A Novel ZCS/ZVS Bidirectional DC-DC Converter for Energy Storage Applications

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Abstract – **In this paper, a new soft-switched non-isolated bidirectional converter is proposed. This proposed converter is operated with soft-switching (zero current switching / zero voltage switching). It is implemented during the turn-on of main switching devices, with the addition of auxiliary resonant circuit that consists of an auxiliary switch, diode, capacitor and an inductor. The switching losses are significantly reduced due to soft-switching operation of the main switches. Therefore, the efficiency of this topology is improved. The additional benefit of this topology is that the auxiliary switches are also operated with soft-switching. The proposed topology observes ZCS turn-on for boost mode and ZVS turn-on for buck mode operations. The principles of operation, design analysis and simulation verifications are discussed in detail. The soft-switching capabilities are obtained from design simulations on the 150V/250V/500W converter system.**

Keywords-Bidirectional DC-DC Converter; Auxiliary Resonant circuit; Soft-switching; Zero Voltage Switching; Zero Current Switching.

I. INTRODUCTION

In the past few decades non-isolated bidirectional converters are widely developed for the industrial applications such as hybrid electric vehicles, auxiliary power supplies, uninterruptable power supplies, renewable energy conversion systems and energy storages systems. In the battery energy storage system applications, bidirectional converters [2] are used to interface ultra-capacitors as sources. In these, the switches are operated with zero voltage transition (ZVT) by utilizing two auxiliary switches and an inductor. Such converters suffer from a reverse recovery problem. To avoid such problem, an inductor is coupled negatively in the buck-boost converter [1]. Nevertheless, this converter has improved efficiency and main switching devices have an increased voltage stress due to coupled inductors. In order to reduce current ripples by the input inductor in a bidirectional converter [3], an auxiliary winding to the input inductor and an additional inductor are included. Ripple free current and soft-switching techniques give better efficiency by reducing switching losses in a bidirectional converter [4] which has a simple structure and consists of a small inductor and two capacitors. The efficiency and volumes are the key parameters in designing converters. To improve the efficiency and reduce the converter volume, a single core coupled inductors and auxiliary switches are included in a bidirectional converter [5]. This converter achieves high efficiency at low output power level when the main switches are operated with zero voltage transition (ZVT). The effectiveness of non-isolated converters [6-7] was improved by auxiliary resonant networks. The auxiliary resonant networks consists of two switches, two diodes, a capacitor and an inductor. In these converters, the soft-switching is achieved for both main and auxiliary switches and performance is improved over the conventional non-isolated converters. However, the number of auxiliary component count is increased and thus volume.

In order to achieve zero voltage switching (ZVS) and improved efficiency, two different bidirectional converters with an additional transformer were reported [8-9], in which the main and auxiliary switches are turned-on with ZVS. As a result, switching losses are reduced and it may increase volume. On the other hand, the high step-up/step-down [10] and interleaved boost converters [11] are realized by integrating a built-in transformer and resonant pulse transformers. These converters can have a high gain, reduced voltage stresses and zero voltage zero current switching (ZVZCS).

The main purpose of this paper is to design a simple soft-switched non-isolated converter for power supply applications. The conventional bidirectional converter is modified with a single auxiliary switch, a resonant inductor and a resonant capacitor. In this converter, regardless of power transfer, the switches are turned-on with ZCS and ZVS in both the boost and buck modes respectively. This topology improves efficiency and reduces the auxiliary component count compared to the existing versions [6-7]. As a result, size and overall cost of the converter are reduced.

This paper is organized is as follows, section II describes the operation principles and design analysis is discussed in section III. The design simulation results are presented in section IV.

II. DESCRIPTION AND OPERATION PRINCIPLES

Fig.1 shows the proposed ZVS bidirectional converter. This converter is comprises of two MOSFETs S_1 (buck mode switch) and S_2 (boost mode switch). The auxiliary resonant cell consists of auxiliary MOSFET S_a, bypass diode D_a, one resonant inductor L_a, and a resonant capacitor C_a. This converter when it is operated in boost mode, the S_1 is turned-on to transfer power flow. While converter operated in boost mode, the switch S_2 is in off state. Similarly, whereas converter is working in buck mode, the switch S_1 is turned-on to transfer the desired output power. Duration of buck mode, the switch S_2 is turned-off. In both the modes, the auxiliary resonant cell will be in active a very short duration prior to turn-on of the main switch (S_1 or S_2).

