UDC 621.314

INCREASING THE ENERGY INDICATORS OF CONVERTERS OF ELECTRIC VEHICLE CHARGING STATIONS

PhD (Tech.) V. P. Nerubatskyi, PhD (Tech.) O. A. Plakhtii, postgraduate D. A. Hordiienko

ПІДВИЩЕННЯ ЕНЕРГЕТИЧНИХ ПОКАЗНИКІВ ПЕРЕТВОРЮВАЧІВ ЗАРЯДНИХ СТАНЦІЙ ЕЛЕКТРОМОБІЛІВ

Кандидати техн. наук В. П. Нерубацький, О. А. Плахтій, асп. Д. А. Гордієнко

DOI: https://doi.org/10.18664/1994-852.204.2023.284153

Abstract. *The article presents the results of the research of semiconductor converters of charging stations for electric vehicles based on lithium-ion cells. Basic energy parameters and charge-discharge characteristics of lithium-ion and lithium-iron-phosphate batteries are given. The topology of the proposed charging station for electric vehicles based on active rectifier circuits is presented. The parameters of the substitution circuits the battery compartment of the Tesla S electric vehicle are described. The method of fast battery charging with constant voltage and constant current is described, which provides a greater number of battery charge-discharge cycles. A simulation model of the proposed charging station structure with an automatic control system in the Matlab program is presented. The efficiency of the proposed charging station system was calculated for different parameters of the charge current and switching frequency. The results of modeling of electromagnetic processes, indicators of electromagnetic compatibility, oscillograms of input and output currents and voltages of the charging station were obtained.*

Keywords: *active rectifier, charging station, charging and discharging characteristics, electric vehicle, energy efficiency, lithium-ion battery.*

Анотація. *Наведено результати дослідження напівпровідникових перетворювачів зарядних станцій для електромобілів на основі літій-іонних елементів. Представлено базові енергетичні параметри та зарядно-розрядні характеристики літій-іонних та літій-залізофосфатних акумуляторів. Наведено топологію запропонованої зарядної станції для електромобілів на основі схем активного випрямляча. Представлено топологію активного* *трифазного випрямляча напруги, що має суттєві переваги порівняно з класичними діодними та тиристорними випрямлячами, а саме можливість забезпечення роботи з коефіцієнтом потужності близьким до одиниці, можливість формування синусоїдальної форми струму, який споживається з електричної мережі, можливість забезпечення корекції коефіцієнта потужності. Описано параметри схеми заміщення акумуляторного відсіку електромобіля Tesla S. Описано метод швидкого заряду батареї постійною напругою і постійним струмом, при якому забезпечується більша кількість циклів заряду-розряду батареї. Представлено імітаційну модель запропонованої структури зарядної станції з системою автоматичного керування в програмному середовищі Matlab. Проведено розрахунок ККД запропонованої системи зарядної станції при різних параметрах струму заряду та частоти комутації. Отримано результати моделювання електромагнітних процесів, показників електромагнітної сумісності, осцилограми вхідних, вихідних струмів і напруг зарядної станції. Запропонована структура зарядної станції електромобілів, що складається з вхідного трансформатора, трирівневого активного випрямляча та навантаження, забезпечує відносно відомих технічних рішень зарядних станцій покращення параметрів коефіцієнта корисної дії, коефіцієнта потужності та коефіцієнта гармонічних спотворень. Отримані результати пояснюються тим, що запропонована зарядна станція реалізує одноетапне перетворення електроенергії в активному випрямлячі з корекцією коефіцієнта потужності.*

Ключові слова: *активний випрямляч, зарядна станція, зарядно-розрядні характеристики, електромобіль, енергоефективність, літій-іонний накопичувач.*

Introduction. In the last decade, the number of electric vehicles in Europe has increased more than 20 times. This is due to the fact that electric vehicles are an environmentally friendly form of transport, and at the same time, the cost of moving an electric vehicle for 100 km is much lower than that of an internal combustion engine [1, 2].

At the moment, the share of electric vehicles in Europe is about 11 % of the total number and continues to grow. At the same time, in some countries the percentage of electric vehicles is much higher, for example, in Norway the share of electric vehicles is 75 %, in Iceland – 45 %, Sweden – 32 %, and the Netherlands – 25 %. In many ways, this growth is connected with the appearance of economical and long-lasting electricity batteries with high energy-dimensional indicators and with a decrease in their cost [3, 4].

Charging stations are an important component of the infrastructure of electric vehicles [5, 6]. Actual there is further development and improvement of power converters of charging stations for electric vehicles with lithium-ion, lithium-iron-phosphate and other types of batteries, which ensure an increase in the energy efficiency of charging stations, as well as an improvement in the electromagnetic compatibility of charging stations with the electric network, a reduction in the emission of higher harmonics and reactive power component [7].

The power circuit with fast charging consists of three stages, namely: an input filter to reduce input harmonics, which also allows to optimize the power factor, a periodic and constant current rectifier, and a constant current converter, which transfers energy to the battery, for fast constant current charging from a hybrid electric vehicle [8, 9].

Literature review and problem statement. In paper [10], a converter with a nine-phase power supply system for a charging station for electric vehicles is considered. However, the disadvantages include the low value of efficiency, which reaches a maximum of 91 %. In addition, the converter presented in the work requires electromechanical decoupling of phases, which significantly increases the cost of the system and increases its weight and dimensions.

In papers [11, 12], a study of the IPT (inductive-power-transfer) type converter is presented, the feature of which is that instead of a diode bridge, fully controlled power transistors are used. According to the study, the efficiency of the converter when using power transistors based on silicon vehiclebide (SiC) and gallium arsenide (GaN) is in the range of 83...98 %. However, it is worth noting that transistors based on SiC and GaN are much more expensive than classic MOSFETs or IGBT transistors. In addition, the paper does not contain data on the integral value of the efficiency of the complete charge process.

The paper [13] presents a study of the efficiency of an electric vehicle charging station based on a converter consisting of a rectifier and a parallel three-channel buck-boost converter. However, the disadvantage of this topology is the lack of galvanic separation of the power source and the load. In addition, according to research, the peak efficiency of the converter is less than 92 %, which is quite low. In addition, the work also lacks data on the integral value of the efficiency of the complete process of charging the battery of an electric vehicle.

A general drawback of the considered systems is the very concept of multi-stage energy conversion, which causes power losses in converters and, accordingly, a decrease in the efficiency of the charging station [14, 15].

Thus, the issue of further improving the energy efficiency of charging stations for electric vehicles is an urgent and unsolved task.

