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EFFICIENCY OF ENERGY STORAGE CONTROL IN THE ELECTRIC TRANSPORT SYSTEMS

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Abstract:

The problems of storage and supplying the energy, together with reducing energy intensity for transport, are now crucial for developing sustainable and reliable transport systems. The energy network must be gradually adapted to new loads and power consumption patterns, especially in railways. The article aims to develop the simulation model to investigate the energy storage systems in its use in the electric transport infrastructure.

The authors review selected technical solutions for electric energy storage in transport. The theoretical aspects of energy exchange in the energy storage systems were presented as a base for a continuous simulation model of electric transport power supply. In the non-periodic random voltage input applied to the storage unit, it is proposed to use the calculation method based on the Duamel integral to analyze its charge-discharge processes. The resistance functions were applied to analyze the traction power supply mode with variable in time and space by active loads. The simulation showed that the direct connection of the unit to the traction network significantly reduces the traction energy consumption.

Keywords: *energy storage, transport, Duamel integral, charge-discharge processes, traction power supply, simulation*

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1. Introduction

In view of global environmental and energy problems, the power capacity of transport systems has always been and still remains the subject of scientific research, decent analysis and assessment of technological development opportunities.

This is a global trend implemented by developed countries to change the technical bases of means of transport and replace diffuse sources of CO_2 and harmful exhaust gas emissions with point sources (power plants). Point sources can be better controlled using advanced, greener, renewable energy sources.

However, such a change requires vehicles with energy storage units, providing them with the necessary mobility and appropriate motion parameters. Currently considered for practical application are mainly batteries, supercapacitors, and sources using green chemical reactions (e.g., hydrogen-based). Research on such solutions is carried out in organizational and technical matters (Jacyna et al., 2018 and 2021).

The power storage devices are a way to reduce power capacity and increase energy performance on electrified transport systems, as was discussed in the literature (see chapter 3.). One of the issues in the electrified transport systems is the oscillations in the power consumption modes caused by the inertia of movement and recuperative inhibition. Energy storage units are used to dampen these oscillations, improve the efficiency of recuperated energy utilization, and reduce energy losses and the power of installed traction power systems. In addition, the temporary storage of regenerative power takes priority over its returning to the primary network since it does not depend on the operation modes of separate loads and does not cause organizational issues when compensating for the cost of energy supplied to the external power supply system.

Searching for alternative fuels, the car producers develop technologies for manufacturing the conversion equipment and devices for electricity accumulation and storage.

The Toyota Prius, the world's first mass hybrid car, appeared in 1997. The internal combustion engine was combined with an electric motor to move the vehicle. Thirteen years later, the Tesla electric car appeared, capable of driving up to 300 km on a single charge. Tesla set things in motion. The era of electric vehicles (Liu, 2017) started and triggered the industry of autonomous vehicles. After that, most automakers with a worldwide reputation started releasing electric cars with batteries.

Today there are more than 17.5 million electric cars, and their number is continuously increasing. Among the countries, Norway is the leader in switching to electric vehicles; among the 2.6 million registered cars, there are about 100 thousand electric cars in Norway. For example, in Ukraine, there are approximately 33.5 thousand electric vehicles. Nearly 40 thousand electric cars are registered in Poland (Bosyi et al., 2020).

Due to the growing number of energy-intensive devices, it is necessary to build their effective interaction with the energy infrastructure of electrified transport to reduce the transportation process energy intensity. This is due to the need to gradually adapt the electricity network to new loads and power consumption patterns.

This article aims to develop the simulation model for the energy storage systems investigation on its use in the electric transport infrastructure.

The structure of the rest of the article is as follows. Chapter 2 reviews selected technical solutions in transport for electric energy storage as a base for the literature review in chapter 3. In the chapter 4. The theoretical aspects of energy exchange in the energy storage systems are presented as a base for continuous simulation model of electric transport power supply in chapter 5. The results from the model are presented and discussed in chapter 6. and concluded in chapter 7.

2. Review of selected technical solutions in transport for electric energy storage

The energy storage units are successfully used in subway and urban electric transport solutions. The different types of units are used. The transport substations use inertia mechanical energy storage units since they are the most consistent with the electromechanical properties of transport loads. The combination of 2-5 units allows accumulating energy in the capacity of 1.5 - 2.5 MW. This solution enables starting and turning up two electric trains to 60 km/h (ZhDM, 2010). Using super-condenser and superconducting inductive energy storage units in traction networks is not common and is in the testing phase. The indexes that determine the properties of the energy storage unit main types are shown in Table 1 (Vulturescu et al., 2010).

Table 1. Energy and discharge rates of different storage unit types

Energy storage unit type		**Energy density, (J/g)**	**Energy output time, (sec)**
With static active zone	Chemical	$10^2 – 10^5$	$1 – 10^5$
	Inductive	1 – 10	$10^{-3} – 10$
	Capacity	0,1 – 0,5	$10^{-6} – 10^{-2}$
With dynamic active zone	Mechanical	$10 – 10^3$	$1 – 10^3$
	Electromechanical	1 – 10	$10^{-2} – 10$
	Electrodynamic	0,05 – 1	$10^{-3} – 10^{-2}$

Figure 1 shows selected energy storage unit types. Besides, the energy density (the ratio of accumulated energy to the unit mass) and the specific power output (charge/discharge power to the unit mass) are given to compare their efficiency.

At present, electric car engineering is developing rapidly in the fields of both personal and public electric transport. Thus, visitors could see a unique exhibit at the InnoTrans 2017 (Berlin) 11th annual largest international exhibition of transport equipment and technologies - the E433 Vitovt Max Electro (Fig. 2, d) articulated electric bus. There were also vehicles introduced by the Polish company Solaris Bus & Coach S.A., the Dutch VDL Bus & Coach bv, and the German-Turkish Sileo GmbH. The Dnipro T203 hybrid trolleybus (Fig. 2, e), equipped with an electric motor with a capacity of 180 kW, can travel autonomously up to 20 km on the GMI lithium-ion battery at 100 A·h, at a nominal voltage of 550 V. Charging time from the catenary is up to 40 minutes. The weight of the battery section with 160 batteries is 576 kg.

The Urbino 12 electric bus, recognized as the "2017 Bus" in Europe, is equipped with the ZF AVE130 portal axle with two built-in electric motors (rated power of each is 60 kW, and the peak is 125 kW) and lithium-titanium batteries (Grischenko, 2016). The batteries feature three ways of charging: through the network, the pantograph mounted on the roof - during en-route stops, or the induction system.

The Citea SLF-120 Electric bus from the VDL Bus & Coach bv has a similar conception: it is equipped with lithium-ion batteries capable of charging through the network between changes. Besides, it is possible to charge it through the pantograph during operation. It can reach at least 200 km mileage on one charge.

