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APPLICATION OF MATLAB SIMULINK LIBRARIES FOR THE INVESTIGATION OF THE EFFICIENCY OF ENERGY STORAGE DEVICES USE IN ELECTRIC TRACTION SYSTEMS

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Abstract. *This paper presents the results of a study on the use of energy storage systems in electric traction systems, conducted using the Matlab Simulink software environment. The relevance of implementing energy storage systems lies in the current inability to fully utilize regenerated energy during braking. The analysis of available types of electrical energy storage devices reveals that several variants exist, each requiring specific charging parameters. By applying an analytical approach to modeling electric traction loads, various scenarios of integrating storage devices into subway power supply systems were examined. The simulation results demonstrate that, under cost constraints for the storage system, lithium-ion batteries provide the highest efficiency among the considered technologies.*

Key words: *energy storage, battery, supercapacitor, electric traction, modeling, Matlab Simulink.*

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1. INTRODUCTION

Electric traction systems are one of the competitive structures in the passenger and freight transport industry. Regarding railways, this is primarily due to the operational length of the main railway tracks, which reaches 19,787 km, including 9,319 km of electrified ones [1]. Over the past year, railways transported approximately 25 million passengers and 148.4 million tonnes of cargo. This is a fairly large indicator among other modes of transport. Like any other type of transport, electrified vehicles are equipped with braking system, but specific to its field. The main types of braking are pneumatic, regenerative and rheostat.

Today, regenerative braking is not sufficiently high-priority type of braking, as it is hindered by several factors related to the fact that, in most cases, there are no consumers of regenerative energy. This is due to the fact that, during regenerative braking, the generated electrical energy, which is returned to the contact network, can result in the increase of voltage in the contact network and subsequently to the operation of the overvoltage protection system [2]. And if this energy is converted using inverters at substations and fed into the primary network, another problem related to the deterioration of the operating mode and quality of electricity arises. But if excess recuperation energy could be stored directly in storage devices, this would solve several current problems related to regenerative braking and enable the electric traction systems to be considered as a modern and economical mode of transport. It can be argued that the use of recuperated energy is more efficient, since now it can be reused if necessary. These installations can be located directly on the rolling stock, at substations or inside the feeder area.

If we consider storage batteries as on-board equipment of rolling stock, then the stored energy can be used immediately when the train starts moving [3–4]. While starting the movement from the place, quite large currents arise in traction motors resulting in the deterioration in the operating mode of the contact network. When using storage devices in such cases, it is possible to reduce the starting currents that will occur in the contact network improving the network operating mode and, accordingly, reduce power losses. However, with such installation of energy storage devices, it is necessary to predict the increased complexity in the design of the rolling stock.

Considering the need to increase the energy efficiency of electric traction systems, to study modern types of storage devices and choose their application options is an important task. Due to the technical complexity of electric traction systems and the stochastic nature of their operation, full-scale studies of their use are quite difficult, therefore to achieve this goal, the Matlab Simulink software product is used with analytical representation of power consumption processes in electric traction systems during modeling.

The objective of the paper is to analyse the advantages and disadvantages of existing types of storage devices, to determine the efficiency of their application in electric traction systems using the Matlab Simulink computer modeling technology.

2. OVERVIEW OF EXISTING TECHNOLOGIES FOR COMPUTER MODELING OF ELECTRICITY CONSUMPTION PROCESSES IN ELECTRIC TRACTION SYSTEMS WITH THE POSSIBILITY OF TAKING INTO ACCOUNT ENERGY STORAGE PROCESSES

Among the well-known technologies for computer modeling of traction power supply systems with functions which take into account energy storage processes are the following: Sitras Sidytrac, OpenPowerNet and Matlab Simulink.

Sitras Sidytrac is the development of the German company Siemens, designed for simulation and calculation of AC and DC traction networks. Due to Sitras Sidytrac, design becomes more versatile and automated, which increases work efficiency and reduces the probability of errors [5]. The development makes it possible to model sections of electrified railways with storage devices, however, their control algorithms are set by the developer, which restricts the scope of use of this solution only to commercial projects.

OpenPowerNet is the software designed for modeling and calculating electrical networks, developed by Dresden Institute of Railway Engineering [6]. OpenPowerNet is capable of simulating AC and DC railway traction networks, taking into account the electrical structure of the network. It can be used as energy forecasting and analysis tool and for planning and optimizing power supply devices. OpenPowerNet is used together with the Swiss railway operation simulator OpenTrack, as a compatible simulator. The module is capable of simulating AC and DC railway traction networks, taking into account the electrical structure of the network.

Matlab Simulink is an interactive tool for modeling, simulating, and analyzing dynamic systems, including discrete, continuous, and hybrid, nonlinear, and discontinuous systems. It was created by the American company The MathWorks [7]. It is the most popular tool for modeling power supply systems due to the large number of ready-made blocks, user-friendly interface, good model visualisation and extensive analysis capabilities. It is the best choice for modeling traction power supply systems when used for scientific research purposes. Since Matlab Simulink contains ready-made blocks for modeling energy storage devices and makes it possible to set algorithms for controlling them, you can choose this solution for modeling research of the efficiency of using storage devices in electric traction systems.

At present, technology is developing quite rapidly, and this has resulted in rapid development in the field of energy storage. The main types of common electricity storage devices that can be used in electric traction are as follows:

- lead-acid (*Pb*);
- nickel-cadmium *(Ni-Cd*);

- nickel-metal hydride (*Ni-Mh*);
- lithium-ion (*Li-Ion*);
- lithium-polymer (*Li-Pol*).

Let us consider each type of electricity storage device in detail, as well as some features of their charge/discharge cycles:

Lead-acid batteries. This type of battery [8] is the most common among others. This is caused by the fact that they are quite cheap due to the availability of materials for their manufacturing. In addition, the technology for production of these batteries is already quite well developed. The main consumable material of these batteries is lead, which is placed in sulfuric acid. These batteries are divided into the following main groups: starter, stationary, traction and portable (sealed).

The main advantages of this type of battery include:

- simplicity of manufacturing;
- low cost;
- low self-discharge;
- ability to withstand high discharge rates.

The disadvantages are:

- not enough charge/discharge cycles;
- use of environmentally harmful electrolyte;
- relatively low energy consumption (approximately 10–30 Watt-hours/kg).

