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DETERMINATION OF THE WORKING ENERGY CAPACITY OF THE ON-BOARD ENERGY STORAGE SYSTEM OF AN ELECTRIC LOCOMOTIVE FOR QUARRY RAILWAY TRANSPORT DURING WORKING WITH A LIMITATION OF CONSUMED POWER

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Abstract:

The use of specialized rail rolling stock which is used for transporting ore from the quarry to the crushing plant at mining enterprises is analyzed here. Electric locomotives with an asynchronous traction electric drive and an on-board energy storage system are considered for use. The calculated dependencies of the electric locomotive tractive power were analyzed and it was established that on flat sections of the track profile, the movement is carried out with a power that does not exceed 50% of the nominal one. The movement with the nominal power is carried out on the controlled uphill during the cargo half-passage. To ensure the necessary power for movement in such areas, the use of an on-board energy storage system is proposed, which should feed the traction system while limiting the power consumed from the catenary. This happens when the voltage on the pantograph drops to a minimum level. The aim of this work is to determine the on-board energy storage system parameters during the operation of the electric locomotive with limitation of the power consumed from the traction network. Mathematical models of the energy exchange processes in the electric locomotive traction system have been developed. The criteria for comparing options for calculating the parameters of the on-board energy storage system have been proposed. The criteria take into account the reduction of energy consumption during movement, the efficiency of energy storage, and the complete use of the on-board energy storage system in terms of power and working energy capacity. Based on the calculation results, it was determined that the use of an energy storage device with a power of 3,540 kW and an operating energy capacity of 63.5 kWh provides a 10% reduction in energy consumption, which is being consumed while moving along the sample section of the road. The current that can be consumed by an electric locomotive with such parameters of the on-board energy storage system is limited by 600 A.

Keywords: *railway transport, electric locomotive, on-board energy storage system, traction drive, induction motor*

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1. Introduction

Increasing efficiency and reducing the harmful impact on the environment is an important goal for the EU countries and Ukraine (A European Green Deal, 2022; Postanova KMU, 2021).

Ukraine is a large mineral and raw material base with iron ore reserves of 30 billion tons that makes about 6% of world reserves. Iron ore raw materials that are used for the manufacture of metallurgical products are produced by mining enterprises for both, the domestic market and supplies to foreign consumers. The constant increase in fuel and energy resource costs, the transition to carbon-neutral production, and the need to increase product competitiveness and improve the environmental impact force the enterprises of the mining industry to widely implement innovative technologies at all stages of production (Lyadenko, 2019; Frolov et al., 2020).

Currently, mining enterprises of Ukraine use traction units produced by JSC Dnipro Electric Locomotive Plant (DEVZ) (Balon et al., 1987) to transport iron ore on electrified sections of internal railways. These machines were developed in the 70-80s of the last century using the technologies available at that time. Modernization of traction units, which is performed by various enterprises, involves the use of modern equipment, which has a positive effect on their reliability and efficiency. However, there are no significant changes in the traction and energy indicators of the electric rolling stock.

A significant improvement in traction and energy indicators is possible when using electric traction with asynchronous drives. In (Bratash, 2007), the necessity of creating an electric locomotive for quarry railway transport using traction with asynchronous drives is substantiated. In (Riabov et al., 2022a), the use of an on-board energy storage system (ESS) on such an electric locomotive is proposed. The advantages of using an on-board ESS can be seen in the possibility of storing energy during electrodynamic braking and its subsequent use in traction modes and autonomous driving.

In (Riabov et al., 2022a), mathematical modeling of the movement of an electric locomotive was performed to determine its main parameters. The analysis of the results, in particular, showed that the movement of the electric locomotive with nominal power in traction mode is carried out only on uphills, and most of the time - 70.5% of the total time of movement in traction mode - the traction drive operates with a power not exceeding 1500 kW. Fig. 2a shows the dependence of the tangential power for a loaded half-passage, and Fig. 2b shows the dependence of the tangential power for an empty half-passage (Riabov et al., 2022a).

It can be seen from Fig. 2 that in most cases the value of the tangential power does not exceed 3500 kW, which makes 6700 kW or 52.2% of the nominal power. Work with a power close to nominal in the traction mode is performed during acceleration and on uphills, as well as in the electrodynamic braking mode (EDB).

Based on this, a possible algorithm of the on-board ESS operation for powering the electric locomotive traction system consists of the simultaneous powering of the traction system in the traction mode when working with a power exceeding 50% of the nominal. In the EDB mode, the energy produced during braking is directed to charge the energy storage (ES).

Some structure variations of the traction system, where the specified work algorithm is provided, are shown in Fig. 3.

Fig. 1. OPE1AM traction unit №040

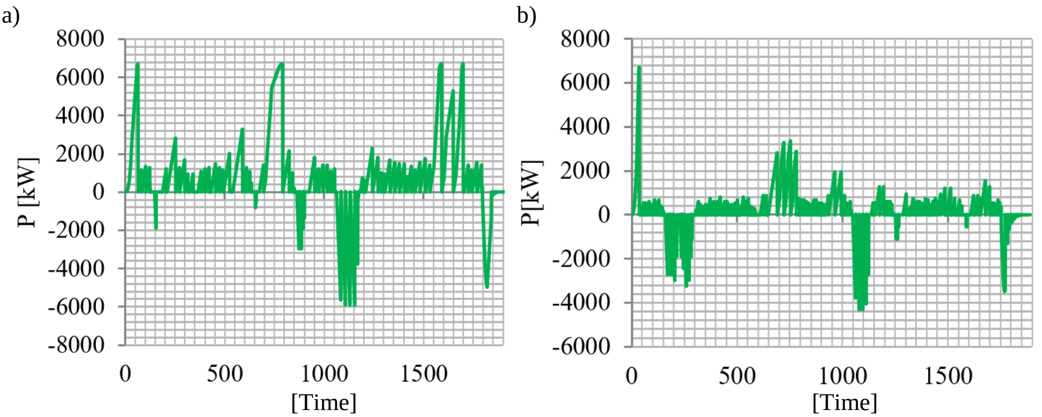

Fig. 2. Dependence of the tangential power of the electric locomotive (a – for a loaded half-passage; b – for an empty half-passage)

