STUDY OF THE EFFICIENCY OF A CHARGING STATION FOR ELECTRIC VEHICLES USING AN ACTIVE RECTIFIER IN A MICRO-GRID SYSTEM

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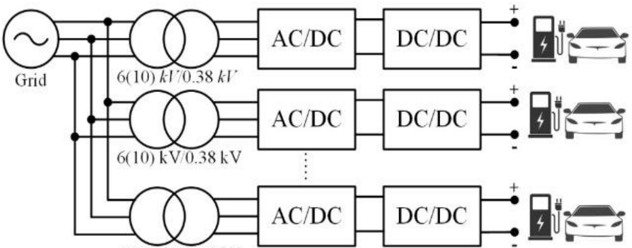
Introduction. Every year, electric vehicles become more attractive compared to vehicles with internal combustion engines (ICE). The development of electric vehicles (EVs) has received significant attention from governments, manufacturers and researchers. In this case, an important issue is the creation of energy-efficient charging stations with the highest power efficiency parameters. Another quite important parameter is the charging time of electric vehicle batteries. In this regard, topologies of external charging stations with fast charging mode (DC, Mode 4) are quite promising. In addition, one of the requirements for charging stations is the ability to provide bidirectional energy transfer, which corresponds to the vehicle-to-grid (V2G) concept (Deilami et al., 2011).

Traditional fast charging stations typically contain two conversion stages, namely an AC/DC input rectifier and an output DC/DC converter (see Figure 1).

Figure 1

Schemes of fast charging stations based on AC/DC-DC/DC



In this topology, the DC/DC converter provides regulation of the output voltage and current of the charging station over a wide range. The DC/DC converter is also used to provide galvanic isolation of the electric vehicle from the network. At the same time, two-stage conversion of electricity leads to additional losses and a decrease in the efficiency of the charging station power.

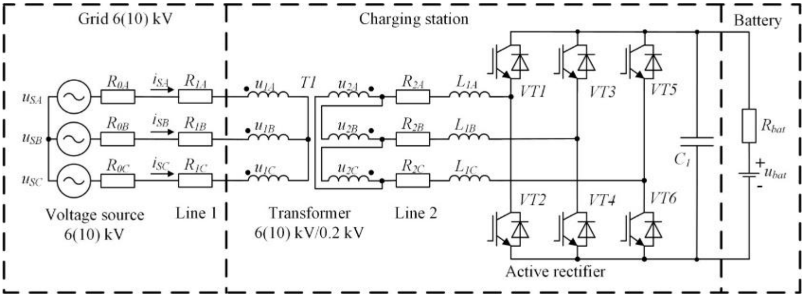
Presentation of the main research. This paper proposes a topology concept for an external DC charging station based on an active three-phase rectifier (AB) with power factor correction (see Figure 2). In this case, the active rectifier performs the function of regulating the output voltage and charging current, and the galvanic isolation is provided by the input transformer. The advantages of the proposed charging station with AV include: high power factor close to unity, low harmonic distortion of the consumed current (THD < 5 per cent), higher efficiency relative to two-stage charging stations of the AC/DC-DC/DC type, as well as the ability to provide bidirectional energy transfer (Sortomme, 2010).

Parameters of the system under consideration. The characteristics of the supply network are determined by the parameters of the three-phase transformer of the supply substation type TMN4000/35/6, for which the phase resistance R0A = 1.4 Ohm (Perelmuter, 2020). The parameters of line 1 are determined by the distance between the traction substation and the converter transformer, which we take equal to 1 km. The aluminum three-core cable used in line 1 has a phase resistance value of R1A equal to 0.8 Ohm/km, and its cross-section is selected according to the current and is equal to 35 mm2. The SPZ-1000/10U3 series 6(10)/0.2 kV converter transformer has a rated power of 0.878 MW and a short circuit loss of 8 kW. The total equivalent resistance of its RTV phase for it will be equal to 1.73 mOhm. The parameters of line 2 are determined by the distance between the converter transformer T1 and the active rectifier, which is assumed to be 50 m. In this case, the cross-section of the copper cable will be equal to 350 mm2, the value of the R_{2A} phase resistance will be 2.5 mOhm. The inductance value of the active rectifier input chokes is 0.2 mH. CM600DX-13T switches from the manufacturer Mitsubishi Electric with parameters of collector current Ic 600 A and collector-emitter voltage U_{CE} 650 V, output capacitor capacity equal to 20 mF were selected as switches for active rectifiers.

