Soft Switching Bidirectional DC-DC Converter With Only One Auxiliary Switch And Reduced Losses

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Abstract- A soft switching bidirectional DC-DC (BDC) converter with only one auxiliary switch and reduced losses is proposed. Every semiconductor devices are soft switched while their control circuit remains PWM. This condition is achieved only by one auxiliary switch. Also, the resonant diode which constitutes the major power loss is replaced by a switch which reduces the losses comparatively and thereby increasing the efficiency. So, the modified converter has less complexity in comparison with other similar structures. The energy conversion through the converter is highly efficient due to the soft switching condition. This can be used as an interface circuit between renewable energy source and any DC link. A comparative study of performance of conventional, soft switched BDC and the modified topology is presented. The topology is simulated using MATLAB/SIMULINK. Efficiency is calculated as about 98% for R load and a more efficient voltage gain, i.e., 0.43 for Buck mode and 2.4 for Boost mode is obtained.
Keywords – BDC, Soft Switching, Auxiliary Switch

I. INTRODUCTION

The energy crisis around the world, the global warming and the pollution are the major reasons that the researchers try to investigate more on renewable energies such as PV, wind, fuel cell, etc. But, the major drawback is that the power produced by most of these renewable energy sources changes with environmental condition and climate changes. Therefore, these are not constant. Moreover, the output power of each source is different and its dynamic response is low.

Likewise, a bidirectional DC-DC converter (BDC) as an interface circuit between the input source and the DC link is needed to produce a constant electricity while using renewable energy systems. High switching frequency is used to reduce the size and weight of the modified BDC. But, the switching losses and electromagnetic interference (EMI) increases at high switching frequency. As a result, during charging and discharging, a huge amount of energy is wasted. To solve this problem, the concept of soft switching was presented. In this condition, the current flow through the power devices or the voltage across them is limited known as zero current switching (ZCS) or zero voltage switching (ZVS), respectively. So, the switching losses of the interface circuit are eliminated and the efficiency of the converter is improved.

In [6] a converter with the ZVS condition over a wide load variations is proposed. It consists of a coupled inductor in its structure which increases the size and volume of the interface circuit. Also, its voltage gain is low. Another soft switching converter with coupled inductor is suggested in [7]. The windings of the coupled inductor act as a bidirectional switch which controls the power flow between the input and output sides. Here, the converter has high voltage gain. However, the converter complexity increases due to use of three power switches and a coupled inductor in its structure. Another BDC consisting of a dual Buck and Boost and a coupled inductor is offered in [8]. In this, due to hard switching condition and large volume of the coupled inductor, the converter efficiency is decreased.

A ZVS Buck and Boost BDC is proposed in [9]. The control circuit of the converter is complex here. Moreover, the overall efficiency is not very high because the auxiliary circuit is applied twice in each switching cycle to create ZVS. Another soft switching Buck and Boost BDC is suggested in [10]. The auxiliary circuit of the proposed converter has lots of components and it has additional voltage and current stresses on the main switches. In addition to this, the resonant inductor is located in the main power transfer path. As a result, the conduction losses of the converter are increased. The converter discussed in this paper possesses a soft switching Buck and Boost BDC. It has a simple auxiliary circuit that operates only once at switching instant during each switching period. The auxiliary circuit only uses one auxiliary switch to create soft switching condition and controls the power transfer in both directions. This converter can be used as an interface circuit between renewable energy source and DC link.

The rest of the paper is organized as follows. Proposed embedding and extraction algorithms are explained in section II. Experimental results are presented in section III. Concluding remarks are given in section IV.

II. CIRCUIT CONFIGURATION AND OPERATING MODES

The soft switched converter with reduced losses consists of two main switches (S1, S2), one auxiliary switch (Sa1), a resonant switch (S3), resonant elements (Cr, Lr1, Lr2) , one filter inductor (Lf) and three diodes (DS1, DS2, DSa1). The major difference between the BDC discussed in [1] and the converter discussed in this section is that, the diode (Dr) which constitutes for the major power loss (about 6.9W) is replaced by a switch (S3), thereby decreasing the overall losses and hence improving the efficiency. Figure 1.shows the circuit diagram of the soft switched BDC with reduced losses.

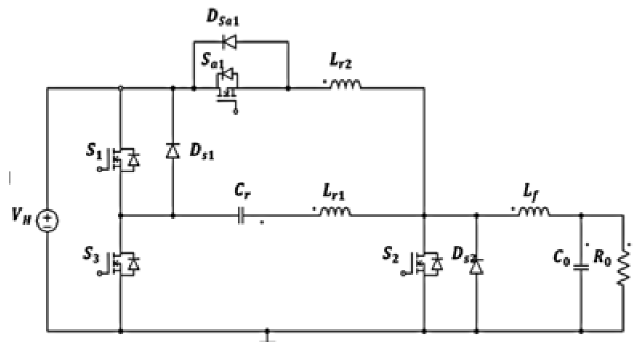


Figure.1. Soft Switched BDC with Reduced Losses

2.1. Buck Mode of Operation

Figure.2. shows the soft switched BDC in Buck mode. Also, the theoretical waveforms of the BDC in Buck mode are depicted in Figure.3. In Buck mode the converter has six time modes during one switching cycle. In Buck mode, S1 is the main switch and Sa1 is the auxiliary switch. It is assumed that all power switches are off before the first interval.

