A NEW NON-ISOLATED ZERO CURRENT SWITCHING BIDIRECTIONAL BUCK-BOOST DC-DC CONVERTER FOR ENERGY STORAGE SYSTEMS

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Key words: Dc-dc, Soft-switching, Zero current switching (ZCS), Bidirectional converter.

This article proposes a new non-isolated ZCS bidirectional buck-boost dc-dc converter for energy storage applications. The conventional bidirectional converter derived with auxiliary edge resonant cell to obtain ZCS turn-on/turn-off condition of the main switches. The proposed converter is operated in boost and buck modes with soft-switching operations in order to have minimized current stresses and reduced switching losses since the resonating current for the zero current switching does not flow through the main switches. The proposed converter improves the overall efficiency over hard-switching converter for high power energy storage applications. This paper mainly describes the operation principles, design analysis, simulation evaluation and its validation by the experimental results which were proved the soft-switching capability of this converter.

1. INTRODUCTION

In recent trends, various kinds of soft-switched converters are proposed for hybrid energy storage systems based on fuel cells, supercapacitors etc., in hybrid electric vehicles (HEV) in order to reduce the switching losses, switching stresses and improve the efficiency. These soft-switching methodologies can increase the switching frequency of the converter with reduced switching losses. There are many zero voltage switching and zero current switching approaches have already been introduced over this decade for energy storage applications in electric vehicles with improved efficiencies at higher switching frequency. But most of the soft-switched converters were proposed for the low-power applications [1]. This paper proposes a soft-switched converter for high power applications; hence the high efficiency and reduced switching losses would be beneficial for future electric vehicle based converters based on energy storage systems (ESS). The hard-switched bidirectional dc-dc converters for electric vehicles have reported in [1]. This valuable paper presents the loss analysis on the topologies of bidirectional buck-boost converters and the converter efficiencies are emphasized on higher switching frequencies of 100 kHz and 200 kHz.

Comparison of cascaded bidirectional converters [2] presented in terms of switching losses and efficiency. The overall system efficiency about 92 % was achieved at higher power levels (10 kW). There are many bidirectional dc-dc converters have already proposed on zero voltage switching techniques obtained by using advanced control techniques, auxiliary resonant circuits, snubbers, etc. Bidirectional cascaded buck-boost converter in [3] presents a new low-loss zero voltage switching (ZVS) modulation technique to obtain ZVS of the main switches. The efficiency of the conventional buck-boost converter has been improved with the proposed control technique. The auxiliary resonant commutated pole (ARCP) based buck/boost converter [4] have been implemented with the ZVS turn-on condition for the main switches with an improved efficiency, but the efficiency may decrease if the switching frequency increases.

Auxiliary resonant circuits based bidirectional dc-dc converter presented in [5] with auxiliary resonant circuit has been used to obtain ZVS for the main switches, and the ZCS for auxiliary switches. Also, the zero voltage switching operation is obtained in [6] by utilizing series resonant elements and [7, 8] with additional coupled inductors, auxiliary switches. Zero voltage switching turn-on conditions were achieved for the main and auxiliary switches of the auxiliary resonant circuit in that presented converter [9].

The proposed converter aims for all energy storage systems in electric vehicles (e.g. dc traction) with 400 V–900 V to 3×125 (super capacitor stack) as output voltage. In this paper simulation and experimental assumptions are made for a system with 200 V/400 V with 30 kHz switching frequency. The main aim of this paper is to develop a new soft-switched bidirectional buck-boost converter for energy storage applications like HEV, super(s) capacitor interfaces, fuel cells, etc. Especially, this converter is developed to achieve higher efficiency at higher output levels with a high switching frequency, and to obtain a zero current switching operation of the main switches without turn-on/turn-off current spikes with an added advantage of reduced switching losses in the auxiliary switches. The conventional converter is improved with the auxiliary circuit which consists resonant inductor, diodes, switches; capacitors are the parts of the auxiliary resonant cell. The following Section 2 presents the description and operation principles of proposed converter, Section 3 presents the design analysis, Section 4 presents the simulation results, and Section 5 presents the experimental investigations of proposed topology in order to verify the theoretical analysis.