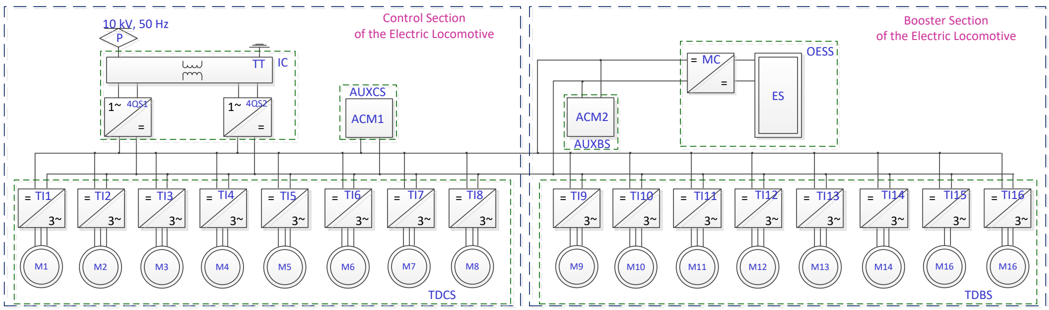

Fig. 3. Structural diagram of the traction system of the electric locomotive (P - pantograph, IC - input converter, TT - traction transformer, 4QS1, 4QS2 - four-quadrant converters; AUXCS – auxiliary systems of electric locomotive control, ACM1 – auxiliary converter module of control section, ACM2 – auxiliary converter module of booster section, OESS – energy storage system, ES – energy storage, MC – matching converter, TDCS – traction electric drive of the control section, TDBS – traction electric drive of the booster section, TI1…TI16 – traction inverters, M1…M16 – traction induction electric motors)

At the same time, monitoring the operation of traction units at mining enterprises shows that the voltage on their pantographs can significantly decrease - down to a minimum voltage of 7.5 kV in the case of an alternating current electric traction system. This mostly happens when a loaded train is moving on uphill. As a result, the speed of the train decreases, and the traction system of the electric locomotive and the traction network operate with currents exceeding the continuous operation currents. Consequently, deviations from the traffic schedule and an increased probability of the electric traction system electrical equipment damage occur.

On a modern electric rolling stock with an asynchronous traction drive, when the voltage on the pantograph is reduced to a minimal level, it stabilizes at this level by limiting the current consumption from the traction network. It is obvious that simultaneously the tractive power decreases and, therefore, the speed of movement is reduced. However, electrical equipment operates with allowable currents. To maintain the necessary power of the electric locomotive in this case, it is possible to use an OESS.Thus, by summarizing the above, the concept of using an OESS on an electric locomotive for quarry railway transport enables ensuring the necessary level of power in case of limiting its consumption from the traction network. Such a concept is widely applicable to rolling stock for various purposes (Sydorenko et al., 2022; Khozia, 2021; Fedele et al, 2021).

Another important aspect of the application of on-board ESS is the provision of autonomous movement of the electric locomotive during maneuvering, which is especially important in the case of maneuvering on the railways of the overload point. This will make it possible to refuse the arrangement of the lateral contact network on the railway in area of the overload point, as a result, the possibility of the excavator bucket touching the contact wire and emergency disconnection of the contact network will be excluded. Also, in the case of powering the electric locomotive systems from the on-board ESS during maneuvering, modes of energy consumption from the traction network, which are characterized by a low power factor, will be excluded. Accordingly, this will reduce losses in the traction network and the total energy consumption from the external power supply system.

Thus, the expected result of the application of on-board ESS on an electric locomotive is a reduction in total energy consumption both due to the accumulation of energy in electrodynamic braking modes and the exclusion of operating modes with low energy indicators.

The aim of this study is to determinate the parameters of the on-board energy storage system during the operation of an electric locomotive with a limitation of the power consumed from the traction network. This mode is considering as the main mode of operation for which an on-board ESS is used on an electric locomotive.

2. Literature review

With the structure of the traction system of the electric locomotive according to Fig. 3, the input converter and the OESS in the traction mode jointly feed the intermediate circuit to which the traction electric drive and auxiliary systems are connected. In the EDB mode, the energy coming from the traction electric drive powers the auxiliary systems of the electric locomotive and is stored in the OESS, or can be transmitted to the traction network. The ES power must provide energy compensation during movement with the limitation of the power consumed from the traction network. For calculations, we will operate with the concept of the current limit that is consumed from the traction network. Then the condition for compensation of the on-board ESS power limitation will be written in the form:

$$P_{ES1} \geq \frac{\left(\frac{P_{Lnom}}{\eta_{TD}}+P_{AUX}\right)-U_{Cmin}I_{CA}\eta_1}{\eta_{BC}}, \tag{1}$$

where P_{Lnom} – nominal tangent power of the electric locomotive.

P_{AUX} – the power of auxiliary systems of the electric locomotive is assumed to be equal to 300 kW,

U_{Cmin} – the minimum voltage on the current receiver is 7.5 kV;

I_{CA} – the active component of the limit current consumed from the traction network,

η_1 – The efficiency of the "traction transformer - input converter - filter" link is taken as 0.96;

η_{TD} – The efficiency of "traction converter - electric motor - reducer" is taken as equal to 0.9;η_{BC} – We take the efficiency of the matching converter of the OESS to be equal to 0.9.

On the other hand, the maximum ES power can be determined from the condition of all energy consumption that is available during electrodynamic braking:

$$P_{ES2} \leq P_{Lnom}\eta_{TD}\eta_{BC} \tag{2}$$

In general, ES power may be in a range of:

$$P_{ES1} \leq P_{ESnom} \leq P_{ES2} \tag{3}$$

And, therefore, there is a problem in determining the optimal parameters of energy storage.

The use of OESS as part of power plants of rolling stock for various purposes makes it necessary to determine their rational parameters to reduce energy resource consumption (Wang et al., 2022; Zhang et al., 2022, Yang et al., 2020).

In (Zhang et al.,2022), the parameters the combined power plant component – diesel generator and on-board energy storage – are determined based on an economic model that takes into account power plant acquisition costs, fuel costs, and battery replacement costs. The objective function of the optimization problem took into account the cost of purchasing the power plant, its mass, and fuel consumption. The studied authors varied the weighting coefficients of the objective function, which allowed them to choose their best combination. In (Yang et al., 2020), the parameters of the tram`s OESS for catenary-free operation are determined, taking into account the costs of creating the entire infrastructure for the functioning of the tram system. The objective function in the optimization problem is determined by the system cost and the energy cost determined for one day of operation. In (Graber et al., 2016), a study was carried out to determine the parameters of the OESS, taking into account the movement according to the «last-mile» principle, when the rolling stock must move without a contact network. According to the results of calculations, it is shown that the use of OESS reduces losses in the traction network by 43%, peak current - by 32%, extends the battery life by 16.3%, and stabilizes the voltage of the traction network. Thesis (Herrera Pérez, 2017) is devoted to the study of OESS of urban transport and the determination of technical and economic indicators of rolling stock. The author considered and researched various management strategies for on-board energy storage devices, which were compared from the viewpoints of the life cycle duration of the storage device and the daily cost of operation. In (Spiryagin et al., 2017), the use of inertial ES and ES based on batteries as part of the combined power plant of a diesel locomotive, which is compared according to the criterion of energy storage in the OESS, is investigated. That is, a purely technical indicator is used to compare options. In (Poline et al., 2015), the optimization of the combined power plant of a shunting diesel locomotive was carried out according to the criterion of equipment cost taking into account the weight and volume of the hybrid system. In (Kapetanović, 2021), the application of OESS on a diesel train is carried out taking into account the reduction of greenhouse gas emissions. The results of the work showed that for traditional diesel-electric rolling stock it is possible to reduce greenhouse gas emissions by 9.43...56.92% and reduce energy consumption by 9.69-55.46% when using energy storage and partial operation from the contact network. In (Liu et al., 2021), the OESS is optimized for the cost of storage elements taking into account its weight. In (Wang et al., 2019), the optimization of the OESS was performed from the standpoint of minimizing fuel consumption and increasing the duration of operation of the OESS and fuel cell. The cost per hour of vehicle operation was chosen as the criterion for comparison. In (Omelyanenko et al., 2021) the effect of ES use is evaluated due to reduced fuel consumption.