The bypass diode D_a conducts from t_0-t_4 intervals and remaining intervals it is in non-conducting state. The operation of boost mode is divided into six intervals with in a switching period is as illustrated in Fig. 4 and equivalent operating modes shown in Fig.5
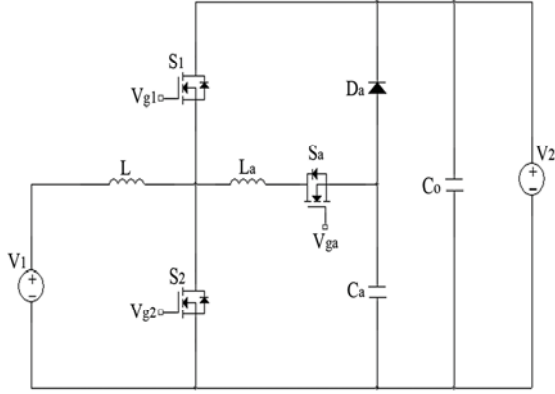

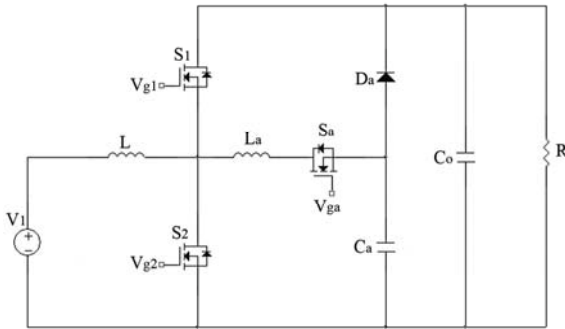Figure 1. Proposed ZCS/ZVS Bidirectional DC-DC Converter
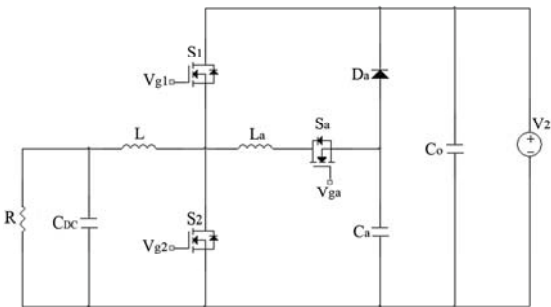

Figure 2. Equivalent circuit : Boost mode

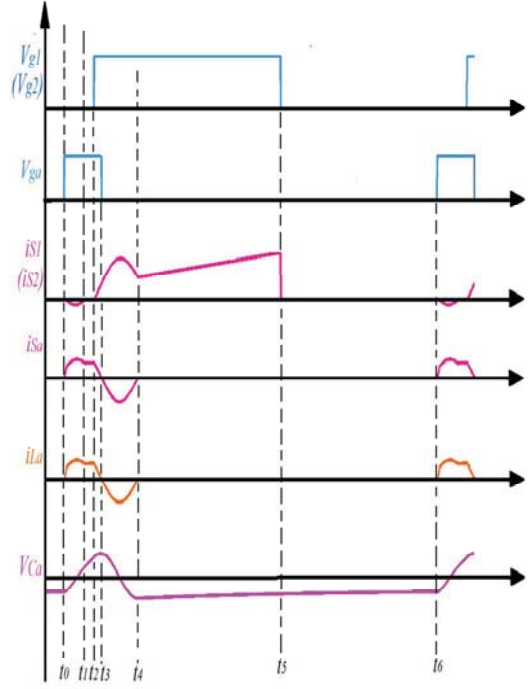Figure 3. Equivalent circuit : Buck mode

A. Boost mode

Figure 4. Keywaveform : Boost mode

Interval (t_0-t_1): At t_0, the auxiliary switch S_a is turned on , then inductor current i_{La} linearly decreasing and capacitor C_a is started discharging. Due to this resonant affect, the diode of S_2 gets forward biased and allows the tank current in to it. During half cycle of this interval, the C_a is discharged and then started to charge. At time t_1, the diode of S_2 is stops conducting. The V_{Ca} and I_{La} are expressed as follows:

$$\sqrt{\frac{L_a}{C_a}} i_{La}(t) = -V_{in}(\sin \omega t) + \sqrt{\frac{L_a}{C_a}} I_o \quad (1)$$

$$V_{Ca}(t) = V_{in}(1 + \cos \omega t) \quad (2)$$

Where $\omega = \dfrac{1}{\sqrt{L_a C_a}}$

Interval (t_1-t_2): This interval starts when current through the switch S_2 is reached zero. Thereby, the ZCS turn-on commutation achieved for S_2. The inductor current i_{La} is at constant, which equals to input current. At the end of this interval, the capacitor C_a is completely charged to $-V_1$ and S_2 is turned-on.

Interval (t_2-t_3): This intervals begins at the S_2 is turned-on and its current increasing gradually from zero. The current through L_a and voltage across C_a are linearly increase by a slope of V_1/L_a. At time t_3, the current through the S_a is reached zero. Therefore, the S_a is achieved ZCS turn-off commutation. The expression for L_a is as follows:
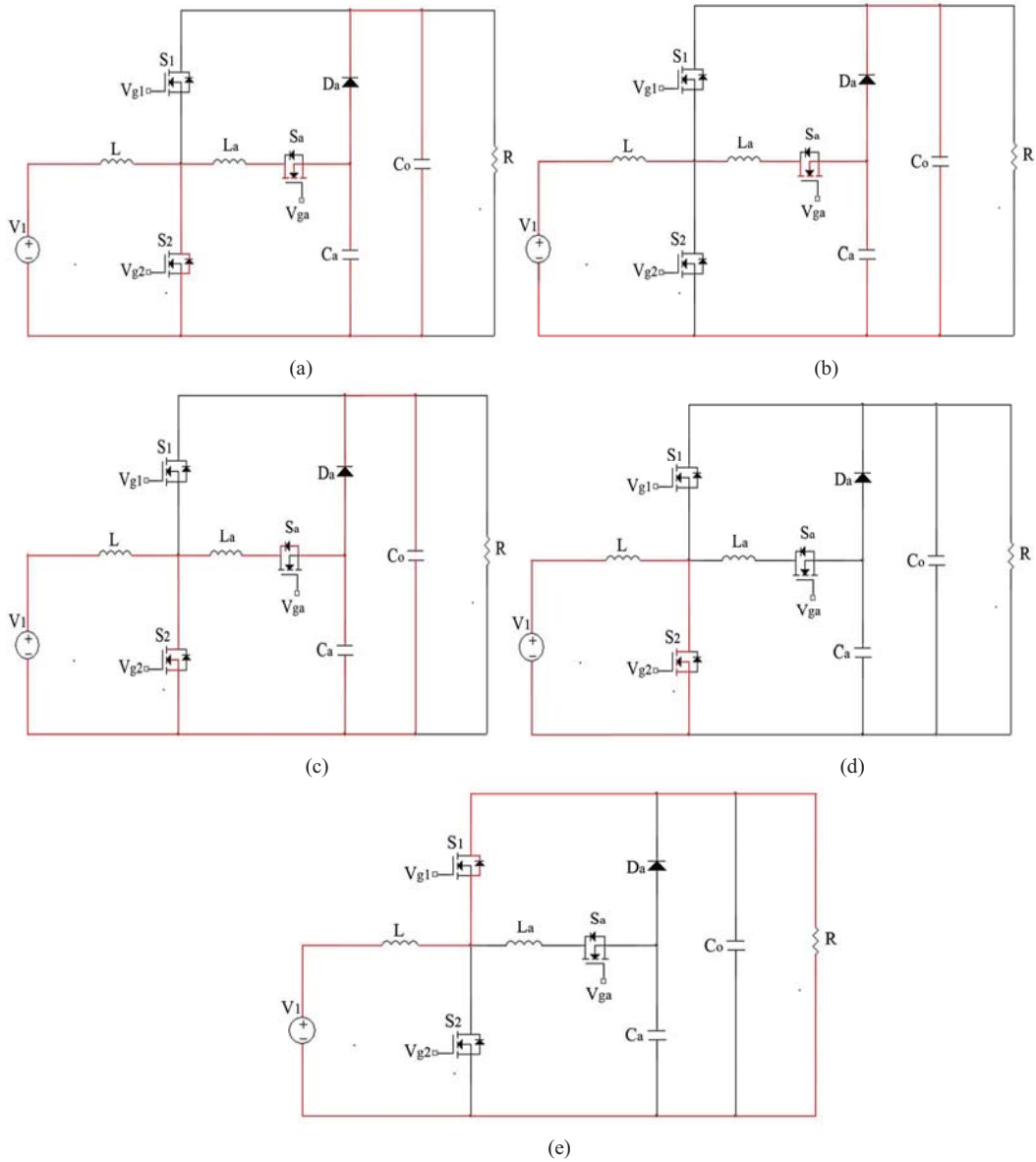
$$i_{La}(t) = \frac{V_{in}}{L_a} \quad (3)$$

