Improved Battery Charger Circuit Utilizing Reduced DC-link Capacitors

Vencislav Valchev [1], Plamen Yankov [1], Orlin Stanchev [1]

[1] *Department of Electronics and Microelectronics, Technical University of Varna, 1 Studentska Str., 9010 Varna, Bulgaria*

***Abstract* – The article presents a comparison of advantages and disadvantages of a battery charger circuit with and without the use of DC-link capacitors in it. The specific application requirements, namely ultra-light electric vehicles, are set as lightness, efficiency and robustness of the design. Prove of greater reliability and improvement on maintenance costs without significant decrease in the quality of charging process with the removal of DC-link capacitors in rectifier and boost converter circuits is accomplished. The proposed circuit parameters are analyzed by carried out simulations.**

***Keywords* – Battery charger, Electric vehicles, Simulation.**

1. Introduction

The design of power electronic equipment reflects the specifics of all electronic components. The dimensioning of DC-link capacitors in different converters is subordinated to few effects and the fact which effect is dominant. The requirements to the transient processes of the designed converter define the values of the DC-link capacitors. Anyhow, too high values could lead to too high pulse charging currents and overloading of power switches. From the other hand, too small capacitors lead to large ripples and thus, more heavy requirements to duty cycle range control. In respect to the volume of the device, capacitors are among the biggest components, thus considering their minimization in respect to the whole PCB area reduction is obligatory. The filter design is consistent with the limit of harmonic content of the line current of mains-connected equipment, which is defined in corresponding standards (IEC 61000-3-2:2014 [1] and IEEE 519, discussed in [2]). A theoretical and practical analysis of AC-DC converter used to feed a DC-DC switch-mode converter from dual-input-voltage operation (230 Vrms, 50 Hz/115 Vrms, 60 Hz) is considered in [3], while calculating capacitor values with accordance to limits of the DC-link capacitors that complies with IEC 61000-3-2. Simple expressions for the currents and voltages in the AC-DC converter that is working as a full-bridge rectifier or as a voltage doubler are also provided [3].

A novel approach for reducing filter capacitance is discussed in [4], based on balanced switching for realizing a smooth energy transfer in a multi-phase DC-DC step-down converter. Reduction up to 30-50% is obtained and also the converter open-loop dynamic response is speeded up. The influence of capacitance values in DC-DC Switched-Capacitor Converters (SCC) is studied in [5] and the theoretical performance limits of two-phase SCC power converters are discussed. Obtained in the paper limits regarding the components and efficiency are useful for further design and selection of SCC power converters. The influence of switch resistances on the performance of regulated SCC is described in [6], comprising both PC (partial charge) and NC (no charge) modes. It is proven that the converter losses are increased in these two modes of operation. Anyhow, the main losses in such circuits could be further reduced by soft switching or improved capacitive snubber circuits to drive the power switches [7]. The concept of multiphase converters for charging the energy storage elements studied in [8], [9] also contributes to smaller values of the converter capacitors.

The purpose of this paper is to analyze a battery charger circuit with and without the use of DC-link capacitors in it and to derive the considerations of its applications. The proposed circuit is analyzed by

DOI: 10.18421/TEM64-12
https://dx.doi.org/10.18421/TEM64-12

Corresponding author: Vencislav Valchev,
Department of Electronics and Microelectronics, Technical University of Varna,Varna, Bulgaria
Email: vencivalchev@hotmail.com

Received: 05 September 2017
Accepted: 20 October 2017
Published: 27 November 2017

carried out simulations. To make the comparison easier, specific application requirements are set, connected with ultra-light electric vehicles (EV): lightness, efficiency and robustness of the device.

2. Investigated battery charger circuit

The load is considered to be 30 LiFePO4 batteries connected in series to form the desired 96 V output voltage battery pack for the EV. Every single one ismonitored by a separate balancer circuit in order to maximize the performance of the battery pack. However, this paper examines the behavior only of the power supply circuit for the batteries without the balancers or their microcontroller control. The investigated battery charger circuit, given in Figure (1) - blue color, consists of a bridge single phase rectifier D1÷D4; full bridge inverter circuit formed by IGBT Q1÷Q4; pulse transformer Tr1; second bridge rectifier of diodes D5÷D8; boost converter formed by L1, Q5, D9, C4, and a Li-ion battery V_{DC}. An input for photovoltaic panels is provided as an option for a renewable energy source of power supply marked with PV on the schematic. Rectifier diodes D5÷D8 and the boost diode D9 are Schottky diodes as they operate at high switching frequency (70kHz) of the DC-DC converters. The reverse voltage is below 100 V and cheaper Si Schottky diodes could be used instead of SiC Schottky diodes. The full bridge inverter efficiency is improved by using a series resonant circuit formed by the non-polar, high-current ceramic capacitor C2 and the pulse transformer primary winding leakage inductance. An EMC/EMI input filter is needed for the battery charger in order to meet legislation requirements, however, it is not drawn on the circuit as the filter is not an object of the presented study.

