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Soft switching bidirectional DC-DC converter for energy storage systems

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ABSTRACT

Bidirectional DC-DC converters are one of the most important parts of energy storage systems such as in plug-in hybrid electric vehicle (PHEV), a fuel-cell vehicle, renewable energy system, and uninterruptible power supply (UPS). Energy storage systems are used for storing energy and use it during fluctuations or supply outage. To improve its efficiency a soft-switching bidirectional DC-DC converter using a lossless active snubber is used. In this converter, Zero Voltage Switching (ZVS) of the main switches and Zero Current Switching (ZCS) of the auxiliary switches are always achieved by utilizing an active snubber which consists of auxiliary switches, diodes, an inductor, and a capacitor. In addition, by utilizing this active snubber, there is no reverse recovery problem induced by the poor dynamic performance of the MOSFETs body diode. Moreover, by adjusting according to loads, it is possible to achieve optimized overall efficiency throughout the whole loading range. This system is analyzed by the simulation in MATLAB/SIMULINK 2017. Hardware is implemented using dsPIC30f2010 microcontroller for 20W and 20 kHz and results are verified.

Keywords: *Plug-in hybrid electric vehicle, Uninterruptible power supply, Soft-switching, Snubber, Zero voltage switching, Zero current switching.*

1. INTRODUCTION

Bidirectional dc-dc converters any energy storage system [1][4]. In PHEV system, the bidirectional dc-dc converter acts as an energy transfer system from a low voltage battery to a DC-link that is an input voltage of an inverter for operating a vehicle motor, or from a DC-link to a battery for charging regenerative energy [1], [2]. In the renewable energy systems, including fuel cell systems, photovoltaic systems, and wind power systems, the bidirectional dc-dc converter is essential for electric power conversion between a low voltage battery where dump power is charged and a high voltage source for home appliances [3][4]

The bidirectional dc-dc converter is divided into an isolated type and a non-isolated type [5], [8]. Because an isolated bidirectional dc-dc converter has more than 4 switches and an isolated transformer, it has higher conduction losses and lower efficiency than a non-isolated bidirectional dc-dc converter. On the other hand, the non-isolated bidirectional dc-dc converter has high efficiency due to simple structure [9], [11]. Also, we can use soft switching techniques which makes it possible to have high efficiency by reducing switching losses and it is necessary for miniaturization and light weight [12][14].

Conventional soft-switching bidirectional DC-DC converter that achieves ZVS of switches by simply adding an auxiliary inductor and a capacitor.[16] But here circulating current through the inductor and capacitor is very large and which increase conduction losses in all components. To overcome this problem, a soft-switching bidirectional dc-dc converter using a lossless active snubber is introduced. Compared with the conventional converter, the total amount of the current flowing through the auxiliary circuit decreases significantly since the active snubber operates during short time intervals. Therefore, conduction losses significantly reduce and thus overall efficiency is improved soft switching.

2. BIDIRECTIONAL DC-DC CONVERTER FOR ENERGY STORAGE SYSTEMS

Energy Bidirectional dc-dc converters are one of the most important parts of energy storage systems. Figure .1 shows the block diagram of energy storage system which includes a battery, a bidirectional converter, and an inverter to feed to AC load. During normal condition supply directly feeds the load through an inverter and also charges the battery through the bidirectional converter. When supply outage or fluctuation in supply occurs energy stored in the battery is used to feed the load. That is during charging converter acts as a buck converter and during discharging it acts as a boost converter.

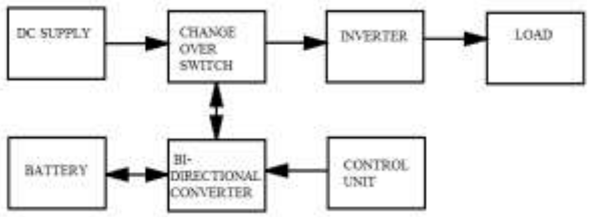

Figure 1: Block Diagram of Soft Switching Bidirectional Converter for Energy Storage System