Figure 5. Operating modes : Boost mode (a) Interval(t_0-t_1) (b) Interval (t_1-t_2) (c) Interval (t_2-t_3) & Interval (t_3-t_4)
(d) Interval (t_4-t_5) (e) Interval (t_5-t_6)

Interval (t_3-t_4): At time t_3, the diode of S_a is starts conducting and it will allow resonant tank current. At t_4, the diode of S_a is stops conducting. The L_a current and voltage across V_{Ca} capacitor are linearly decreases as follows:

$$\sqrt{\frac{L_a}{C_a}} i_{La}(t) = V_{in} \sin \omega t + \sqrt{\frac{L_a}{C_a}} I_o \qquad (4)$$

$$V_{Ca}(t) = V_{in}(1 - \cos \omega t) \qquad (5)$$

Interval (t_4-t_5): At t_4, S_2 is being in conducting state and throughout this interval the inductor L_{dc} energy gets accumulated via V_1-L-S_2.

Interval (t_5-t_6): At time t_6, the switch S_2 is turned off and the output current transferred by energy accumulated by L via V_1-L-diode of S_1-R.

B. Buck mode

The operation of buck mode is described five intervals from t_0-t_5 as shown in Fig.6 and Its operation current flow schematics shown in Fig.7.

Interval (t_0-t_1): At t_0, the auxiliary switch S_1 is turned on at ZCS condition. Prior to this interval, the resonant capacitor C_a is charged to -V_{dc} (V_2) and resonant inductor current is at zero. The current through L_a and voltage across C_a are expressed as below:

$$i_{La}(t) = \frac{V_{Ca}}{L_a}(t - t_1) \qquad (6)$$

$$V_{Ca}(t) = V_{in}(1 + \cos \omega t) \qquad (7)$$

Interval (t_1-t_2): This is a very short time interval, at t_1, the auxiliary switch S_a is turned off and its current reached zero. Due to resonance, the resonant tank current will flows through the body diodes of the main switch S_1 and S_a. Since the voltage of switch S_1 is

zero before the gate pulse of S_1 is applied, the ZVS operation is achieved.