Hence, when determining the parameters of the OESS, various approaches can be applied. The simplest involves comparisons based on one or two criteria, such as reducing energy consumption or carbon emissions. The most advanced models are based on the calculation of the life cycle cost of rolling stock or the entire electric traction system. It is worth noting that in the case of the application of complex models, the correct choice of calculation optimization algorithms is important, on which the reliability of the obtained results depends (Corlu et al., 2020).

In this work, the determination of the parameters of the on-board OESS will be carried out using criteria that characterize the technical parameters of the on-board OESS and provide an assessment of the effectiveness of its use. Economic indicators for evaluating the use of on-board OESS are not used in this study.

3. Research results and discussion

In this work, it is assumed that the power of the OESS is determined by expression (1) (i.e., this provides power compensation when working with current limitations), and, hence, the OESS energy capacity needs to be determined. To compare different options, the criteria considering the following are used:

1) reduction of energy consumption by an electric locomotive when using OESS,
2) efficiency of electrodynamic braking for energy storage;
3) efficiency of use of OESS in terms of power and energy.

The choice of the aspects listed above, firstly, allows us to indirectly evaluate the reduction of operating costs for energy resources, which constitute a significant part of the life cycle cost of an electric locomotive (Hryshechkina, 2021). Secondly, it allows comparing the capital costs required to install an OESS.

To estimate the reduction in energy consumption when using recuperation, the coefficient will be used, which shows the reduction in energy consumed by the electric locomotive, in the form of:

$$K_E = \frac{E_T}{E'_T}, \tag{4}$$

where E_T – the total energy consumed by the electric locomotive in the driving mode with the use of

EDB and energy storage by the OESS,
E'_T – the energy consumed by an electric locomotive when moving without the use of EDB.
The energy consumed by an electric locomotive when moving with the use of EDB is determined by the expression:

$$E_T = E_C + E_I, \quad (5)$$

where E_C – the energy consumed by the electric locomotive from the traction network,
E_I– energy that must be stored in ES before the start of the movement.
The energy consumed by an electric locomotive during moving without recuperation:

$$E'_T = E'_C + E'_I, \quad (6)$$

where E'_C – the energy consumed by the electric locomotive from the traction network,
E'_I– energy that must be stored in ES before the start of the movement.
E_I E'_I and must be stored in the ES before the start of the movement to ensure power compensation in the mode of movement with the current limit.
The energy that is consumed from the traction network during movement using EDB has three components:

- the energy consumed in traction mode to power the traction electric drive and auxiliary systems
- the energy consumed in coasting mode to power auxiliary systems
- the energy consumed in the EDB mode to power auxiliary systems if the power of the electric brake is not sufficient to power them.

The total energy consumed in the traction mode is determined by the expression:

$$E_{C1} = \sum_{h=1}^{g} \int_0^{t_{sh}} P_{Lh} dt, \quad (7)$$

where P_{Lh}– the power consumed by the electric locomotive in traction mode at the g-th stage of consumption,
g – the number of stages of energy consumption from the catenary network in traction mode.
t_{sh} – duration of the g-th stage.
In coasting mode, the power consumed from the catenary network is also used to power auxiliary systems and is determined by expression (5).

The total energy consumed from the catenary network in run-out mode is determined by the expression:

$$E_{C2} = \sum_{u=1}^{v} \int_0^{t_v} P_{Lu} dt, \quad (8)$$

where P_{Lu}– the power consumed by the electric locomotive in coasting mode at the u-th stage of consumption,
u – the number of stages of energy consumption from the catenary network in coasting mode.
t_v – duration of the u-th stage.
Energy consumed from the traction network to power auxiliary systems during electrodynamic braking for the duration of the stage t_e:

$$E_{C3} = \sum_{e=1}^{f} \int_0^{t_e} P_{Le} dt, \quad (9)$$

where P_{Le}– the power consumed by the electric locomotive in coasting mode at the u-th stage of consumption,
f – the number of stages of energy consumption from the catenary network in coasting mode.
The energy consumed by the electric locomotive from the traction network:

$$E_C = E_{C1} + E_{C2} + E_{C3} \quad (10)$$

The energy that is consumed from the network for charging ES is determined by the expression:

$$E_I = \frac{E_{ES0}}{\eta_C \eta_{ES}}, \quad (11)$$

where E_{ES0} – the initial energy that must be stored in the ES before the start of movement (determined by simulation results);
η_{ES} – The efficiency of the energy storage ,which is estimated as 0.98 for all modes of operation;
η_C– The efficiency of the circles through which ES charging is carried out. In the case of ES charging from the contact network, this indicator is determined through the efficiency of the input converter and the efficiency of the matching converter, and to simplify calculations it can be determined in the form:

$$\eta_C = \eta_1 \eta_{BC} \quad (12)$$

The energy consumed by an electric locomotive from the contact network when moving without EDB is determined by the expression:

$$E'_C = \int_0^T P_L dt, \tag{13}$$

where T– total travel time,
$P_L = P_L(t)$ – the dependence on the power consumed by the electric locomotive from the catenary network on time.
The energy that is consumed from the network to charge the storage device is determined by the expression:

$$E'_I = \frac{E'_{ES0}}{\eta_C \eta_{ES}}, \tag{14}$$

where E'_{ES0} – the initial energy that must be stored in the ES before the start of movement (determined by simulation results).
To evaluate the efficiency of energy storage in the ES when using EDB, a coefficient that shows how much energy is stored in the ES is used:

$$K_R = \frac{E_B}{E_T} \tag{15}$$

E_B– energy that is stored in ES during the operation of the electric locomotive,
The energy stored in ES when the electric locomotive is operating in EDB mode is determined by the expression:

$$E_B = \sum_{j=1}^{m} \int_{t_{1j}}^{t_{2j}} P_{ESj} \eta_{ES} dt, \tag{16}$$

where $P_{ESj} = P_{ESj}(t)$ – dependence of ES power on the j-th ES charging interval,
m – the number of ES charging intervals during the studied period;
t_{1j}, t_{2j} – the moment at which the ES charging begins and ends at the j-th interval, respectively.
To estimate the use of ES, a coefficient that determines the full use of the installed capacity of ES was used,

$$K_P = \frac{E_F}{E_N}, \tag{17}$$

where E_F – the actual energy that "passes" through the ES terminals,
E_N – the theoretical value of the energy that can "pass" through the ES terminals.
The energy that "passes" through the ES terminals in the charge and discharge modes is determined by the expression:

$$E_F = \sum_{i=1}^{n} \left(\int_{t_{1i}}^{t_{2i}} |P_{ESi}| dt \right), \tag{18}$$

where $P_{ESi} = P_{ESi}(t)$ – dependence of the power of ES on the i-th interval of operation from time;
n – the number of work intervals (charging and discharging) during the studied period;
t_{1i}, t_{2i} – the point in time at which the ES operation begins and ends on the i-th interval, respectively.
The theoretical value of energy that can "pass" through the ES terminals is defined as follows:

$$E_N = P_{ESnom} \sum_{i=1}^{n} (t_{2i} - t_{1i}), \tag{19}$$

where P_{ESnom} – nominal power of the energy storage.
In addition, to evaluate the use of NE, apply a coefficient is applied that determines the full use of the energy intensity of NE,

$$K_C = \frac{\Delta E_C}{E_B}, \tag{20}$$

where ΔE_C – working ES capacity, which is calculated as the difference between the maximum and minimum energy value of the storage device.
Mathematical models for calculations are presented below. The analysis of the dependence of the tangential power was performed based on the methodology (Syvenko et al., 2021). The input value is the tangential power of the electric locomotive, calculated in (Riabov et al., 2022a). The mathematical model for solving the traction task, based on the results of which the dependences of the tractive power are obtained, is given in (Riabov et al, 2022a; Riabov et al/, 2022b) and takes into account the recommendations of (Balon, 1987; Kuznetsov et al, 2022; Sablin et al., 2022; Buriakovskyi et al., 2019).
In the basic version of movement - without the use of electrodynamic braking - the calculation of energy exchange parameters in the traction system of an electric locomotive is carried out according to the following model. Figure 4 shows the diagram of energy flows in the traction system for the investigated case.

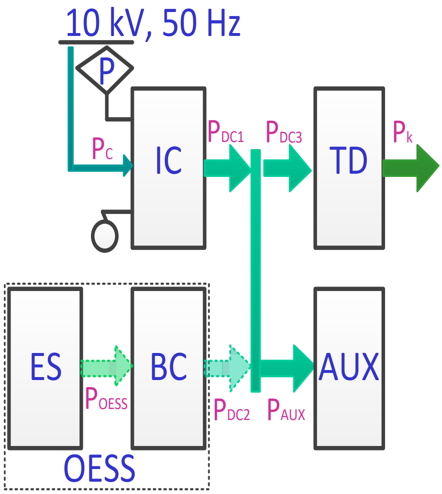

Fig. 4. Diagram of energy flows in the traction system (P - pantograph, IC - input converter, TD – traction electric drive, OESS – on-board energy storage system, ES – energy storage, BC – matching converter, AUX – auxiliary systems P_C – power that is consumed from the traction network, P_{DC1} – power that enters the intermediate circuit from the input converter, P_{DC2} – the power that comes from to the intermediate circuit from OESS, P_{OESS} – power that is consumed from ES, P_{DC3} – power that is transmitted to the traction electric drive, P_{AUX} – power consumed by auxiliary systems, P_k – tangent power of the electric locomotive)

In traction mode, the power in the intermediate circuit consumed by the traction electric drive and auxiliary systems from the input converter:

$$P_{DC1} = \begin{cases} \frac{P_k}{\eta_{TD}} + P_{AUX}, & \left(\frac{P_k}{\eta_{TD}} + P_{AUX}\right) \le U_C I_{CA} \eta_1 \\ U_C I_{CA}, & \left(\frac{P_k}{\eta_{TD}} + P_{AUX}\right) > U_C I_{CA} \eta_1 \end{cases} \tag{21}$$

The power in the intermediate circuit consumed by the traction electric drive and auxiliary systems with ES:

$$P_{DC2} = \begin{cases} 0, & \left(\frac{P_k}{\eta_{TD}} + P_{AUX}\right) \le U_C I_{CA} \eta_1 \\ \frac{P_k}{\eta_{TD}} + P_{AUX} - U_C I_{CA} \eta_1, & \left(\frac{P_k}{\eta_{TD}} + P_{AUX}\right) > U_C I_{CA} \eta_1 \end{cases} \tag{22}$$

The power consumed by the electric locomotive from the catenary network:

$$P_L = \frac{P_{DC1}}{\eta_1} \tag{23}$$

The power consumed from ES:

$$P_{ES} = \frac{P_{DC2}}{\eta_{BC}}. \tag{24}$$

In coasting mode and braking with a pneumatic brake, the power consumed from the contact network goes to power the auxiliary systems of the electric locomotive:

$$P_L = \frac{P_{AUX}}{\eta_1} \tag{25}$$

ES does not participate in energy exchange, therefore:

$$P_{ES} = 0 \tag{26}$$

The energy consumed by the electric locomotive from the traction network at the end of the v-th stage of consumption by duration t_v:

$$E_{Lv} = E_{Lv0} + \int_0^{t_v} P_{Lv} dt, \tag{27}$$

where E_{L0v} – the energy consumed from the contact network at the beginning of the v-th stage,
$P_{Lv} = P_{Lv}(t)$ – dependence on the power consumed by the electric locomotive from the traction network at the v–th stage.
The energy consumed by the traction electric drive and auxiliary systems from ES at the end of the r-th stage is determined by the expression:

$$E'_{ESr} = E'_{ES0r} + \frac{1}{\eta_{ES}} \int_0^{t_r} \left| P_{ES_r} \right| dt, \tag{28}$$

where $P_{ESr} = P_{ESr}(t)$ – the dependence of the power consumed by the electric locomotive from the energy storage during the stage of energy extraction from ES, duration ist_r,
E'_{ES0r}– the initial ES energy at the r-th stage.
The initial energy, which must be stored in the ES before starting the movement, is determined from the condition:

$$E'_{ES0} \ge E'_{ES\Sigma}, \tag{29}$$

where $E'_{ES\Sigma}$ – total energy consumed from ES.
In further calculations, it is assumed that the initial energy is equal to the energy calculated by expression (29). Power is ES determined by (1). The results of the calculations are given in Table 1.
Fig. 5 shows the dependences of tractive power (a), power consumed from the traction network (b), ES power (c), energy consumed from the traction network (d), and energy consumed from ES (e) at a limiting current of 600 A.
As shown in Fig. 4, energy consumption from ES occurs at a tangential power exceeding 4200 kW. This happens when a loaded train starts and moves on a controlled uphill.
During movement with the use of electrodynamic braking, the energy processes in the traction system of an electric locomotive are described by the following model. Figure 5 shows the diagram of energy flows in the traction system for the investigated scenario.
In the traction mode, the power consumed from the catenary network and the power consumed from the ES is determined by expressions (21) – (24), respectively.
In coasting mode, the power consumed by the electric locomotive from the contact network and the power consumed from the ES is determined by expressions (25) and (26), respectively.
In the mode of electrodynamic braking, auxiliary systems of the electric locomotive are powered by the energy supplied from the traction electric drive. The rest of the energy is used for charging and if the power is sufficient, it is sent to the traction network.
The power supplied to the DC link from the traction electric drive:

$$P'_{DC3} = P_k \eta_{TD} \tag{30}$$

where P_k – tangent power of the electric locomotive.
The power that is available for charging the OESS:

$$P'_{DC2} = \begin{cases} 0, & P'_{DC3} \le P_{AUX} \\ P'_{DC3} - P_{AUX}, & 0 < (P'_{DC3} - P_{AUX}) \le \frac{P_{ESnom}}{\eta_{BC}} \\ P_{ESnom}, & (P'_{DC3} - P_{AUX}) > \frac{P_{ESnom}}{\eta_{BC}} \end{cases} \tag{31}$$

The power at the terminals of the input converter, which is returned or consumed from the contact network:

$$P'_{DC1} = \begin{cases} P_{AUX} - P'_{DC3}, & P'_{DC3} \le P_{AUX} \\ 0, & (P'_{DC3} - P_{AUX}) < \frac{P_{ESnom}}{\eta_{BC}} \\ -\left(P'_{DC3} - P_{AUX} - \frac{P_{ESnom}}{\eta_{BC}}\right), & P'_{DC3} > P_{AUX} + \frac{P_{ESnom}}{\eta_{BC}} \end{cases} \tag{32}$$

The power consumed from the traction network (case $P'_{DC3} \le P_{AUX}$):

$$P_L = \frac{P'_{DC1}}{\eta_1} \tag{33}$$

The power that is recuperated to the traction network (case $P'_{DC3} > P_{AUX} + \frac{P_{ESnom}}{\eta_{BC}}$):

$$P_R = P'_{DC1} \eta_1 \tag{34}$$

The energy consumed by the electric locomotive from the traction network at the end of the u-th stage of consumption by duration t_u:

$$E_{Lu} = E_{Lu0} + \int_0^{t_u} P_{Lu} dt, \tag{35}$$

where E_{Lu0} – the energy consumed from the contact network at the beginning of the v–th stage,
$P_{Lu} = P_{Lu}(t)$ – dependence on the power consumed by the electric locomotive from the traction network at the v-th stage.

Table 1. Calculation results of ES power, consumed energy, and initial ES energy during movement without ES charging

	The active component of the limiting current consumed from the catenary network, A						
	1000	**900**	**800**	**700**	**600**	**500**	**400**
ES power, kW	632	1359	2086	2813	3540	4267	4994
The energy consumed by the electric locomotive from the traction network, kWh	1296	1287	1270	1247	1214	1171	1112
Energy consumed for charging ES before movement, kWh	4,5	14,3	31,5	56,5	90,5	136,0	198
Working ES capacity, kWh	4,5	14,3	31,5	56,5	90,5	136,0	198