Nowadays, there are several methods of charging lead-acid batteries, including: unstabilized current charging, stabilized current charging (CC), stabilized voltage charging (CV), and two-stage charging using the CC/CV method.

In the case of unstabilised current charging, power supply is used, usually in the form of transformer and rectifier diode bridge. The charging current is set by the rheostat. The advantage is simplicity and, consequently, low cost. Disadvantages include the dependence of the charging current on the network voltage and the battery charge level, the need for constant monitoring of the charging process and regulation of the charging current, the possibility of overcharging or undercharging the battery with the resulting consequences, and low efficiency due to the dissipation of excess power on the rheostat.

In the stabilized current charging method, the control device measures the voltage at the battery terminals and, if it is below the lower limit value, the switch is turned on and charging occurs at the set current. When the upper threshold is reached, the control device turns off the key and the charge stops. In the event of a voltage drop, the whole process is repeated.

The advantages are that the charging current does not depend on fluctuations in the network voltage and the degree of battery charge, it has higher efficiency, and automation of the charging process.

The disadvantages include more complex and expensive device, the possibility of not charging the battery up to 100% capacity, and the possibility of overcharging.

We should also keep in mind that when charging with high current, the voltage at the battery terminals increases relatively quickly and the battery does not have time to gain the required capacity before it is disconnected. At low current, the voltage at the terminals increases more slowly, but the battery can reach 100% capacity. But this current can not be enough to reach the upper trip limit. The battery starts to boil and, if the charger is not disconnected, overcharging is possible.

Stabilized voltage charging is typically used in cars when it is necessary to restore the battery charge quickly. In this case the voltage stabilizer is DC generator, the voltage of which is maintained automatically using relay-regulator. The voltage of the on-board network should be 2.4 V per cell (or 14.4 V per 12-volt battery). At the beginning of charging, the current is the highest due to the significant difference between the source voltage and the battery voltage. At the same time, the greater the power of the charging current source and the more discharged the battery, the greater the charging current. As the battery charges, the voltage increases and the charging current drops to the minimum value.

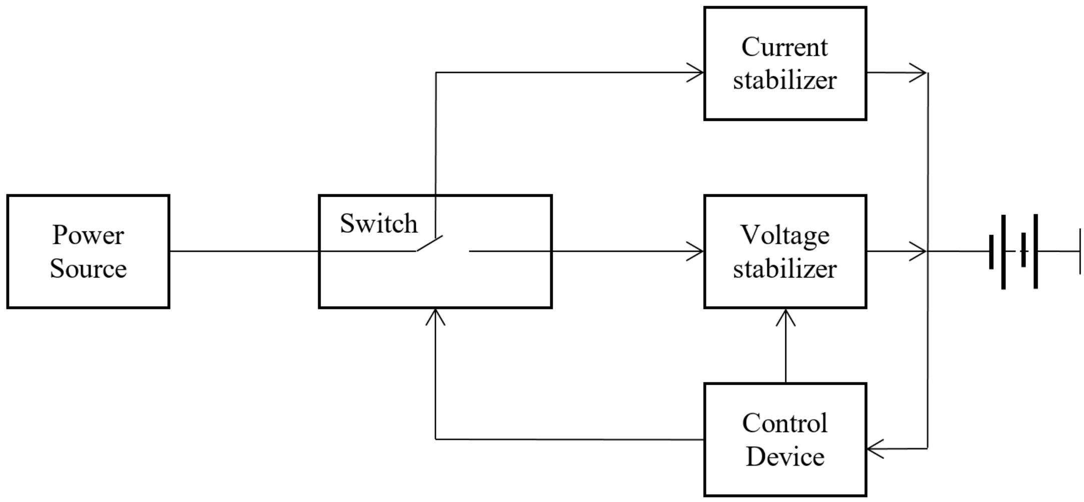

Figure 1. Block diagram of two-stage charger

The advantages are short charging time and automatic reduction of the charging current as the battery is charged.

The disadvantages are the need to set the voltage of the charging current source precisely in order to avoid systematic undercharging or overcharging and the large initial charging current.

In contrast to the previous ones, two-stage charging by the CC/CV method (Fig. 1) takes place in two stages. The first is the charge with stabilized current, the second is the charge with stabilized voltage.

The voltage stabilization threshold is 13.8 V per battery or 2.3 V per cell. Despite its complexity, the charging algorithm proves to be completely justified. The first stage of charging makes it possible to reach the battery main capacity relatively quickly without bringing the electrolyte to boiling. If you charge the battery using only current stabilization mode, then for complete charge it would be necessary to increase the voltage to more than 2.3 V per cell and exceed the boiling point of the electrolyte. This increases the intensity of the battery electrochemical processes and, as a result, reduces its service life. The second stage is used to eliminate these disadvantages. The charger switches to this mode when the voltage reaches 2.3 V per cell. In this case, there is a «soft» transition from one mode to another, without current surges characteristic of the voltage-only stabilization mode. The current starts to drop gradually and after some time decreases to the value equal to the battery self-discharge current. Depending on the quality and capacity of the battery and the ambient temperature, this value ranges from tens to hundreds of milliamps. This charging algorithm minimizes the sulfation process, eliminates overcharging and makes it possible to charge the battery up to 100% capacity. At the same time, you can't disconnect the battery from the charger for a long time, keeping it in constant readiness for operation. The disadvantages include longer charging time and higher price of the charger.

The principle of operation of nickel-cadmium batteries [9] is based on the formation of cadmium hydroxide at the anode and nickel hydroxide at the cathode. This type of battery is capable of operating in the most severe conditions. These batteries are used to power mine electric locomotives, hoists, and to start diesel and aircraft engines. They require careful handling because they have the memory effect. These batteries should be discharged slowly until their capacity is completely exhausted, and then they should be quickly recharged.

The advantages of nickel-cadmium batteries include the possibility of rapid charging, low cost, stable characteristics at low temperatures, good load capacity, and the greatest adaptability to be used in difficult conditions.

Among the disadvantages, one should be aware of the memory effect and special methods of its elimination, relatively high self-discharge after prolonged storage, and toxicity.

Nickel-metal hydride batteries are almost identical in design to nickel-cadmium batteries, except the fact that nickel oxide electrode is used as the positive electrode, and the electrode made of the alloy of nickel with rare earth metals is used as the negative electrode [9]. This design resulted in several advantages of such battery compared to nickel-cadmium batteries, namely: the increase in capacity by approximately 30–40%, smaller memory effect, small amount of toxic substances, and the possibility of further recycling. Disadvantages include small number of charge/discharge cycles (approximately 200–300 cycles when completely discharged), high self-discharge, and 20% increase in manufacturing costs compared to nickel-cadmium batteries.

