows the time dependence of the power of one motor for various scenarios, Fig. 7b shows the graph of the change in the number of working electric motors for scenario №2. As can be seen from Fig. 7a, in scenario № 2, electric motors operate with a power of 250…400 kW. In scenario No. 1, electric motors operate with a power of 50…100 kW.

The efficiency of electric motors in the first case is higher than the efficiency in the low-power mode, accordingly.

From Fig. 7b, became clear that during movement with the disconnected traction electric motors, no more than 5 electric motors from 16 are working for a significant period.

Fig. 8 shows the dependence of losses in the traction electric drive for a half-passage from the crushing plant to the quarry with empty wagons.

As we can see from Fig. 8, the greatest losses in the traction electric drive occur when working according to scenario No. 1 when driving with magnetized electric motors. The smallest losses are when working according to scenario №2. Energy consumption for movements with magnetized electric motors will be 316 kWh, with de-energized electric motors – 285 kWh, with scenario No. 2 – 230 kWh. That is, when driving with partially disconnected electric motors, energy consumption is reduced by approximately 27%. When the traction electric drive is operating in EDB mode, 89 kWh of energy is returned to the intermediate circuit by all electric motors. When working with a partial shutdown of electric motors – 98 kWh, that is, the return of energy increases by 10%.

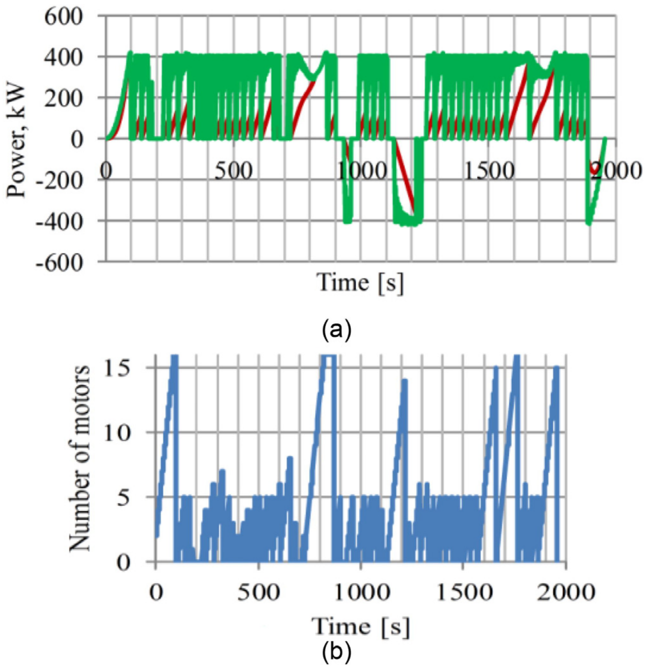


Fig. 7. Mode of operation of the traction electric motor.

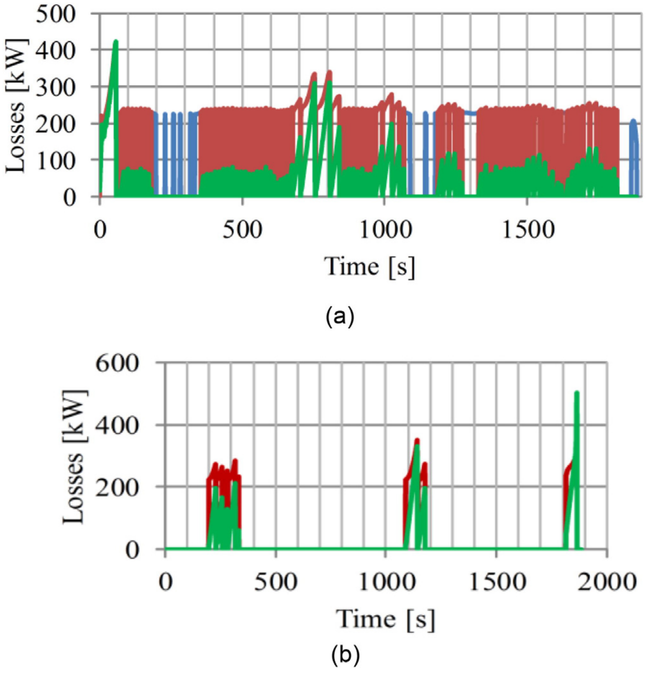
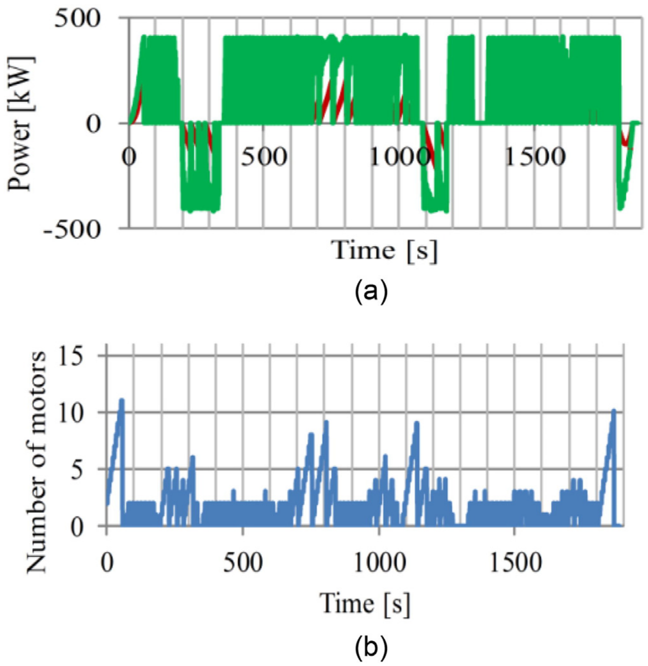