2.1 Basic Circuit Scheme of the Converter

The circuit diagram of the soft switching bidirectional converter is shown in Fig. 2. The switch S1 acts as a boost switch in boost operation and a synchronous switch in buck operation. The switch S_2 acts as a synchronous switch in boost operation and as a buck switch in buck operation. The lossless active snubber, which consists of an auxiliary inductor L_2, an additional capacitor C_a, blocking diodes D_1 and D_2, and auxiliary switches S_3 and S_4 are added into the conventional bidirectional DC-DC converter. In order to minimize the conduction loss in the active snubber and provide soft switching operation of the main switches and the lossless active snubber operates during short time intervals. The diodes D_{S1}, D_{S2}, D_{S3} and D_{S4}, and are the intrinsic body diodes of S_1, S_2, S_3, and S_4. The diodes D_3 and D_4 and are clamping diodes to clamp the voltages across the auxiliary switches and the blocking diodes in the snubber circuit. The capacitors C_{S1} and C_{S2} represent the parasitic output capacitances of S_1 and S_2. Assuming that the capacitance of Ca is large enough, can be considered as a voltage source V_{Ca} during a switching period.

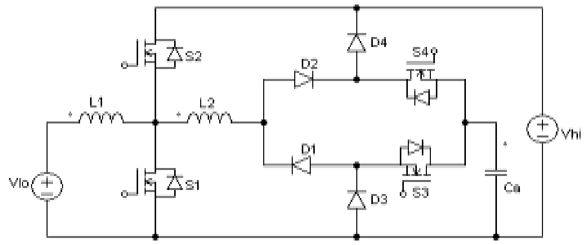

Figure 2: The basic circuit scheme of Soft Switching Bidirectional DC-DC Converter Snubber

2.2 Modes of Operation of the Converter

It has two modes boost mode and buck mode, that is when the input is given at primary side and output is taken from the secondary side it is boost mode and vice versa. The only difference is current direction. Here we explain boost mode, in buck mode current direction reverses. Before t_0, the switches S_2 and S_4 are conducting. The inductor currents i_{L1} and i_{L2} decrease linearly and reach their minimum values Im2 and -Is2 and respectively at t_0.

- Mode 1

The switch is turned off at t_0. The parasitic output capacitor C_{S1} starts to discharge and C_{S2} begins to charge. Assuming that the parasitic output capacitors C_{S1} and C_{S2} have very small capacitance and the time interval in this mode is very short, the inductor currents i_{L1} and i_{L2} can be regarded as constant and the voltages v_{S1} and v_{S2} vary linearly.

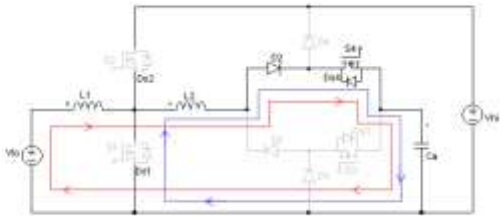

Figure 3: Mode 1 Operation

- Mode 2

At t_1, the voltage v_{S2} arrives v_{hi} at and v_{S1} reaches zero with the turn-on of D_{S1}. Since the switch voltage v_{S1} is zero before the gate pulse of S_1 is applied, the ZVS of is achieved. Since the voltages v_{L1} and v_{L2} across each inductor are v_{lo} and v_{Ca} respectively, the inductor currents i_{L1} and i_{L2} increase linearly.

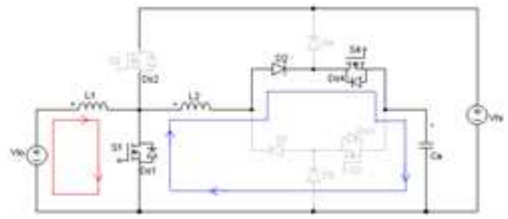

Figure 4: Mode 2 Operation

- Mode 3

This mode begins when the inductor current i_{L2} becomes zero and the blocking diode D_2 is turned off. After that, the auxiliary switch S_4 is turned off in the zero current switching (ZCS) condition. The switch current iS1 is equal to the main inductor current i_{L1}.