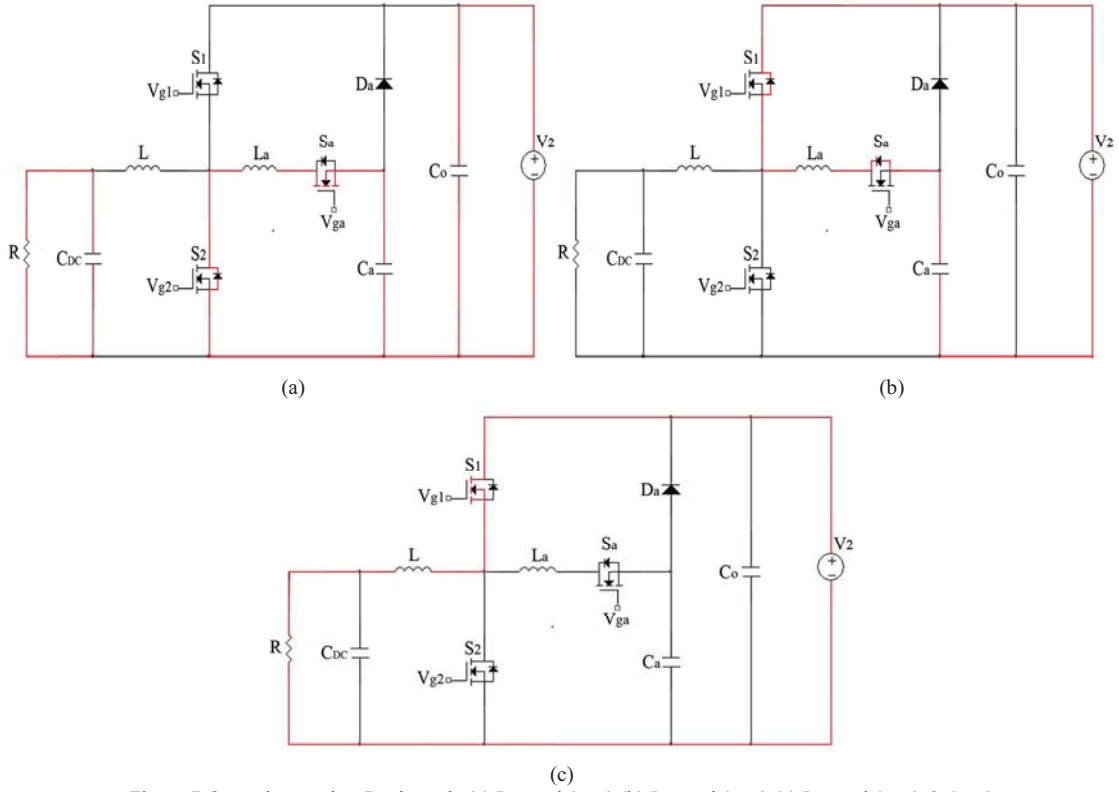$$i_{La}(t) = I_o - \frac{V_o - V_{Ca}}{L_a}(t - t_2) \qquad (8)$$

Interval (t_3-t_4): Throughout this interval, the output power transfer via V_2-S_1-L-R.

Interval (t_4-t_5): During this mode, there is no output power will be delivered.

(a)

(b)

(c)

Figure.7 Operating modes: Buck mode (a) Interval (t_0-t_1) (b) Interval (t_1-t_2) (c) Interval (t_2-t_3) & (t_3-t_4)

Interval (t_2-t_3): At t_2, the S_1 is turned on. The inductor L_a current reached zero and C_a is completely charged to $+V_{dc}(+V_2)$.
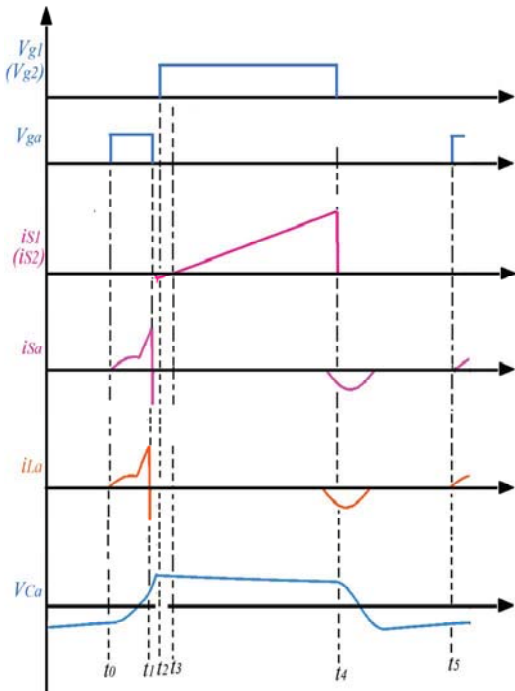
Figure 6. Keywaveform : Buck mode

III. ZERO CURRENT SWITCHING AND ZERO VOLTAGE SWITCHING CONDITIONS

The soft-switching turn on conditions ZCS and ZVS are obtained only when the following condition is satisfied.