The electrolytic DC-link capacitors at different levels of the battery charger are C1, C3 and C4. All components' values of the investigated circuit are given in Table (1). It is designed to charge the 30 LiFePO4 batteries with an average current of 15 A resulting into total power about 1600 W. The input voltage is standard grid 230 V/50 Hz. The pulse frequency transformer Tr lowers the voltage down to 75 V and the boost converter regulates the charging current. Figure (2) describes the proposed removal of all DC-link capacitors. In order to assess the advantages or disadvantages of the investigated circuit, a direct comparison of waveform diagrams is accomplished in the next chapter. Colors of circuits and waveforms correspond to each other.

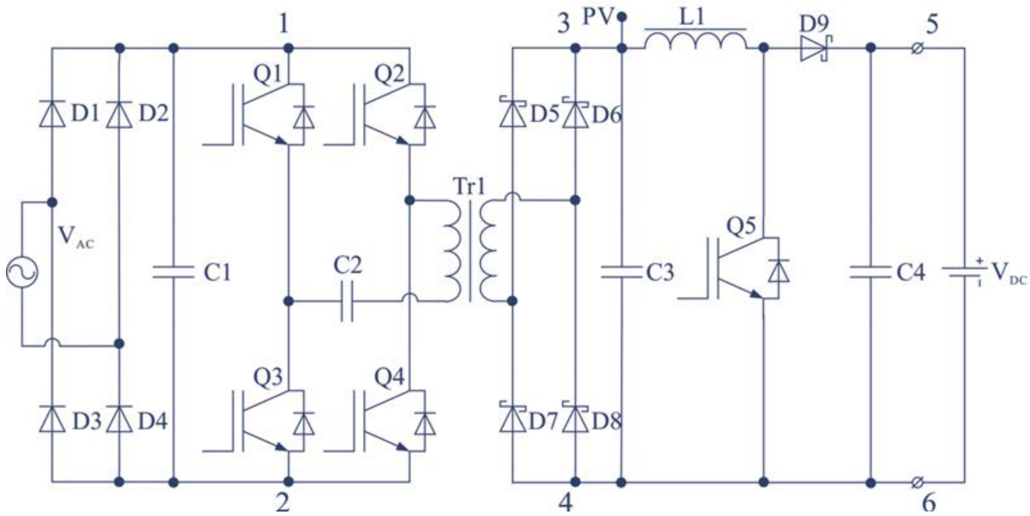

Figure 1. Battery charger circuit with DC-link capacitors

3. Simulation analysis

Both circuits are implemented into simulation environment (MATLAB/Simulink). The battery pack is modelled as a voltage source and series resistor, representing the equivalent series resistance (ESR). It determines the boost converter output voltage so that in most of the time it acts like a current source. The battery ESR results in output voltage ripple and also output current ripple. The Simulation is accomplished within the following limitations: there is no feedback regulator or stabilization network (for simplification of the model of multi converter circuit); the battery cells are at nominal voltage; the transistors' switching is instantaneous; there is no EMC/EMI input filter. The waveform diagrams for the battery charger circuit with DC-link capacitors are given in Figure (3) to Figure (8) in blue color. The rectified grid voltage is given in Figure (3). The voltage peak value is 324 V with voltage ripple about 9 % at full load which is determined by the DC-link capacitor C1.

