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Experimental Verification of Novel Bi-Directional qZSI Based DC/DC Converter for Short Term Energy Storage Systems

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Abstract. This paper presents a new bi-directional isolated DC/DC converter for supercapacitor (SC) interfacing. During the SC charging mode, the converter operates as a VSI-based step-down DC/DC converter and during the energy recovery mode, as a qZSI-based step-up DC/DC converter. For galvanic isolation and voltage matching a medium frequency transformer was implemented. To achieve higher SC voltage boost the qZSI with the two-stage quasi-Z-source (qZS) network was introduced. The paper discusses the PSIM simulation and experimental results of proposed converter operating with a 14.4 V 142 F supercapacitor.

Key words

DC/DC converter, quasi-Z-source inverter (qZSI) supercapcitor, energy storage.

1. Introduction

Today's supercapacitors (SC) represent an innovative solution for energy storage applications. One of the most challenging applications of a SC is the energy buffering in distributed power generation systems with fuel cells (FC) and/or photovoltaic (PV) cells. Since FC and/or PV powered residential power supply systems cannot respond fast on short, high power demand spikes, a short-term controllable energy storage buffer (supporting system) should be introduced at the main system (supported system) DC bus. The supported system (SS) side DC bus voltage (U_{SS}) should be 600 V for residential applications with 1-phase (230 VAC) or for 3-phase (400 VAC) loads.

In high-power applications with a SC, it necessary to elaborate suitable power electronic interfaces, which enable an efficient and reliable transfer of energy between SC storage and a supported energy system [1]. To control both the charging and discharging processes of the SC, the interface converter should be two-quadrant (bi-directional).

This paper reports the results of work continued by the power electronic group of Tallinn University of Technology in 2009 [2]. A brand new interface converter for SC interfacing was developed and experimentally tested. The topology presented (Fig. 1) consists of a voltage-source half-bridge inverter (VSI) on the supported energy system side, a medium frequency voltage matching transformer and a voltage-fed quasi-Z-source inverter (qZSI) on the SC side. In this study, the half-bridge VSI on the SS side is proposed in order to decrease the transformer's turns ratio.

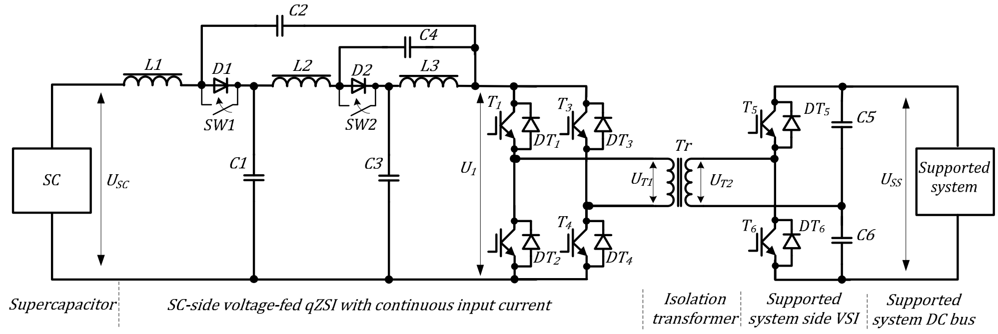


Fig. 1. Simplified power circuit diagram of the proposed converter.

During the charging of the SC, the converter operates in the voltage buck mode and the charging process of the SC is controlled by the SS side VSI. In the energy recovery mode, the supported energy system is being supplied from the SC. To ensure constant DC-link voltage level in the conditions of the discharging of the SC the qZSI with the shoot-through PSM control is used to boost the decreasing voltage of the SC. To provide higher boost of the SC voltage the qZSI with the two-stage quasi-Z-source (qZS) network was introduced [3]-[7].

2. Operation Modes of the Converter

A. SC charging mode

As it was explained above, the proposed converter has two basic operating modes: the charging and the discharging mode. When the DC bus voltage of the supported system (U_{SS}) is near the nominal value, the SC is being charged to its rated voltage and the converter operates in the buck mode transferring power from the SS side DC-bus to the SC. In this mode the converter acts as a traditional step-down isolated DC/DC converter with a half-bridge voltage source inverter (VSI), a step-down isolation transformer and a full-bridge rectifier (Fig. 2). The integrated freewheeling diodes DT1...DT4 of transistor modules T1 and T4 act as rectifier diodes. The diodes D1 and D2 of the qZS-network should be shorted during the charging mode to ensure proper power transfer to the SC and the two-stage qZS-network operates as a low-pass filter.