Fig. 8. Losses in the traction electric drive at empty half-passage: blue line – losses during operation of all electric motors and coasting movement with magnetized electric motors; red line – losses during operation of all electric motors and coasting movement with de-energized electric motors; green line – losses with partial disconnection of traction electric motors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

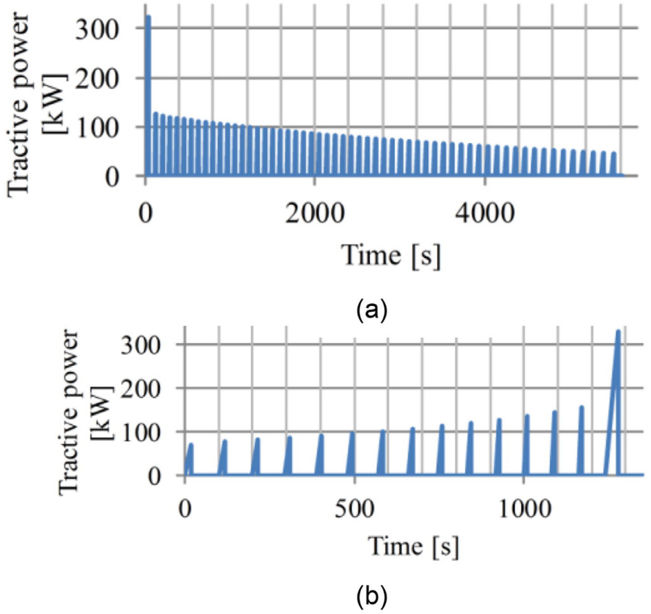
Fig. 9a shows the dependence of the power of one motor at an empty half-passage for various scenarios, Fig. 9b shows the graph of the change in the number of working electric motors for scenario №2. As can be seen from Fig. 7a, in scenario No. 2, electric motors operate with a power of 250…400 kW. In scenario No. 1,



(a)

(b)

Fig. 9. Mode of operation of the traction electric motor.



(a)

(b)

Fig. 10. Tractive power during maneuvering.

electric motors operate with a power of 10…50 kW. That is, work with a higher load of part of the motors should be a priority mode of operation.

It should be noted that the movement of the train during an empty half-passage is mostly carried out by two electric motors.

Thus, working with de-energized electric motors when moving along a section of the path provides a reduction in energy consumption by 10…27%.

Let's consider scenarios for controlling the traction electric drive during maneuvering. Calculations based on Eqs. (9) and (11) show that the minimum number of electric motors that provide movement during maneuvering is 2, while the traction force should be at least 150 kN. It should be noted that the maneuvering procedures described below are somewhat idealized, but it give an idea of the processes that occur during maneuvering.

Maneuvering during loading begins with the supply of the wagons under the excavator. Loading begins with the first dumpcar, so the length of the movement is 210 m, 20% of which the train passes under traction. To load one Dumpcar with an EKG10 type excavator, 4 loading cycles of two buckets are required. The duration of the loading of two buckets is equal to 1 min. Therefore, in the future, the wagons are "pulled up" to a distance of 3.75 m, which is ¼ of the length of the dumpcar. We take the length of movement under traction equal to 1.0 m. We have a total of 56 shocks with loaded ore.