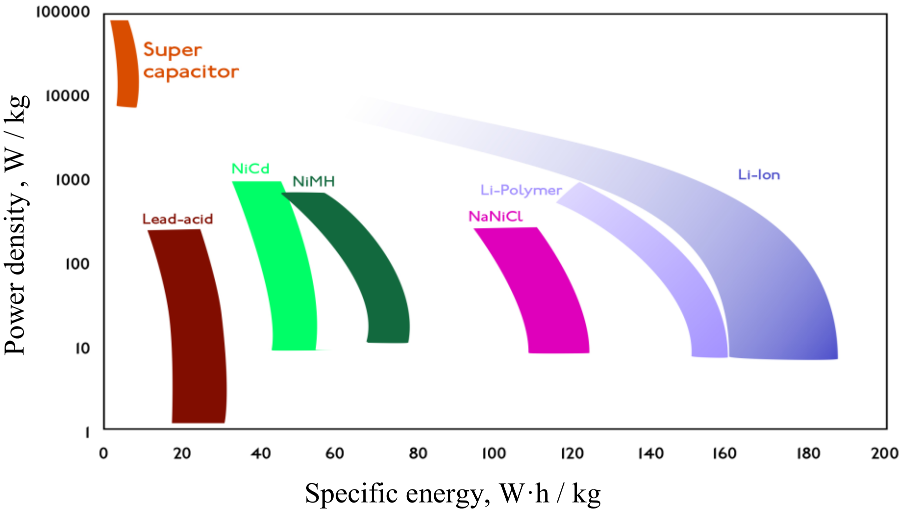

Fig. 1. Energy density vs specific power output of energy storage unit types

Fig. 2. Modern electric buses of different manufacturers:
a) Polish Urbino 12 electric, Solaris Bus & Coach S.A.
b) Dutch VDL Citea SLF-120 Electric, VDL Bus & Coach bv
c) German-Turkish E-Bus S18, Sileo GmbH company
d) Belorussian Vitovt Max Electro, Belkommunmash company
e) Ukrainian Dnipro T203, Southern Machine-Building Plant

The Sileo Company produced an 18-meter E-Bus S18 equipped with an accumulator of 474 lithium-iron-phosphate batteries with a capacity of 300 kWh, which is enough to drive 250 kilometers on one charge. Four electric motors with 120 kW each act as the electric drive, reaching a speed of up to 75 km/h.

Unlike other electric buses, the Belorussian Vitovt Max Electro is equipped with an advanced system of electric drives based on supercapacitors (ionizers). This solution allows for fast charging on the final stops using charging stations (Grischenko, 2016). Recharging is automatic via the semi-pantograph. When the battery charge is lower than 30%, the recharging takes about 5 - 7 minutes. During this time, the electric bus must have time to accumulate enough energy to drive at least a 12-km distance with a full load. Superconductors for Belkommunmash electric buses will be manufactured in partnership with the Chinese Xinzhu Corporation in the Chinese-Belarussian industrial park "Veliky Kamen" (Smolevitsky district). Supercapacitors are relatively reliable and durable: the number of charge-discharge cycles is over 100 thousand, and the resource is about ten years.

Also, there is another project worth considering: the Hedgehog Applications project (https://www.hedgehogapplications.nl), on using a power supply system of charging stations for electric buses and electric vehicles from high-energy storage batteries in the Netherlands (Fig. 3). The batteries are supposed to be installed at railway stations, which are powered by electrical train motor braking (RG, 2017). Thus, the amount of energy that can be obtained meets the needs of bus companies in small towns.

3. Literature review

Energy storage is being studied for a wide range of applications, one of which is transport. Research in this area has been carried out for years, but in the last twenty years, it has become imperative due to the increased importance of the climatic factor and living conditions in cities.

The legitimacy of introducing electric vehicles is an element of the current research on the organization of road and rail transport systems and public transport systems. The conditions of using electric vehicles result directly from the parameters of their batteries, charging characteristics, or energy recovery systems.

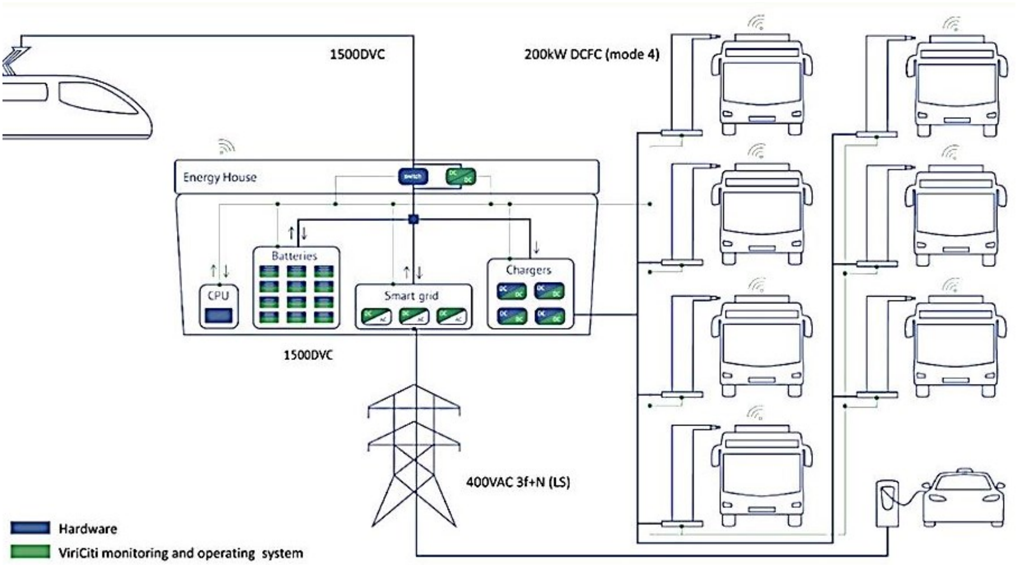

Fig. 3. Structural scheme of energy infrastructure interaction of city electric transport and electrified railway

Various aspects of the application and production of energy storage are considered. For example, these are systemic and organizational aspects. Izdebski and Jacyna (2021) presented a hybrid algorithm for energy expenditure estimation for electric vehicles in urban service enterprises to respond to the need to modify fleet vehicles operating in cities to a zero-emission fleet. One of the main problems in this regard is the battery capacity and the resulting variable range and charging time. Such studies are justified by studies related to the reduction of air pollution by introducing electric vehicles, such as that presented by Jacyna et al. (2021) or Szczepański et al. (2018). Here, too, the ability to store energy is a critical factor. The use of electric vehicles as a function of their battery parameters is the subject of critical decisions for the shaping of extensive public transport systems (cf. Jacyna et at., 2018, Jacyna, Gołębiowski and Szczepański 2015 or Liu et al. 2022) and local supply chains (cf. Jacyna and Semenov, 2020 and Semenov and Jacyna, 2022). Shu et al. (2021) study the life cycle environmental impact of $LiFePO_4$ and $Li(NiCoMn)O_2$ batteries, which are popularly used in EV passenger cars.

Therefore, the technical and technological aspects of energy storage are primarily the result of practical requirements justifying the use of electric vehicles in various modes of transport, including rail, which is primarily predestined for electric powering due to the specific solutions of traction infrastructure.

