Comparison of Standard and Fast Charging Methods for Electric Vehicles

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Abstract. *This paper describes a comparison of standard and fast charging methods used in the field of electric vehicles and also comparison of their efficiency in terms of electrical energy consumption. The comparison was performed on three-phase buck converter, which was designed for EV's fast charging station. The results were obtained by both mathematical and simulation methods. The laboratory model of entire physical application, which will be further used for simulation results verification, is being built in these days.*

Keywords

Battery charging, electric vehicle, fast charging station, power losses, three-phase buck converter.

1. Introduction

The present energetic development is oriented into the considerable incorporation of alternative and renewable energy sources into the standard electrical grids in an effort to build very efficient, economic and reliable smart grids. This approach produces series of technical problems, which have to be solved. One of the most actual ones is the electric energy accumulation. The solar plant systems and especially the fast charging stations for electric vehicles and many other applications, which will be discussed further, are typical examples of energy accumulation issues.

To satisfy an efficient and economic functioning of such station, the energy surplus has to be stored into the batteries and extracted back when needed. It is also necessary to ensure sufficient battery power for fast charging of the electric vehicle's traction batteries. Voltage converters are needed to provide an efficient and reliable energetic power flow between the accumulation units and others devices. This paper discusses the efficiency of standard and fast charging in order to decide whether is more advantageous to charge an electric vehicle economically (standard charging) or user-defined (fast charging).

2. Charging Station for Electric Vehicles

Both charging methods were carefully reviewed in the sense of their implementation on the wholly charged system including models of buck converter and Li-ion batteries in order to meet initial requirements, which were defined in the abstract of this paper. The laboratory sample of three-phase buck converter for this application has been created and its wiring diagram with 3D model is described below.

The charging station unit for electric vehicles is a part of complex structure used for accumulation of electric power. Structure depicted on Fig. 1 represents an accumulation element typical for smart grids, which is eliminating time inefficient operation of alternative energy sources, for example solar power plant. High instant power for EV's fast charging will be provided from this accumulation source. Utilization of this source do not create peaks in the power grid and allows to partly regulate the energy supply system.

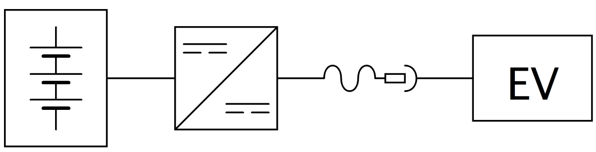

Fig. 1: Location of the converter in EV circuit topology.

The overall scheme from the point of view of charging an electrical vehicle is pictured above on the Fig. 1. The power source creates an accumulation system, which is connected directly to the power grid.

The power converter is a controllable unit between the power source and electric vehicle, which is being charged. This converter is built as a three-phase buck converter.

The inside scheme of the converter is pictured at the Fig. 2 below. The input of the converter is created by the capacitor battery used for energetic exchange caused by the fast switching of the converter. The power part contains the insulated IGBT modules with implemented freewheeling diodes. These modules are assembled on the liquid cooled heat sink, which is used for dissipation of loss heat to the coolant. On the output of the power circuit is the choke-block used for current ripple reduction, which allows the connection of individual phases to the charged battery.

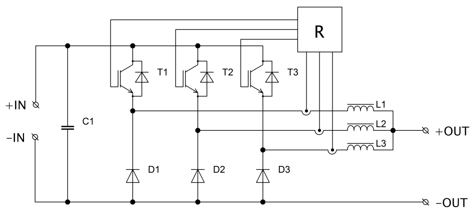

Fig. 2: Power schematic of the three-phase buck converter.

The combined AC/DC charging system according to the standard IEC 62196-3 enables connection between the power converter and the electric vehicle. This connector allows charging currents up to 125 A and voltages up to 850 V DC. Power level of this converter is preset to 70 kW. This performance is chosen to maximize the possibility of battery charging for electric vehicles.

The input voltage applied on the capacitor battery is about of 800 V DC. The voltage of charged battery must always be lower than the source voltage. The current and voltage sensors are distributed in the power circuit providing feedback for the PI controllers. The control algorithms are provided by control system equipped with a signal processor TMS320F28335 and were developed on the Department of Electronics [1].