The aim and objectives of the study. The purpose of the paper is to increase the energy performance of the electric vehicles charging station by using an active rectifier that works in the power factor correction mode. To achieve this purpose, the following tasks are set:

– analyze the basic energy parameters and charge-discharge characteristics of batteries used in electric vehicles;

– to present the proposed structure of a charging station for electric vehicles based on an active rectifier;

– conduct a study of energy indicators, namely power losses and electricity quality indicators in the developed simulation model of a charging station based on an active rectifier.

The main part of the study. ***High-power lithium-ion batteries and their converters in charging stations.*** Traditional charging stations for electric vehicles, containing two stages of electricity conversion, consist of an input AC/DC rectifier and an output DC/DC converter (Fig. 1) [16, 17].

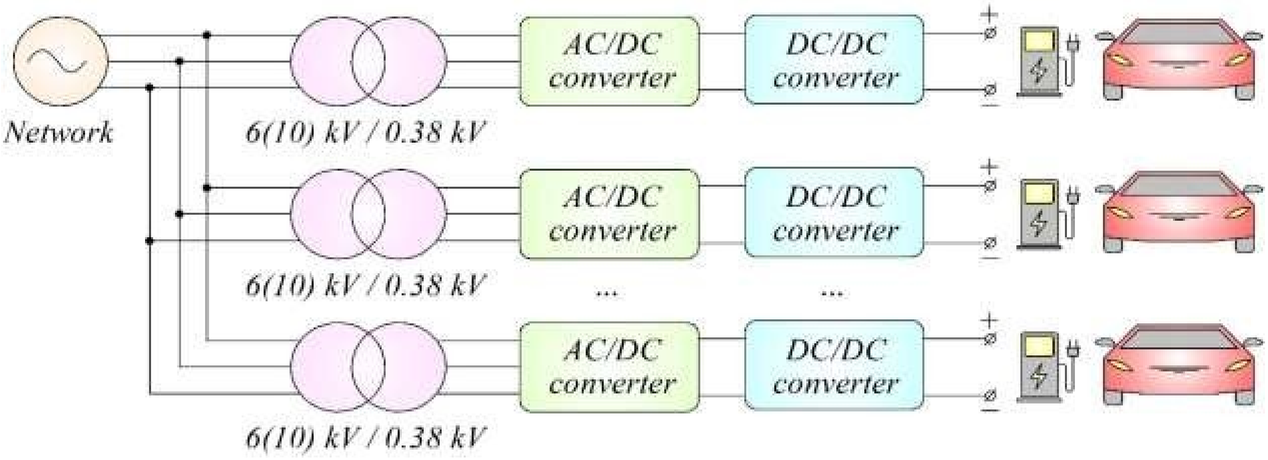

Fig. 1. Structural diagram of a traditional charging station for electric vehicles

In this topology, input rectifiers are used to create a constant voltage circuit. Next, the DC/DC converter provides regulation of the voltage and charge current of each individual electric vehicle in a given range. In some cases, the DC/DC converter is also used to provide galvanic separation of the electric vehicle from the network [18, 19].

The most common element of electric vehicle batteries are lithium-ion batteries [20, 21]. The main parameters of lithium-ion and lithium-iron-phosphate batteries are given in Table 1.

Table 1

Parameters of lithium-ion and lithium-iron-phosphate batteries

Parameter	Li-Ion	Li-Fe-PO$_4$	Li-Ti-O
Specific energy, Wh/kg	100…265	90…160	60…110
Energy density, Wh/L	240…693	325	170…180
Charge / discharge efficiency, %	80…90	≥90	–
Energy / consumer price, Wh/US$	7.6	1…4	–
Cycle durability	400…1200	2750…12000	≥15000
Capacity, A·h	2.6	–	–
Max voltage, V	4.2	3.5	2.7
Nominal voltage, V	3.7	3.2	2.4
Discharge-cut voltage, V	3	2.1	1.5
Max charge voltage, V	4.2	3.65	–
Internal impedance of single battery, mOhm	≤70	≤15	–
Operating temperature, °C	0…+45 (charge) –20…+60 (discharge)	–	–
Recommended charge current, A	0.52 (standart, 0.2C) 1.3 (fast, 0.5C)	–	–

The charge-discharge characteristics of the LIR18650 lithium-ion battery at currents from 0.52 A to 7.2 A are shown in Fig. 2.

As can be seen from Fig. 2 lithium-ion batteries allow to deliver a fairly large current, but due to the presence of internal active resistance, at high currents there is a significant drop in the voltage delivered by the storage device.

At the same time, the amount of internal power losses in the battery will also increase, which will lead to its overheating. At the same time, the operating range of lithium-ion batteries in charge mode is from –20 °C to +45 °C, and in discharge mode from –20 °C to +60 °C.

When the temperature regime is exceeded, the battery loses a significant part of its capacity, and with a significant exaggeration of the temperature, the battery may catch fire and destroy [22, 23].

The recommended charging mode for Li-Ion batteries is the CV–CC (constant voltage – constant current) mode, which is shown in Fig. 3 [24, 25].

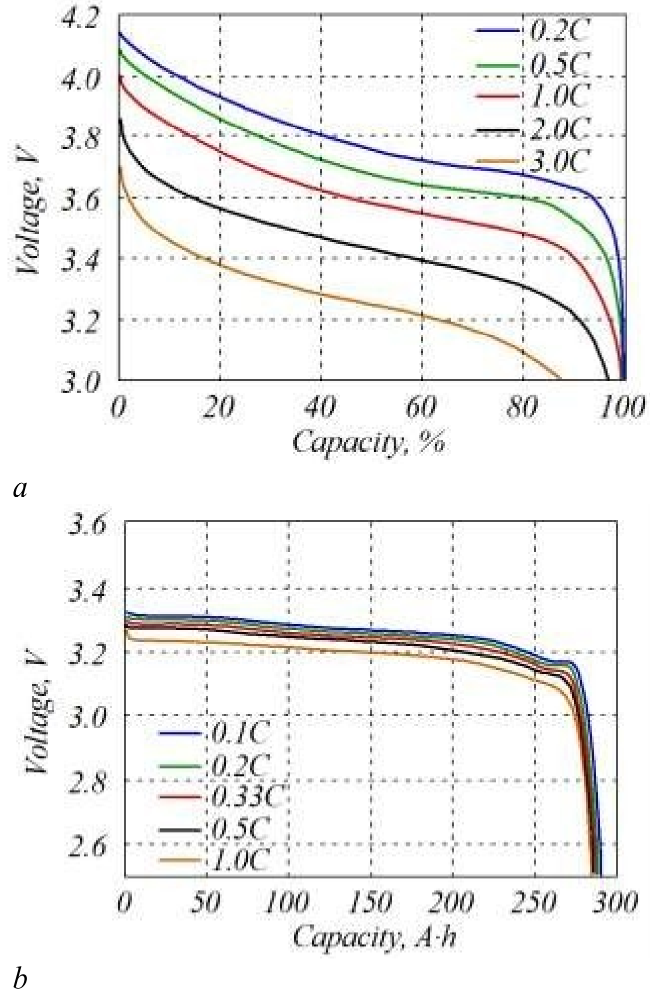

Fig. 2. Charge-discharge characteristics:
a – lithium-ion battery LIR18650; *b* – lithium-iron-phosphate battery LF280