Zhao and Baker (2022) propose to use electric vehicle batteries as storage units for energy system to dump peak demand through vehicle to grid and battery swapping schemes. Ahmad, Khalid and Panigrahi (2021) present technological advancement of energy storage for electric vehicles and name the Li-ion batteries superior in terms of various parameters (capacity, sizing, life cycle). They focus on the battery management systems, including thermal management, charging infrastructure and provide the analyze of the alternative storage systems like supercapacitors or ultracapacitors, flywheels, superconducting magnetic energy storage (SMES), pneumatic batteries, fuel cells and compare their energy density (cf. Biernat et al., 2013 or Pielecha, 2021).

Capacitators are in general important research topic. Castaings et al. (2016) investigate effective energy management strategies for a battery–supercapacitor system and supercapacitor voltage limitations. Supercapacitors are in general considered as alternative power storage system for electric cars (cf. Horn et al., 2019). Rimas et al. (2022) provided a comprehensive review of energy management storage systems on electric vehicles, and state that enhancing energy storage systems efficiency, cost and weight is vital for massive adoption of EVs as well as precise methods to monitor battery characteristics. Ultracapacitors offer many advantages, but battery life extension must be over 50% so that investments are economically acceptable. Mir et al. (2009) present the use of a supercapacitor storage based light rail vehicle. They provide storage system rating, supercapacitor bank modeling, power electronic converter design and system control and management algorithms. They propose bidirectional multichannel buck-boost converter modules connected to supercapacitor banks to achieve an improved efficiency and circulate in autonomous mode (without catenary) (cf. Barrero and Tackoen, 2008).

Vulturescu et al. (2010) present a study on a battery ageing methodology of a storage system formed by supercapacitors and lead-acid battery. The hybrid system based on a power flow management allows to outline the main benefit of the hybridization: the reduction of losses within the battery.

Other considered energy storage systems are based on kinetic or thermal energy. Xie et al. (2022) consider thermal energy storage as a supportive system in battery-driven vehicle to save the power for the motion, which is especially important for large EV like busses. Strasik et al. (2007) as well as Lafoz et al. (2007) are investigating an alternative way of storing energy in vehicles using a flywheel and show that it can be an alternative to batteries for larger vehicles. Langari and Won (2003) test the intelligent agent for energy management of parallel hybrid vehicles to take into account the external conditions of drive and driving modes.

Energy control and management systems also are of great importance. Molina-Ibáñez et al. (2021) discuss the hybrid and control systems to optimize their performance to make it the real alternative to gas-powered engines. They analyze the implementation of the Superconducting Magnetic Energy Storage system for the future of electric vehicles. Sun et al. (2019) present methods to develop an efficient and operating in the real-time driving energy management for a front-and-rear-motor-drive electric vehicle equipped with an induction motor and a permanent magnet synchronous motor. Mutarraf et al. (2022) compare technical solutions for charging and storing energy on ships and cars and mention railway traction. They provide the conditions for developing power grids and energy conversion necessary to maintain charging systems in the near future (cf. Ciccarelli, 2014 or Lohner and Evers, 2004).

Szeląg (2017) presents solutions introduced on Polish railway and aiming at adjusting the power supply used to the TSI requirements. Characteristics of traction vehicles with asynchronous drives enables run at voltage lower than the rated voltage, however, it entails decrease of consumed power and loss of motion dynamics.

The literature review allows for the conclusion that various types of batteries and other techniques can now be used as energy storage devices to provide coverage for both short-term and long periods of electricity consumption and recovery. At the same time, for stationary installation, the mechanical or chemical secondary sources of electric energy are used, and the onboard equipment requires a combination of chemical and super-condenser elements. Other solutions can also be used for energy storage, as an interesting usage of electric cars can as temporary batteries when transported in trains (Bosyi, et al., 2018).

4. Theory of the energy exchange process in the energy storage unit

To illustrate the problem, the well-known scheme for replacing a capacitive supercapacitor battery with the C capacity is used. This is the most versatile type of storage device; its replacement circuit includes the resistance of the condenser leakage and its active resistance R_B (Fig. 4).

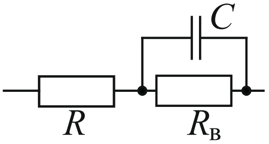

Fig. 4. Capacitive storage replacement scheme

Charging up from the constant voltage is described by the equations of the storage charging current and the voltage on its capacities:

$$i_{chg}(t)=\frac{U}{R+R_B}+\frac{UR_B}{R\left(R+R_B\right)}e^{-\frac{t}{\tau}} \tag{1}$$

$$u_{C\,chg}(t) = \frac{UR_B}{R+R_B}\left(1-e^{-\frac{t}{\tau}}\right) \tag{2}$$

where:

- U is the constant voltage of charge,
- $\tau = \dfrac{RR_BC}{R+R_B}$ is the circle time constant.

When calculating the voltage on the storage capacitive element with the charge under the nonperiodic voltage action (from the unstable power supply, namely, the recuperative train), the Duamel integral is most convenient. In the case of the piecewise-continuous function (or with breaks of the first kind), it looks as follows:

$$\begin{gathered} u_{C\,chg}(t) = \sum_{n=1}^{m} \Delta U_n(t_n) h_U\left(t-t_n\right) + \\ \sum_{n=1}^{m} \int_{t_n}^{t_{n+1}} \frac{dU_n(t)}{dt} h_U\left(t-\tau\right) d\tau + \\ \int_{t_m}^{t} \frac{dU_m(t)}{dt} h_U\left(t-\tau\right) d\tau \end{gathered} \tag{3}$$

where:

- $h_U(t) = \dfrac{R_B}{R+R_B}\left(1-e^{-\frac{t}{\tau}}\right)$ – transient voltage function for a given circle,
- $\Delta U_n(t_n) = U_{n+1} - U_n$ – voltage jump at a given time moment t_n.

When considering the $U(t)$ function as a piecewise constant, the derivatives under the integral are zero, and the expression (1) consists only of the product sum of the voltage jumps on the transition function shifted to the jump time:

$$u_{C\,chg}(t) = \sum_{n=1}^{m} \Delta U_n(t_n) h_U\left(t-t_n\right) \tag{4}$$

When considering $U(t)$ function as continuous, then the component (4) does not take into account in (3). Having simplified (3), we obtain a piecewise-continuous function $u_{C\,chg}(t)$, which is valid for separate time intervals. The expression of the voltage on the capacitance, depending on the current value of the applied voltage at the time interval $t_n \le t < t_{n+1}$, looks as follows

$$u_{C\,chg}(t) = \frac{R_B}{R+R_B}\sum_{n=1}^{m}\left(U_{n+1}-U_n\right)\left(1-e^{-\frac{t-t_n}{\tau}}\right) \tag{5}$$

For a piecewise-continuous function, this equation is more complicated yet more precise:

$$\begin{gathered} u_{C\,chg}(t) = \frac{R_B}{R+R_B}\sum_{n=1}^{m}\frac{U_{n+1}-U_n}{t_{n+1}-t_n} \times \\ \left(\left(t_{n+1}-t_n\right) - \tau\left(e^{-\frac{t-t_{n+1}}{\tau}} - e^{-\frac{t-t_n}{\tau}}\right)\right) \end{gathered} \tag{6}$$

The storage charging current can be defined as:

$$i_{chg}(t) = C\frac{d}{dt}u_{C\,chg}(t) + \frac{u_{C\,chg}(t)}{R_B} \tag{7}$$

Its graph is presented for the corresponding dependence of voltage on the storage capacitive element on Fig. 5.