$$k < 1 \qquad (9)$$

Where $k = \frac{I_{max}}{V_{i\,min}}\sqrt{\frac{L_a}{C_a}}; I_{max} = \frac{P_{max}}{V_o}$

The parameters L_a and C_a of resonant circuit are given by equations (10) and (11).

$$L_a C_a = \frac{1}{(2\pi f_r)^2} \qquad (10)$$

$$\frac{L_a}{C_a} = \left(\frac{V_{i\,min}k}{I_{max}}\right)^2 \qquad (11)$$

IV. SIMULATION RESULTS

In order to verify the performance of proposed topology, the design simulations were performed on Matlab Simulink. The converter design parameters are mentioned as Table I. The simulations are performed for both the boost and buck modes separately. Fig.8 shows the current and voltage waveforms of S_2, S_a. It can be seen from the simulation results, the soft-switching operation was achieved for main switch S_2

and S_a, as theoretical expectations. As it is observed, the ZCS turn on operation obtained for main switch S_2 and auxiliary switch S_a is turned on at ZCS and turned off at ZCS. Hence, this proposed converter operated in boost mode, the turn-on switching losses are reduced and there are no additional losses by auxiliary circuit. Fig.9 shows the L_a current and C_a voltage waveforms. The peak current through L_a is 2A and C_a is charged and discharged to the level of input voltage i.e 150V. Fig.10 shows voltage and current waveforms of S_1 and S_a for buck mode of operation. The currents through S_1 are 5.7A and S_a is 0.5A. There is a turn off current peak across S_a is observed. It can be seen that, the zero voltage switching turn on achieved for S_1. It is also observed that the S_a is obtained ZCS turn on and ZCS turn off. Fig.11 shows the L_a current and C_a voltage waveforms. The peak current through the L_a is 0.5A. The resonant capacitor C_a is charged and discharged to the level of 10 V. Fig.11 shows the zero current switching turn-on transition to the switches S_2 and S_a for boost mode. Fig.12 depicts the zero voltage switching and zero current switching transitions for the S_1 and S_a for buck mode.

Figure 9. Resonant inductor L_a current and C_a voltage waveforms : Boost mode : (a) i_{La} (b) V_{Ca}

TABLE I.	SIMULATION PARAMETERS	

Parameter	Symbol	Value
Input voltage	V_1	150 V
Ouput voltage	$V_o(V_2)$	250 V
Switching frequency	f_s	50 kHz
Input inductor	L	100µH
Resonant Inductor	L_a	20µH
Resonant Capactitor	C_a	40nF
Output capacitor	C_o	470µF

Figure 10. Voltage and current waveforms of S_1 and S_a: Buck mode (a) V_{S1} (b) i_{S1} (c) V_{Sa} (d) i_{Sa}
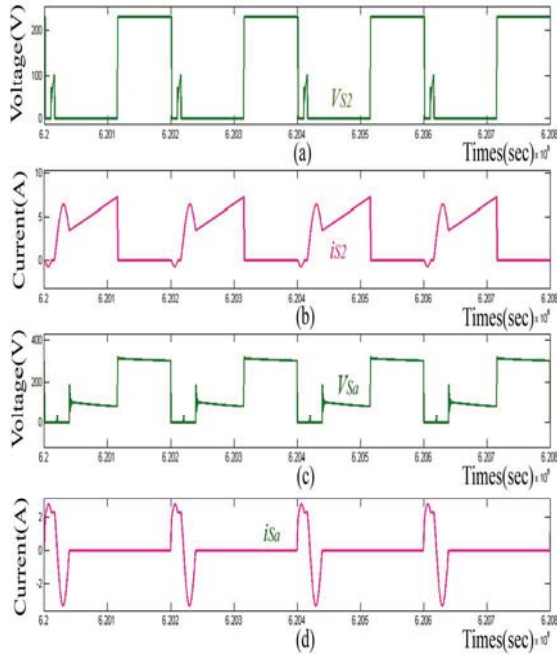

Figure 8. Voltage and Current waveforms of S_2 and S_a : Boost mode (a) V_{S2} (b) i_{S2} (c) V_{Sa} (d) i_{Sa}