Table 1. Components values

Description	Value	Unit
Amplitude (V_{AC})	325	V
Frequency (V_{AC})	50	Hz
Forward voltage drop (D1÷D4)	1.1	V
Capacitance (C1)	3·470	µF
Collector-emitter saturation voltage (Q1÷Q5)	1.8	V
Switching frequency (Q1÷Q5)	70	kHz
Capacitance (C2)	100	nF
Voltage ratio (Tr)	4:1	-
Leakage inductance (Lk)	20	µH
Forward voltage drop (D5÷D9)	2	V
Capacitance (C3)	220	µF
Inductance (L1)	30	µH
Capacitance (C4)	100	µF
Battery voltage (V_{DC})	30·3.2	V
Battery equivalent series resistance	30·1.5	mΩ

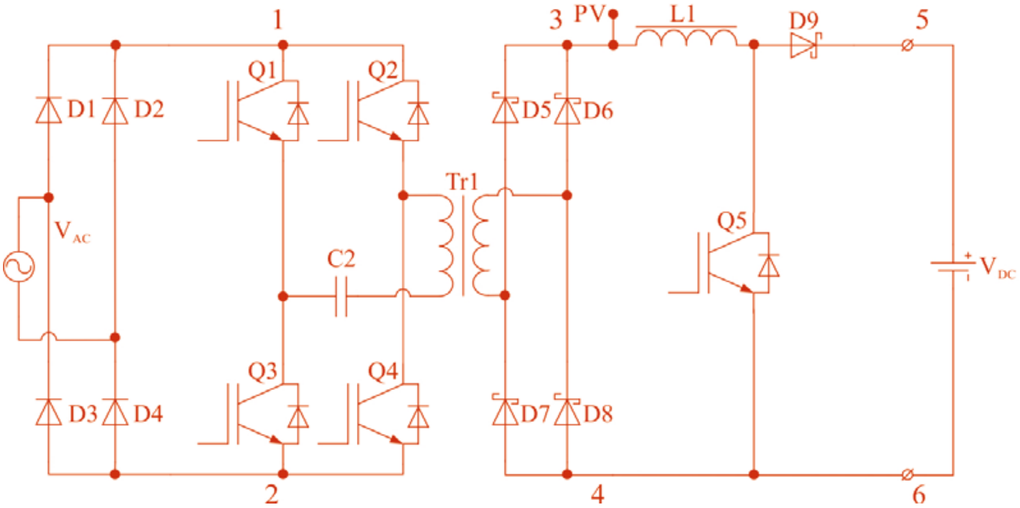

Figure 2. Battery charger circuit without utilizing DC-link capacitors

The current peak value is less than 8 A. The rectified voltage from the secondary winding of the pulse transformer is given in Figure (5). The voltage peak value is 77 V with voltage ripple about 10 % at full load which is determined by the DC-link capacitor C3. The current peak value is about 27 A. The charger output voltage is given in Figure (7). The ripple is about 0.5 % and is determined by the output boost capacitor C4, battery ESR and the charge current. The charge current waveform, given in Figure (8), is averaged according to the switching frequency (70 kHz). However its mean value is about 15.1 A.

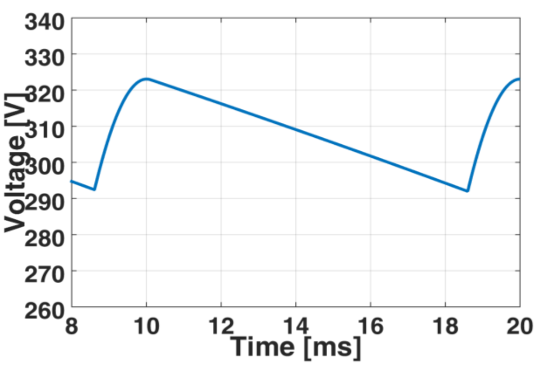

Figure 3. Low frequency bridge rectifier output voltage (between nodes 1 and 2) with all DC-link capacitors

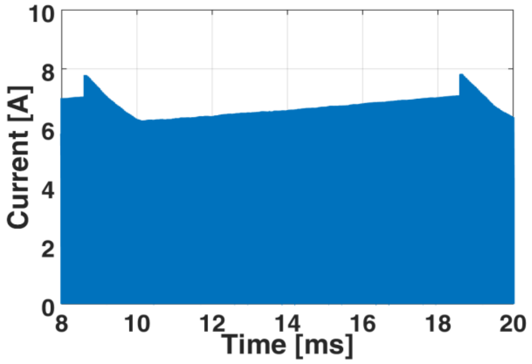

Figure 4. Low frequency bridge rectifier output current with all DC-link capacitors

All power converters that form the battery charger use conventional topologies and operate in typical conditions. The output capacitor C4 of the boost converter can be removed without any significant effect onto circuit performance. This results in bigger output voltage ripple that is increased up to 1.2 % (more than two times but still negligible for battery charging). The output voltage waveform is given in Figure (9). This effect is present because of the huge capacitance of the load. However, special attention should be taken when the battery is disconnected and the boost converter is operating unloaded.