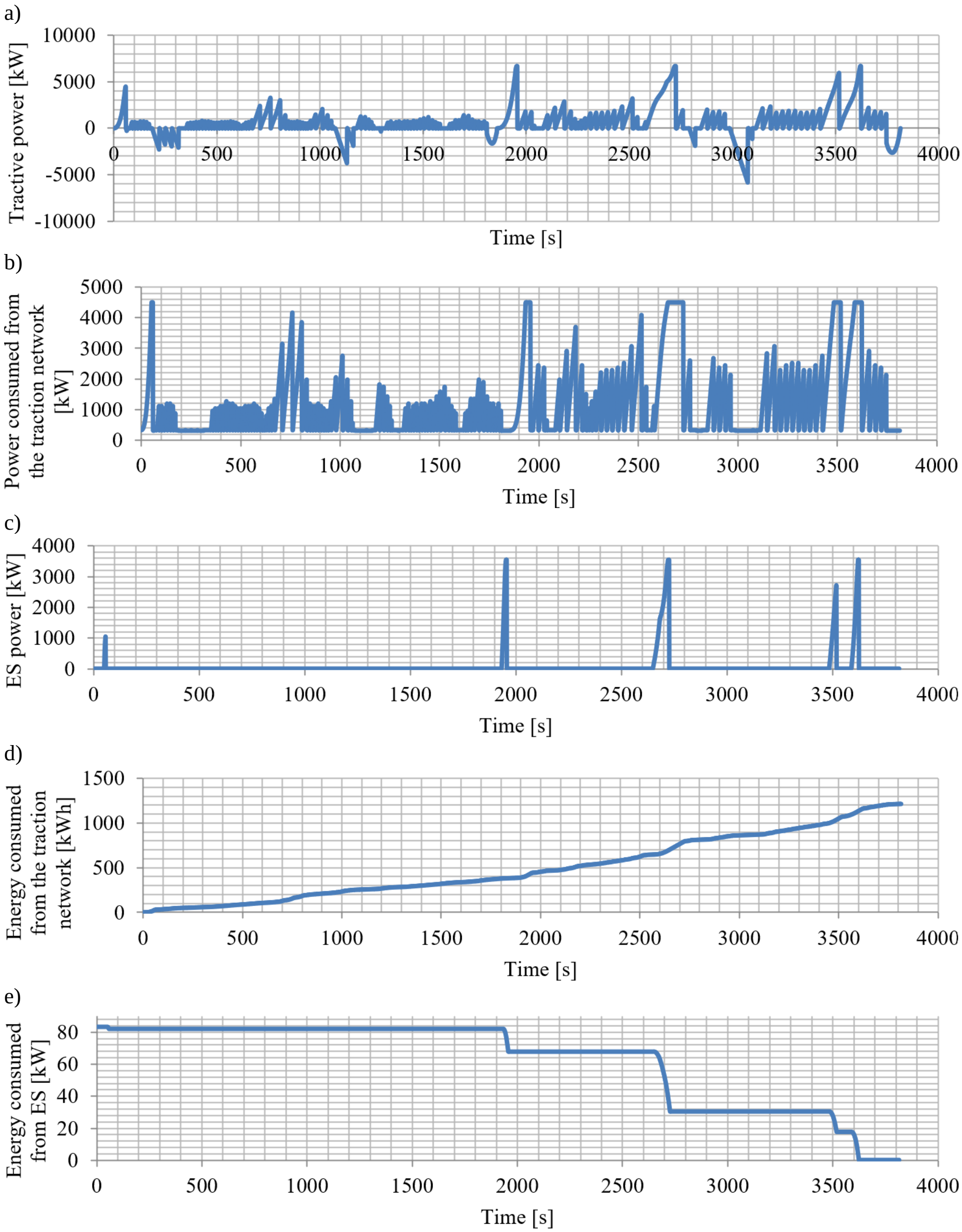

Fig. 5. Calculation results for operation without EDB

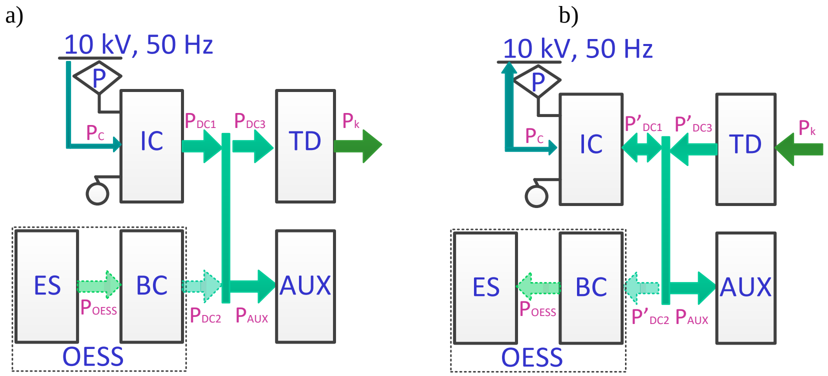

Fig. 6. Diagram of energy flows in the traction system: a – traction and coasting mode, b – EDB mode (P'_{DC3} – power that comes from the traction electric drive, P'_{DC2} – the power that is transferred to the OESS, P'_{DC1} – the power consumed from the traction network in EDB mode (other – see Fig.4))

Energy consumed from the traction network during recuperation, at the end of the q-th stage of consumption by duration t_q:

$$E_{Lq} = E_{Lq0} + \int_0^{t_q} P_{Rq} dt, \tag{36}$$

where E_{Lq0} – the energy consumed from the contact network at the beginning of the v-th stage,
$P_{Rq} = P_{Rq}(t)$ – dependence on the power consumed by the electric locomotive from the traction network at the q-th stage.
The ES power:

$$P_{ES} = \eta_{BC} P'_{DC2} \tag{37}$$

ES energy after the charge phase lasts t_q:

$$E_{ES} = E_{ESq} + \eta_{ES} \int_0^{t_q} P_{ES} dt \tag{38}$$

where E_{ESq} – ES energy at the beginning of the q-th stage of charging.
Table 2 shows the results of the calculations. Fig.7 and 8 show the dependencies for movement scenarios without ES charging in electrodynamic braking modes and with ES charging.

Table 2. Calculation results of ES power, consumed energy, and initial ES energy during movement with ES charging

	The active component of the limiting current consumed from the traction network, A						
	1000	**900**	**800**	**700**	**600**	**500**	**400**
ES power, kW	632	1359	2086	2813	3540	4267	4994
ES working capacity, kWh	58,3	93,3	98,3	85,4	63,5	75,8	114
The energy consumed by the electric locomotive from the traction network, kWh	1259	1250	1234	1210	1178	1135	1076
Energy consumed for ES charging before movement, kWh	0	0	0	0,2	1,4	22,7	70,4
The coefficient that shows the reduction of energy consumed by the electric locomotive	0,97	0,96	0,95	0,93	0,9	0,88	0,87
The coefficient that shows which part of the energy is stored in the ES	0,05	0,09	0,10	0,115	0,12	0,128	0,13
The coefficient that determines the full use of the installed ES power	0,85	0,67	0,53	0,45	0,39	0,35	0,32
The coefficient that determines the completeness of the use of ES energy intensity	0,92	0,87	0,76	0,61	0,44	0,51	0,77

As can be seen from Fig. 7 and 8, with the same limiting current in the scenario where charging is provided for ES with electrodynamic braking, there is less energy consumption. This is related to both, the power supply of the auxiliary systems from the traction drive in the EDB mode, and to the energy reduction that must be stored in the ES before the start of the movement.

Fig. 9 shows the dependence of the ES power, which is linear according to formula (1).

Fig. 10 shows the dependence of the ES operating energy capacity on the limiting current.

For the scenario of operation without charging in EDB modes, the operating energy capacity increases during the decrease of the current limit. This is because, the smaller the limit current (and therefore the power and energy consumed from the contact network), the more energy must be stored in the ES before the start of the movement to ensure the necessary power for the electric locomotive movement.

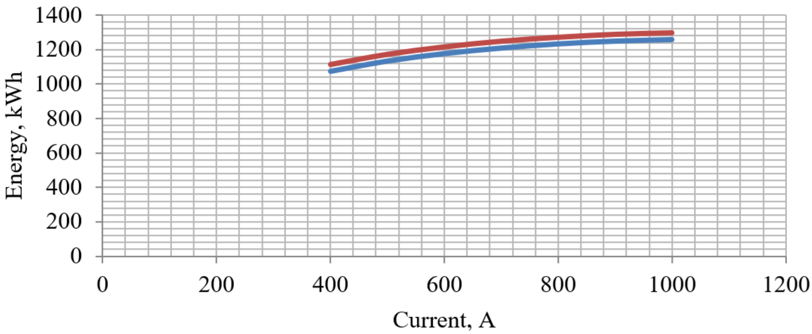

Fig. 7. Dependence of the energy consumed from the traction network on the limit current (red line – ES is not charging during movement, blue line – ES is charging during movement)