Unloading at the crushing plant takes place from the first dumpcar. The dumpcar is unloaded by overturning the body in one operation. Therefore, the number of jolts is 14, the train moves over a length of 15 m. The duration of unloading one dumpcar is assumed to be equal to 1 min. The length of the path under traction is assumed to be equal to 3 m. After unloading, the train moves from the crushing plant. The length of this movement is 210 m, of which the train moves 20% of the way under traction.

Fig. 10a shows the dependence of the tractive power when the train is loaded, Fig. 10b – when unloading.

To assess the influence of the number of working electric motors during maneuvering on energy consumption, the energy consumed from the intermediate circuit was calculated. Table 1 shows the results of the calculations.

As seen, in both cases, when working with four traction electric motors, the energy consumed from the intermediate circuit is minimal. That is, working with partially disconnected electric motors ensures a reduction of energy consumption even in maneuvering mode.

Thus, disconnection of the electric motors of the traction electric drive of the electric locomotive for quarry railway transport ensures a reduction in energy consumption both when moving on a section of the path and when maneuvering. Thus, to minimize energy consumption by an electric locomotive with a multi-motor electric drive, it is advisable to use operating modes with disconnected traction electric motors. This applies both to movement along a section of the railway and to maneuvering.

The obtained results of the calculations show the expediency of disconnection of the traction asynchronous electric motors in operating modes with an incomplete load of the electric locomotive for railway quarry transport. As can be seen from the calculations, the operation of the electric locomotive with nominal power occurs when moving on sections where the slope is close to the maximum gradient, as well as during acceleration and braking. Moreover, working with the full number of electric motors is due to the impossibility of ensuring the tangential effort of the electric locomotive. However, the duration of such modes of operation is a small part of the total operating time, during which the traction electric drive works with a partial load. As a result, with uniform distribution of the load, traction electric motors operate in modes with low efficiency, which causes increased energy consumption.

The obtained results both for the mode of movement on the section of the railway and during maneuvering confirm the need for further research into the modes of operation of the traction multi-motor electric drive of the electric locomotive, as well as auxiliary systems that ensure the operation of the traction electric drive. To determine the rational modes of operation of the traction electric drive and auxiliary systems, it is advisable to solve optimization task to ensure minimum energy consumption [32,33].

4. Conclusions

1 The increase in the energy efficiency of the multi-motor traction electric drive of an electric locomotive for railway quarry transport with partially disconnected electric motors is substantiated using mathematical modeling,

2 According to the simulation results, it was established that during movement with the partially disconnected traction electric motors, energy consumption decreases by 10% for a loaded half-passage and by 27% for an empty half-passage. Maneuvering with disconnected traction motors also allows to reducing energy consumption.

3 The obtained results confirm the need of research aimed at improving the energy efficiency of the multi-motor traction electric drive of an electric locomotive for railway mining transport. Further research will be aimed both at improving the researched method, which consists of disconnected of traction electric motors, and at finding other ways to increase energy efficiency. The results will be presented in future scientific works.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Tables A1–A5

Table A4
Geometric dimensions of the electric motor.

Parameter	Unit	Value
Outer diameter of the stator	m	0,68
The inner diameter of the stator	m	0,48
The axial length of the stator magnetic circuit	m	0,45
One side air gap	m	0,0018
The number of stator slots	–	72
The number of rotor slots	–	62

Table 1
Performance indicators of the traction electric drive.

The number of working traction electric motors	2	4	6	8
Energy consumed from the intermediate circuit, kWh	62,0	55,6	59,0	63,8
Energy consumed from the intermediate circuit, kWh	15,1	13,8	14,6	15,9

Table A1
Parameters of the nominal operating mode of the electric motor.

Parameter	Unit	Value
Power	kW	430
Line voltage	V	760
Phase current	A	395
Frequency	Hz	25,5
Rotational speed	rpm	501
Torque	Nm	8200
Efficiency	%	93,6
Power factor	–	0,88
The highest rotation speed	rpm	1800
Number of phases	–	3
Number of poles	–	6

Table A2
Parameters of the electric motor replacement scheme.

Parameter	Unit	Value
Phase resistance of the stator winding at 20 °C	Om	0,0237
The reduced resistance of the rotor winding at 20 °C	Om	0,0135
Inductance of the dissipation of phase of the stator winding	mH	0,576
The reduced inductance of the dispersion of rotor winding	mH	0,525

Table A3
Dependence of the inductance of the magnetization circuit of the electric motor.

Parameter	Unit	Value				
Flux	Wb	0	2,43	3,223,85	4,48	4,91
Inductance of the magnetization circuit	mH	21	21	1916	12	10

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