2. DESCRIPTION AND OPERATION PRINCIPLES OF PROPOSED ZCS BIDIRECTIONAL BUCK-BOOST DC-DC CONVERTER

2.1. DESCRIPTION OF PROPOSED CONVERTER

The schematic diagram of the proposed new ZCS non-isolated bidirectional buck-boost converter shown in Fig. 1.
This converter comprises of two main switches ($S_1$ and $S_2$), auxiliary switches ($S_a$ and $S_b$), input inductor ($L_{dc}$), resonant inductors ($L_a$, $L_b$, and $L_z$), diodes ($D_a$ and $D_b$), resonant capacitors ($C_a$ and $C_b$), switches ($sw_1$, $sw_2$), and output capacitor ($C_o$). This converter is mainly operated in boost mode with the input voltage ($V_i$) and buck mode with the input voltage ($V_i$). For each mode, there is only one auxiliary cell used to obtain soft-switching operation of the main switches. In boost mode of operation, the switches are open and close, respectively. Similarly, in the buck mode of operation, the auxiliary cell elements ($S_a$, $D_a$, $L_a$, $C_a$) are used to achieve the soft-switching conditions and $sw_2$ is open. In the proposed converter, auxiliary cell can be operated to achieve either ZCS turn-on or ZCS turn-off of the main switches. The key waveforms of this converter are illustrated in Fig. 2, and the stages of operations ($t_0$-$t_5$) are explained in the stage between the auxiliary switches ($S_a$ and $S_b$) turned on and turned off.

![Fig. 1 – Proposed bidirectional buck-boost dc-dc converter.](image1)

2.2. BOOST MODE

**Stage 1 ($t_0$-$t_1$):** at $t_0$, $S_2$ is in turn off and the auxiliary switch $S_a$ turned on with zero current switching (ZCS). Zero current switching operation is obtained by the resonant $L_b, C_b$. When voltage of the resonant capacitor ($C_b$) reaches zero at $t_1$, diode $D_a$ turns on at the end of this stage. The voltage of resonant capacitor $V_{cb}$ and current through the main switch are expressed as:

$$V_{cb}(t) = V_o \cos(\omega (t - t_0)),$$

(1)

$$I_{S_b}(t) = \frac{V_o}{Z} \sin(\omega (t - t_0)),$$

(2)

where $\omega = \frac{1}{\sqrt{L_b C_b}}$ and $Z = \sqrt{\frac{L_b}{C_b}}$.

**Stage 2 ($t_1$-$t_2$):** at $t_1$, the $S_2$ is gated and diode $D_a$ begins to conduct. The resonant capacitor is resonating with $L_a$ and $L$ and the resonant current $i_{lb}$ flows through the auxiliary switch $S_b$ and antiparallel diode of $S_2$. At the end of this stage, auxiliary switch current has reached zero.

$$V_{cb}(t) = -\frac{V}{\sqrt{1 + \frac{L_b}{C_b}}} \sin(\omega_c (t - t_1)),$$

(3)

$$I_{S_1}(t) = I_{S_1} - \frac{L_a}{L} \frac{V_o}{Z} \left[ 1 - \cos(\omega_c (t - t_1)) \right],$$

(4)

$$I_{S_b}(t) = I_{S_b} - \frac{L_b}{L_b} \frac{V_o}{Z} \left[ 1 - \cos(\omega_c (t - t_1)) \right],$$

(5)

where $\omega_c = \frac{1}{\sqrt{L C_b}}$ and $L_e$ is the equivalent inductance defined as $L_e = \frac{L_b}{L}$.

**Stage 3 ($t_2$-$t_3$):** at the beginning of this stage, the auxiliary switch $S_a$ is turned-off. The anti-parallel diode of the auxiliary switch $S_b$ and main switch $S_2$ gives the path for resonant current. Meanwhile, the resonant capacitor ($C_b$) is continuously with the resonant inductors ($L$ and $L_a$). End of this stage main switch ($S_2$) current decreases towards zero.

**Stage 4 ($t_3$-$t_4$):** at $t_3$, the main switch $S_2$ is gated, the switch current linearly increases from negative to maximum. End of this stage the current of the anti-parallel diode of $S_2$ reaches zero and it is turns-off.

**Stage 5 ($t_4$-$t_5$):** at $t_4$ the power transfer through the input inductor ($L_{dc}$) and the main switch $S_2$. At $t_5$, the diode $D_a$ turns off and the capacitor $C_b$ is charged to the voltage to $V_o$ (output voltage).

$$I_{S_2}(t) = I_k(t) = \frac{V_o}{L} (t - t_5).$$

(6)

For simplicity, the buck mode of operation is not explained, where the boost mode stages are similar to the buck mode. In buck mode operation, the switches $S_1$ act as a main switch and $S_a$ as auxiliary switch, diode $D_b$, and
resonating elements $L$, $L_a$, $C_a$ provides the soft-switching condition for main switch and auxiliary switches.