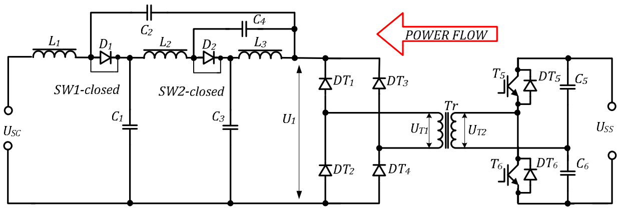


Fig. 2. Power circuit configuration in the SC charging mode.

The charging process of the SC could be simply controlled by the duty cycle variation of transistors T5...T6. Neglecting losses in the components, the voltage U_{SC} during the charging mode (Fig. 2) is

$$U_{SC} = \frac{D \cdot U_{SS}}{n}, \quad (1)$$

where U_{SS} is the main system voltage, D is the duty cycle of the VSI switches (T5...T6) and n is the turns ratio of the isolation transformer:

$$n = \frac{U_{T2}}{U_{T1}}, \quad (2)$$

where U_{T1} and U_{T2} are the amplitude voltages of the primary (SC side) and secondary (SS side) windings of the isolation transformer, respectively.

B. SC discharging mode

In the discharging operation mode, the power flows from the SC to the supported energy system, thus performing the energy recovery function. The configuration of the power circuit in the discharging mode is presented in Fig. 3.

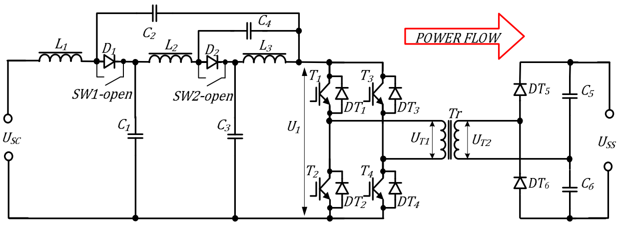


Fig. 3. Power circuit configuration in the discharging mode.

Switches SW1 and SW2 (contactors or semiconductor switches) should be open and power flow from the SC to the DC bus of the main system is controlled by the quasi-impedance-source inverter (qZSI) [8], [9]. In the discharging mode the integrated freewheeling diodes DT5, DT6 of transistor modules T5, T6 and capacitors C5, C6 act as the voltage doubler rectifier (VDR).

During discharging, the operating voltage of the SC is decreasing and to boost the voltage to some predefined voltage level special shoot-through switching states are introduced to the PWM control of the qZSI. The shoot-through switching state is the simultaneous conduction of both switches of the same phase leg of the inverter. This switching state is forbidden for the traditional voltage source converters (VSI) because it causes the short circuit of the DC-link capacitors. In the qZSI, the shoot-through states are used to boost the magnetic energy stored in the DC-side inductors L1...L3 without short-circuiting the DC-capacitors C1...C4. This increase in inductive energy in turn provides voltage boost seen on the transformer's primary winding during the traditional operating states (active states) of the inverter.

During the discharging mode, the converter must ensure stabilized voltage on the DC bus of the supported system that could be evaluated as

$$U_{SS} = 2 \cdot n \cdot U_1 \quad (3)$$

As the operating voltage of the SC could drop during the discharge by 50 %, the qZSI must provide the voltage pre-regulation function to ensure the demanded DC-link voltage (U_1) within the whole operating voltage range of the SC. The shoot-through duty cycle could be obtained by

$$U_1 = U_{SC} \cdot \frac{1}{1 - 3D_S}. \quad (4)$$

The maximal shoot-through duty cycle ($D_{S,max}$) should be associated with the minimal SC voltage:

$$D_{S,\max} = \frac{1}{3} \cdot \left(1 - \frac{U_{SC,\min}}{U_1}\right) \quad (5)$$

The minimal shoot-through duty cycle ($D_{S,min}$) is associated with the rated operating voltage of the SC:

$$D_{S,\min} = \frac{1}{3} \cdot \left(1 - \frac{U_{SC}}{U_1}\right) \quad (6)$$

3. Simulation Results

To verify the analysis [2] a simulation model was developed in PSIM simulation software. In the research both operation modes - SC charging and discharging (Figs. 2 and 3) were covered. The parameters of the SC of Maxwell Technologies SC module (PCM14014) with a total capacitance value of 142 F, rated voltage 14.4 V and equivalent series resistance 10 mΩ were taken as an example for the simulations. General operating and component ratings for the proposed converter are summarized in Table I.

