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V. Nerubatskyi[1], Cand. Sc. (Eng.), Assoc. Prof., ORCID 0000-0002-4309-601X
D. Hordiienko[1], Ph. D. student, ORCID 0000-0002-0347-5656
[1]Ukrainian State University of Railway Transport

TOPOLOGY OF EFFICIENT USE OF ENERGY BY A CHARGING STATION FOR ELECTRIC VEHICLES

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 is presented. The efficiency of the proposed charging station system was calculated for different parameters of the charge current and switching frequency.

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

Introduction

Over 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 it is much cheaper to drive 100 km in an electric car than in a car with an internal combustion engine [1, 2].

Charging stations are an important component of electric vehicle infrastructure. Further development and improvement of power converters for charging stations of electric vehicles with lithium-ion, lithium-iron-phosphate and other types of batteries will lead to an increase in the energy efficiency of charging stations, better electromagnetic compatibility between charging stations and the power network, lower emissions of harmonics and components of reactive power [3, 4].

The power circuit with fast charging consists of three stages, namely: an input filter to reduce input harmonics and optimize the power factor, a rectifier for cyclic DC currents, and a DC-DC converter to transfer energy to the battery for fast DC charging from a hybrid electric vehicle [5, 6].

Analysis of Recent Research and Publications

In paper [7] converters with 9-phase power systems for charging stations of electric vehicles are considered. However, their disadvantages include low efficiency, which reaches 91 %. In addition, the converter presented in this article requires electromechanical phase separation, which significantly increases the cost of the system and increases its weight and size indicators.

The paper [8] presents a study of the efficiency of a charging station for electric vehicles based on a converter consisting of a rectifier and a parallel three-channel buck converter. However, the disadvantage of this topology is that the power source is not galvanically isolated from the load. Studies also show that the peak efficiency of the converter is lower than 92 %. In addition, there is no data on the integral value of the efficiency of the entire 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 [9, 10].

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

Purpose and Objectives of the Study

The purpose of the study 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;

– 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.

Main Material of the Study

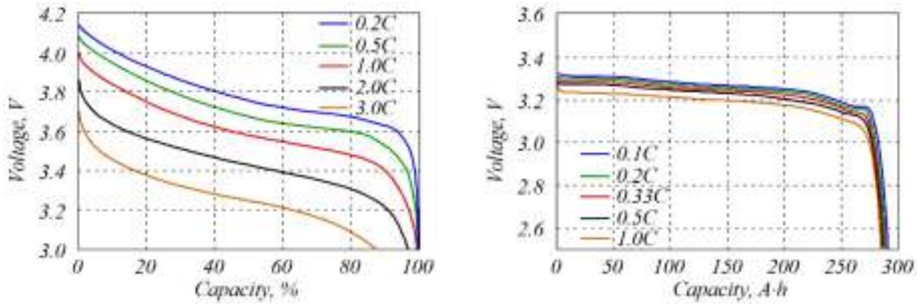
Traditional charging stations for electric vehicles include a two-stage energy conversion and consist of an input AC/DC rectifier and an output DC/DC converter [11, 12]. In this topology, an input rectifier is used to create a DC voltage circuit. Then the DC/DC converter regulates the voltage and charging current of electric vehicles in a certain range. DC/DC converters are also used for galvanic isolation of electric vehicles from the network.

The most common element of electric vehicle batteries are lithium-ion batteries [13, 14]. 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. 1.



a *b*

Figure 1 – *Charge-discharge characteristics:*
a – lithium-ion battery LIR18650; b – lithium-iron-phosphate battery LF280

As can be seen from Fig. 1 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. The recommended charging mode for Li-Ion batteries is the CV–CC (constant voltage – constant current) mode, which is shown in Fig. 2 [15, 16].

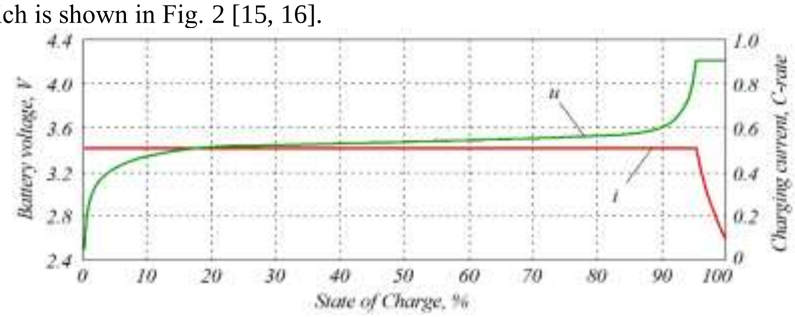


Figure 2 – *Characteristics of the Li-Ion battery charge mode*

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 [17].