Charging of nickel-cadmium and nickel-metal hydride batteries is mainly carried out from a DC source. The charger is powered by DC source controlled by microcontroller, which in turn monitors the battery voltage.

The peculiarity of nickel batteries is the fact that while charging to their nominal capacity, the voltage at the terminals decreases by several tens of mV. It is on this principle that the so-called «negative delta voltage method» ($-\Delta V$) is built. The method consists in charging the battery with constant current, which has the value of $0{,}5C$–$1{,}0C$, where C is capacity in A-hours. During charging, the battery voltage rises to a certain peak value, after which it drops slightly. This indicates that the battery is charged and then the controller turns off the charger.

Recently, lithium-ion batteries have become increasingly popular. Nowadays, any portable device is equipped with such batteries and they are used in electric vehicles [9].

The advantages of lithium-ion batteries include high energy density, fast charging process, relatively low self-discharge rate, fairly high number of charge/discharge cycles (approximately 1000 times), and significantly higher voltage of the individual cell compared to lead-acid and nickel-cadmium batteries (3.6 V).

Disadvantages include explosiveness, high manufacturing cost, and relatively rapid battery aging.

The creation of lithium-polymer batteries is due to rather high explosive hazard of lithium-ion batteries [9], which can occur in the event of mechanical damage and when they are overcharged to sufficiently high level. In lithium-polymer batteries, the liquid electrolyte was replaced by polymer electrolyte, which solved the problem of possible electrolyte leakage, and also increased the safety of operation. The use of polymer electrolyte resulted in the emergence of such advantages as compactness, low weight, and improved operational safety. Among the disadvantages are lower energy consumption, fewer charge/discharge cycles, and high manufacturing cost.

The process of charging lithium batteries consists of two or three stages depending on the degree of rarefaction. In the case of deep discharge, the so-called pre-charge with the current of I_{nom} is used. After raising the voltage to the minimum operating level, the charge is performed with the current in the range of $0{,}5$–$1{,}0I_{\text{nom}}$. In the third stage, after the battery voltage reaches its maximum value, it is charged with constant voltage, while the current gradually decreases as the battery reaches full capacity. After the charging current decreases below $0{,}05\ I_{\text{nom}}$ the charger turns off.

3. INVESTIGATION OF THE BATTERY CHARGING MODES

Let us carry out the investigation of the efficiency of the charger with different types of storage devices, followed by the analytical comparison of the obtained indicators.

The following parameters were chosen as the basic ones:

- battery type: lead-acid, lithium-ion, nickel-cadmium;
- nominal battery voltage: 550 V;
- nominal battery capacity: 200 A·h;
- charging current: 100 A, 200 A, 300 A, 400 A
- charging voltage: 640 V.

The developed model of the charger for the investigation by CC/CV (constant current/constant voltage) method is shown in Fig. 2. The charging time is determined from the battery charge waveform at *SOC* output. The obtained results of charging time and electricity consumption for selected battery types and their charging currents are summarized in Table 1.

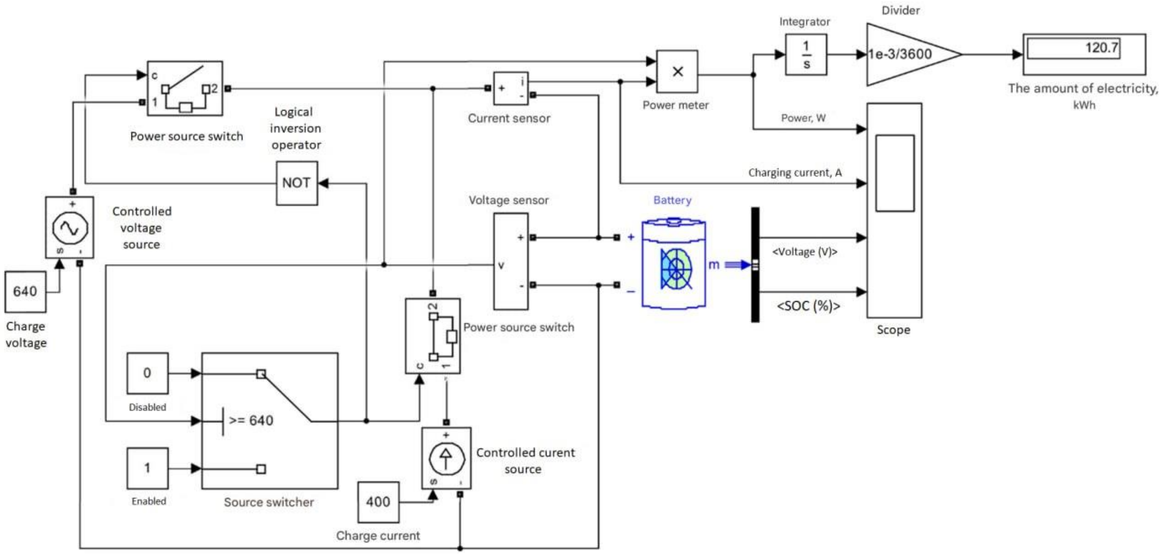

Figure 2. Model of the charger by CC/CV method

Table 1

Results of the charging process investigation

Battery type	Charging current *I*, A	Charging time *t*, min	Electricity consumption *W*, kWh
Pb	100	128.5	116.84
	200	76.7	119.42
	300	62.6	121.26
	400	56.4	122.74
Li-Ion	100	125.0	117.08
	200	70.8	118.36
	300	43.9	119.58
	400	33.3	120.7
Ni-Cd	100	150.8	138.04
	200	100.0	139.08
	300	84.7	139.78
	400	76.4	140.3

Based on the research results, histograms of charging time versus charging current (Fig. 3) and electricity used versus charging current (Fig. 4) were constructed for each type of battery.