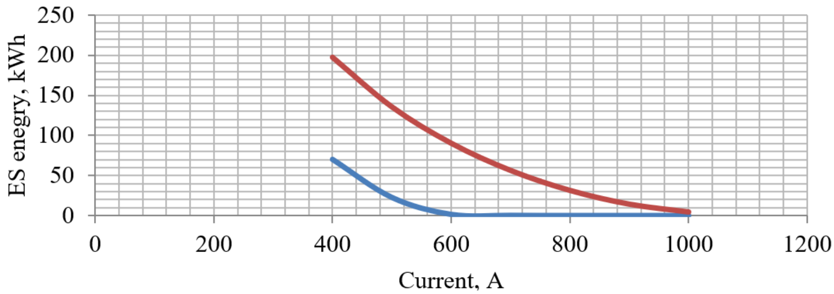

Fig. 8. Dependence of the energy that must be transferred to the ES before the start of movement (red line – ES is not charging during movement, blue line – ES is charging during movement)

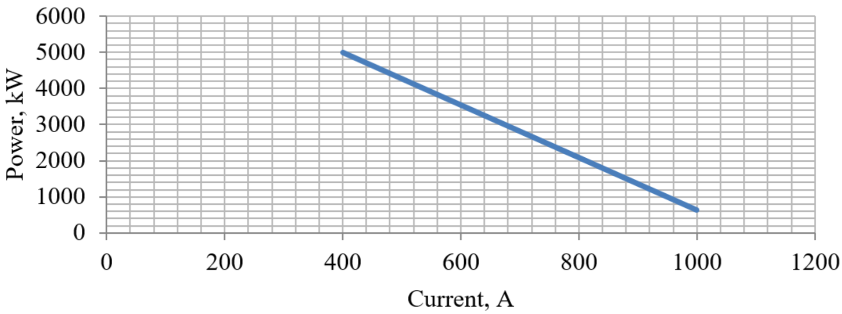

Fig. 9. Power dependence of ES

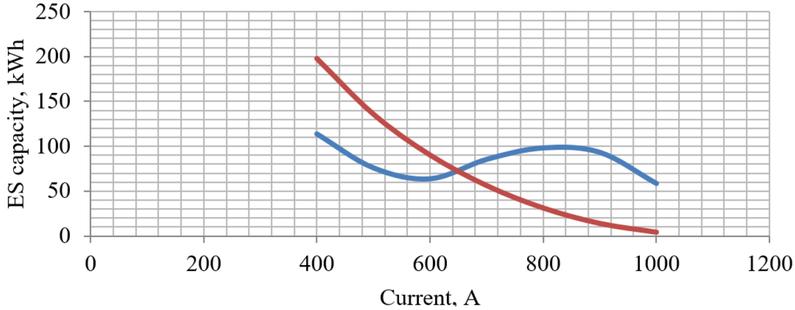

Fig. 10. Dependence of the working energy capacity of ES (red line – ES is not charging during movement, blue line – ES is charging during movement)

When charging ES in EDB modes, the dependence of the working energy capacity is non-linear. At the same time, it is worth mentioning that according to the calculation results, at high values of the limiting currents, the ES works only for energy storage in the EDB mode. For example, Fig. 11a shows the energy dependence of the ES at a limiting current of 800 A. At a limiting current of 500 A (Fig. 11b), the ES ensures both, energy storage and a significant power supply of the traction system.

The dependence of the coefficients characterizing the energy exchange processes is shown in Fig. 12.

The K_E coefficient decreases with a decrease in the limiting current, i.e., with a decrease in the limiting current, the total energy consumption of the electric locomotive decreases.

The K_R coefficient increases with a decrease in the limiting current, i.e., with a decrease in the limiting current, the share of energy stored in the ES increases.

The K_P coefficient decreases with a decrease in the limiting current. This indicates that the duration of ES use below nominal power increases.

The K_C coefficient has a non-linear character with a minimum near the limiting current of 600 A. At the same time, the smaller the value of this coefficient, the more intensively the energy exchange with ES occurs.

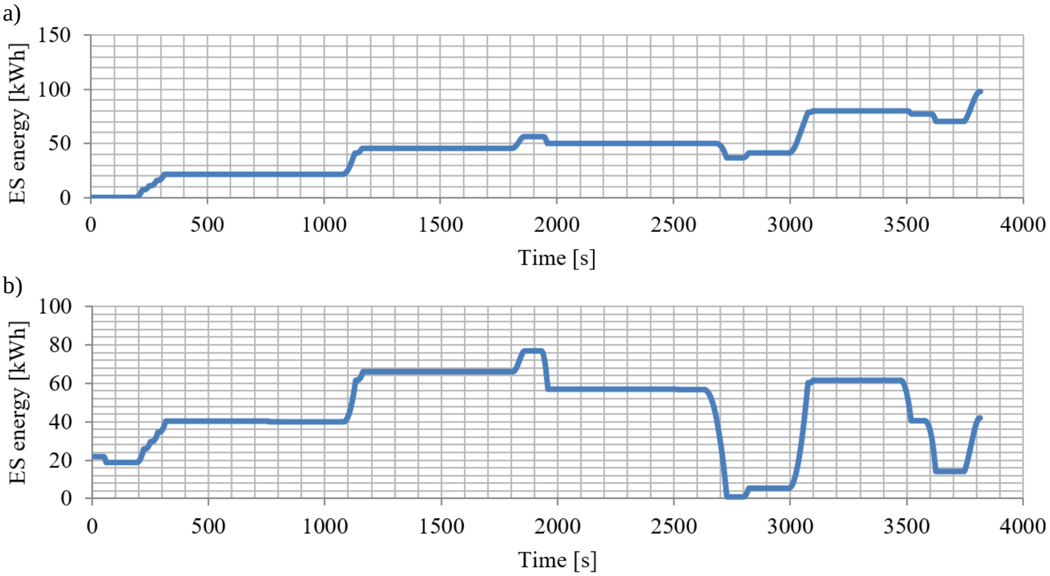

Fig. 11. ES energy at the limit current of 800 A (a) and 500 A (b)

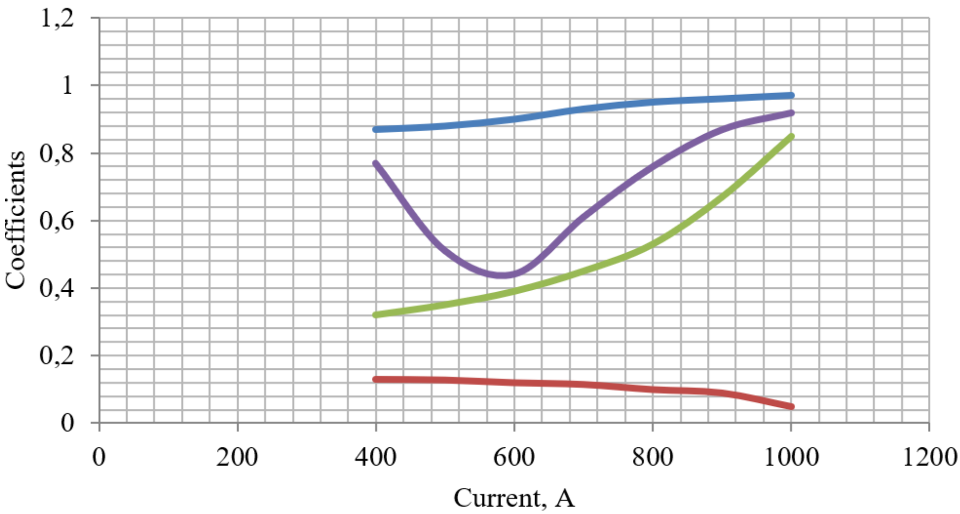

Fig. 12. Dependence of coefficients (blue line – K_E, red – K_R, green – K_P, purple – K_C)

By analyzing the obtained results, it is clear that at a current limit of about 600 A:

– there is no need to store energy before starting the movement,

– the working energy intensity is ES the least important,

– the best use is ensured ES by criterion, which determines the full use of energy intensity.