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. 3.

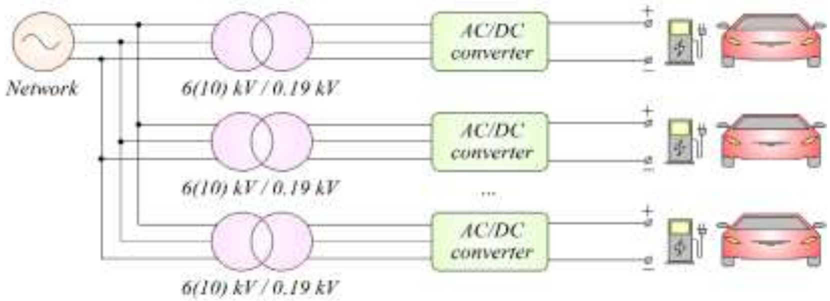


Figure 3 – *Structural diagram of a single-link charging station for electric vehicles*

Promising topologies that can provide the listed requirements for charge-discharge modes of powerful storage devices are an active three-phase voltage rectifier, the circuits of which are shown in Fig. 4, 5.

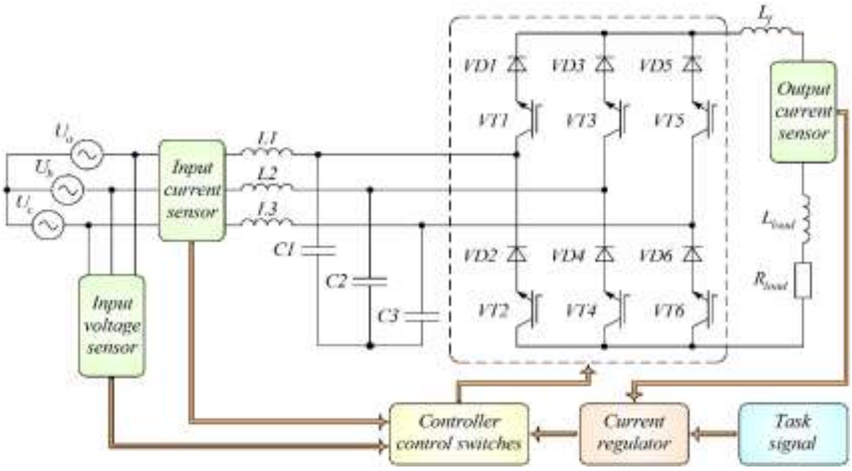


Figure 4 – *Topology of an active three-phase current rectifier*

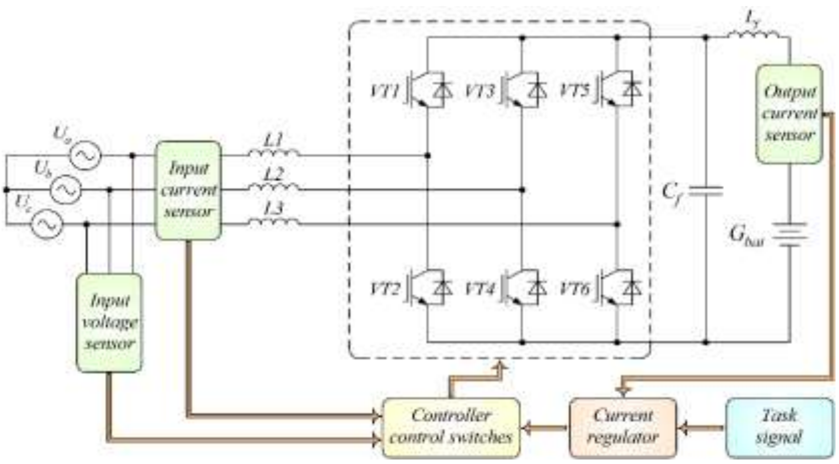


Figure 5 – *Topology of an active three-phase voltage rectifier*

These topologies have significant advantages over conventional diode and thyristor rectifiers. These advantages are threefold: the ability to operate in near-unity power factor mode, the ability to generate a sinusoidal form of current drawn from the network, and the ability to provide power factor correction. A simulation model was developed to study the energy and electromagnetic compatibility of electric vehicle charging stations and the power network (Fig. 6).