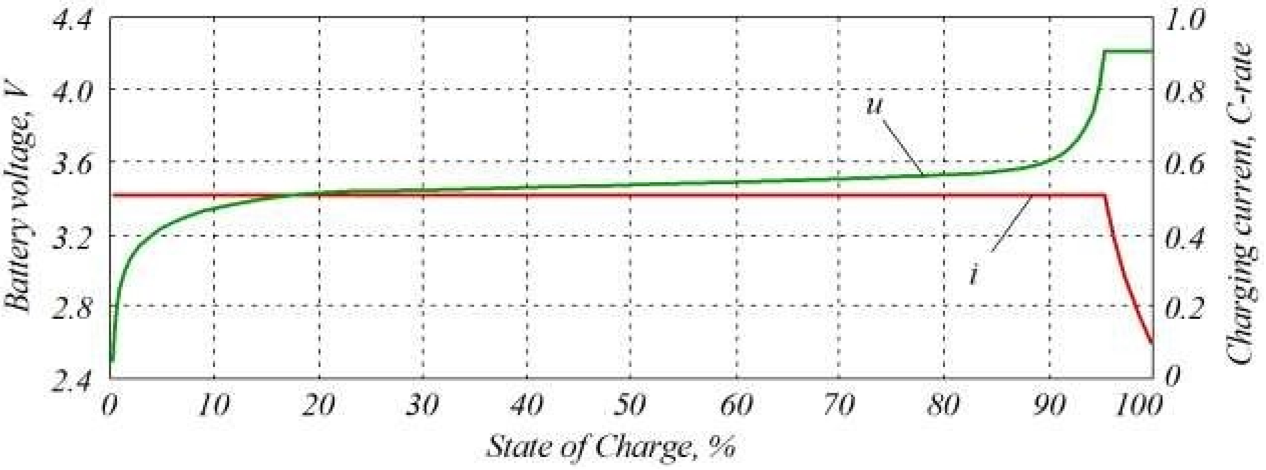

Fig. 3. Characteristics of the Li-Ion battery charge mode

Thus, there are several promising types of storage batteries, between which there is a fairly close correlation between cost and operational characteristics, namely, the resource of the amount of charge-discharge, charge time, degradation, and others.

At the same time, the main requirements of charging station systems are regulation and stabilization of charging current and voltage. In addition, it is also important to ensure the requirements for increasing the efficiency of the converter, and to ensure the requirements for electromagnetic compatibility.

Proposed topology of the single-link converter of electric vehicle charging stations. Based on the recommended charge modes of lithium-ion storage devices, there are requirements for regulation and feedback of the output current and output voltage to the converters implementing the charge. In addition, in the case of power supply from the general industrial electrical network, electromagnetic compatibility requirements are imposed on them, namely the limitation of the harmonic spectrum of higher harmonics of currents that are consumed from the electrical network or generated to it. The topology of a single-link transformation of a charging station for electric vehicles is shown in Fig. 4.

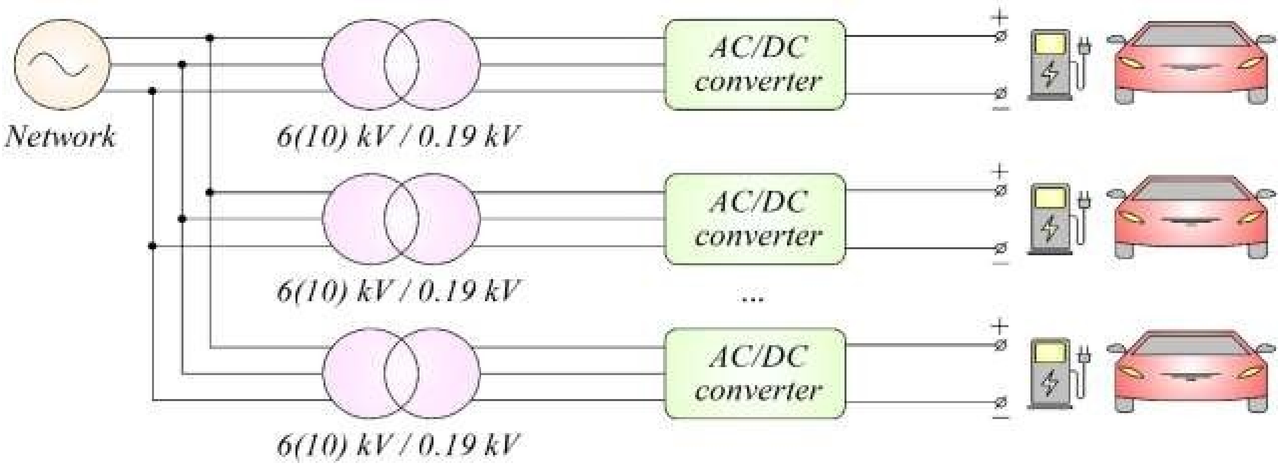

Fig. 4. Structural diagram of a single-link charging station for electric vehicles

Promising topologies that can provide the listed requirements for charge-discharge modes of powerful storage devices are an active three-phase current rectifier and an active three-phase voltage rectifier, the circuits of which are shown in Fig. 5, 6.

These topologies have significant advantages over classic diode and thyristor rectifiers, namely, the possibility of ensuring operation in a mode with a power factor close to unity, the possibility of forming a sinusoidal form of the current consumed from the electrical network, the possibility of providing power factor correction.

Simulation modeling of the proposed charging station. A simulation model was developed in the Matlab program to conduct a study of energy indicators and indicators of electromagnetic compatibility of electric vehicle charging stations with the power supply network. The model of a charging station based on an active rectifier is shown in Fig. 7.