The system for automatically regulating the current and voltage of battery charging is implemented on the basis of an integral regulator with further PWM formation of the input current shape (Sokol et al., 2018). The automatic control system is described in more detail below by modeling the system (see Figure 2).

Figure 2

Diagram of a Micro grid charging station for electric vehicles with single-stage energy conversion



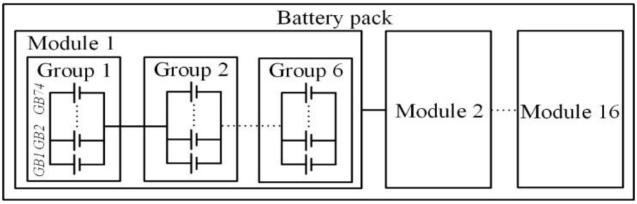
Equivalent EV battery model. The work examined the charge of an equivalent model of the battery compartment of the Tesla S electric car, which contains 7104 Panasonic NCR-18650 batteries with a total capacity of 85 kWh (Nerubatsky et al., 2019). The battery connection diagram in the Tesla Model S electric car is shown in Figure 3.

In the battery compartment, individual NCR-18650b batteries are connected in parallel into groups of 74 pcs. With a parallel connection, 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, six groups are connected in series to form a module.

In this case, the module voltage is summed up from the group voltages and equals 25.2 V. Next, the modules are connected in series to form a battery. In total, the battery contains 16 modules (total 96 groups). The voltage of all modules is summed up and amounts to 400 V.

Figure 3

Battery connection diagram in the Tesla Model S electric car

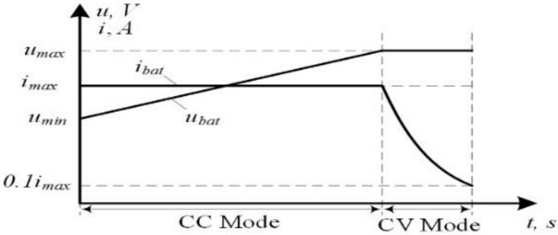


The equivalent resistance of the battery pack is also calculated. Based on the fact that the average resistance of one R_{NCR} battery is 37 mOhm, the equivalent resistance of the R_{bat} battery is 27 mOhm. Battery charging algorithm. When implementing fast battery charging, the method (algorithm) that will be used to charge the battery plays a significant role. The most popular battery charging method is the Constant Current - Constant Voltage (CC-CV) method (see Figure 4).

The basic idea of the method is that the battery is charged with a constant maximum current (imax), which is determined by the battery manufacturer up to a certain cutoff voltage (umax), and then charged at this voltage until the current consumption decreases to approximately 0.1C or less, providing a full charge (Nerubatsky et al., 2019). It should be noted that when switching from CC mode to CV mode (this occurs at approximately 80 per cent of the battery charge), the charging speed is significantly reduced.

Figure 4

Charge mode using the CC-CV method



The work assessed the efficiency of the proposed charging station, shown in Figure 2. The efficiency was estimated based on the total energy losses and useful energy received by the battery during the full charging interval (Tugay et al. (2019). The formula was used to calculate the efficiency:

$$\eta = \frac{E_{Load}}{E_{Load} + \Delta E_{\Sigma}}, \tag{1}$$

where E_{Load} – is the useful energy transferred to the battery during charging; ΔE_{Σ} - is the total energy loss in the micro-grid system under consideration.

$$\Delta E_{\Sigma} = E_S + E_{L1} + E_{TV} + E_{L2} + E_L + E_{AR} + E_{bat}, \tag{2}$$

where E_S – is the energy of losses in the source 6(10) kV; E_{L1} – loss energy in line 1; E_{TV} – energy losses in the transformer; E_{L2} – loss energy in line 2; E_{AR} – loss energy in active rectifier switches; E_{bat} – is the energy loss in the battery.

Useful energy transferred to the load:

$$E_{Load} = \int_0^{T_з} (u_{Load} \cdot i_{Load}) \cdot dt, \tag{3}$$

where $T_з$ – time to fully charge the EV battery; u_{load} – instantaneous value of the output voltage supplied to the battery compartment of lithium-ion batteries (when charging, the range is from 340 to 420 V); i_{load} - is the instantaneous value of the load current (battery charge), which during the charging process varies from 15 to 400 A.

Losses in the 6(10) kV source, in line 1, in transformer T1, in line 2 and in the battery are calculated using the formula:

$$E = \int_0^{T_з} (i^2 \cdot R) \cdot dt, \tag{4}$$

where i and R – are the instantaneous current value and resistance in the calculated section of the circuit.