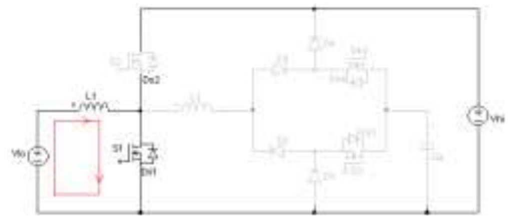

Figure 5: Mode 3 Operation

- Mode 4

At t_3, the auxiliary switch is turned on. Since the voltage across the inductor is, the inductor current increases linearly with a slope of V_{Ca}/L_2. At the end of this mode, the inductor currents i_{L1} and i_{L2} arrive at their maximum values i_{m1} and i_{s1}, respectively. And during which the auxiliary inductor L2 is storing energy, to one switching period.

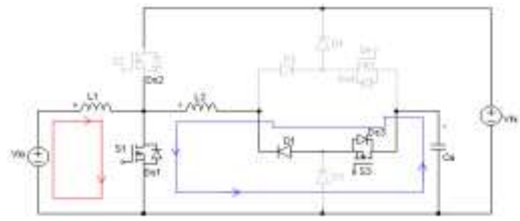

Figure 6: Mode 4 Operation

- Mode 5

The switch S_1 is turned off at t_4. The parasitic output capacitor C_{S1} starts to charge and C_{S2} begins to discharge. Assuming that the parasitic output capacitors C_{S1} and C_{S2} have very small capacitance and the time interval in this mode is very short, the inductor currents i_{L1} and i_{L2} can be regarded as constant and the voltages v_{S1} and v_{S2} vary linearly.

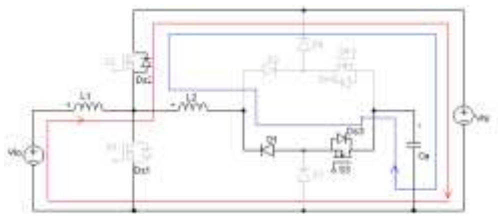

Figure 7: Mode 5 Operation

- Mode 6

At t_5, the voltage v_{S1} arrives at v_{hi} and v_{S2} reaches zero with the turn-on of D_{S2}. Since the switch voltage is zero before the gate pulse of S_2 is applied, the ZVS of S_2 is achieved. Since the voltages, v_{L1} and v_{L2} across each inductor are $-(v_{hi}-v_{lo})$and $(v_{hi}-v_{Ca})$ respectively, the inductor currents and decrease linearly.

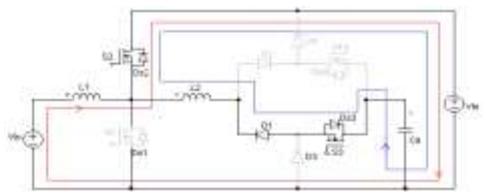

Figure 8: Mode 6 Operation

- Mode 7

This mode begins when i_{L2} becomes zero and the blocking diode D_1 is turned off. After that, the auxiliary switch S_3 is turned off in the ZCS condition.

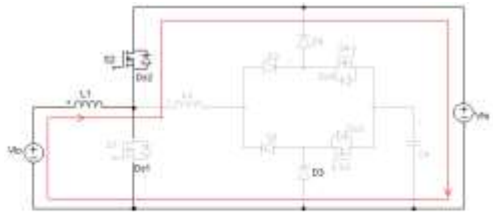

Figure 9: Mode 7 Operation

- Mode 8

At t_7, the auxiliary switch S_4 is turned on. Since the voltage v_{L2} across the inductor L_2 is $-(v_{hi}-v_{Ca})$, the inductor current decreases linearly.

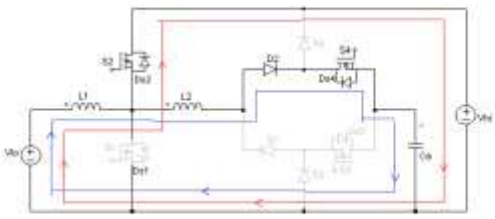

Figure 10: Mode 8 Operation

3. SIMULATION OF BIDIRECTIONAL CONVERTER FOR ENERGY STORAGE SYSTEM WITH RESULTS

Simulation of Soft Switching Bidirectional DC-DC Converter for energy storage systems is done using MATLAB/Simulink 2017.