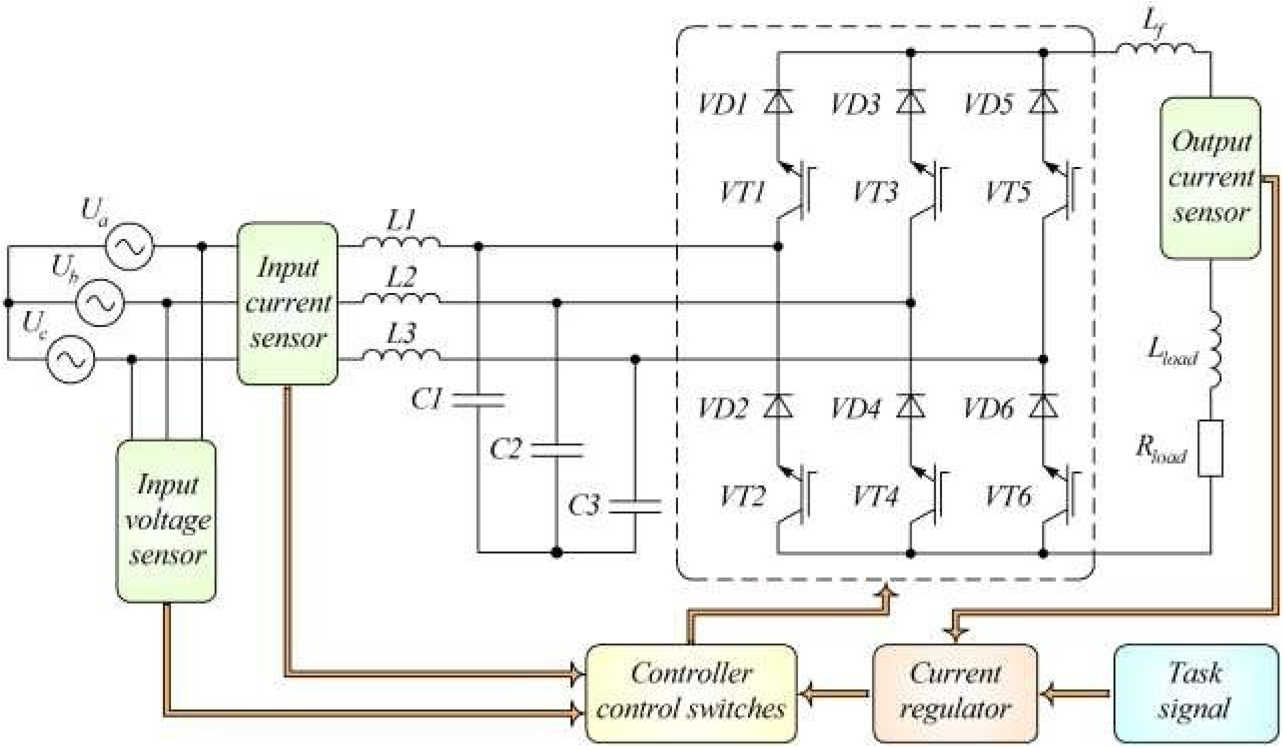

Fig. 5. Topology of an active three-phase current rectifier

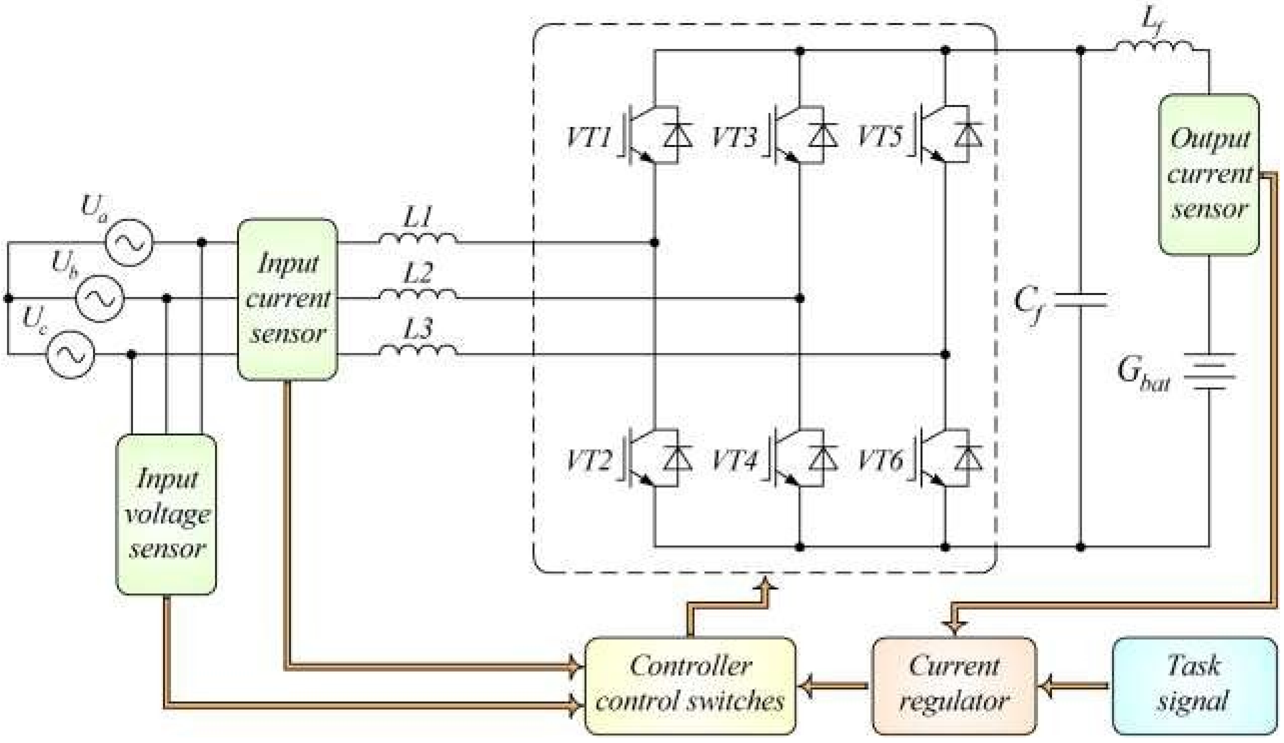

Fig. 6. Topology of an active three-phase voltage rectifier

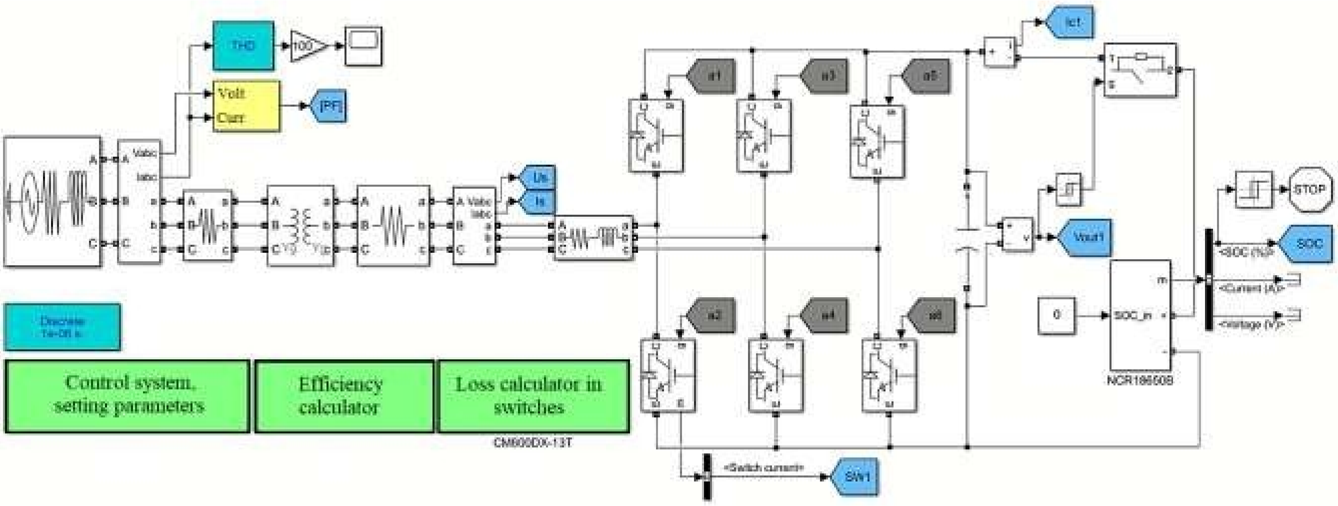

Fig. 7. A model of a charging station for electric vehicles

The proposed structure of the charging station for electric vehicles consists of an input transformer, a three-level active rectifier and a load. Tesla S electric vehicle was chosen as the load. The batteries compartment in the Tesla S vehicle has a capacity of 85 kW·h and consists of 7104 pieces (16 modules, in which there are 6 groups of 74 cells each) lithium-ion batteries manufactured by Panasonic, type NCR18650b (Fig. 8).

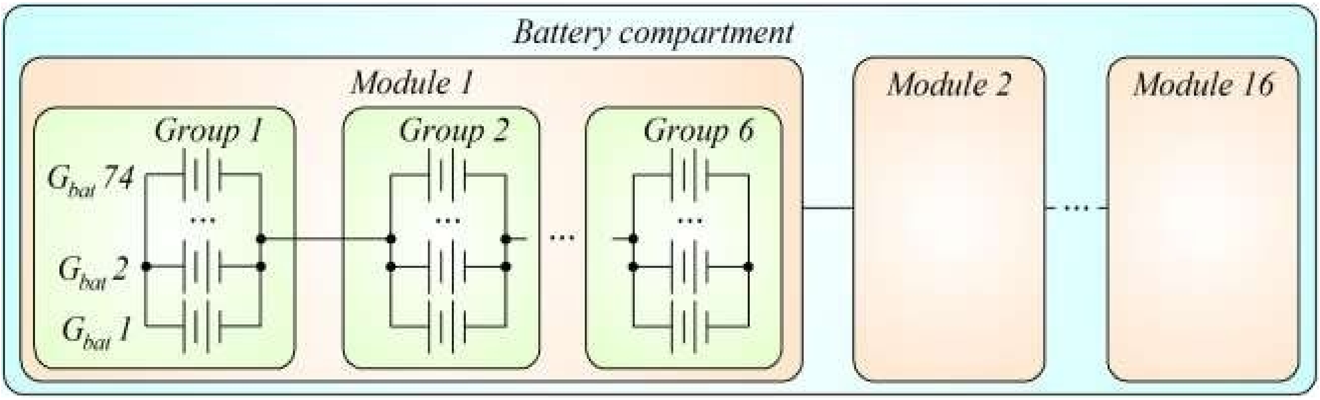

Fig. 8. The battery compartment in the Tesla S electric vehicle

In the battery compartment, individual batteries of the NCR18650b type are connected in parallel in groups of 74 cells. When connected in parallel, the voltage of the group is equal to the voltage of each of the elements (4.2 V), and the capacity of the group is equal to the sum of the capacities of the elements (250 A·h). Next, 6 groups are connected sequentially into a module. At the same time, the voltage of the module is summed up from the voltages of the groups and is equal to 25.2 V. Then the modules are connected in series in the battery. In total, the battery contains 16 modules (a total of 96 groups). At the same time, the voltage of all modules is summed up and is 400 V. The equivalent resistance of the battery block is also calculated. Based on the fact that the average resistance of one battery R_{NCR} = 37 mΩ is equivalent to the battery resistance R_{bat} = 27 mΩ.

The simulation results, namely the oscillograms of the input current and input voltage of the active rectifier are shown in Fig. 9.