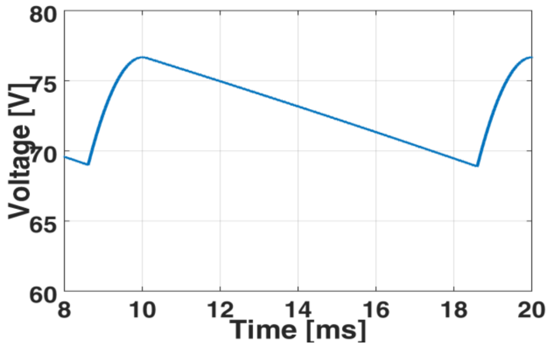

Figure 5. High frequency bridge rectifier output voltage (between nodes 3 and 4) with all DC-link capacitors

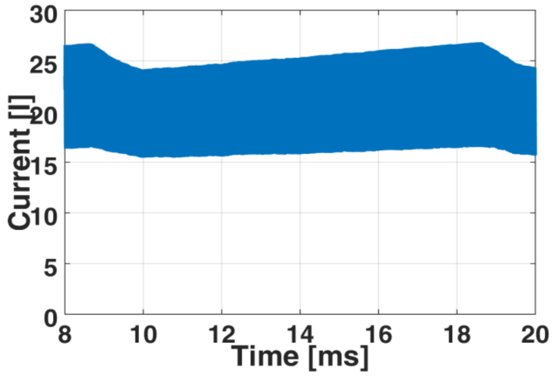

Figure 6. High frequency bridge rectifier output current with all DC-link capacitors

If the DC-link capacitor C3 is removed, the rectified voltage from the secondary winding of the pulse transformer became a rectified sine wave and the boost inductor current is not linear anymore. This effect cannot be compensated by the duty cycle as the switching frequency of the boost converter is two times lower. So, special care should be taken so that the inductor core do not saturate. Duty ratio is also slightly increased in order to compensate the mean output current. There is not any significant effect onto load of power elements.

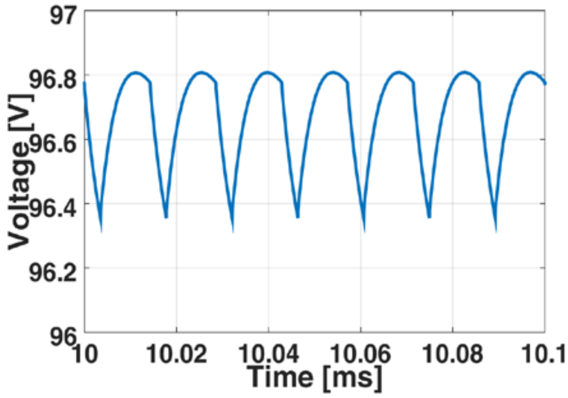

Figure 7. Battery charger output voltage (between nodes 5 and 6) with all DC-link capacitors

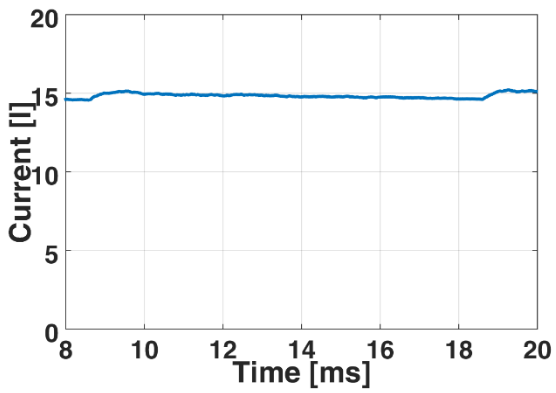

Figure 8. Battery charger average output current with all DC-link capacitors

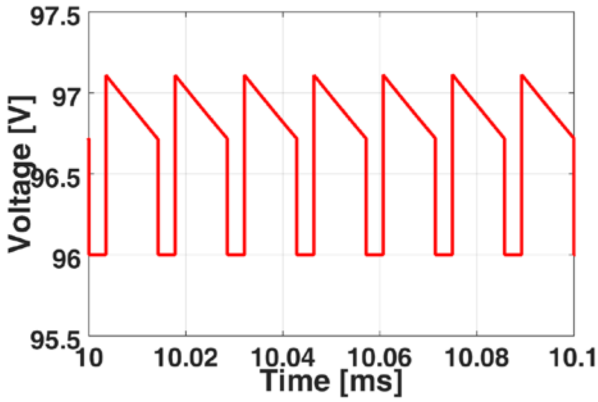

Figure 9. Battery charger output voltage (between nodes 4 and 5) with reduced boost capacitor C4