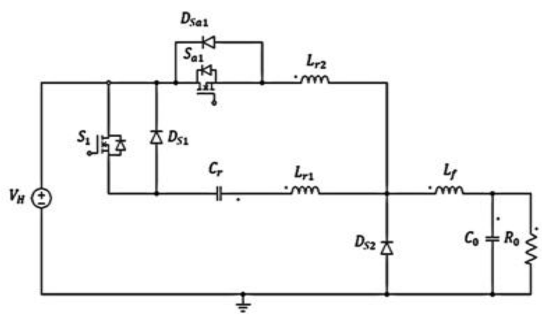


Figure.2.The configuration of the proposed BDC in Buck mode

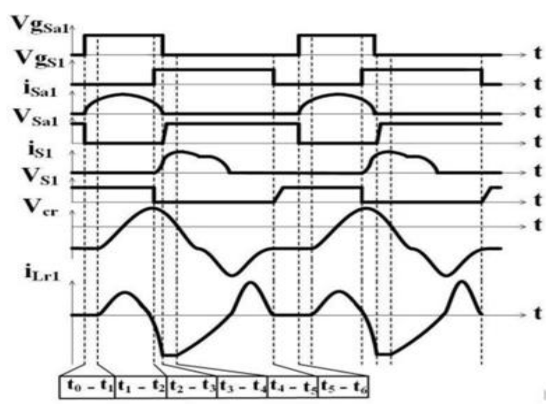


Figure.3. Theoretical Waveforms in Buck mode

Mode 1: (t0-t1) [refer Figure.4 (a)]: Before t0, the D2 was on and the output current I0 flows through it. This mode starts when the Sa1 is turned on. The auxiliary switch is connected in series with the resonant inductor Lr2. Hence, the Sa1 is turned on under ZCS condition. Due to the existence of VH across Lr2, its current increases linearly from zero. This mode ends when the current ILr2 reaches to I0 and the diode D2 turns off.

Mode 2: (t1-t2) [refer Figure. 4 (b)]: At t=t1, the current ILr2 reaches to I0 and the diode DS2 is turned off under ZCS condition. So, a resonance starts between Lr1 and Cr through DS1, Sa1 and Lr2. The capacitor voltage at t1 is negative. Hence, the capacitor starts to charge and the value of the resonant inductor current (ILr1) increases from zero. The value of ILr2 is equal to summation of the resonant current (ILr1) and the output current (I0) during this mode.

This mode ends when the VCr reaches to its maximum value and the current ILr1 will be zero. Therefore, the current ILr2 will be equal to the output current at the end of this mode.