TABLE I
General Operation and Component Ratings for Proposed Converter

PARAMETER	VALUE
Capacitance of *C1... C4*	730 µF
Capacitance of *C5 and C4*	220 µF
Capacitance of SC C_{SC}	142 F
Transformer turns ratio, *n*	1:1.75
Transformer operation frequency, f_{TR}	5 kHz
Charging mode	
SS DC bus voltage, U_{SS}	60 V
SC voltage, U_{SC}	14.4 V
Duty cycle of VSI switches, *D*	0.49
Discharging mode	
Rated SC voltage, U_{SC}	14.4 V
Minimal SC voltage, $U_{SC,min}$	7.2 V
Desired DC-link voltage amplitude, U_1	17 V
Duty cycle of qZSI switches in active states, D_A	0.35
Duty cycle of qZSI switches in shoot-through states, D_S	0.05...0.19

A. *Charging Mode*

It was assumed that during the charging mode the SC was charged up to 14.4 V. The supported system side VSI was operated without dead time at the highest possible duty cycle D=0.49. In order to decrease high current overshoot at the very beginning, initial voltage of SC was set at 6 V. Also, wire active resistances and inductances were taken into account. The operation frequency of the isolation transformer during the charging mode is 5 kHz.

Fig. 4 shows the charging process of the SC in the interval of 40 s. It can be seen that the SS system DC bus voltage U_{SS} does not change, but the SC current I_{SC} decreases proportionally to SC voltage U_{SC} growth.

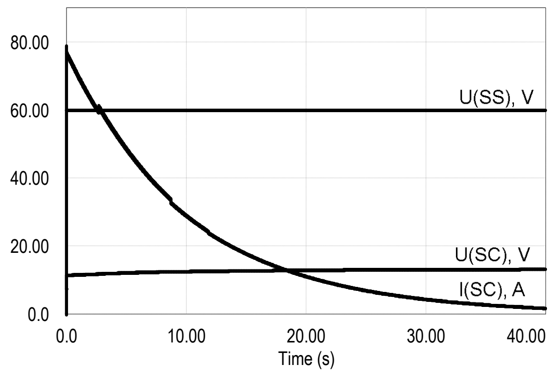


Fig. 4. Operating waveforms of the proposed converter during the SC charging process: SS side DC bus voltage (U_{SS}), SC voltage (U_{SC}) and SC current (I_{SC}).

Fig. 5 shows the waveforms of the SS side DC bus voltage U_{SS}, transformer primary voltage U_{T1}, transformer secondary voltage U_{T2} and SC voltage U_{SC}. Since the half-bridge VSI was used on the SS side, the transformer secondary voltage U_{T2} amplitude (30 V) is half of the SS side DC bus voltage U_{SS} amplitude (60 V).

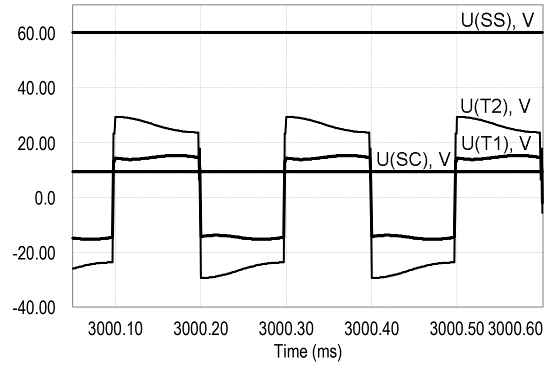


Fig. 5. Simulation results of the proposed converter during the SC charging mode: SS side DC bus voltage (U_{SS}), transformer primary voltage (U_{T1}), transformer secondary voltage (U_{T2}), SC voltage (U_{SC}).