3. DESIGN ANALYSIS

Figure 3 shows the detailed current waveforms of main switch $S_2$ and auxiliary switch $S_b$. To achieve ZCS for these switches, $I_{S_2}$ and $I_{S_b}$ are given by (4) and (5), reduced to zero during the time interval of $t_2-t_3$. The following conditions should be satisfied to obtain ZCS operation

\[ K_1 = \frac{I_m}{I_S} = \frac{2V_oI_b}{ZL_S(L + L_b)} \geq 1, \quad (7) \]

\[ K_2 = \frac{I_a}{V_o/Z} = \frac{2I_b}{(L + L_b)} \geq 1, \quad (8) \]

where $I_m = \frac{2V_o}{Z} \times \frac{L_c}{L}$, $I_a = \frac{2V_o}{Z} \times \frac{L_c}{L_b}$, $I_S$ is the peak value of input current, $I_m$ is the main switch and $I_a$ is auxiliary switch peak currents and $K_1$, $K_2$ are constants values obtained from (7) and (8).

To minimize the circulating current, $K_1$ and $K_2$ should be chosen as small as possible with satisfying (7) and (8).

The proper turn-on time for $S_2$ and $S_b$ is calculated when the $I_{S_2}$ and $I_{S_b}$ reach their negative peak values; the turn-on time for auxiliary switch is given by,

\[ T_S = \frac{1}{2} \pi \sqrt{I_bC_b} + \pi \sqrt{I_bC_b}. \quad (9) \]

The $T_S$ is only determined by the resonant parameters and independent of input and output conditions. The voltage stress of the output rectifier diode is below $2V_o$ since the two resonant inductors decrease the current charging in capacitor ($C_b$) as mentioned in (4) and (5). The maximum voltage of the diode $D_b$ is expressed as

\[ V_{D_b}^{\text{max}} = \left( 1 + \frac{L}{L + L_b} \right) V_o. \quad (10) \]

4. SIMULATION RESULTS

The simulations of the proposed topology were obtained by using MATLAB-PLECS environment in order to verify the theoretical analysis, the simulation parameters for this converter are considered as follows:

Input voltage: 200 V, output voltage: 400 V, switching frequency: 30 kHz, output power: 16 kW, input inductor ($L_{d_0}$): 100 µH, resonant inductor ($L$): 4.7 µH, resonant inductor ($L_a$ and $L_b$): 0.35 µH, resonant capacitors ($C_a$ and $C_b$): 2 µF.

Figure 4 depicts the voltage and current waveforms for boost mode (ZCS turn-on) of the main switch $S_2$, $S_{b}$, resonant inductor ($L_b$), resonant capacitor ($C_b$). Figure 5 shows the voltage and current waveforms for boost mode.
Veera Venkata Subrahmanya Kumar Bhajana, Pavel Drabek

186

5. EXPERIMENTAL RESULTS

The experimental setup for the proposed converter has been implemented and tested on a 20 V/30 W system to verify the soft-switching capability of this converter. The design specifications of this topology are given as follows:

- Input voltage: 6 V
- Output voltage: 20 V
- Input inductor ($L_{dc}$): 100 µH
- Switches ($S_1-2$, $S_{a-b}$): IKW40H1203 diodes
- Output capacitor: 1000 µF
- Resonant inductors ($L_a$, $L_b$): 0.2 µH
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Figure 6 shows the voltage and currents of $S_2$ during turn-on and the turn-off process when the converter operates in ZCS turn-on and ZCS turn-off operations by using the same auxiliary edge resonant cell.

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6. CONCLUSION

This article proposed a new non-isolated ZCS bidirectional buck-boost dc-dc converter. This converter can be applied for both high power and low power energy storage applications. The simulations and experimental investigations were carried out when the ZCS turn-on of the main switches by using the same auxiliary edge resonant cell in the proposed converter. The simulation evaluation of the proposed converter was verified with the tested results on low power laboratory setup. The ZCS turn-on of the main switches has been obtained with low turn-on current stresses. The obtained results are proven the expected theoretical

Fig. 7 – a) turn-on transition of main switch ($S_2$); b) turn-off transition of the main switch ($S_2$).

Fig. 8 – a) Measured waveform of resonant inductor ($L$) current waveforms; b) measured waveform of resonant inductor ($L_b$).

Fig. 9 – a) Collector-emitter voltage and current current waveforms of main switch ($S_2$); b) collector-emitter voltage and current of main switch ($S_2$).

Fig. 10 – Experimental setup of the proposed converter.
analysis and useful for further implementation of laboratory prototype of this converter for high power applications. The obtained results show the proposed converter can be applied for high power energy storage applications with minimized current stresses during turn-on and turn-off conditions and lower switching losses. ZCS turn-off of the main switches can also be obtained by utilizing the same auxiliary edge resonant cell.

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