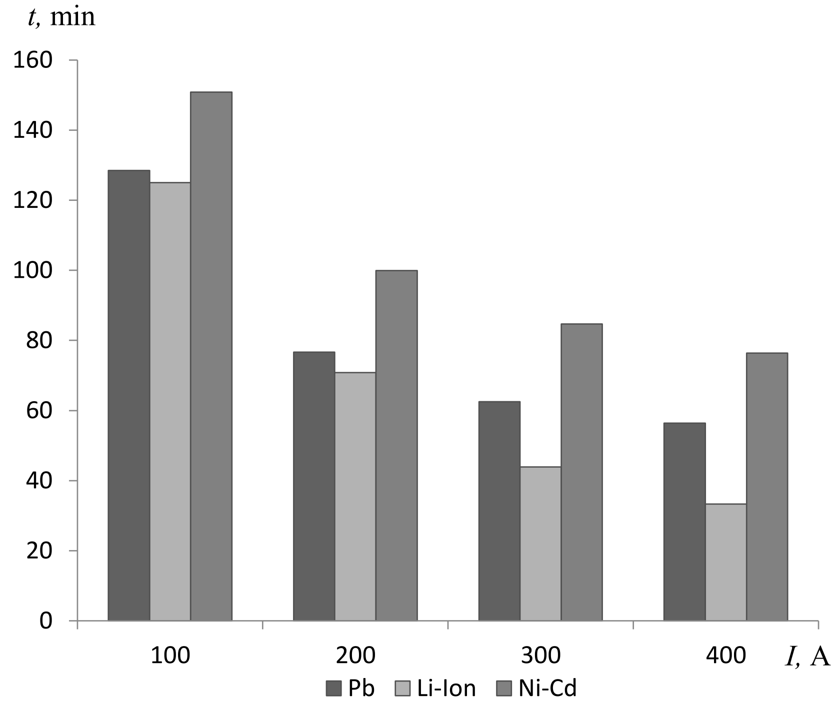

Figure 3. Dependence of charging time on charging current for each type of battery

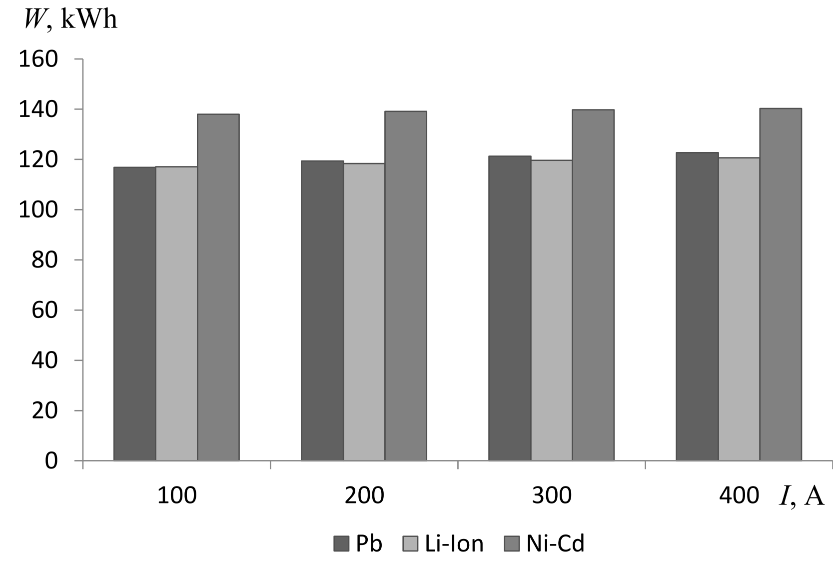

Figure 4. Dependence of the amount of electricity consumed on the charging current for each type of battery

After analysis of these dependencies, the following conclusions can be made. The shortest charging time is achieved by the charger with the highest charging current (400 A).

Among the considered types, the lithium battery proves to be the most efficient in terms of charging time in the energy storage system.

Considering the dependencies shown in Fig. 4, it should be noted that among the considered batteries, *Pb* and *Li-Ion* types show the smallest amount of electricity consumed to charge the battery to 100% and this amount in both batteries is within 120 kWh.

So, summarising the obtained results, for further investigation we choose the charger with the following parameters:

- charging current – 400 A;
- charging voltage – 640 V;
- charger power – 256 kW.

It is also reasonable to choose the battery with the following characteristics:

- type – Li-Ion;
- nominal voltage – 550 V;
- nominal capacity – 200 A·h.

Analyzing the investigation data, we can say that the efficiency of using batteries with chargers as on-board equipment is not aimed at reducing overall electricity consumption. However, considering that trolleybuses are at different distances from traction substations at any given time and consume current from the contact network, then the effect of using onboard energy storage device becomes apparent – specifically due to the partial power supply to the engines from the battery.

In addition, the use of onboard energy storage devices makes it possiblle to eliminate the contact network completely; however, it is necessary to provide power sources at the terminal stops of trolleybus routes for recharging the storage systems [10–13].

It is also possible to combine electrified sections with non-electrified ones, which makes it possible to develop new routes within cities. This, in turn, results in the abandonment of vehicles based on internal combustion engines, which has positive impact on the environment [14–17].

4. ANALYSIS OF THE EFFICIENCY OF STORAGE DEVICES APPLICATION IN THE ELECTRIC TRACTION SYSTEM

In order to analyze the efficiency of using storage batteries in the electric traction system, we will carry out the investigation for the traction power supply scheme of the subway (Fig. 5).

In the investigation, we will compare the following types of batteries [8-9]:

- Pb (2 OPzS 100-12V);
- Li-Ion (Panasonic NCR18650B Protected);
- Ni-Mh (Panasonic Eneloop BK-3MCCE).

Since each storage device has characteristic parameters according to its type, for their correct comparison, we will take as the base the element of lead-acid battery 2 OPzS 100-12V with 12V voltage and 100 Ah capacity. To obtain similar parameters for lithium-ion and nickel-metal hydride batteries, the parameters are recalculated taking into account the parallel-series connection of cells in the battery. We get:

- Li–Ion: 30 parallel-connected links (providing capacitance) of 3 series-connected elements (providing voltage);
- Ni–Mh: 50 parallel-connected links (providing capacitance) of 10 series-connected elements (providing voltage).

Parameters of the obtained batteries are summarized in Table 2.