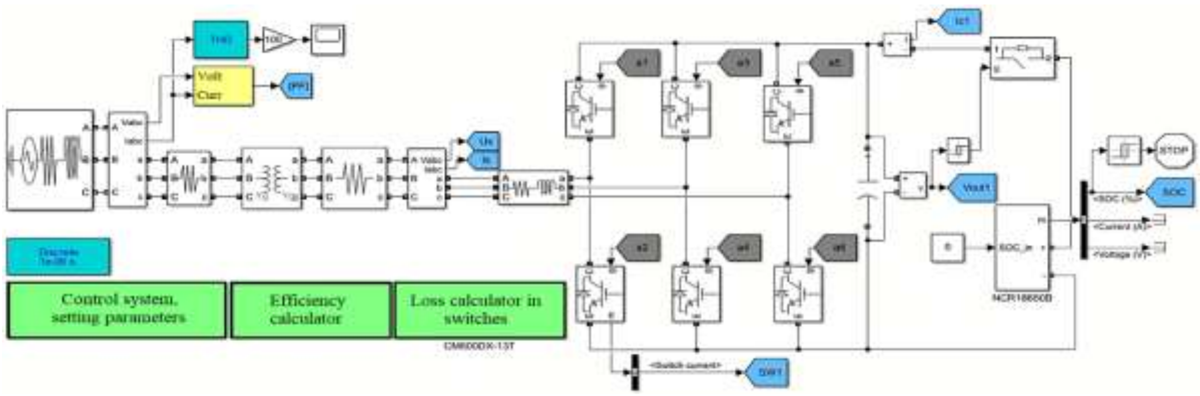


Figure 6 – *A model of a charging station for electric vehicles*

The structure of the proposed charging station consists of an input transformer, a three-level active rectifier and a load. The Tesla S electric car is chosen as the load. The battery compartment of the Tesla S has a capacity of 85 kW·h and consists of 7104 lithium-ion batteries of the Panasonic NCR18650b type (16 blocks containing 74 cells in 6 groups) [18, 19]. In the battery compartment, individual NCR-18650b batteries are connected in parallel in groups of 74 pieces. When connected in parallel, the voltage of the group is equal to the voltage of each element (4.2 V), and the capacity of the group is equal to the total capacity of the element (250 A·h). Then the six groups are connected in series, forming a module. The voltage of the module is equal to the sum of the voltages of the groups and is 25.2 V. The modules are connected in series, forming a battery. The battery contains a total of 16 modules (a total of 96 groups). The total voltage of all modules is 400 V. The equivalent resistance of the battery is also calculated. The average battery resistance R_{NCR} = 37 mΩ is based on the equivalent battery resistance R_{bat} = 27 mΩ. The simulation results, that is, the oscillograms of the input current and input voltage of the active rectifier, are shown in Fig. 7.

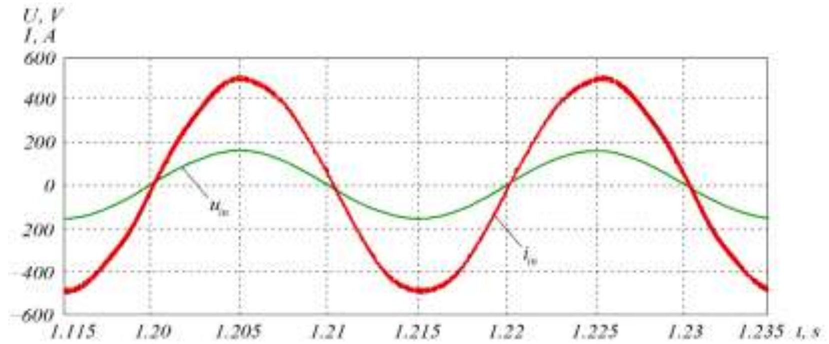


Figure 7 – *Oscillograms of the input current and voltage of the active rectifier*

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:

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

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 %.

Table 2 – Parameters of energy indicators of the charging station

PWM frequency, kHz	Charge current in CC mode, A	Efficiency, %	Charging time, s,$\cdot 10^3$	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

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 %.

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.

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В. П. Нерубацький[1], канд. техн. наук, доцент, ORCID 0000-0002-4309-601X
Д. А. Гордієнко[1], аспірант, ORCID 0000-0002-0347-5656
[1]Український державний університет залізничного транспорту

ТОПОЛОГІЯ ЕФЕКТИВНОГО ВИКОРИСТАННЯ ЕНЕРГІЇ ЗАРЯДНОЮ СТАНЦІЄЮ ЕЛЕКТРОМОБІЛІВ

Наведено результати дослідження напівпровідникових перетворювачів зарядних станцій для електромобілів на основі літій-іонних елементів. Наведено базові енергетичні параметри та зарядно-розрядні характеристики літій-іонних та літій-залізо-фосфатних акумуляторів. Наведено топологію запропонованої зарядної станції для електромобілів на основі схем активного випрямляча. 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. Проведено розрахунок ККД запропонованої системи зарядної станції при різних параметрах струму заряду та частоти комутації.

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

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