3.1 Simulation Parameters

Simulation parameters are shown in table 1.

Table 1: Simulation Parameters

COMPONENTS	PARAMETERS
Output Power (P_o)	200 W
Frequency (f_s)	50 kHz
Input Voltage (V_{lo})	48 V
Output Voltage (V_{hi})	160 V
Inductor(L_1 & L_2)	183 µH, 6.7µH
Capacitor (C_a)	2 µF

3.2 Simulation of Bidirectional Converter without Controller

It is realized a soft switching bidirectional DC-DC converter for energy storage system by 200 W and 20kHz in MATLAB/Simulink model.

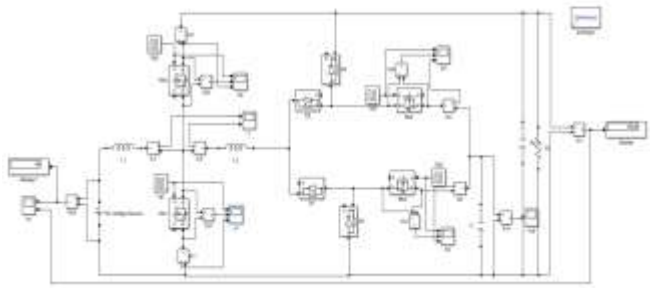

Figure 11: Simulation of Soft Switching Bidirectional DC-DC Converter without Controller

- Simulation Results

Input and corresponding output voltage by simulating soft switching bidirectional DC-DC Converter Using Lossless Active Snubber are shown in figure 12. From which it is clear that by giving 48V as input we get 160V as output and ripple is negligible.

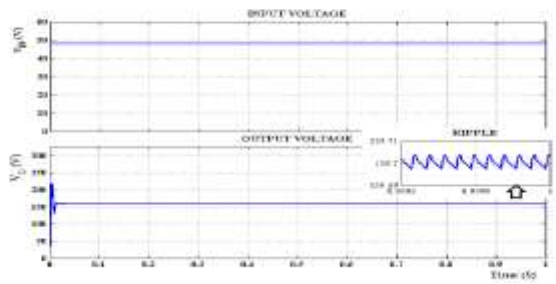

Figure 12: Output (a) voltage and (b) Current of Converter

The control signal, voltage and current waveforms of the main switches are shown in Figure 13.and 14. As shown in figures, the main switches S1 and S2 perfectly turn on with ZVT. Additionally, it is shown that the extra current and voltage stresses do not occur on the main switches.

Figure 13: Waveforms of the switch s1 (a)gate pulse (b) voltage (c) current

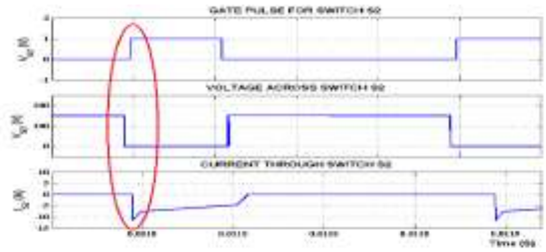

Figure 14: Waveforms of the switch s2 (a) gate pulse (b) voltage (c) current

The current and voltage waveforms of the auxiliary switches are shown with simulation results in Figure 15 and 16. As shown in waveforms, the auxiliary switch turns on with ZCS. The current stress of auxiliary switch is an acceptable level.

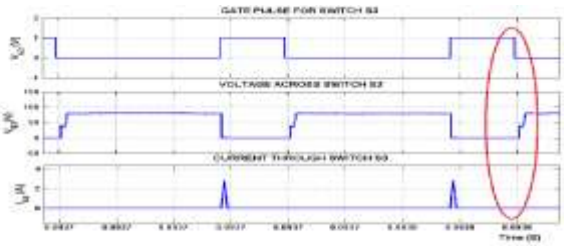

Figure 15: Waveforms of the switch s3 (a) gate pulse (b) voltage (c) current

Figure 16: Waveforms of the switch s4 (a) gate pulse (b) voltage (c) current

The current through inductors and voltage across the capacitor are shown with simulation results in Figure 17 and 18.