Based on this, the current limit has been acquired to be equal to 600 A. At the same time, the power of ES will be 3540 kW, the working energy capacity is 63.5 kWh. In this case, the reduction of energy consumption by the electric locomotive is 10%, and the energy stored in the ES makes 12% of the total energy consumed for traction. However, the coefficient that determines the full use of ES by capacity is 0.39, i.e., only 39% of the total operation time ES is working at nominal capacity.

Fig. 13 shows the dependences of the tractive power (Fig. 13a), the power consumed from the traction network (Fig. 13b), the ES power (Fig. 13c), and the ES energy (Fig. 13d). As shown below, when the power consumed from the traction network is exceeded, the ES "turns on" to operate. ES charging occurs in EDB modes. It is necessary to highlight the fact that at the end of the passage, the energy accumulated in the ES exceeds the initial energy in the ES, which is necessary for movement. This "surplus" can be further used to provide autonomous movement for maneuvering during loading and unloading.

Thus, according to the results of the conducted research, the parameters of the OESS electric locomotive for quarry railway transport were determined.

4. Conclusions

In the article, the energy exchange processes in the traction system of an electric locomotive for quarry railway transport have been considered. The peculiarity of the processes is that the majority of train movement sections are carried out with power not exceeding 50% of the nominal. Movement with nominal power is required only in adverse conditions – on the controlled rise with minimum voltage on the pantograph and limitation of the power consumed from the traction network. To ensure the necessary power, it is proposed to use an OESS.

2 To determine the parameters of the OESS - power and working energy capacity - mathematical models and criteria for selecting the ES parameters, quantitatively represented by the proposed energy coefficients, have been developed. Dependences of the ES parameters and criteria as a function of the current limit that may be consumed from the traction network were obtained. The processing of the acquired results showed that, according to the proposed criteria, the power of the ES is 3540 kW. The working energy capacity is 63.5 kWh.

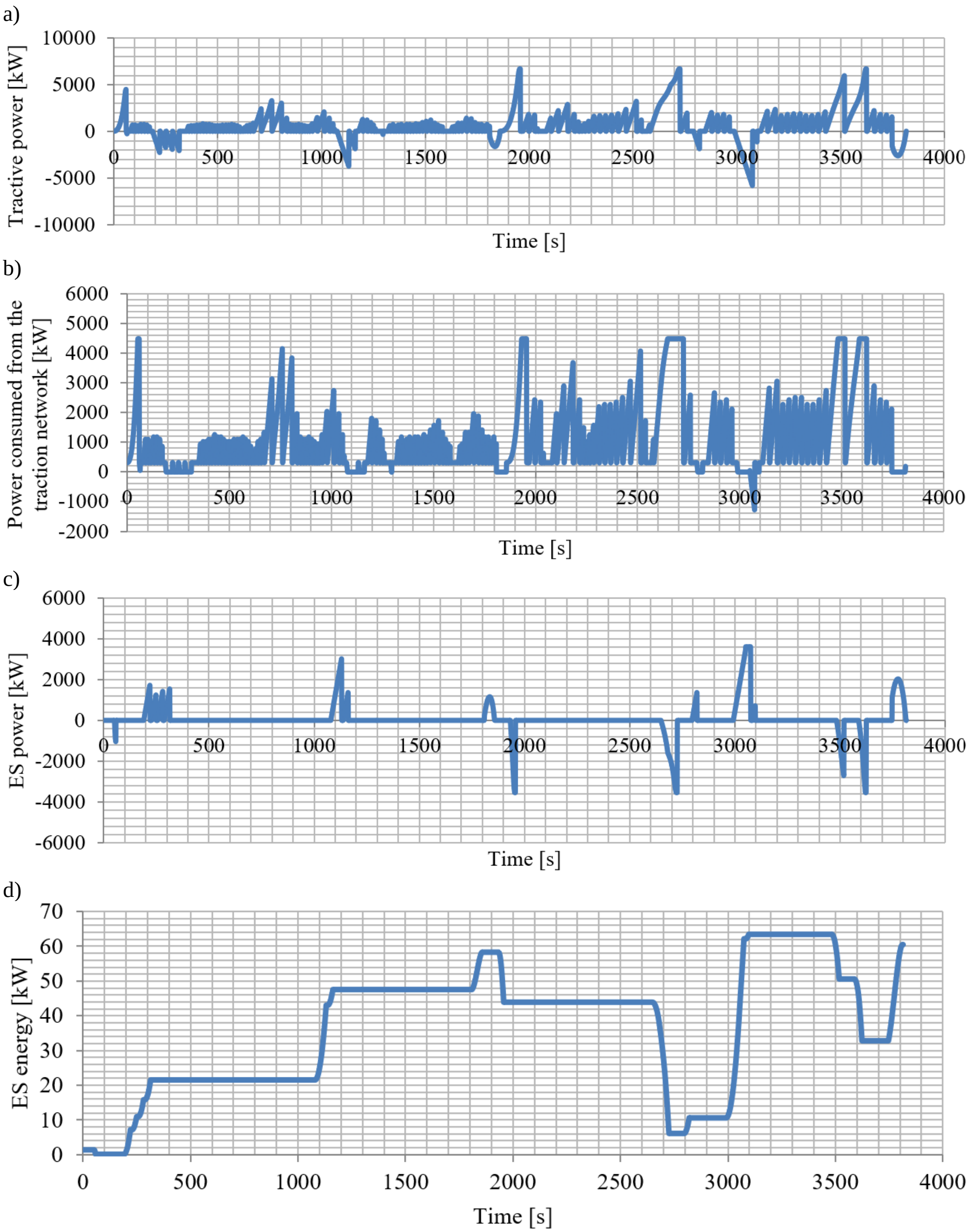

Fig. 13. Dependencies of power and energy at a limit current of 600 A

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