Transformer secondary voltage U_{T2} and current I_{T2} waveforms in more detail are presented in Fig. 6.

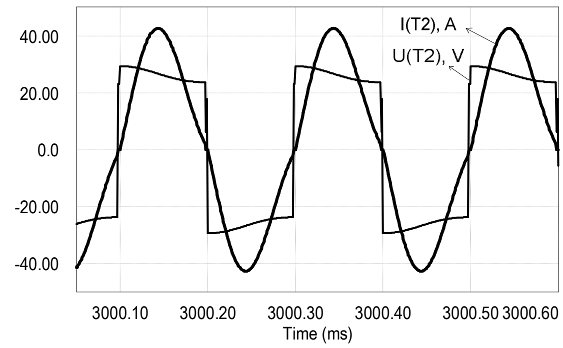


Fig. 6. Simulation results of the proposed converter during the SC charging mode: transformer secondary voltage (U_{T2}) and transformer secondary current (I_{TR}).

Finally, Fig. 7 shows the 500 µs interval of whole charging process of SC. As it was stated before the SC is being charged up to the rated voltage U_{SC} in conditions when the interface converter SS side DC bus voltage U_{SS} is at the predefined value (60 V).

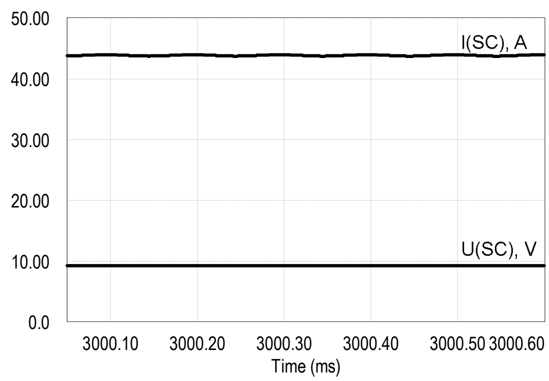
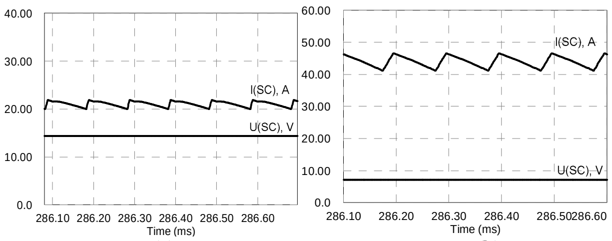


Fig. 7. Simulation results of the proposed converter during the SC charging mode: SC voltage (U_{SC}) and SC current (I_{SC}).

B. Discharging Mode

The circuit configuration shown in Fig. 3 was used in the simulations made at two extremes: when the SC voltage U_{SC} is at its rated value (14.4 V) and at half of the rated value (7.2 V). It means that in order to provide constant DC-link voltage U_{DC} also the minimal shoot-through duty cycle $D_{S,min}$ and maximal shoot-through duty cycle $D_{S,max}$ of the qZSI should be introduced. $U_{SC,max}$ should be associated with $D_{S,min}$=0.05 and $U_{SC,min}$ should be associated with $D_{S,max}$=0.19. The operation frequency of the isolation transformer during the discharging mode is 5 kHz. The load resistance is 12 Ω.

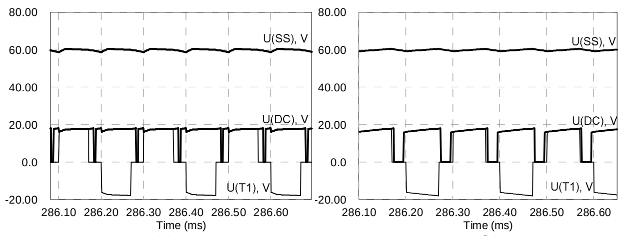
Fig. 8 shows two conditions when the SC voltage U_{SC} is nominal (Fig. 8 a) and when the SC voltage is half of the nominal 0.5U_{SC} (Fig. 8 b). It is obvious that to provide the constant power rating of the converter the SC current I_{SC} increases (Fig. 8 b).