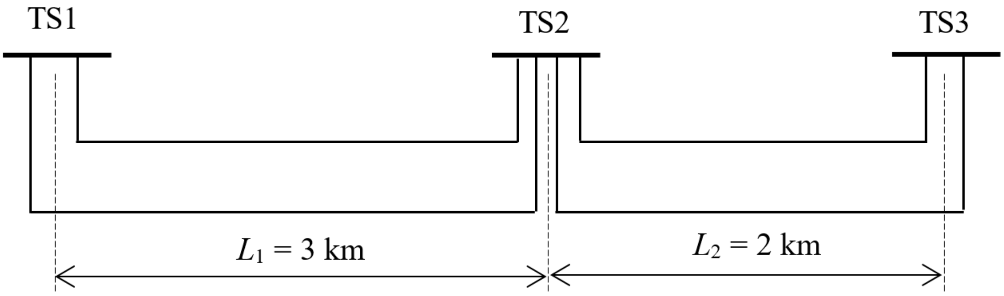

Figure 5. Schematic diagram of the traction power supply system of the site

For numerical calculations, initial conditions will be set. For this purpose, the uniform traffic schedule and the periodic current load schedule (Fig. 6) will be used. When forming the traction substation current under the given conditions, the load currents from trains moving in both the even and odd directions are taken into account [18–19].

Table 2

Battery parameters

Parameters	Battery types		
	FAAM 2STA55-12 (2 OPzS 100-12V)	Panasonic NCR18650B Protected	PanasonicEneloop BK-3MCCE
Voltage, V	12	3.7/11.1	1.2/12
Capacity, Ah	100	3.4/102	2/100
Length, mm	272	69/600	50/650
Width, mm	205	20/60	13/130
Height, mm	380	69	50
Battery volume, mm^3	21 188 800	2 484 000	4 225 000
Number of «charge-discharge» cycles at depth of discharge:			
100%	1100	1500	1500
75%	1600	2000	2000
50%	3250	5000	4000
25%	5500	7000	6000
Weight, kg	50	0.05/4.5	0.027/13.5
Quantity, pieces	1	90	500
Price, $	525	6.25/562	2.6/1285

Note: the numerator shows the parameter for a single cell, and the denominator shows the parameter for the assembled battery.

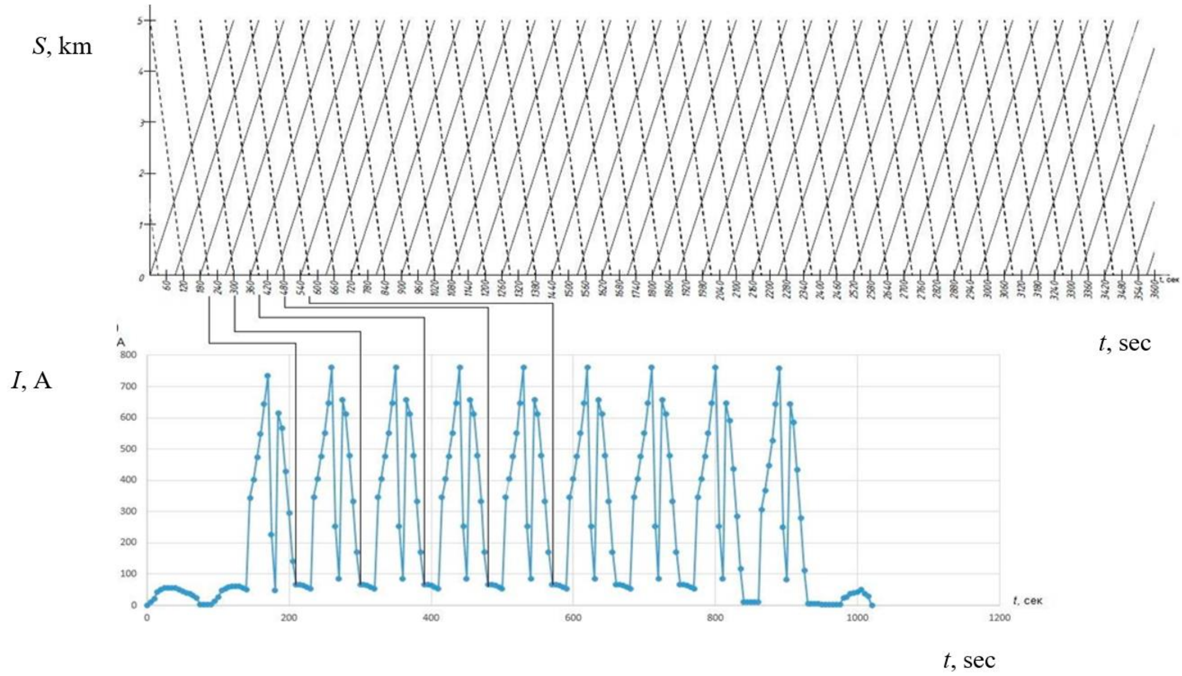

Figure 6. Formation of traction substation current according to the traffic schedule

The implementation of calculations in the traction power supply system is performed in Matlab Simulink, the system model is shown in Fig. 7. The current value acts as a load, so the data is entered using the «SignalEditor» block, the output of which controls the current source. Additionally, parameters such as the internal resistance of the substation, the resistance of the traction network, and the no-load voltage of the substations are also specified. When the energy storage system is used, the model is modified by adding the corresponding components, as shown in Fig. 8.