The 3D design of three-phase buck converter is pictured at the Fig. 3 below. The converter prototype will be manufactured in the near future. The calculated and simulated results, which are presented further in this paper, will be later verified on a real system with LiFePO4 batteries, as soon as the converter will be prepared.

3. Calculation of the Charging Efficiency in Various Modes

The efficiency of fast charging is an issue that has recently been told much about. The influence of charging current size on total charging efficiency is discussed within this paper. Total charging time is indirectly proportional to the value of charging current. This ratio creates a fundamental condition for power losses assessment in particular parts of the charging system. Dependences of losses in following parts of the power circuit will be further investigated below: the power source battery; the power semiconductor converter; choke-block for ripple current reduction and the charged battery.

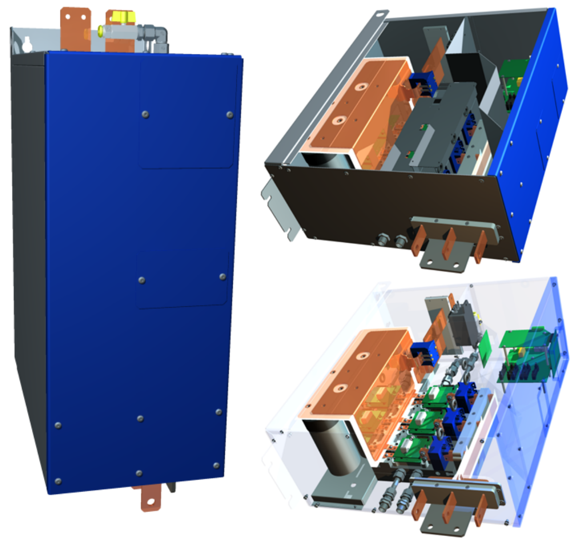

Fig. 3: Sample of design solutions of the fast charger for electric vehicles. The left image of the charger is shown in the basic position, on the other illustrations, there are several views inside of the charger.

3.1. Losses in the Battery

The electrical battery is heated during operation by both the charging and discharging process. The internal impedance of the accumulator is used for evaluation of power losses in the battery. The impedance is always defined in the datasheet of the particular accumulator. Its value is usually about 1 mΩ for one couple of LiFePO4 blocks. Couples of lithium batteries are connected in series for increasing the rated voltage of the whole battery. The energy loss in power source battery respectively in the charged battery is given by:

$$E_{Batt} = I^2 \cdot r_{int} \cdot t_{charge}, \tag{1}$$

where I is the effective value (RMS) of the taken respectively supplied current from/in the battery and t_{charge} is the time for which the energy was supplied or taken.

The energy loss is increased with the square of the current, as it can be seen from Eq. (1) and Fig. 4, which is very disadvantageous situation for fast charging.

3.2. Losses in the Buck Converter

Power losses in the semiconductor device (three-phase buck converter) are especially composed by their two main components – conduction and switching power losses. The other types of electrical power losses also emerge during converter's operation (power losses in the control circuit or capacitor battery) but these losses are negligible in comparison with the first two cases [2].

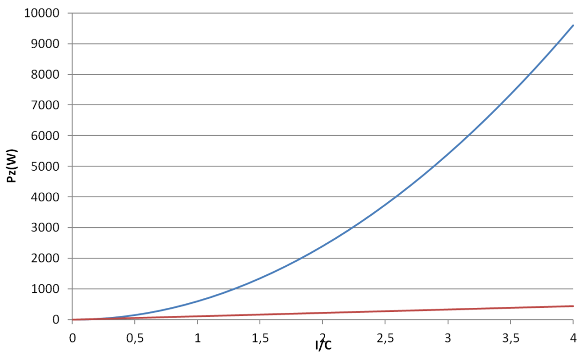

Fig. 4: The dependency of power losses on the charging current. Red line describes linear increase of the current while the blue line represents the quadratic dependency on the charging current.

1) Conducting Power Losses

Losses caused by conduction of the current are defined according to the following equation:

$$E_{Cond} = \left(I_{av} \cdot V_{CE0} \cdot I_{RMS}^2 \cdot r_d\right) \cdot t_{charge}, \qquad (2)$$

where I_{av} is the average value of the current, I_{RMS} the effective current value and V_{CE0} and r_d are threshold voltage and differential resistance of the IGBT switch.