The waveform diagrams for the battery charger circuit without any DC-link capacitors (C1, C3, C4) are given in Figure (10) to Figure (14) in red color. The rectified grid voltage is given in Figure (10). The voltage peak value is 328 V and the voltage ripple is 100 % no matter the load. The current peak value is 58 A which is 7 times more than if C1 is present. The rectified current from the secondary winding of the pulse transformer is given in Figure (12). Its peak value is 85 V which is 3 times more than if C3 is present.

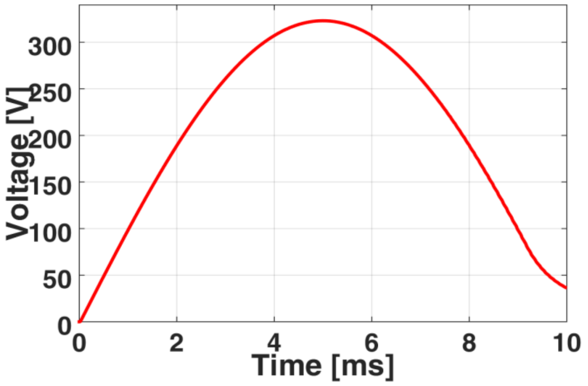

Figure 10. Low frequency bridge rectifier output voltage (between nodes 1 and 2) with reduced DC-link capacitors

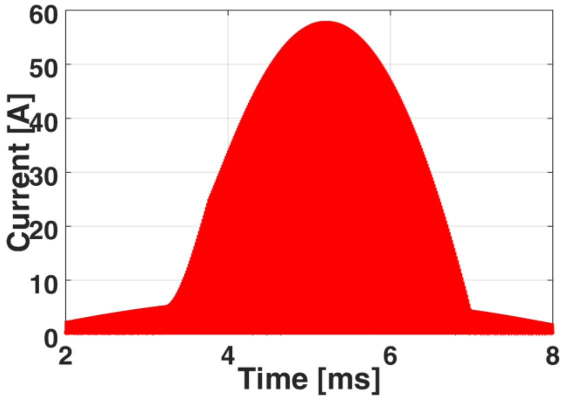

Figure 11. Low frequency bridge rectifier output current with reduced DC-link capacitors

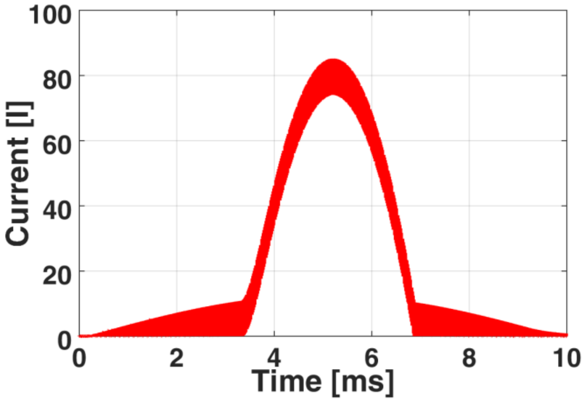

Figure 12. High frequency bridge rectifier output current with reduced DC-link capacitors

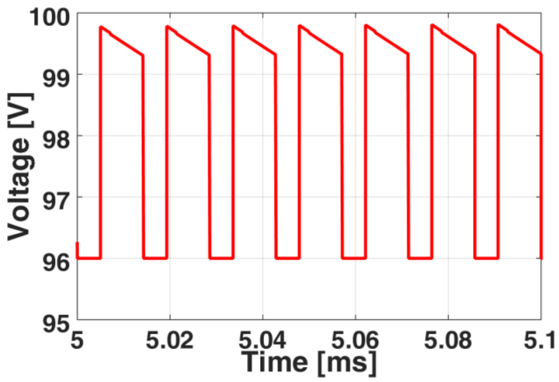

Figure 13. Battery charger output voltage (between nodes 4 and 5) with reduced DC-link capacitors