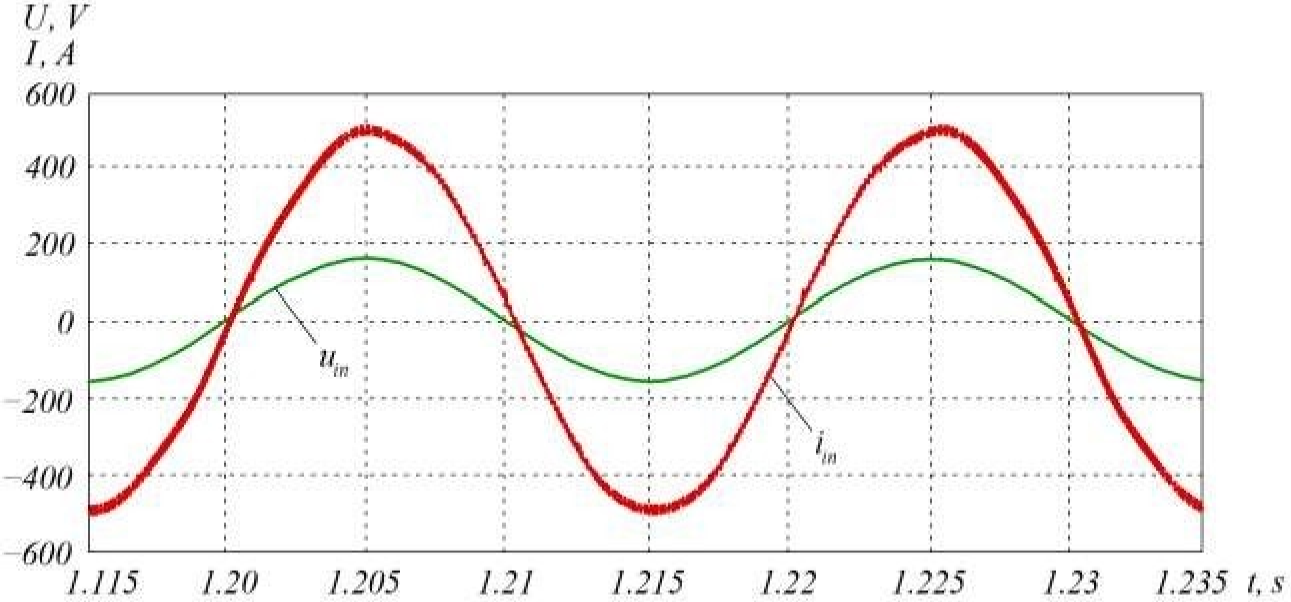

Fig. 9. Oscillograms of the input current and voltage of the active rectifier

The charge process, namely, the dynamics of changes in the output voltage, battery charge current, as well as the SoC (State of Charge) value of the battery over the entire charge interval are shown in Fig. 10.

The paper evaluates the efficiency of the proposed charging station. The efficiency was estimated based on the total energy losses and useful energy received by the battery during the full charge interval. The efficiency is calculated using the expression [26, 27]:

$$\eta = \frac{E_c}{E_c + \Delta E_\Sigma} \qquad (1)$$

where E_c is the useful energy transferred to the battery during charging; ΔE_Σ is the total energy losses in the considered system.

Table 2 shows the values of efficiency, power factor, and harmonic distortion factor of the charging station system at different charge currents and PWM frequency.

Based on the conducted research, it can be seen that the efficiency of the proposed structure of the charging station is quite high. The dynamics of the fact that the higher the charge current, the lower the efficiency is clearly visible. With different parameters of the charge current and switching frequency, the efficiency of the charging station, taking into account the power losses in the battery of the electric vehicle, ranges from 91.3 % to 95.6 %.

Conducted studies of the energy indicators of the charging station based on a three-level active rectifier showed that the power factor of the charging station lies in the range from 0.985 to 0.993.

The coefficient of harmonic distortion in the charging process ranges is 2.5…11.8 %.

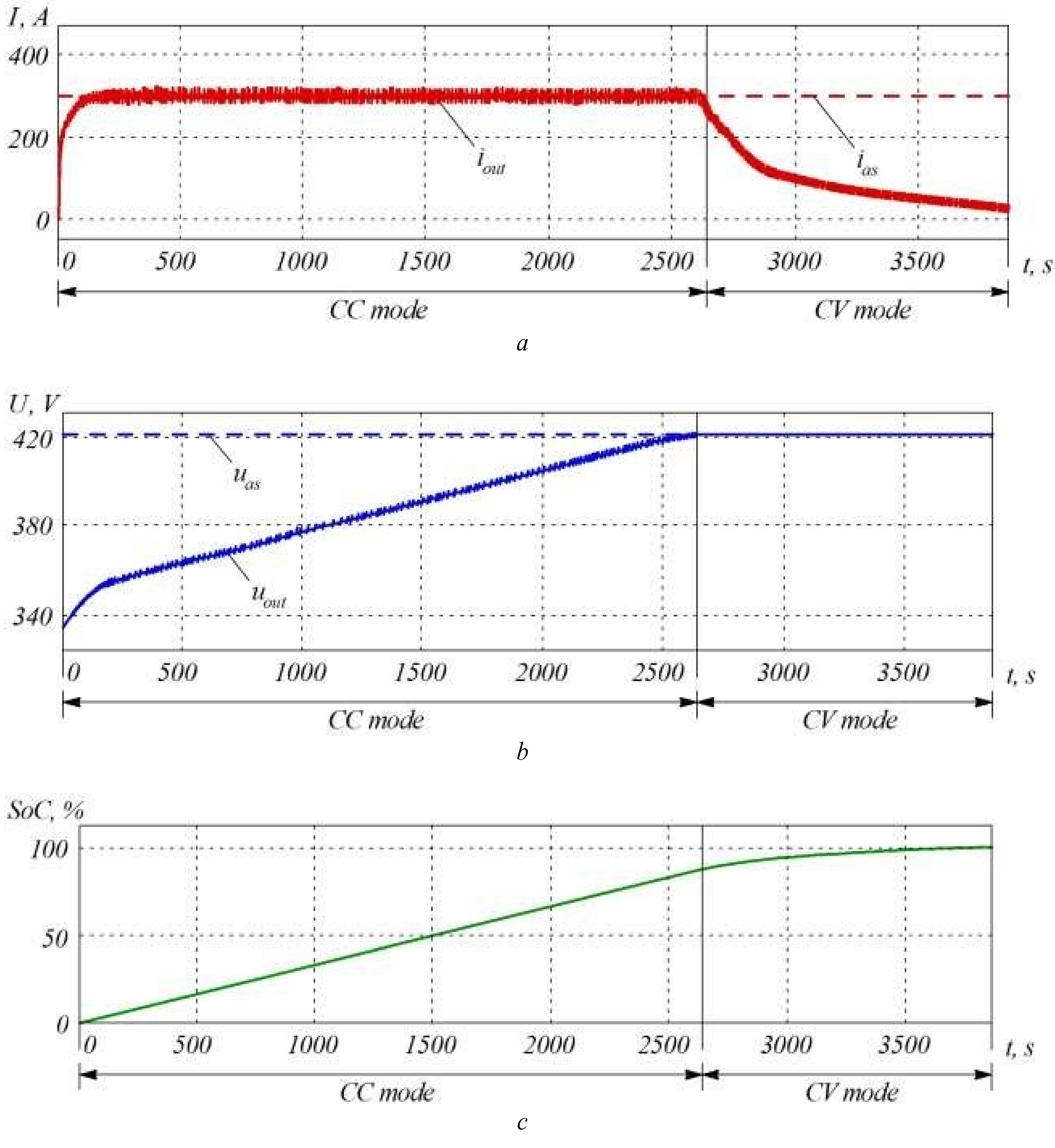

Fig. 10. Oscillograms of charging station operation:
a – output current and task current (CC);
b – output voltage and task voltage (CV);
c – battery charge level