Dependence of the energy given by the storage unit when discharging on the given load from the residual voltage on its clamps U_{res} is shown in Fig. 4 and defined by the expression

$$\begin{gathered} E(U_{res}) = \int_0^{t(U_{res})} p(t)dt = \int_0^{t(U_{res})} u(t)i(t)dt = \\ \int_0^{\frac{U}{RC}\ln U_{res}} Ue^{-\frac{t}{RC}}\, Ie^{-\frac{t}{RC}} dt \end{gathered} \tag{8}$$

where RC is the equivalent active resistance of the discharge loop and the storage unit capacitance. The high bound of the integral $t(U_{res})$ determines the time of the storage discharge to the voltage value U_{res}. Fig. 6 shows that, for example, with storage discharging to the nominal voltage of 50%, its residual energy reserve is 25%.

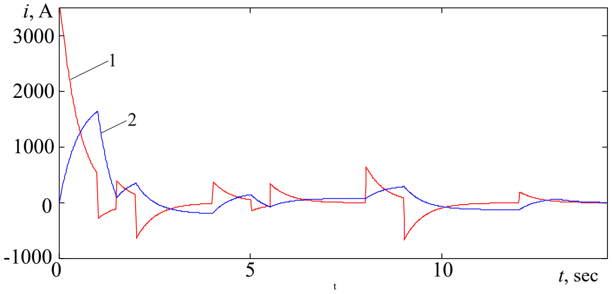

Fig. 5. Charging current of a storage device with piecewise constant (curve 1) and with piecewise linear (curve 2) approximations for the applied voltage

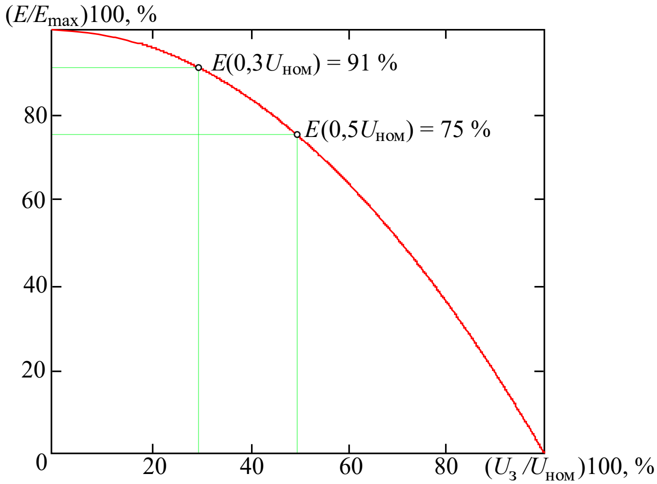

Fig. 6. The residual and nominal voltage ratio dependence in terms of energy supplied by the storage

The standard SoC (State of Charge) index is used for monitoring the current level of the storage charge (Bosyi et al., 2020; Vulturescu et al., 2010):

$$\mathrm{SoC}(t) = \mathrm{SoC}(t_0) + \frac{100}{U_{nom}C}\int_{t_0}^{t} i(t)dt \tag{9}$$

where:

- $\mathrm{SoC}(t_0)$ is the initial storage charge (%),
- $i(t)$ is storage current and U_{nom} is the nominal voltage.

Since $\frac{1}{C}\int_{t_0}^{t} i(t)dt = u_C(t)$, for a capacitive storage unit, the dependence (9) is reduced to the ratio of its residual and nominal voltage:

$$\mathrm{SoC}(t) = \mathrm{SoC}(t_0) + \frac{u_C(t)}{U_{nom}}100 \tag{10}$$

5. Simulation model of electric transport power supply

As a rule, calculations of complex electric consumption modes on electric transport are performed on specially designed models (Abrahamsson, 2008). Environments such as MatLab Simulink are unsuitable for directly performing such calculations. But the apparent advantages of these environments can be exploited by using the dynamic modeling of traction network regimes. This approach combines controlled current sources and traction network resistance with variable analytical functions. Thus, current value changes allow calculating the mode of separate load consumption in time, while the traction resistance change allows defining its movement in space under the displacement-time diagram.

Fig. 7 shows such concept for a single-edged area with console feed, arm length x_0, and specific traction network resistance of r_0. This example demonstrates all possible cases of three loads on a site.