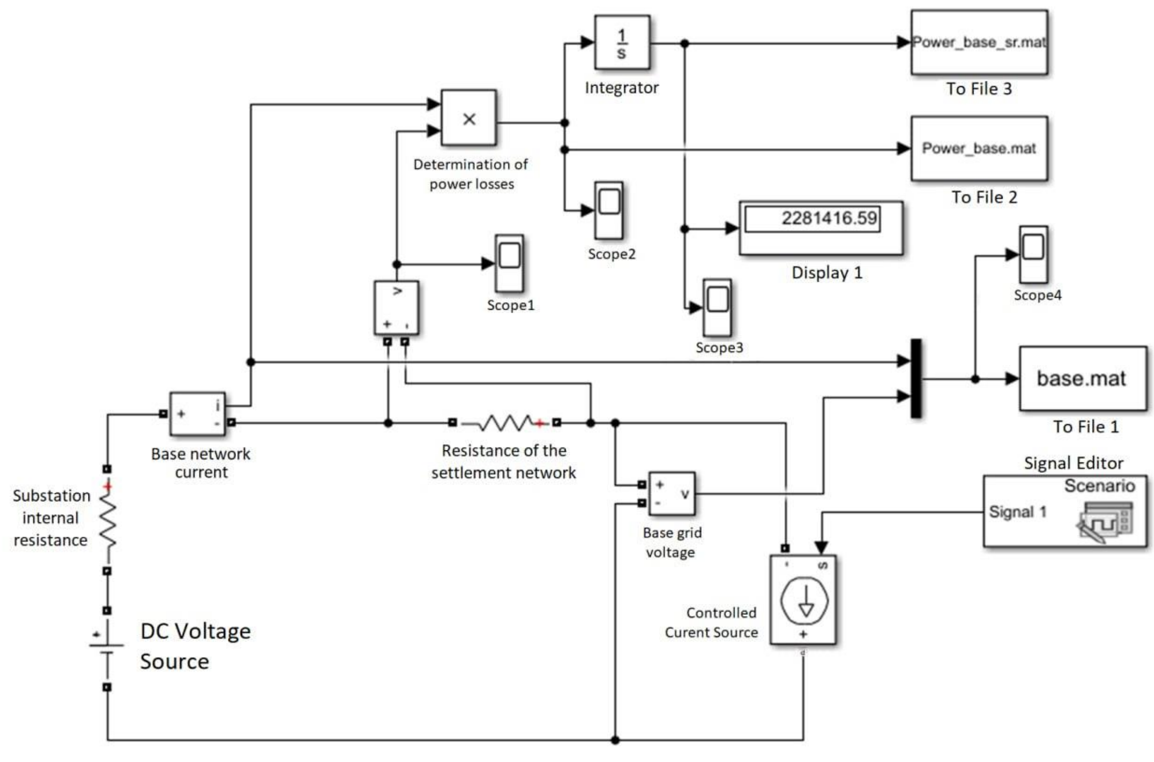

Figure 7. Formation of traction substation current according to the traffic schedule

Since different types of storage devices can be used for electric traction system, and they have a large number of types and classifications, we set the additional constraint in the form that 1 million UAH is allocated for the electricity storage system. After analysis of the prices of storage devices as of 2018, we summarise the data in Table 3, which takes into account the number of cells, capacity, number of series and parallel connected cells.

Table 3

Parameters of selected options for electricity storage systems

Parameter	Storage type				
	Li-Ion	*Ni-Cd*	*Ni-Mh*	Lead-acid	Supercapacitor
Price of one element, UAH	180	55	61	14692	492.1
Capacity of one element, Ah	3.4	2	2	100	400 F
Voltage of one element, V	3.7	1.2	1.2	12	2.7
Number of series-connected elements	223	688	688	69	306
Number of parallel branches	24	26	23	1	6
Total system capacity, Ah	81.6	52	46	100	1.3 F
Total system voltage, V	825.1	825.6	825.6	828	826.2
Expenses, kUAH	963. 36	983.84	965.264	1013.748	903.496

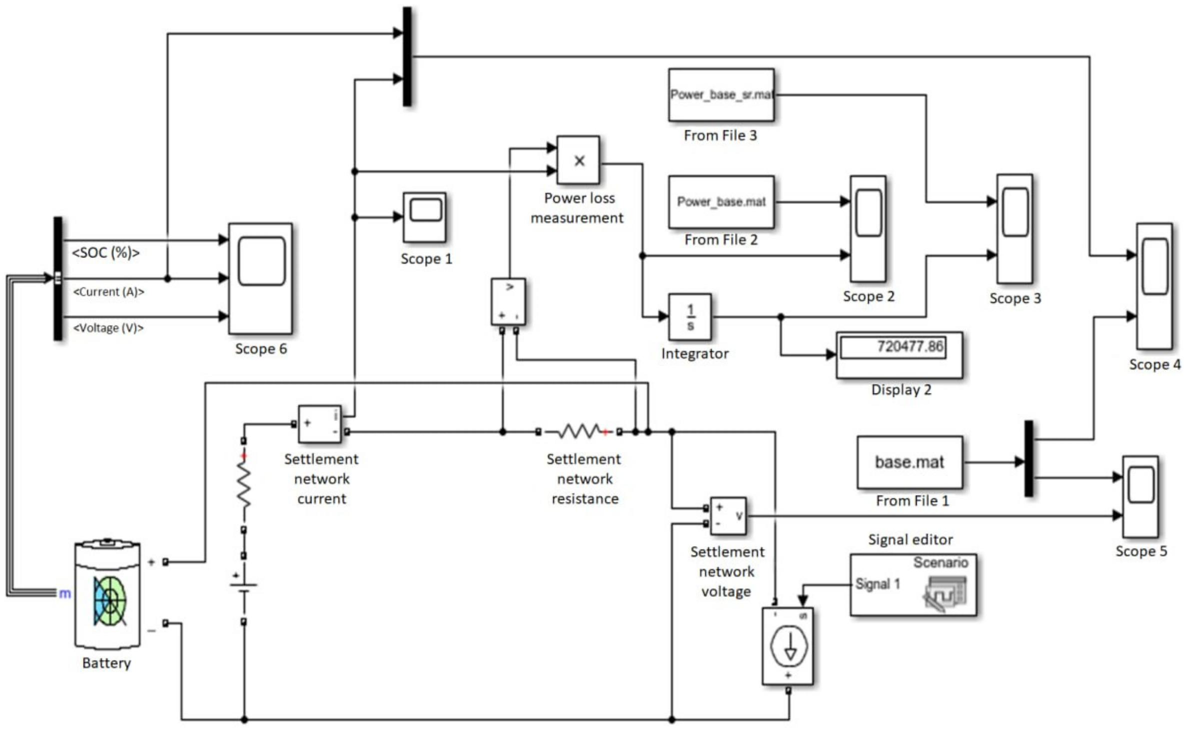

Figure 8. Model of the traction power supply system using battery pack

As the result of the modeling, the dependences of the voltage change in the network in the basic version and with the use of the storage device, as well as the total power losses in the system, which will be considered an indicator of efficiency, are obtained. Comparisons of voltages and currents in the corresponding modes are shown in Fig. 9, 10.