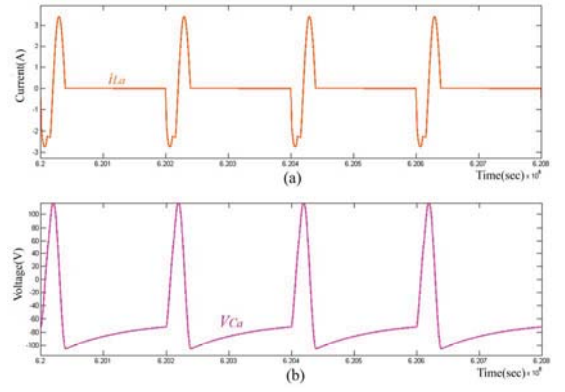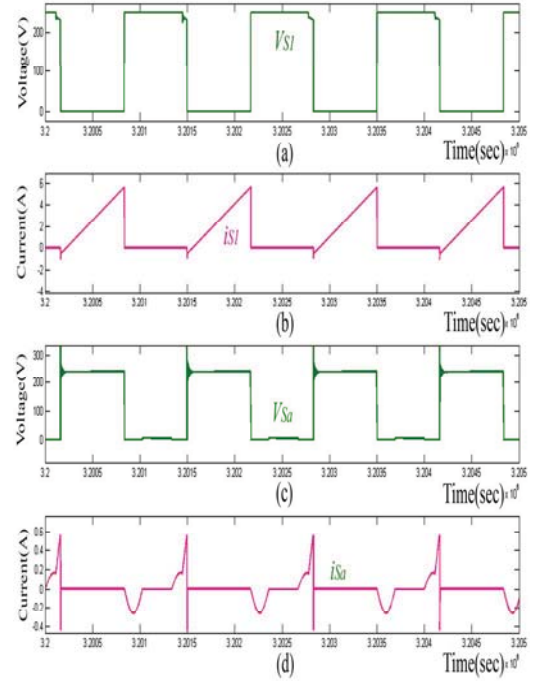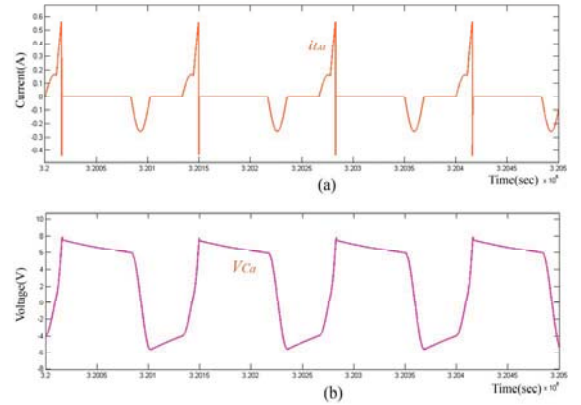Figure 11. Resonant inductor L_a current and C_a voltage waveforms : Buck mode (a) i_{La} (b) V_{Ca}
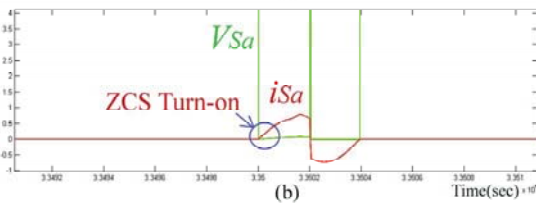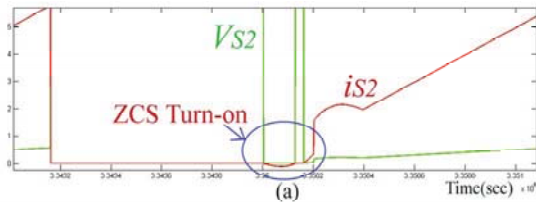
Figure 12. ZCS Turn-on Transition (a) V_{S2} & i_{S2} (b) V_{Sa} & i_{Sa} : Boost mode
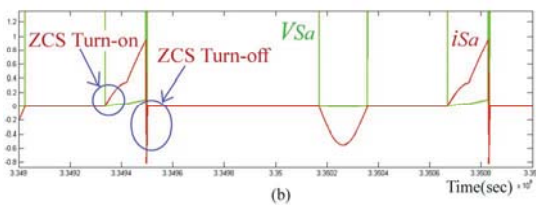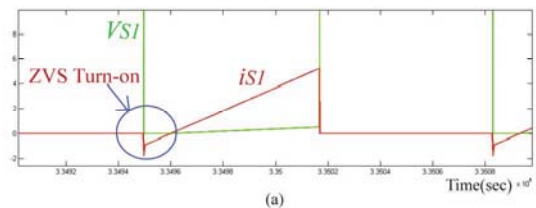