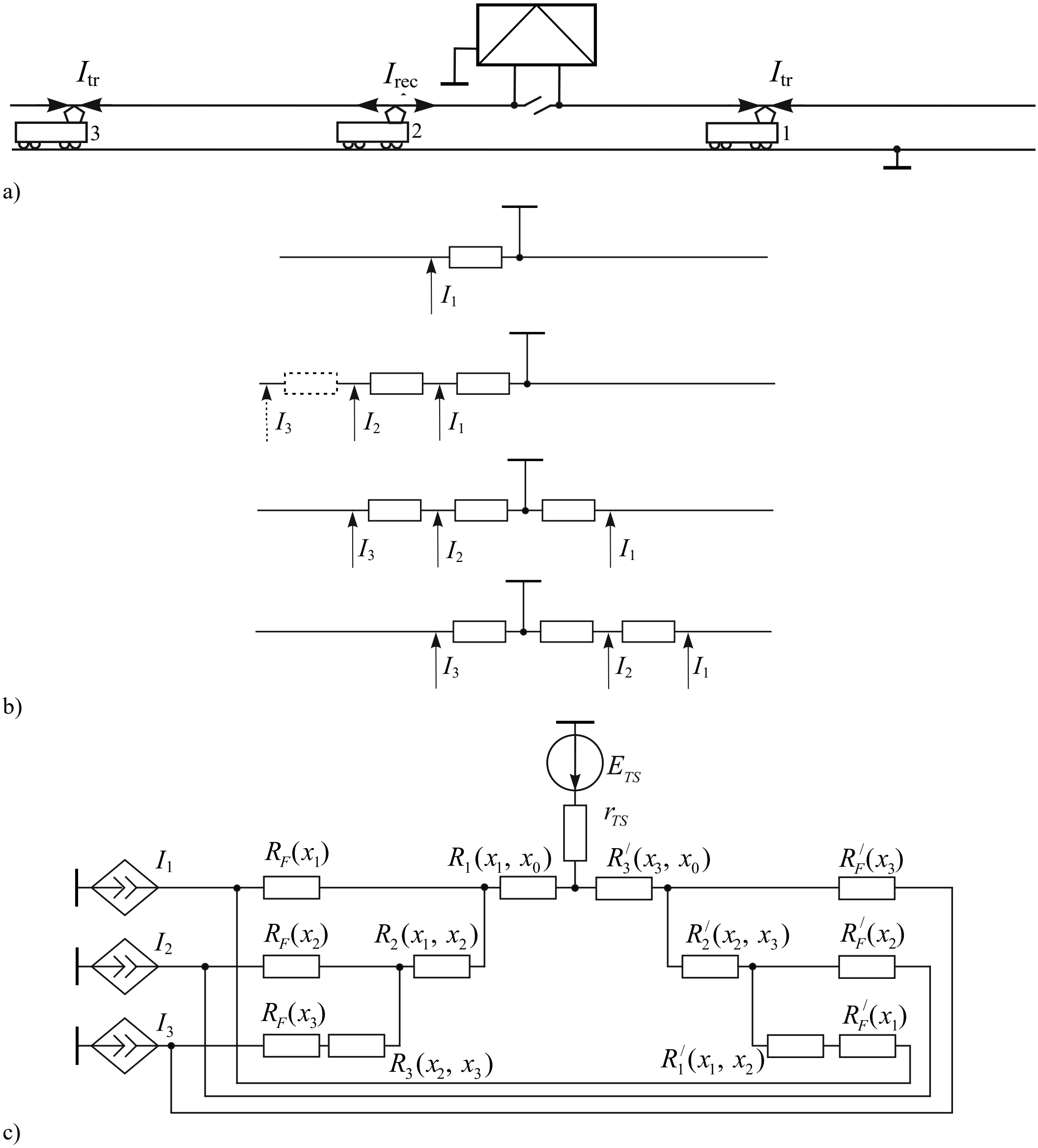

Fig. 7. One-track section of a traction power system (a), scheme of its loading (b), and its instantaneous replacement scheme (c)

The following expressions describe the resistance functions in this area for one of the arms:

$$R_1(x_1)=\begin{cases} r_0\left(x_0-x_1\right),\ x_0\le x_1 \\ 0,\ x_0>x_1 \end{cases}, \tag{11}$$

$$R_2(x_1,\,x_2)=\begin{cases} r_0\left(x_1-x_2\right),\ x_1\le x_0,\ x_2\le x_0 \\ r_0\left(x_0-x_2\right),\ x_0>x_1,\ x_2\le x_0 \\ 0,\ x_1>x_0,\ x_2>x_0 \end{cases}, \tag{12}$$

$$R_3(x_2,\,x_3)=\begin{cases} r_0\left(x_2-x_3\right),\ x_2\le x_0,\ x_3\le x_0 \\ r_0\left(x_0-x_3\right),\ x_2>x_0,\ x_3\le x_0 \\ 0,\ x_2>x_0,\ x_3>x_0 \end{cases}, \tag{13}$$

$$R_F(x_1)=\begin{cases} 0,\ x_1\le x_0, \\ \infty,\ x_1>x_0, \end{cases} \tag{14}$$

$$R_F(x_2)=\begin{cases} 0,\ x_2\le x_0, \\ \infty,\ x_2>x_0, \end{cases} \tag{15}$$

$$R_F(x_3)=\begin{cases} 0, x_3\le x_0, \\ \infty, x_3>x_0, \end{cases} \tag{16}$$

where $R_1(x_1)$, $R_2(x_1,\,x_2)$, $R_3(x_2,\,x_3)$ are the resistance of the traction network between trains and traction substations, which depends on its location and other trains' location.

The resistance defined by the last three expressions (14)-(16) is a dummy. These expressions supply the train current to the traction network power supply, which corresponds to the train coordinate.

Fig. 8 demonstrates the general appearance of the simulation model based on the proposed concept for the MatLab environment. The structure of the model contains the following elements:

1. blocks of the external power supply system,
2. units for determining the electricity consumption,
3. blocks of traction network variable resistances,
4. blocks of controlled current sources
5. storage subsystems connectable through the converter and direct connection.

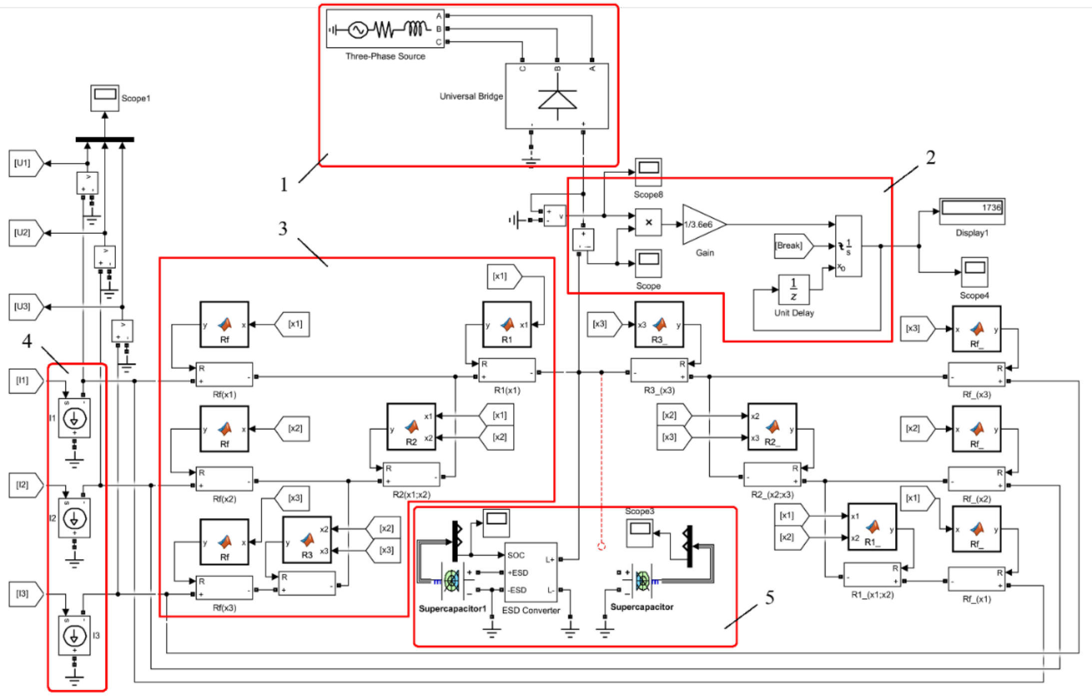

Fig. 8. Simulation model of the traction power system in the MatLab Simulink environment

An external power supply system is modeled by a three-phase power source and a converter, which can act both as a rectifier and an inverter. The product integration of the substations current supply and the voltage on the tires are used to determine the electricity consumption. To avoid the current and voltage drops that occur during regeneration failures, the integrator resets to the initial value obtained in the previous step.

The variable resistance of the traction network within the solution of this problem following the compensation theorem is modeled by a controlled voltage source (Bosyi et al., 2020). The product of the current flowing determines the source voltage value through it and the required resistance value *R*, which is obtained by the formulas (11)-(13) that were given before in the form of MatLab functions. When *R* can be an infinite value, together with the voltage source, it is necessary to include arbitrary resistance, which is shunted by the switch in other cases.