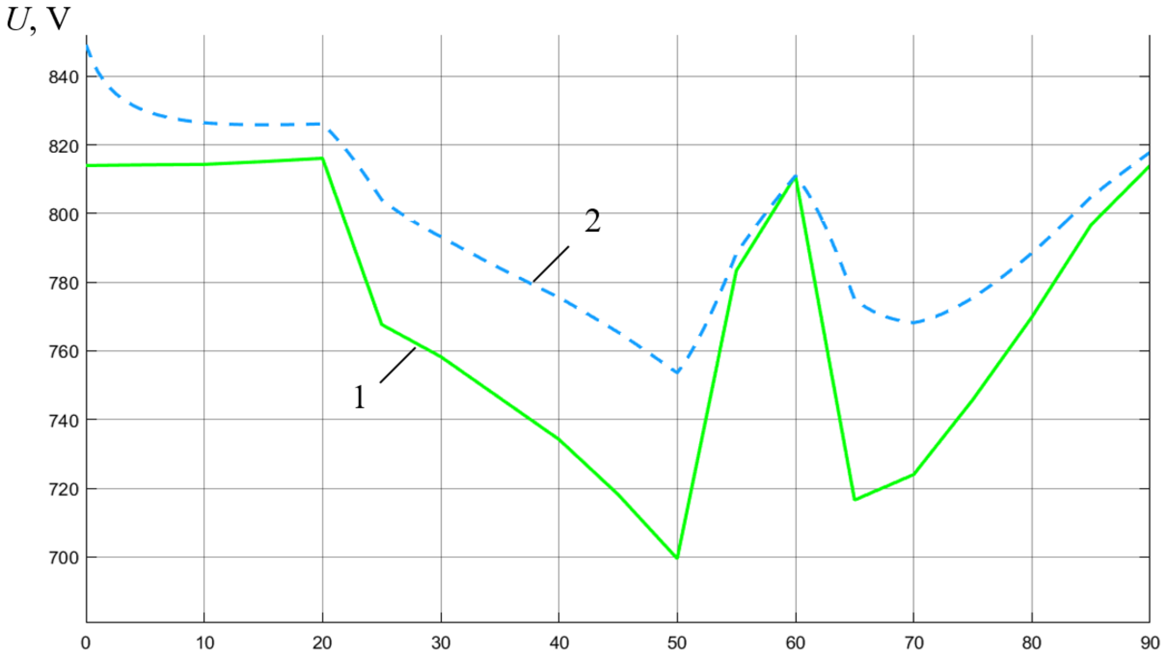

Figure 9. Comparison of voltage in the initial case (1) and in the calculated mode of the storage device application (2)

The results of the investigation show that the application of storage devices has positive effect on the power supply system, this is primarily due to the fact that the current load is reduced, which results in the decrease of power losses in the traction network. Data on power losses when using different types of storage batteries are given in Table 4.

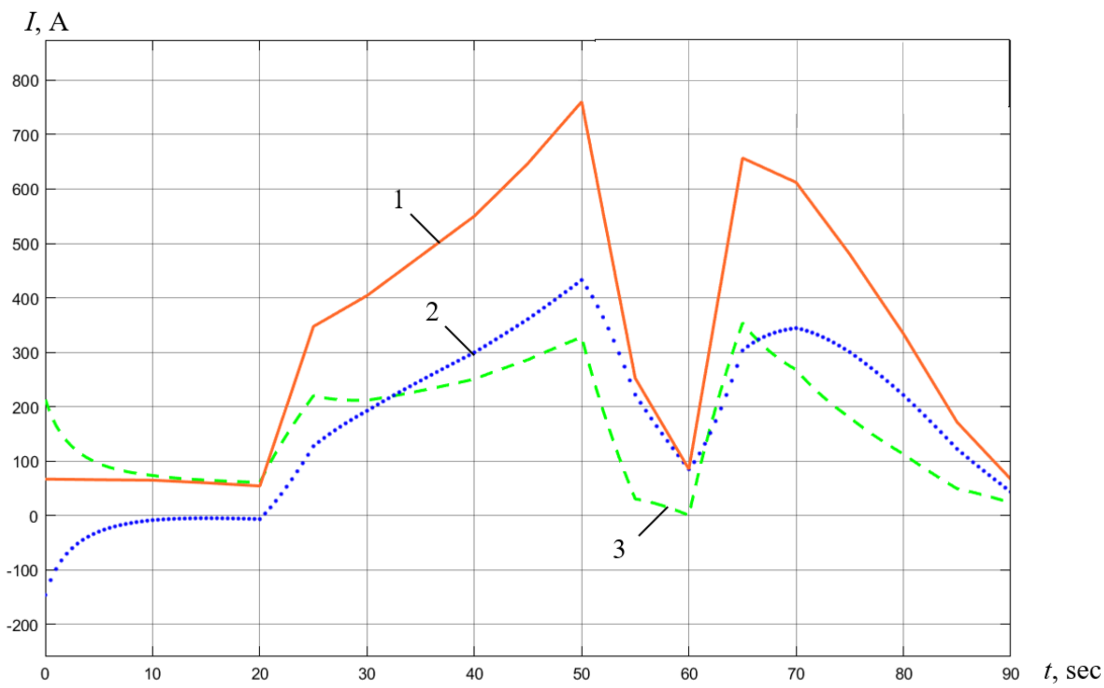

Figure 10. Comparison of load currents in the basic version and in the calculated mode of the storage device application: 1 – initial current of the network, 2 – current of the network with energy storage, 3 – current of the energy storage

Table 4

Efficiency indicators of energy storage devices application

Options for using energy storage devices application	Power losses in the traction network, kW	Efficiency of storage device application, %
Without energy storage device (basic scheme)	2 281.416	–
Lead-acid	720.477	68.4
Li-Ion	378.371	83.4
Ni-Cd	475.115	79.1
Ni-Mh	531.598	76.6
Supercapacitor	444.263	80.5

5. CONCLUSIONS

Based on the results of computer simulation of the interaction between electric traction power supply systems and energy storage devices, the following conclusions can be drawn:

1. Lithium-ion batteries demonstrated the highest efficiency among the analyzed storage technologies (lead-acid, nickel-cadmium, nickel-metal hydride, and supercapacitors) in terms of the «cost-power loss reduction» criterion. This is due to their ability to provide high discharge currents and superior cycle stability.
2. The traction power supply system model developed in Matlab Simulink enabled a clear assessment of voltage and current dynamics in the network with and without energy storage. The simulation results showed that using storage devices reduces current in the contact network and decreases power losses by up to 83% compared to the baseline case.
3. The use of energy storage systems allows for peak load compensation, reduction of starting currents, and stabilization of network voltage, thereby improving power quality and operating conditions of traction substations.
4. The proposed model can be effectively used as an engineering tool for analyzing, planning, and optimizing the energy infrastructure of electric transport, as well as for selecting appropriate storage technologies under specified technical and economic conditions.