(a) (b)

Fig. 8 Simulation results of the proposed converter during the SC discharging mode: SC voltage (U_{SC}) and current (I_{SC}) at nominal (14.4 V) (a) and half of nominal (7.2 V) (b) voltage.

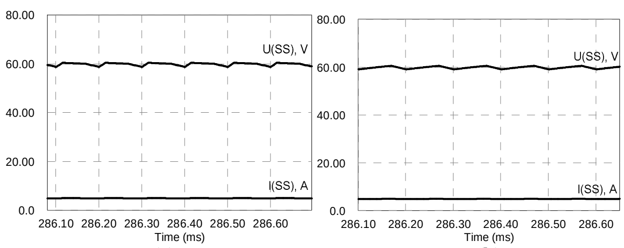
Despite the higher load power, variations of the SC voltage do not deteriorate keeping U_{DC}, U_{T1} and U_{SS} in the predefined level (Fig. 9 a and b).



(a) (b)

Fig. 9. Simulation results of the proposed converter during the SC discharging mode: DC-link voltage (U_{DC}), transformer primary voltage (U_{T1}), SS DC bus voltage (U_{SS}), at SC nominal (14.4 V) (a) and half of nominal (7.2 V) (b) voltage.

Also, U_{SS} and I_{SS} in both SC voltage extremes is the same (Fig. 10 a and b).



(a) (b)

Fig. 10 Simulation results of the proposed converter during the SC discharging mode: SS side voltage (U_{SS}) and current (I_{SS}) at SC nominal (14.4 V) (a) and half of nominal (7.2 V) (b) voltage.

4. Experimental Results

This section presents experimental verification of the proposed converter (Fig. 1) on the 1 kW laboratory prototype developed (Fig. 11). The converter was studied in both operating modes (Figs. 2 and 3).

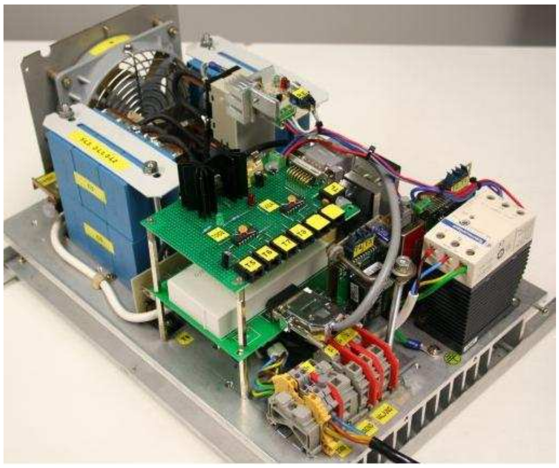


Fig. 11. kW laboratory prototype of the proposed converter.

The SC module PCM14014 manufactured by the Maxwell Technologies with a total capacitance value of 142 F and rated voltage 14.4 V was used for the experiments. General operating parameters and component ratings of the investigated system are listed in Table I.

First, the system was tested in the charging mode. The SC was precharged to 6 V and after that charged up to its rated voltage of 14.4 V within 45 seconds. During the experiments no control of the charging process was performed. VSI was operated without dead time with the constant duty cycle D=0.49. Fig. 11 shows the experimental results of the proposed bi-directional converter in the charging mode. It is seen that the SS side voltage during the charging process is constant (60 V) and the SC voltage grows up to its nominal value (U_{SC}=14.4 V). At the starting stage of the charging process, when the voltage on the SC is low, the inrush current (I_{SC}=80 A) is seen on the SC. During the charging process the SC current was exponentially decreased to 12 A.

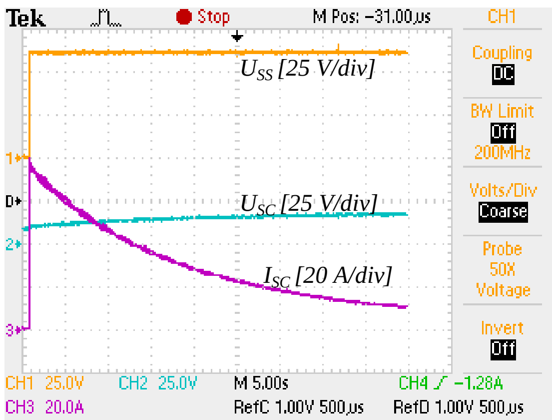


Fig. 12. Operating waveforms of the proposed bi-directional converter during the SC charging mode (SS side DC bus voltage U_{SS}, SC voltage U_{SC} and SC current I_{SC}).