Determination of the dependence for power losses on the current is more complicated in this case. The average current component is dependent linearly, while the effective current component increases with the square of the current. Significance of the second part is substantially lower depending on the mutual ratio between both components.

2) Switching Power Losses

Switching power losses are defined according to the following equation:

$$E_{SW} = [(E_{on} + E_{off}) \cdot f_{SW}] \cdot t_{charge}, \qquad (3)$$

where E_{on} is the switch-on energy loss of the semiconductor switch (IGBT), E_{off} is the switch-off energy loss of the IGBT and f_{SW} is the applied switching frequency.

All of these partial switching losses are linearly dependent on the current. Power semiconductor converter also contains freewheeling diodes. Losses in these bypass diodes arise equivalently as in IGBT transistors, so the current dependencies are just the same.

3.3. Losses in Chokes

The most significant component of losses in chokes is dependent on active electrical resistance of used chokes. The resulting energy loss for chokes, which are carrying the current, is given by the following equation:

$$E_L = I^2 \cdot R_L \cdot t, \qquad (4)$$

where I is the effective value of the current and R is an active electrical resistance of used chokes.

Also in this case the main part of energy losses in chokes increases with the square of the current. (There are also power losses in the core, which are usually negligible compared to the mutual ratio between electrical and magnetic losses [3].)

3.4. Evaluation of Power Losses on the Real Model of Fast Charging Station

Parameters of the solved circuit were set precisely to enable determination of total power losses on the high-fidelity computational model of the fast charging station, which is described in the first part of this paper.

The whole system is supplied from the accumulation unit with rated voltage of 800 V and rated capacitance of 100 Ah. The structural model of charged battery in the load is of the same type as the power source battery model. The charged battery has rated voltage of 400 V and rated capacitance of 100 Ah.

To compare partial and total power losses during standard and fast charging modes, the charging current was chosen to I = 0.3 C for standard charging and I = 2 C for fast charging.

The results, which were obtained for 5 % capacity increase, are listed in the Tab. 1 below. Power losses are calculated with respect for comparison with the simulation results, which will be presented further. Total charging time is 684.5 seconds for standard charging and 102.5 seconds for fast charging.

Energy losses in particular parts of the solved circuit and their total sum (E_{Total}) are written in the Tab. 1. for both standard and fast charging modes.

Tab. 1: Comparison of power losses for standard and fast charging.

Method of charging	Power losses [kJ]					
	E_{Source}	E_{Cond}	E_{SW}	E_L	E_{Load}	E_{Total}
0.3C	34.059	22.359	222.414	0.425	73.955	353.252
2C	253.750	24.602	75.024	3.655	494.107	851.138

Based on the obtained results it is possible to draw the following conclusions: Energy losses with quadratic dependence on the current (especially losses on batteries and chokes) have significantly changed and are about 7 times higher for fast charging in comparison with standard charging. On the other hand, the conducting power losses on the semiconductor devices did not almost change and switching power losses are even higher for standard charging than for fast charging. The change of these losses does not so heavily depend on the value of current. Total power losses for standard charging mode are approximately half those for the fast charging.

4. Simulation and Analysis of the Charging Efficiency in Various Modes

Simulation and analysis of the standard and fast charging was performed in the simulation software Matlab Simulink. Solving of the whole charging cycle has very high demands on the operating memory of the computer, therefore, the simulation was performed only to 5 % increase of state of charge (SoC). However, the results are not affected, because the simulation is always performed with constant currents. The charging modes were chosen the same as in the evaluation analysis presented in the previous chapter (I = 0.3 C for standard charging and I = 2 C for fast charging).

The Simulink model of charging station is depicted below. Some of the included elements are used from the Simscape library, which includes many useful models from energetics and power electronics, e.g. primary and secondary LiFePO4 battery blocks shown in Fig. 5. These blocks are configured to behave as a real lithium iron phosphate battery with nominal parameters. The high-fidelity simulation model of three-phase buck converter accurately represents the datasheet parameters of used IGBT switches [4], [5].

Tab. 2: Simulation results – power losses for standard and fast charging.

Method of charging	Power losses [kJ]			
	E_{Source}	E_{Conv}	E_{Load}	E_{Total}
0.3 C	36.664	47.681	82.42	166.765
2 C	196.358	47.952	463.62	707.93

Important parameters of the simulated circuit were recorded in the simulation output files, to enable subsequent analysis. The obtained results are making an overview about standard and fast charging processes in the solved circuit and are summarized and compared in the following Tab. 2.