Table 2

Parameters of energy indicators of the charging station

PWM frequency, kHz	Charge current in CC mode, A	Efficiency, %	Charging time, s,·10^3	Power factor	THD, %
5	150 (0.6C)	95.6	6.55	0.985	11.8
	200 (0.8C)	94.8	5.18	0.987	9.8
	250 (1C)	93.9	4.38	0.989	7.2
	300 (1.2C)	93.1	3.84	0.991	6.0
	350 (1.4C)	92.2	3.47	0.992	5.1
	400 (1.6C)	91.4	3.2	0.992	4.5
10	150 (0.6C)	95.4	6.55	0.987	6.1
	200 (0.8C)	94.5	5.19	0.99	4.6
	250 (1C)	93.7	4.38	0.991	3.7
	300 (1.2C)	92.9	3.85	0.992	3.1
	350 (1.4C)	92.1	3.48	0.992	2.7
	400 (1.6C)	91.3	3.2	0.993	2.5

Conclusions. On the basis of the conducted research, the following conclusions can be drawn:

– basic energy parameters and charge-discharge characteristics of lithium-ion and lithium-iron-phosphate batteries used in electric vehicles are presented. The main requirements for charging station systems are regulation and stabilization of the charging current and voltage, increasing the efficiency of the converter and ensuring electromagnetic compatibility;

– the proposed structure of an electric vehicle charging station, consisting of an input transformer, a three-level active rectifier and a load, provides relative to the known technical solutions of charging stations, improvement of the parameters of efficiency, power factor and harmonic distortion factor. The obtained results are explained by the fact that the proposed charging station implements a single-stage conversion of electricity in an active rectifier with power factor correction;

– the calculation of the efficiency of the charge process of the proposed system was vehicleried out at different parameters of the charge current and switching frequency. Taking into account the power losses in the battery of the electric vehicle, the maximum efficiency of the system is achieved in the mode of minimum charging current.

The article was prepared as part of the support of the grant of young scientists of Ukraine «Development of scientific bases for improving energy efficiency and improving the quality of electricity in electricity networks» (State Registration Number 0121U109440).

Reference

1. Frincu R., Misso F. E., Repetto C. E-light vehicles in European cities: Starting from “Ele. C. Tra.-Electric City Transport” experience, ready to take up new challenges. *2017 Electric Vehicles International Conference (EV)*. 2017. P. 1–6. DOI: 10.1109/EV.2017.8242114.

2. Dell'Amico M., Hadjidimitriou N. S., Renzi G. Assessing the Impact of Shared L-Category Electric Vehicles in six European cities. *2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC)*. 2020. P. 1–5 DOI: 10.1109/ITSC45102.2020.9294355.

3. Matanov N., Zahov A. Developments and Challenges for Electric Vehicle Charging Infrastructure. *2020 12th Electrical Engineering Faculty Conference (BulEF)*. 2020. P. 1–5. DOI: 10.1109/BulEF51036.2020.9326080.

4. Marinelli M., Calearo L., Ried S., Pfab X., Cesar J., Spalthoff C., Braun M. Electric Vehicles Demonstration Projects – An Overview Across Europe. *2020 55th International Universities Power Engineering Conference (UPEC)*. 2020. P. 1–6. DOI: 10.1109/UPEC49904.2020.9209862.

5. Pareek S., Sujil A., Ratra S., Kumar R. Electric Vehicle Charging Station Challenges and Opportunities: A Future Perspective. *2020 International Conference on Emerging Trends in Communication, Control and Computing (ICONC3)*. 2020. P. 1–6. DOI: 10.1109/ICONC345789.2020.9117473.

6. Saldarini A., Barelli L., Pelosi D., Miraftabzadeh S., Longo M., Yaici W. Different Demand for Charging Infrastructure along a Stretch of Highway: Italian Case Study. *2022 IEEE Industrial and Commercial Power Systems Europe (I&CPS Europe)*. 2022. P. 1–6. DOI: 10.1109/EEEIC/ICPSEurope54979.2022.9854643.

7. Pliakostathis K. Research on EMI from Modern Electric Vehicles and their Recharging Systems. *2020 International Symposium on Electromagnetic Compatibility – EMC EUROPE*. 2020. P. 1–6. DOI: 10.1109/EMCEUROPE48519.2020.9245742.

8. Oliinyk M., Dzmura J., Pal D. The impact of a electric vehicle charging on the distribution system. *2020 21st International Scientific Conference on Electric Power Engineering (EPE)*. 2020. P. 1–5. DOI: 10.1109/EPE51172.2020.9269213.

9. Weiss M., Zerfass A., Helmersb E. Fully electric and plug-in hybrid cars. An analysis of learning rates, user costs, and costs for mitigating CO_2 and air pollutant emissions. *Clean Prod*. 2019. Vol. 212. P. 1478–1489. DOI: 10.1016/j.jclepro.2018.12.019.

10. Bodo N., Levi E., Subotic I., Espina J., Empringham L., Johnson C. M. Efficiency Evaluation of Fully Integrated On-Board EV Battery Chargers With Nine-Phase Machines. *IEEE Transactions on Energy Conversion*. 2017. Vol. 32, No. 1. P. 257–266. DOI: 10.1109/tec.2016.2606657.

11. Taylor A., Lu J., Zhu L., Bai K., McAmmond M., Brown A. Comparison of SiC MOSFET-based and GaN HEMT-based high-efficiency high-power-density 7.2kW EV battery chargers. *IET Power Electronics*. 2018. Vol. 11, No. 11. P. 1849–1857. DOI: 10.1049/iet-pel.2017.0467.

12. Huang Z., Lam C.-S., Mak P.-I., Martins R., Wong S.-C., Tse C. K. A Single-Stage Inductive-Power-Transfer Converter for Constant-Power and Maximum-Efficiency Battery Charging. *IEEE Transactions on Power Electronics*. 2020. Vol. 35, No. 9. P. 8973–8984. DOI: 10.1109/TPEL.2020.2969685.

13. Kim D.-H., Kim M.-J., Lee B.-K. An Integrated Battery Charger With High Power Density and Efficiency for Electric Vehicles. *IEEE Transactions on Power Electronics*. 2017. Vol. 32, No. 6. P. 4553–4565. DOI: 10.1109/tpel.2016.2604404.