An IGBT module of type CM600DX-13T was selected as AB keys. The total losses in the IGBT module consist of dynamic and static losses in the IGBT transistor and reverse diode (Zhemerov et al., 020) calculated:

$$E_{loss.IGBT} = E_{loss.VT} + E_{loss.VD}\ ; \qquad (5)$$

$$E_{lossVT} = E_{VT.DC} + E_{VT.SW}\ ; \qquad (6)$$

$$E_{lossVD} = E_{VD.DC} + E_{VD.SW}\ , \qquad (7)$$

where $E_{VT.DC}$ – is the energy of static waste in IGBT transistors; $E_{VT.SW}$ – energy of dynamic losses in IGBT transistors; $E_{VD.DC}$ – energy of static losses in parallel diodes; $E_{VD.SW}$ – energy of dynamic losses in parallel diodes.

$$E_{VT.DC} = \int_0^{T_3} (i_c \cdot u_{ce})dt\ , \qquad (8)$$

where i_c – collector strum; $u_{ce}(i_c)$ – the voltage between the collector and the emitter, which lies below the value of the collector flow.

Dynamic losses in IGBT transistors are calculated according to the following formula:

$$E_{VT.SW} = \int_0^{T_3} \left[E_{on}(I_c) + E_{off}(I_c)\right] \cdot dt\ , \qquad (9)$$

where $E_{on}(I_c)$ and $E_{off}(I_c)$ – are the energy that is dissipated in the transistor when it is energized and ignited, which is stored in the volume of the collector stream.

Static losses in freewheeling diodes:

$$E_{VD.DC} = \int_0^{T_3} (u_{fwd} \cdot i_{vd}) \cdot dt\ , \qquad (10)$$

where u_{fwd} – is the voltage drop across the reverse diode; i_{vd} – reverse diode current.

Dynamic losses in freewheeling diodes:

$$E_{VD.SW} = \int_0^{T_3} E_{rec}(i_{vd}) \cdot dt \qquad (11)$$

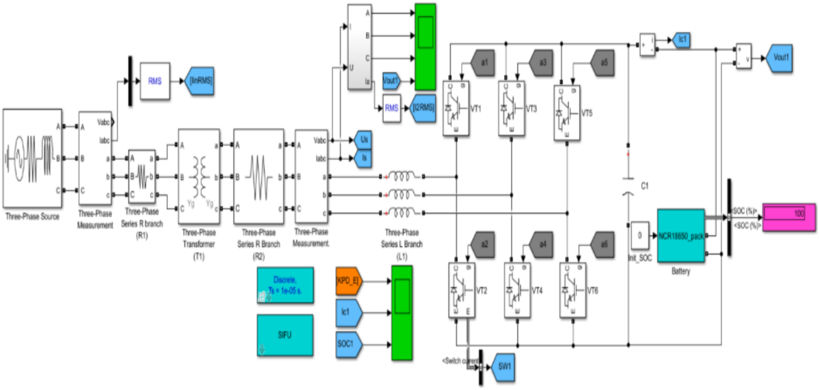
where E_{rec} – is the recovery energy of the reverse diode.

Data $E_{on}(i_c)$, $E_{off}(i_c)$ и $E_{rec}(i_c)$, $u_{ce}(i_c)$, $u_{fwd}(i_{vd})$ were taken from the datasheet for the CM600DX-13T module.

Simulation of charging station operation. To experimentally test the theoretical assumptions, a Matlab model of the proposed charging station was developed (see Figure 5).

Figure 5

Matlab model of Micro-grid charging station system for electric vehicles



The automatic control system (ACS) for an active rectifier is built on the basis of an integral regulator with further pulse-width modulation (Tomashevskyi et al., 2014). The developed ACS provides the specified dynamics of changes in voltage and charge current in CC-CV modes.

Conclusions. The article presents the results of a study of the energy efficiency parameters of an external DC EV charging station using an active rectifier.

The parameters of the proposed structure of the ES are described, the parameters of the equivalent circuit of the battery compartment of the Tesla model S electric car are presented, which are reduced to one equivalent battery. A method for quickly charging a CC-CV battery is described, which provides a greater number of charge-discharge cycles. Formulas are given for calculating the components of losses and efficiency during the interval of full battery charge. A Matlab model of the charging station system and simulation results are presented. The studies have shown that the maximum efficiency of the system power is achieved in the minimum charge current mode. At the same time, a decrease in the charge current leads to an increase in the charging process time, as well as a slight deterioration in power quality parameters.

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