Separately, there are subsystems for organizing the input data and corrections (Bosyi et al., 2020). These subsystems serve to generate information about the location of each load ($x1, x2, x3$) based on the global variable of *Time* modeling, current consumption ($I1$, $I2$, $I3$), and the current collector voltage ($U1$, $U2$, $U3$) according to the traction calculations for the loads.

In the recovery mode, a load model acts as a controlled current. This can be represented analytically as follows:

$$I_{rec}\left(U_c\right)=\begin{cases} I_{rec},\ U_c<U_c^{\max}, \\ I_{rec}-I_{ex\,rec},\ U_c=U_c^{\max}, \\ 0,\ U_c>U_c^{\max}, \end{cases} \tag{17}$$

where $I_{ex\,rec}=f\left(U_c\right)$ is the excess recuperation current, determined by a compatible traction calculation and calculation of the traction power supply system instantaneous scheme.

The input data correction ensures that the load power consumption corresponds to the simulation result and the actual voltage level in the traction network. The correction is performed based on the load current recalculation by assigning a specific traction power calculation to the average traction network voltage. The subsystem also implements simulation of recuperation failures that arise when voltage increases over 4000 V. In this case, the load output current from the beginning of the recuperation failure to the end of the braking interval is zero. It is also possible to configure the subsystem so that the recuperation current can be reduced to the maximum possible level the power supply system allows.

Studying the power supply system operation with storage units can be performed with a direct connection to the traction network and through a charging-bit converter. The storage nominal voltage is selected following the traction network operation modes in the first case. When using the converter, the SU nominal voltage may be lower. The converter model is proposed in the form of two controlled current sources with the follow-up system for the given shift characteristic between the modes of accumulation, storage, and electricity output (Bosyi et al., 2020).

6. Simulation results

To study the efficiency of the storage power transfer mode in the traction system, a single-walled section of the direct current traction network with a nominal voltage of 3.3 kV was selected. It includes three traction substations, one of which can be equipped with a power storage unit. The capacity of the SU is 300 F. It is issued to be an acceptable value for technological availability and value parameter (Lafoz et al., 2007).

Let’s consider the case when three trains pass according to the schedule (Fig. 9) so that a heavy-tonnage train, equipped with a recovery system, follows between two lightweight trains.

The track profile on the site is chosen so that trains on the substation sections 1-2 are in traction and run mode, and on the substation sections 2-3 partly in runoff and regenerative braking mode (Fig. 10). The modes are chosen such that the traction electric power consumption and recovery processes in adjacent sections do not coincide in time, which is the most widespread occurrence (Langari and Won, 2003).

When train 1 leaves the area under consideration, and the heavy train 2 enters the substation sections 2-3, train 3 enters sections 1-2. The last train consumes energy according to the same schedule as train 1. In this case, train 3 can partially be charged by the storage unit.

Based on the traction calculations for this section (substations 1-3), the graphs of train currents formed by the profile, the movement mode, and the mass of the train are determined (Fig. 11).

The following variants of the traction substation equipment assembly were considered:

- rectifier and inverter converter;
- rectifier converter with a controlled and unmanaged storage unit;
- inverter converter with a controlled and unmanaged storage unit.

The variants of the structural schemes used in the simulation are shown in Fig. 12.

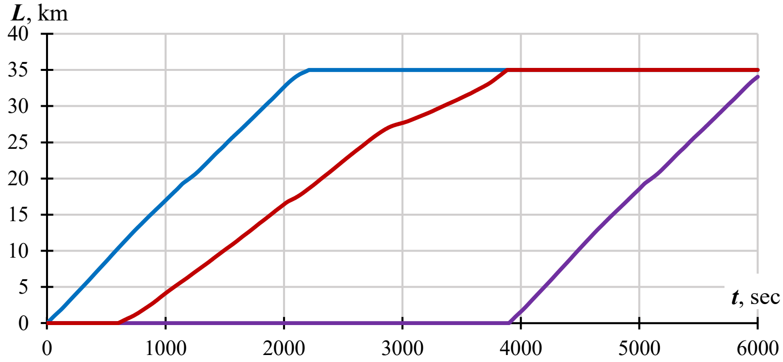

Fig. 9. Schedule of trains on the site

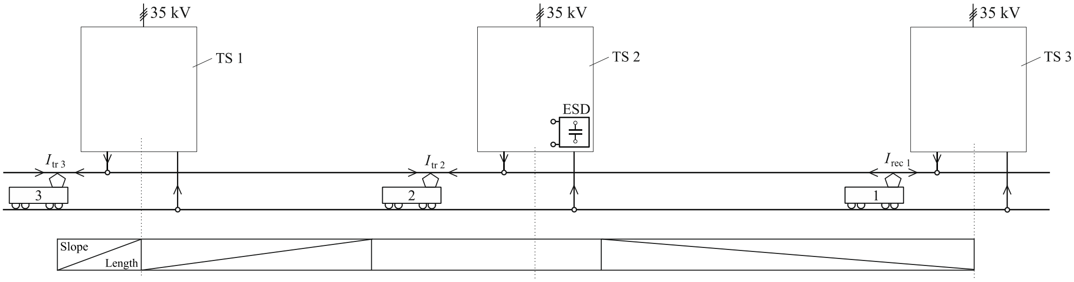

Fig. 10. Structural scheme of the experimental site

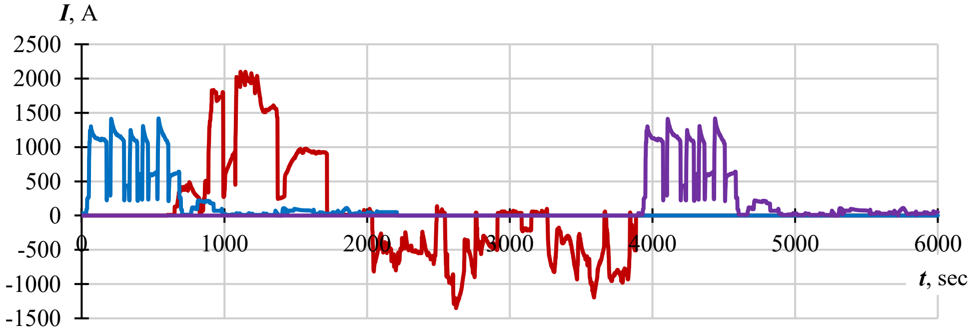

Fig. 11. Output charts of train current consumption

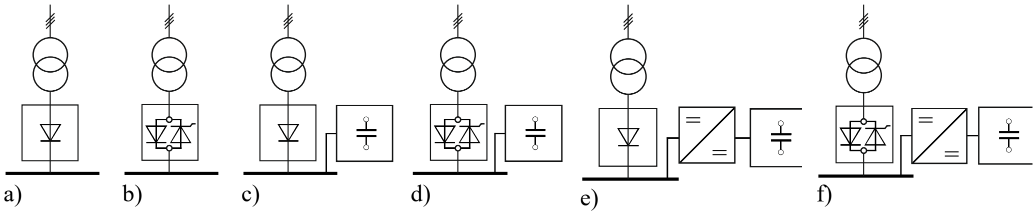

Fig. 12. Options of the substation structural scheme: a - a rectifier without a SU; b – an inverter without a SU; c – a rectifier with an unmanaged SU; d – an inverter with an uncontrolled SU; e – a rectifier with a controlled SU; f – an inverter with a cont rolled SU

Fig. 13 shows the voltage-ampere characteristic of the charger-bit device, which is a constant-voltage converter designed to control the power-exchange mode of the SU in the required range. The parameters of the converter are voltage $U_1 \ldots U_4$ and currents I_0, $I_{\min}$, and $I_{\max}$. The last values can regulate the depth and speed of the unit charge and discharge.