References

1. Ministry of Communities and Territories Development of Ukraine. Statistical data on Ukrainian railways. Available at: https://web.archive.org/web/20221103103048/https://mtu.gov.ua/content/statistichni-dani-pro-ukrainski-zaliznici.html.
2. Energy efficiency Technologies for Railways – Regenerative braking in DC systems. Available at: https://www.railway-energy.org/static/Regenerative_braking_in_DC_systems_103.php.
3. Benefits and Application of Energy Storage Systems – Veolia UK. Available at: https://www.veolia.co.uk/benefits-and-applications-energy-storage-systems
4. Rabobank. Energy storage and demand response as stabilizers in evolving US wholesale electricity markets. Rabobank Insights. 2023. Available at: https://research.rabobank.com.
5. Siemens Mobility. Sitras Sidytrac is simulation software for traction power supply. Available at: https://www.mobility.siemens.com/global/en/portfolio/digital-solutions-software/infrastructure/rail-electrification/sidytrac.html.
6. OpenPowerNet – Simulation software for traction power supply systems. Available at: https://www.openpowernet.de/.
7. Xue D., Pan F. (2024). MATLAB and Simulink in Action: Programming, Scientific Computing and Simulation. Springer, Singapore. https://doi.org/10.1007/978-981-99-1176-9

8. Qi Z., Koenig G. M. (2017) Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena. J. Vac. Sci. Technol. B., vol. 35, no. 4. Available at: https://pubs.aip.org/avs/jvb/article/35/4/040801/592713. https://doi.org/10.1116/1.4983210
9. Sterner M., Stadler I. (2019). Handbook of Energy Storage. Springer-Verlag GmbH Germany. https://doi.org/10.1007/978-3-662-55504-0
10. Liu W. (2017). Hybrid electric vehicle system modelling and control. Wiley, 584 p. https://doi.org/10.1002/9781119278924
11. Sablin O. et al. (2022) Efficiency of Energy Storage Control in the Electric Transport Systems. Arch. Transp, vol. 62, no. 2, pp. 105–122. https://doi.org/10.5604/01.3001.0015.9569
12. Riabov B., Liubarskyi I., Overianova L. et al. Mathematical Model of the Electric Traction System of Quarry Railway Transport. Transport Means 2022: Proc. of the 26th Int. Sci. Conf., Kaunas: KUT, 2022. Pt. 1. P. 330–335.
13. Riabov I., Goolak S., Neduzha L. (2024) An Estimation of the Energy Savings of a Mainline Diesel Locomotive Equipped with an Energy Storage Device. Vehicles, vol. 6, pp. 611–631. https://doi.org/10.3390/vehicles6020028
14. Amiryar M. E., Pullen K. R. (2017) A Review of Flywheel Energy Storage System Technologies and Their Applications. Appl. Sci, vol. 7. Article 286. https://doi.org/10.3390/app7030286
15. Jakubowski A. et al. (2021) Modeling of Electrified Transportation Systems Featuring Multiple Vehicles and Complex Power Supply Layout. Energies, vol. 14. Article 8196. https://doi.org/10.3390/en14248196
16. Xiao Z. et al. (2020) Modeling and Energy-Optimal Control for High-Speed Trains // IEEE Trans. Transp. Electrif, vol. 6, pp. 797–807. https://doi.org/10.1109/TTE.2020.2983855
17. Kondratieva L. et al. (2024) Reduction of Energy Consumption by Electric Rolling Stock of Quarry Railways. In: Proceedings of the Int. Conf. Sustainable Solutions in Energy and Environment. Springer, pp. 573–584. https://doi.org/10.1007/978-3-031-52652-7_51
18. Kuznetsov V. et al. (2024) Progress and Challenges Connected with the Integration of Renewable Energy Sources with Railway Distribution Networks. Energies, vol. 17. Article 489. https://doi.org/10.3390/en17020489
19. Gotovych V., Nazarevych O., Shcherbak L. (2018) Mathematical modeling of the regular-mode electric power supply and electric power consumption processes of the organization. Scientific Journal of TNTU, vol. 91, no. 3, pp. 134–142. https://doi.org/10.33108/visnyk_tntu2018.03.134

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ВИКОРИСТАННЯ БІБЛІОТЕК MATLAB SIMULINK ДЛЯ ДОСЛІДЖЕННЯ ЕФЕКТИВНОСТІ ЗАСТОСУВАННЯ НАКОПИЧУВАЧІВ ЕНЕРГІЇ В СИСТЕМАХ ЕЛЕКТРИЧНОЇ ТЯГИ

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Резюме. *Представлено результати дослідження доцільності та ефективності застосування систем накопичення електроенергії в електротягових системах з використанням комп'ютерного моделювання у середовищі Matlab Simulink. Актуальність теми зумовлена неможливістю повного повторного використання електроенергії, що генерується під час рекуперативного гальмування електротранспорту. Надлишкова енергія в більшості випадків не знаходить споживача в контактній мережі, що призводить до її втрати або навіть негативних наслідків, зокрема спрацювання захистів від перенапруги. Застосування накопичувачів дозволяє уникнути цих проблем, зберігаючи енергію для подальшого використання, що підвищує енергоефективність та екологічність транспортної системи.*

Проаналізовано сучасні типи накопичувачів електроенергії (свинцево-кислотні, нікель-кадмієві, нікель-металогідридні, літій-іонні, суперконденсатори), їх технічні характеристики, режимів заряджання, циклічної стабільності, питомої енергоємності та вартості. З урахуванням цих параметрів змодельовано варіанти застосування накопичувачів у системі електропостачання метрополітену. За допомогою моделі, створеної у Matlab Simulink, проведено чисельні експерименти, *що враховують реальні режими роботи тягових підстанцій, графіки навантаження та структуру контактної мережі.*

Результати моделювання показали, що найефективнішим варіантом за співвідношенням «вартість – зменшення втрат потужності» є використання літій-іонних акумуляторних батарей. Їх застосування дозволяє суттєво знизити пускові струми, компенсувати пікові навантаження та зменшити загальні втрати електроенергії в мережі. Отримана модель також дає змогу оцінювати вплив накопичувачів на параметри електропостачання за різних схем підключення, що дозволяє використовувати її як інструмент для інженерного аналізу та подальшої оптимізації енергетичної інфраструктури електротранспорту.

Ключові слова: *накопичувач енергії, акумулятор, суперконденсатор, електротяга, моделювання, Matlab Simulink.*

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