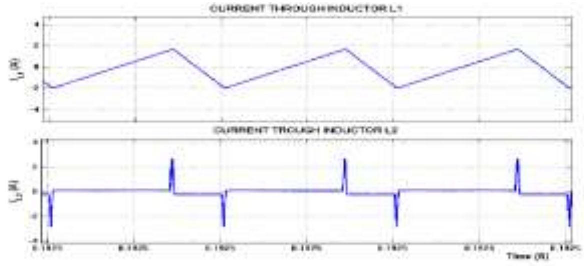

Figure 17: Current through the inductor (a) L1, (b) L2

Figure 18: Voltage across capacitor Ca

Here figure 18 shows the voltage across the capacitor Ca, which is half of the secondary voltage that is nearly 80V.

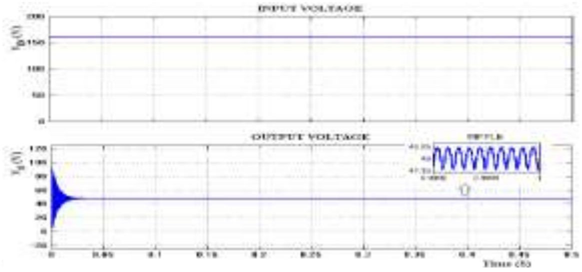

Figure 19: Output (a) voltage and (b) Current of Converter

Input and corresponding output voltage by simulating Soft Switching Bidirectional DC-DC Converter Using Lossless Active Snubber in buck mode are shown in figure 19. From which it is clear that by giving 160V as input we get 48V as output and ripple is negligible. All other wave forms are same as in boost mode.

3.3 Simulation of Bidirectional Converter with PI Controller

Here we are applying close loop control to the converter. Figure 18 shows the simulation model of the bidirectional converter with PI controller.

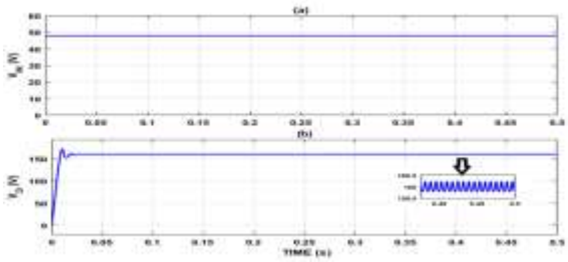

Figure 20: Output (a) voltage and (b) Current of Converter

3.4 Simulation of Bidirectional Converter With FuzzyController

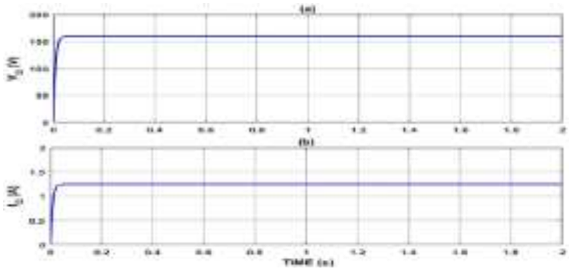

Figure 21: Output (a) voltage and (b) Current of Converter

Figure 21 shows the output voltage and output current at boost mode. Here it is clear that the rise time, settling time and peak time of the output is very much less than that of PI controller and also ripple is negligible

Table.2: Comparison of PI Controller and Fuzzy logic Controller

Controller	Rise Time (T_r)	Peak Time (T_p)	Settling Time(T_s)	Peak Overshoot (%M_p)
PI	0.025	0.03	0.3	5
Fuzzy	0.01	0.02	0.04	0