The traction substation idle speed is taken at 3.5 kV for all cases.

To ensure identical simulation conditions in various structural schemes, the initial level of a SU charge is selected as follows. In circuits with an uncontrolled SU, the initial charge level of supercapacitors is equal to the idle voltage at the connection point, which excludes the transient processes at the initial simulation moment and its effect on the total electricity consumption. For controllable units, it should be so that the initial unit charge level equals its charge at the end of the considered time interval.

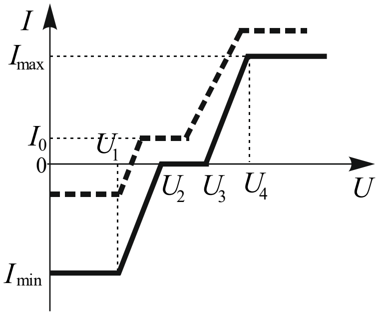

Fig. 13. General view of the voltage-current characteristics of a charger-bit converter

The operation simulation of the various traction power systems (Fig. 12) has shown the time dependencies of the voltages at collectors (Fig. 14), the electric locomotive currents in the traction and recovery modes (Fig. 15), and the voltage on the traction substation tires, their currents, and the currents of a power storage unit (Fig. 16).

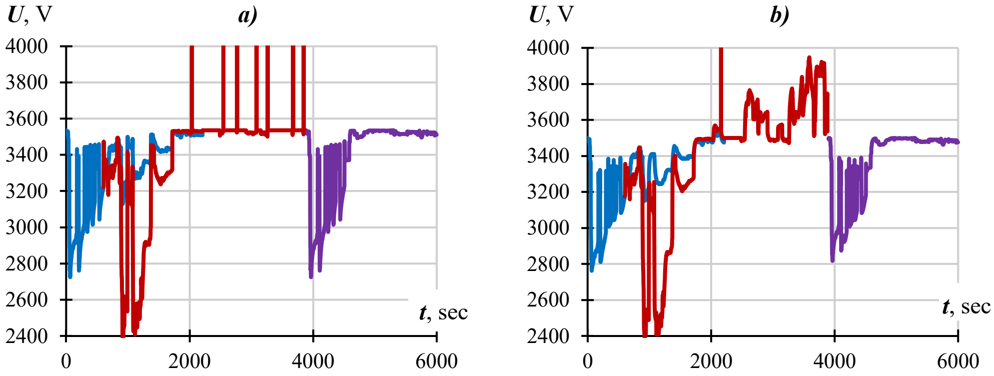

Fig. 14. Current collector voltages of electric locomotives in different operation modes of the traction substation equipment: a –a rectifier without a SU; b – an inverter with a controlled SU

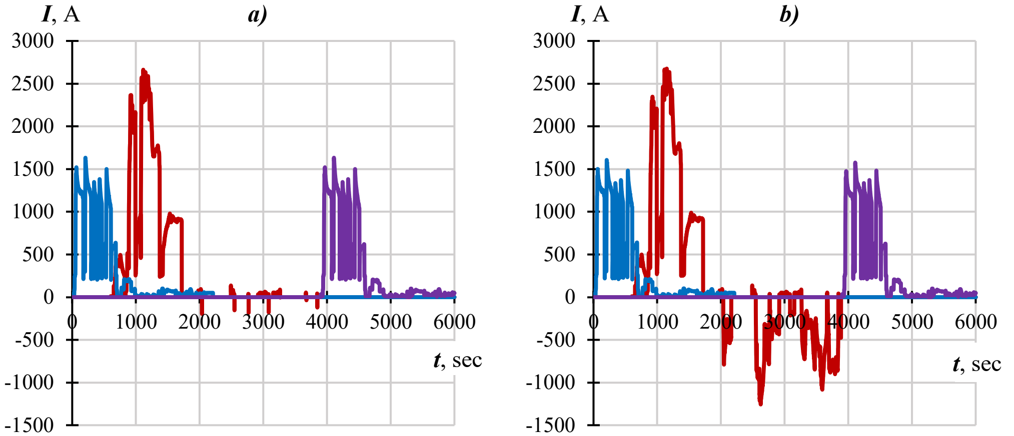

Fig. 15. Electric locomotive currents in different operation modes of the traction substation equipment: a - a rectifier without a SU; b – an inverter with a controlled SU

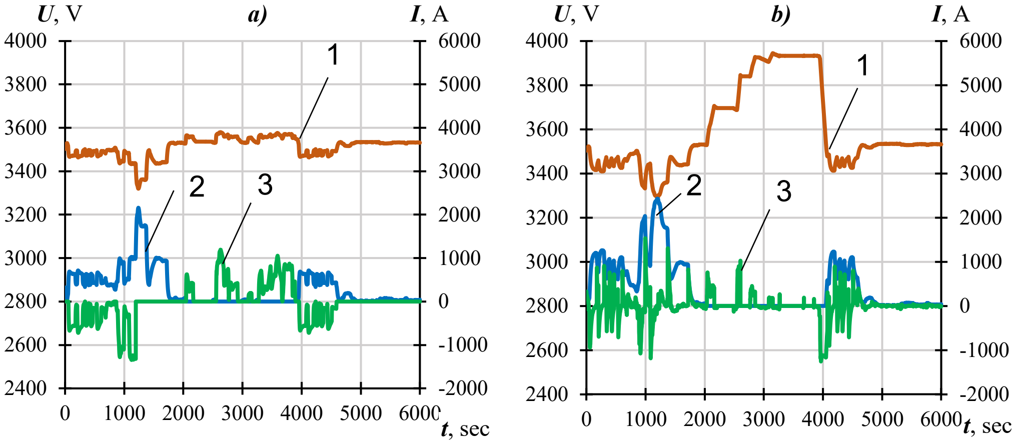

Fig. 16. Voltages on the buses of the traction substation (1), currents of substation (2), currents of SU (3) in different operation modes: a – a rectifier with a controlled SU; b – a rectifier with an unmanaged SU

Fig. 14a shows the expressed voltage jumps on the current collector and the moments of recovery breaks. When using inverters, jumps don't occur, and the excess energy flows to the external network (Fig. 14b). There are voltage jumps and recovery failures when using only unmanaged storage units.

The analysis of electric locomotive currents in the recovery mode at different substation structures shows that the recovery energy realization in full (100%) occurs only in cases with a substation inverter or a controlled storage unit. In the cases of Fig. 12a and 12b, the recovery energy is realized only partially, in volumes 2% and 12%, respectively. The graph analysis in Fig. 16 shows that the substation storage unit decreases the peak and abrupt nature of the current consumption from the external network. So, the coefficient of the current form on the substation with SU is 3.25 compared with 4.8 without SU. At the same time, the most energy-efficient scheme is shown in Fig. 12d.