14. Lee W.-S., Kim J.-H., Lee J.-Y., Lee I.-O. Design of an Isolated DC/DC Topology With High Efficiency of Over 97% for EV Fast Chargers. *IEEE Transactions on Vehicular Technology*. 2019. Vol. 68, No. 12. P. 11725–11737. DOI: 10.1109/TVT.2019.2949080.

15. Nerubatskyi V. P., Plakhtii O. A., Tugay D. V., Hordiienko D. A. Method for optimization of switching frequency in frequency converters. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*. 2021. Vol. 1, No. 181. P. 103–110. DOI: 10.33271/nvngu/2021-1/103.

16. Vinoth Kumar K., Radhakrishnan P., Kalaivani R., Devadoss V., Vijay Anand L. D., Vinodha K. Implementation of Smart Electric Vehicle Charging Station Driven Using Experimental Investigation. *2021 2nd Global Conference for Advancement in Technology (GCAT)*. 2021. P. 1–5. DOI: 10.1109/GCAT52182.2021.9587788.

17. Plakhtii O., Nerubatskyi V., Hordiienko D. Efficiency analysis of DC-DC converter with pulse-width and pulse-frequency modulation. *2022 IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO)*. 2022. P. 571–575. DOI: 10.1109/ELNANO54667.2022.9926762.

18. Aggarwal S., Bajaj M., Singh A. K. Analysis of Electric Vehicle Charging Station Allocation in Deregulated Electric Power System. *2020 IEEE 9th Power India International Conference (PIICON)*. 2020. P. 1–6. DOI: 10.1109/PIICON49524.2020.9113022.

19. Nerubatskyi V., Plakhtii O., Hordiienko D., Khoruzhevskyi H. Study of energy parameters in alternative power source microgrid systems with multi-level inverters. *International scientific journal «Industry 4.0»*. 2020. Vol. 5, Issue 3. P. 118–121.

20. Nuamkoksung P., Buayai K., Kongjeen Y. Impact of Fast Charging on Lithium-ion Battery in Electric Vehicle Application. *2020 8th International Electrical Engineering Congress (iEECON)*. 2020. P. 1–4. DOI: 10.1109/iEECON48109.2020.244120.

21. Nabi Akpolat A., Yang Y., Blaabjerg F., Dursun E., Emin Kuzucuoglu A. Li-ion-based Battery Pack Designing and Sizing for Electric Vehicles under Different Road Conditions. *2020 International Conference on Smart Energy Systems and Technologies (SEST)*. 2020. P. 1–6. DOI: 10.1109/SEST48500.2020.9203196.

22. Plakhtii O., Nerubatskyi V., Hordiienko D., Sushko D., Syniavskyi A., Shelest D. Thermal-powerloss approximation method for determination of efficiency in semiconductor devices. *2022 IEEE 41st International Conference on Electronics and Nanotechnology (ELNANO)*. 2022. P. 456–461. DOI: 10.1109/ELNANO54667.2022.9926756.

23. Nerubatskyi V., Hordiienko D. Analysis of the control system of a wind plant connected to the AC network. *Power engineering: economics, technique, ecology*. 2023. No. 1. P. 87–91. DOI: 10.20535/1813-5420.1.2023.276028.

24. Park M., Seo M., Song Y., Kim S. W. Capacity Estimation of Li-Ion Batteries Using Constant Current Charging Voltage With Multilayer Perceptron. *IEEE Access*. 2020. Vol. 8. P. 180762–180772. DOI: 10.1109/ACCESS.2020.3028095.

25. Huang X., Li Y., Acharya A., Sui X., Meng J., Teodorescu R., Stroe D.-I. A Review of Pulsed Current Technique for Lithium-ion Batteries. *Energies*. 2020. Vol. 13. 2458. DOI: 10.3390/en13102458.

26. Milushev G. Measurement of the Efficiency of Electric Vehicle Charging Stations. *2020 XXX International Scientific Symposium Metrology and Metrology Assurance (MMA)*. 2020. P. 1–5. DOI: 10.1109/MMA49863.2020.9254255.

27. Plakhtii O., Nerubatskyi V., Mykhalkiv S., Hordiienko D., Shelest D., Khomenko I. Research of energy characteristics of three-phase voltage source inverters with modified pulse width modulation. *2021 IEEE 2nd KhPI Week on Advanced Technology (KhPIWeek)*. 2021. P. 422–427. DOI: 10.1109/KhPIWeek53812.2021.9570071.

Nerubatskyi Volodymyr Pavlovych, PhD (Tech.), Associate Professor, Department of Electrical Energetics, Electrical Engineering and Electromechanics, Ukrainian State University of Railway Transport. Tel.: +38 (095) 045-78-01. E-mail: NVP9@i.ua. ORCID iD: 0000-0002-4309-601X.

Plakhtii Olexandr Andriiovych, PhD (Tech.), Associate Professor, Department of Electrical Energetics, Electrical Engineering and Electromechanics, Ukrainian State University of Railway Transport. Tel.: +38 (093) 917-60-20. E-mail: a.plakhtiy1989@gmail.com. ORCID iD: 0000-0002-1535-8991.

Hordiienko Denys Anatoliiovych, Postgraduate, Department of Electrical Energetics, Electrical Engineering and Electromechanics, Ukrainian State University of Railway Transport. Tel.: +38 (099) 612-02-12.
E-mail: D.Hordiienko@i.ua. ORCID iD: 0000-0002-0347-5656.

Нерубацький Володимир Павлович, канд. техн. наук, доцент, доцент кафедри електроенергетики, електротехніки та електромеханіки, Український державний університет залізничного транспорту.
Тел.: +38 (095) 045-78-01. E-mail: NVP9@i.ua. ORCID iD: 0000-0002-4309-601X.
Плахтій Олександр Андрійович, канд. техн. наук, доцент кафедри електроенергетики, електротехніки та електромеханіки, Український державний університет залізничного транспорту. Тел.: +38 (093) 917-60-20.
E-mail: a.plakhtiy1989@gmail.com. ORCID iD: 0000-0002-1535-8991.
Гордієнко Денис Анатолійович, аспірант кафедри електроенергетики, електротехніки та електромеханіки, Український державний університет залізничного транспорту. Тел.: +38 (099) 612-02-12.
E-mail: D.Hordiienko@i.ua. ORCID iD: 0000-0002-0347-5656.

Статтю прийнято 20.06.2023 р.