The general operating waveforms of the converter during the SC charging mode are shown in Figs. 13 - 14.

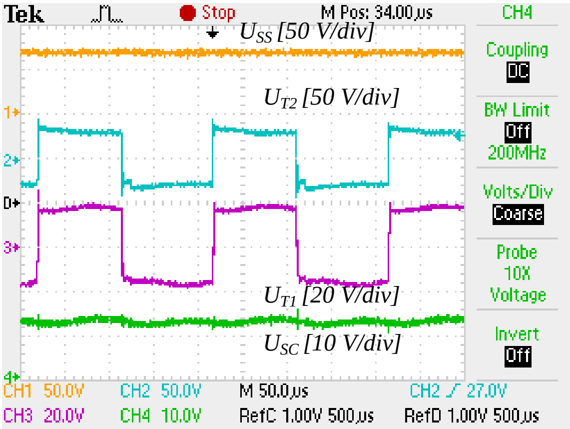


Fig. 13. General operating waveforms of the proposed bi-directional converter during the SC charging mode (SS side DC bus voltage U_{SS}, transformer secondary voltage U_{T2}, transformer winding voltage U_{T1}, SC voltage U_{SC}).

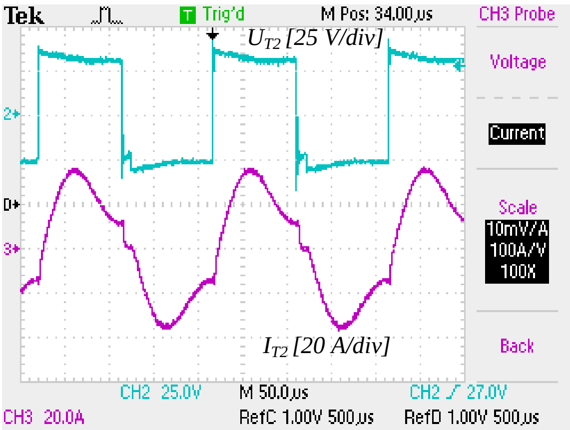


Fig. 14. Transformer secondary voltage (U_{T2}) and current (I_{T2}) waveforms.

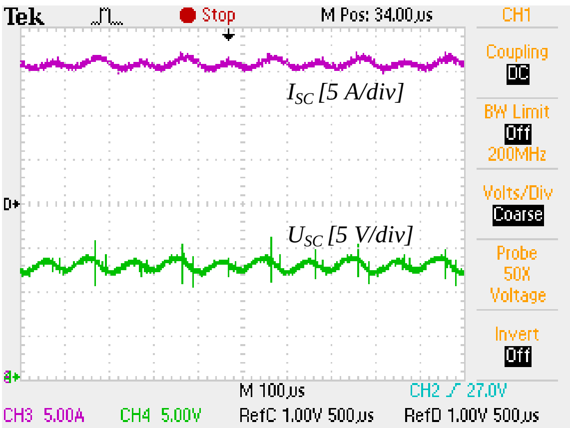


Fig. 15. SC voltage (U_{SC}) and current (I_{SC}) profiles of the proposed converter during the charging mode.

It was observed during the experiments that the proposed converter operates correctly in the SC charging mode, thus ensuring the demanded voltage on the SC terminals. As shown in Fig. 15, the SC voltage and current ripples were 14% and 7%, respectively.

5. Conclusion

This paper introduces a brand new bi-directional DC/DC converter for SC interfacing in energy storage systems. The converter operates as a VSI-based buck DC/DC converter during the SC charging mode and as a qZSI-based boost DC/DC converter during the energy recovery mode. The proposed converter was simulated in both converter operation modes and the results are presented. Experimental verification for proposed converter laboratory prototype operated with a 7.2...14.4 V 142 F supercapacitor was carried out.

It can be concluded that the proposed bi-directional interface converter concept is suitable solution for short-term energy storage applications in distributed power generation systems.

Acknowledgement

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