Using the expression (10), the dependencies of the SU charge level *SOC*(*t*) were compiled under the forced control of its energy-exchange processes. It is also valid for the natural energy exchange that occurred with the directly connected SU to the traction network. Having analyzed this dependence, we can suppose that in the case of the SU direct connection to the traction network (Fig. 17a, 17b), the average storage is 85%, while the minimum charge is not reduced to 80%. This, in turn, characterizes the SU operation only as a voltage stabilizer at the connection points. Besides, its preinstalled power is not used in full, and practically the full charge does not allow providing rational conditions for energy recovery on the sites without traction power consumption. In the case of Fig. 17e, the SU charge and discharge are used in the range of possible values, creating the necessary conditions for the absorption of recovery energy at moments of voltage increase in the traction network. To absorb recovery energy before this process, the unit should release the accumulated energy in the traction, or an external network, which requires more modern control algorithms for its operation.

Fig. 18 shows the energy consumption dynamics in the input of the traction substation, depending on its structure. Over time, the power consumption decrease corresponds to returning the recovery energy to the external network for cases of substations equipped with inverter transducers. The final power consumption values for the considered variants of the substation are shown in Fig. 18, which corresponds to the end of the simulation (t = 6000 sec). The values of energy consumption and energy savings are given in Table 2. It also confirms that the most energy-efficient scheme is demonstrated in Fig. 12e.

7. Conclusions

The following conclusions can be formulated:

1) Energy storage units are massively implemented in virtually all technology areas, especially transport - not only in electric vehicles. There is a growing need for storage units in the transport system energy infrastructure, including integrating different electric traction vehicles for more efficient energy recovery.
2) In the non-periodic random voltage input applied to the storage unit, it is proposed to use the calculation method based on the Duamel integral to analyze its charge-discharge processes. This method allows performing various approximations of the applied voltage.
3) To evaluate the efficiency of the storage unit's preinstalled capacity, it is proposed to use the dependence of its voltage-residual charge. It is a nonlinear characteristic, which, for example, indicates that the capacitor has a residual energy reserve of 25% if the voltage decreases by 50% from the nominal level.

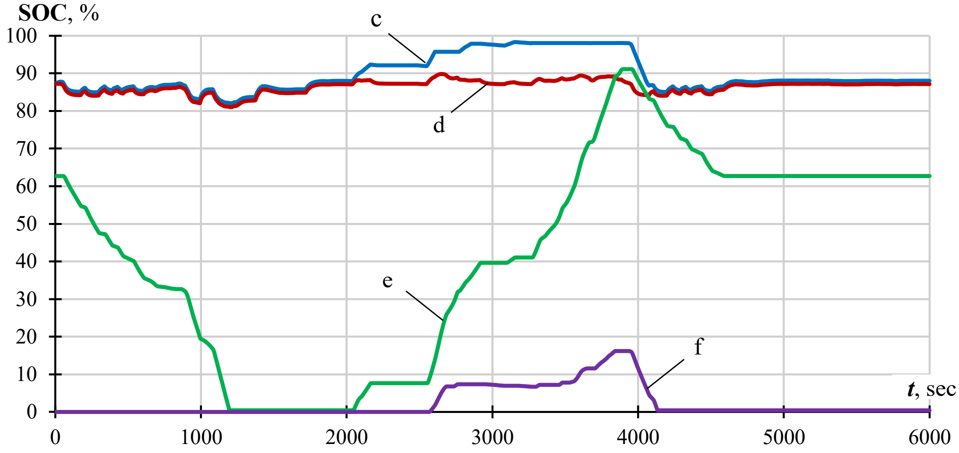

Fig. 17. The SU charge level in different operation modes of the traction substation equipment: a - a rectifier without a SU; b - an inverter without a SU; c – a rectifier with an uncontrolled SU; d - an inverter with an uncontrolled SU; e – a rectifier with a controlled SU; f – an inverter with a controlled SU

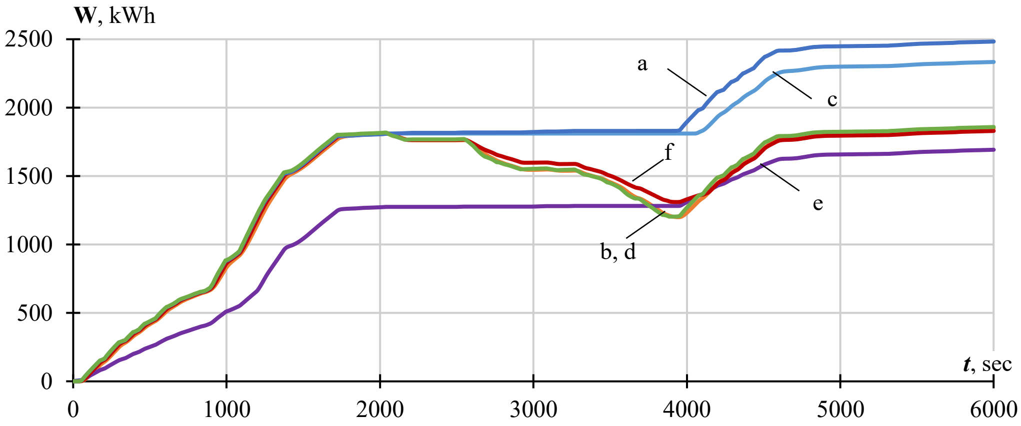

Fig. 18. Electricity consumption in different operation modes of the traction substation equipment: a – a rectifier without a SU; b – an inverter without a SU; c – a rectifier with an uncontrolled SU; d – an inverter with an uncontrolled SU; e – a rectifier with a controlled SU; f – an inverter with a controlled SU

Table 2. Results of the electricity consumption calculation

Operation mode of the equipment	Electricity consumption, kWh	Energy saving, kWh	Energy saving,%
a)	2482,5	–	–
b)	1858,1	624,4	25,2
c)	2333,1	149,4	6,0
d)	1849,2	633,3	25,5
e)	1692,0	790,5	31,8
f)	1829,3	653,2	26,3

4) The resistance functions were applied to analyze the traction power supply mode with variable in time and space by active loads. It allows us to describe the power supply process in the modes of traction and recovery. This allows the simulation approaches in software environments with ready libraries of a wide range of electrical elements, including storage units and energy converters with specifications of real power stabilization systems for vehicles in the traction and recovery modes.
5) The storage unit energy-exchange process simulation has shown that the direct connection of the unit to the traction network significantly reduces the traction energy consumption by 6%. Nevertheless, it is not to be compared with savings when the unit is connected through the charging device (in this case, the energy consumption can be reduced by 32%). Using a managed storage unit, combined with the inverters for the cases considered, reduces energy by about 25-26%. It does not take into account the priority of the energy distribution between the storage unit and the external network (which requires additional research, a study of the external network regimes, and the energy supply company's readiness to pay for the returned energy).

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