Fractional values of energy losses in the three-phase buck converter structure (conducting and switching power losses) are not possible to determine positively from the simulation. However, their sum, represented as total power losses of the converter block E_{Conv} is reported in the Tab. 2. The simulation confirms the assumption about increasing power losses on batteries during fast charging, while the energy losses in the converter block are in both examined charging modes approximately the same. This is probably caused by the calculation method within the simulation model.

5. Comparison between Calculated and Simulated Results

By the comparison of calculated and simulated results it is possible to conclude, that the fast charging mode, which is very preferred in these days, is not completely advantageous because of power losses, which are several times higher than in standard charging case. This claim is confirmed by both, the calculated and simulated results obtained in Matlab Simulink.

More specific point of view on the situation is given by the comparison of both charging methods in the field of efficiency. The evaluated efficiency of standard charging is almost 95 %, while the efficiency of fast charging is only about 89 %. In other words, increasing the charging current by 6.6 times (from 0.3 C to 2 C) causes the efficiency drop by about 6 %.

The largest deviation between calculation and simulation method was observed in the three-phase buck converter block because of switching power losses, which are in the calculation method multiple times larger during standard charging compared to fast charging. The current dependencies of switching losses for calculation method were determined from power diagrams, which are stated in the datasheets of used IGBT modules, while by the simulation method are these dependencies defined inside the IGBT block and are approximately linearly proportional to the current. Therefore, power losses of the converter block E_{Conv} in the simulation method are approximately the same for both charging modes.

Verification of the simulation results will be performed on the laboratory model of fast charging station, which is currently being built.

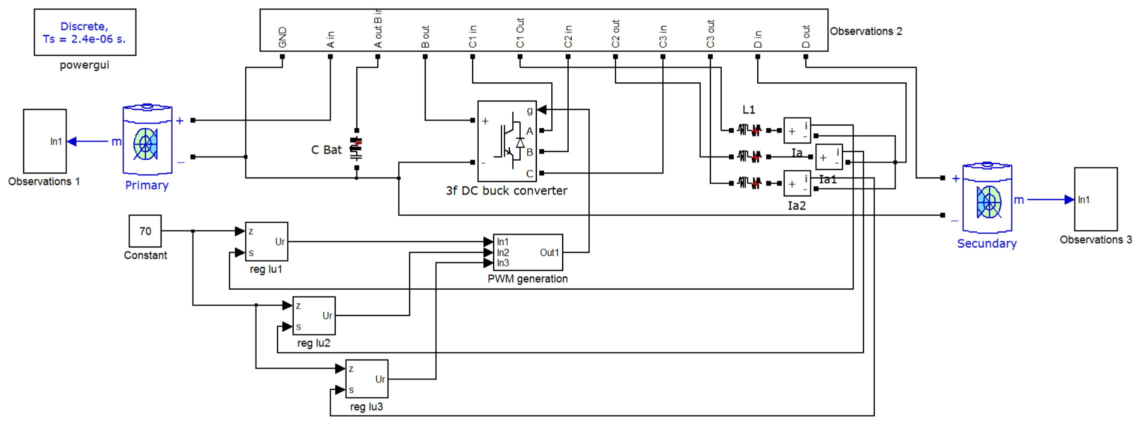

Fig. 5: Simulink model of fast charging station.

6. Conclusion

The aim of this research was to compare standard and fast charging in terms of power losses and total efficiency. Obtained results reveal a significant increase of power losses during application of fast charging. The question to ponder is to what extent is it necessary to apply fast charging on electric and hybrid electric vehicles. Recently growing infrastructure of fast charging stations can lead to inefficient management with electrical energy. According to obtained results, the process of fast charging did not create a substantial increase of power losses in the converter block with chokes (see Tab. 1), however, the situation in the power source and the charged battery is exactly the opposite (see Tab. 1 and Tab. 2).

Acknowledgment

The research described in this paper was partially supported by these projects: SGS project SP2013/80 - Utilizing of Modern SiC Components for MF - Power Semiconductor Converters and ENET CZ.1.05/2.1.00/03.0069 - Energy Units for Utilization of non Traditional Energy Sources and supervised by prof. Petr Chlebis from Department of Electronics, VSB–Technical University of Ostrava.

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