3.5 Simulation of Bidirectional Converter for Energy Storage System

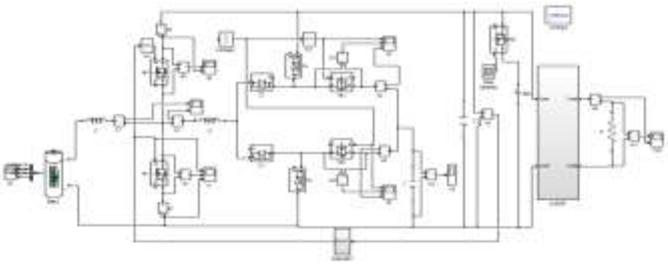

Figure 22: Simulation of Converter for Energy Storage System

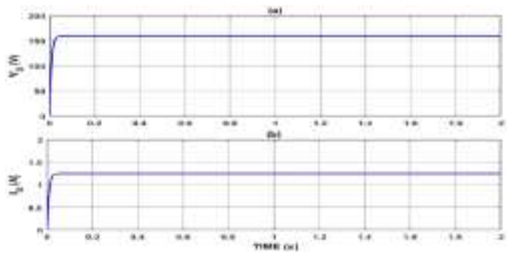

Figure 23: Output (a) Voltage and (b) Current of the converter

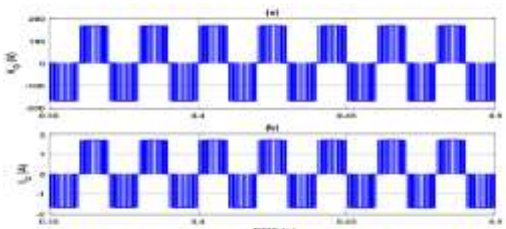

Figure 24: Output (a) Voltage and (b) Current of Inverter

4. EXPERIMENTAL SETUP AND RESULTS

Experimental setup of a driver circuit for the converter is done using TLP 250. DsPIC30F2010 microcontroller is used to obtain the control pulses. Program for generating control pulses is written in the micro.

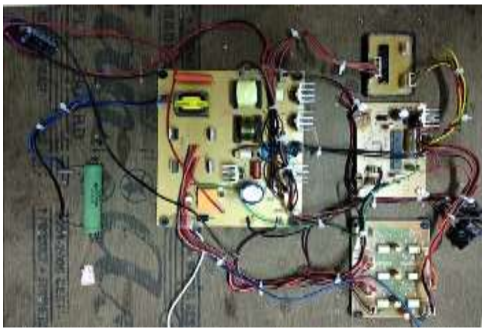

Figure 25: Hardware

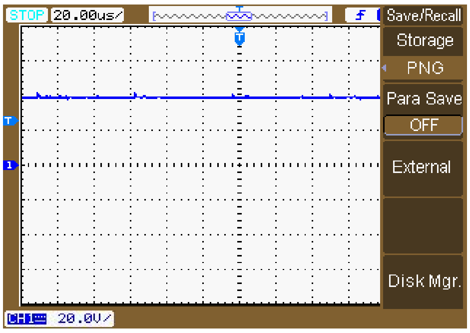

Figure 26: Output from Converter

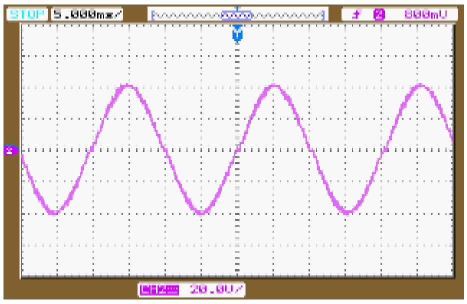

Figure 27: Output of Inverter

5. CONCLUSION

An energy storage system consists of a battery and a bidirectional converter and here it supplies load using an inverter. Here the converter used is a soft switching bidirectional converter. And the converter, ZVS of the main switches and ZCS of the auxiliary switches are always achieved utilizing the active snubber. There is also no reverse recovery problem of the intrinsic body diodes of the switches. Since the active snubber operates in a short time, the increased conduction loss of the proposed converter is relatively lower than the conventional soft-switching bidirectional converter. Thus, the overall efficiency improvement is achieved over a wide range of load. Moreover, by adjusting the dead time ΔT according to loads, it is possible to achieve optimized overall efficiency throughout the whole loading range. So by using this converter the efficiency of the energy storage system is increased

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