The charger output voltage is given in Figure (13). The ripple is about 4 %. The charge current waveform, given in Figure (14), is averaged according to the switching frequency of the boost converter. However, its mean value is about 15.07 A but the peak value is more than 50 A and the shape is far from linear because of the duty cycle limitations and incapability of the boost converter to boost voltage at higher ratios. So, bigger concern is about components oversizing and current capability than about the diodes in the low frequency rectifier and the full bridge inverter. The proposed simulation is accomplished within the previously discussed limitations. An interest of future study would be the experimental investigation and verification of the battery charger circuit utilizing reduced DC-link capacitors that will provide more information about operating conditions of power components.

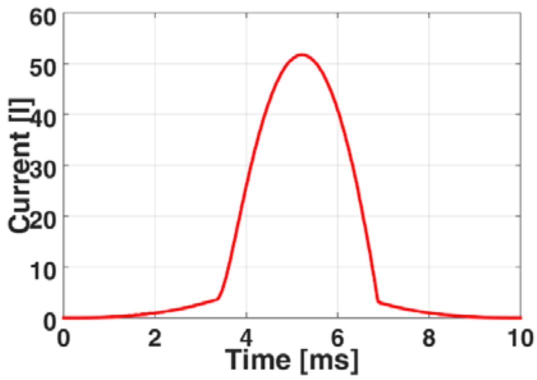

Figure 14. Battery charger average output current with reduced DC-link capacitors

4. Conclusion

Significant reduction of capacitance is possible for some of the DC-link capacitors without need of too expensive oversizing of other power components. The boost converter input and output capacitors could be totally removed and the highly dominating capacitive nature of the load will compensate with certain care of feedback compensator and stability. However, the low frequency input rectifier DC-link capacitor cannot be totally removed but reduced in size with factor of 10 to 100. The input current harmonic values are pretty close to limits, set by regulations, so that a special attention should be given to the EMC/EMI input filter.

Acknowledgements

The paper is developed in the frames of the project "Model Based Design of Power Electronic Devices with Guaranteed parameters", ДН07/06/15.12.2016, Bulgarian National Scientific Fund.

References

[1]. IEC 61000-3-2:2014, Electromagnetic compatibility (EMC) - Part 3-2: Limits - Limits for harmonic current emissions.

[2]. John Cheng, IEEE Standard 519-2014. (2014). https://www.schneider-electric.com.tw/documents/Event/2016_electrical_engineering_seminar/IEEE_STD_519_1992vs2014.pdf (accesed May 2017).

[3]. Doval-Gandoy, J., Castro, C., & Martínez, M. C. (2003). Line input AC-to-DC conversion and filter capacitor design. *IEEE Transactions on Industry Applications*, *39*(4), 1169-1176.

[4]. Ruderman, A. (2012, May). Filter capacitance reduction in DC/DC step-down reconfigurable switched-capacitor converters by a balanced switching. In *Optimization of Electrical and Electronic Equipment (OPTIM), 2012 13th International Conference on* (pp. 776-782). IEEE.

[5]. Makowski, M. S., & Maksimovic, D. (1995, June). Performance limits of switched-capacitor DC-DC converters. In *Power Electronics Specialists Conference, 1995. PESC'95 Record., 26th Annual IEEE* (Vol. 2, pp. 1215-1221). IEEE.

[6]. Ben-Yaakov, S. (2012). On the influence of switch resistances on switched-capacitor converter losses. *IEEE Transactions on Industrial Electronics*, *59*(1), 638-640.

[7]. Bauman, J., & Kazerani, M. (2011). A novel capacitor-switched regenerative snubber for DC/DC boost converters. *IEEE Transactions on Industrial Electronics*, *58*(2), 514-523.

[8]. D. Arnaudov, S. Vuchev.(2016). Multiphase Converters for Charging of Energy Storage Ele-ments, XXV International Scientific Conference Electronics - ET2016, Sozopol 2016, pp. 219-221.

[9]. Kraev, G., Hinov, N., Arnaudov, D., Rangelov, N., & Gilev, B. (2016, May). Serial ZVS DC-DC converter for supercapacitor charging. In *Electrical Apparatus and Technologies (SIELA), 2016 19th International Symposium on* (pp. 1-4). IEEE.