Figure 13 (a) . ZVS Turn-on Transition V_{S2} & i_{S2} (b) ZCS Turn-on and Turn-off transition V_{Sa} & i_{Sa} : Buck mode

V. CONCLUSION

This paper proposes a new soft-switching non-isolated bidirectional converter for energy storage applications. The operating principles and simulations are discussed in detail. The proposed topology operates with 150 V as input and 250 V at 500 W output power. While converter operates in boost mode, the zero current switching turn on operation is achieved on the main switch and on auxiliary switch as well. Similarly, in buck mode, the main switch is turned-on with ZVS and auxiliary switch is turned-on with ZCS. In addition to these ZCS/ZVS operations, the auxiliary circuit, which is used in this topology, is with less number of components as compared with existing versions. It also reduces turn on losses and improves efficiency. This paper provides simulation analysis of the converter, which lays foundation to evaluate it experimentally. It introduces an efficient structure for energy storage applications and in future, the same can be used for wide band gap semiconductor devices such as SiC, GaN.

REFERENCES

[1] H. Wu, J. Lu, W. Shi and Y. Xing, "Nonisolated Bidirectional DC–DC Converters With Negative-Coupled Inductor," *IEEE Transactions on Power Electronics*, vol. 27, no. 5, pp. 2231-2235, May 2012.

[2] H. Farzaneh-fard, D. S. Beyragh and E. Adib, "A Fully Soft Switched Converter for Ultracapacitors Interface Circuit," *2006 IEEE International Conference on Industrial Technology*, Mumbai, 2006, pp. 796-800.

[3] H. Do, "Nonisolated Bidirectional Zero-Voltage-Switching DC–DC Converter," *IEEE Transactions on Power Electronics*, vol. 26, no. 9, pp. 2563-2569, Sept. 2011.

[4] Y. Zhang, X. Cheng, C. Yin and S. Cheng, "Analysis and Research of a Soft-Switching Bidirectional DC–DC Converter Without Auxiliary Switches," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 2, pp. 1196-1204, Feb. 2018.

[5] M. R. Mohammadi and H. Farzanehfard, "New Family of Zero-Voltage-Transition PWM Bidirectional Converters With Coupled Inductors," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 2, pp. 912-919, Feb. 2012.

[6] S. Oh, J. Kim, J. Kim, C. Won and Y. Jung, "The analysis of a novel bidirectional soft switching DC-DC converter," *8th International Conference on Power Electronics - ECCE Asia*, Jeju, 2011, pp. 2154-2159.

[7] J. Yang and H. Do, "Soft-Switching Bidirectional DC-DC Converter Using a Lossless Active Snubber," *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 61, no. 5, pp. 1588-1596, May 2014.

[8] G. Chen *et al.*, "A Family of Zero-Voltage-Switching Magnetic Coupling Nonisolated Bidirectional DC–DC Converters," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 8, pp. 6223-6233, Aug. 2017.

[9] Y. Jang and M. M. Jovanović, "Soft-switched bidirectional buck-boost converters," *IEEE Applied Power Electronics Conference and Exposition (APEC)*, Tampa, FL, 2017, pp. 287-293.

[10] H. Wu, Y. Lu, L. Chen, P. Xu, X. Xiao and Y. Xing, "High step-up/step-down non-isolated BDC with built-in DC-transformer for energy storage systems," *IET Power Electronics*, vol. 9, no. 13, pp. 2571-2579, 2016.

[11] M. R. Ahmed, R. Todd and A. J. Forsyth, "Soft-switching operation of the dual-interleaved boost converter over all duty ratios," *IET Power Electronics*, vol. 10, no. 11, pp. 1250-1258, 2017.