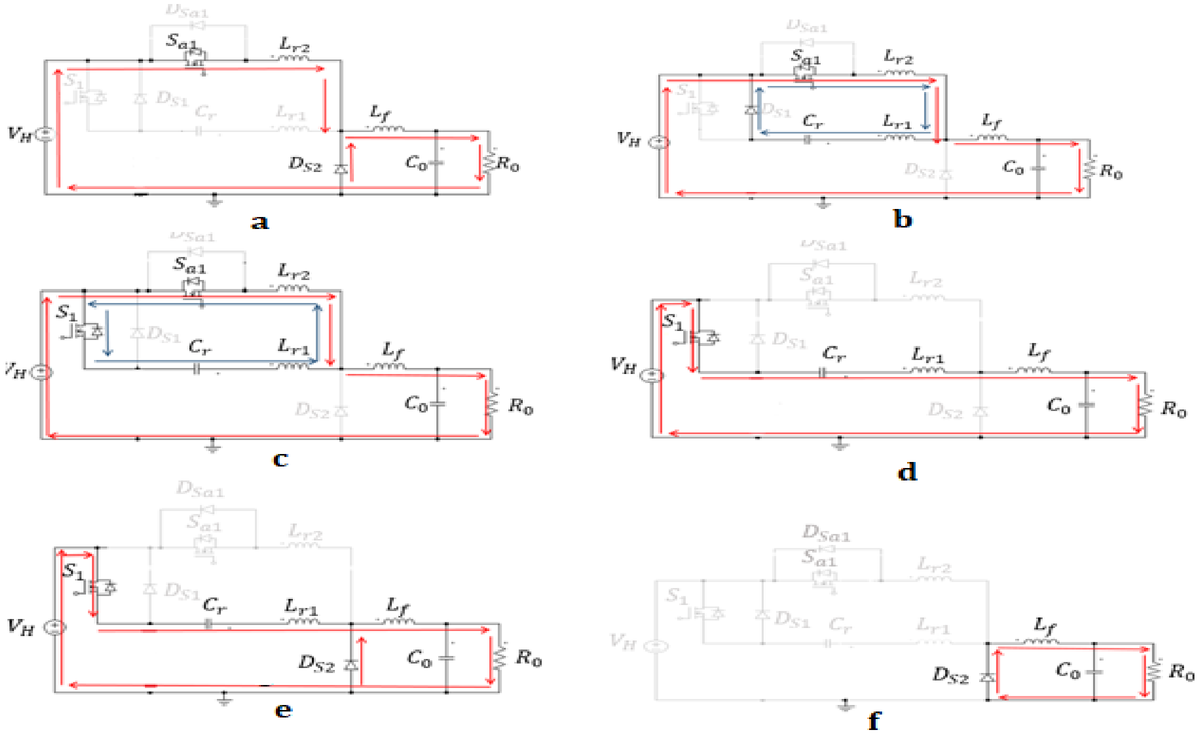


Figure.4. Modes of Operation in Buck mode

Mode 3: (t2-t3) [refer Figure. 4 (c)]: This mode starts when the main switch S1 is turned on at t2. At t2, the diode DS1 is forward biased and the resonant inductor current (ILr1) reaches to zero. So, the main switch S1 is turned on under ZVZCS, while DS1 is turned off under ZCS condition. Hence, the resonance starts between Lr1, Lr2 and Cr through S1 and Sa1. By increasing ILr1, the current ILr2 decreases. This mode ends when ILr2 reaches to zero and ILr1=I0.

Mode 4: (t3-t4) [refer Figure. 4 (d)]: This mode starts when Sa1 is turned off. Since, the current ILr2 is zero, so the switch Sa1 is turned off under ZCS condition. As a result, the resonant capacitor (Cr) is charged by the output current during this mode. Also, the current through Lr1 is equal to the output current. This mode ends when the resonant capacitor voltage, VCr reaches to zero. The operation of the converter in this mode is similar to the conventional Buck converter.

Mode 5: (t4-t5) [refer Figure. 4 (e)]: The resonant capacitor voltage (VCr) reaches to zero at t4. The resonant capacitor starts to charge in the opposite direction during this mode. Also, the value of ILr1 decreases until it becomes less than I0. Moreover, the difference between the currents (I0 - ILr1) causes the diode DS2 to be turned on under ZCS condition. This mode ends when the ILr1 reaches to zero.

Mode 6: (t5-t6) [refer Figure. 4 (f)]: This mode starts when ILr1 reaches to zero. Hence, the main switch S1 is turned off under ZCS condition. By turning off the S1, the inductor current ILr1 remains zero and the capacitor voltage VCr remains negative. The output current flows through the diode DS2 and Lf.

2.2. Boost Mode of Operation

Figure 5. shows the proposed BDC in Boost mode. The converter has seven time intervals during one switching cycle. In Boost mode, only S2 operates as the main switch of the converter and S3 is the resonant switch. It is assumed that all power switches in the presented BDC are off before the first interval. Also, the theoretical waveforms of the BDC in Boost mode are depicted in Figure.6

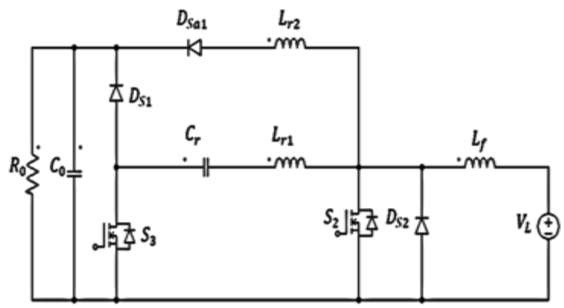


Figure.5. The configuration of the proposed BDC in Boost mode

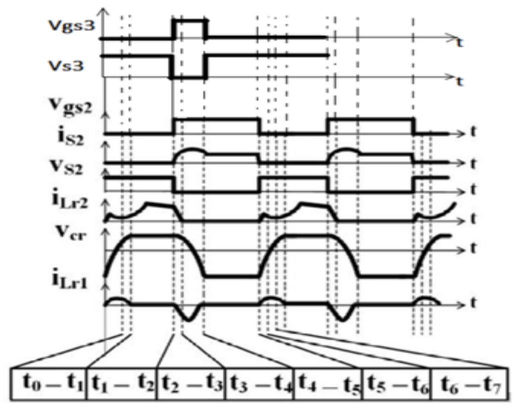


Figure.6. Theoretical Waveforms in Boost mode

Mode 1: (t0-t1) [refer Figure. 7 (a)]: Before t0, ILf flows through the inductor Lr1. Also, the resonant capacitor voltage (VCr) increases and its current ILr1 decreases. By reduction of ILr1, the difference between ILf and ILr1 flows through Lr2 and DSa1. Thus resonance occurs between Lr1, Cr and Lr2 during this mode. Hence, the diode DSa1 is turned on under ZCS condition. S2 is off during this mode. This mode ends when the inductor current (Lr1) reaches to zero.

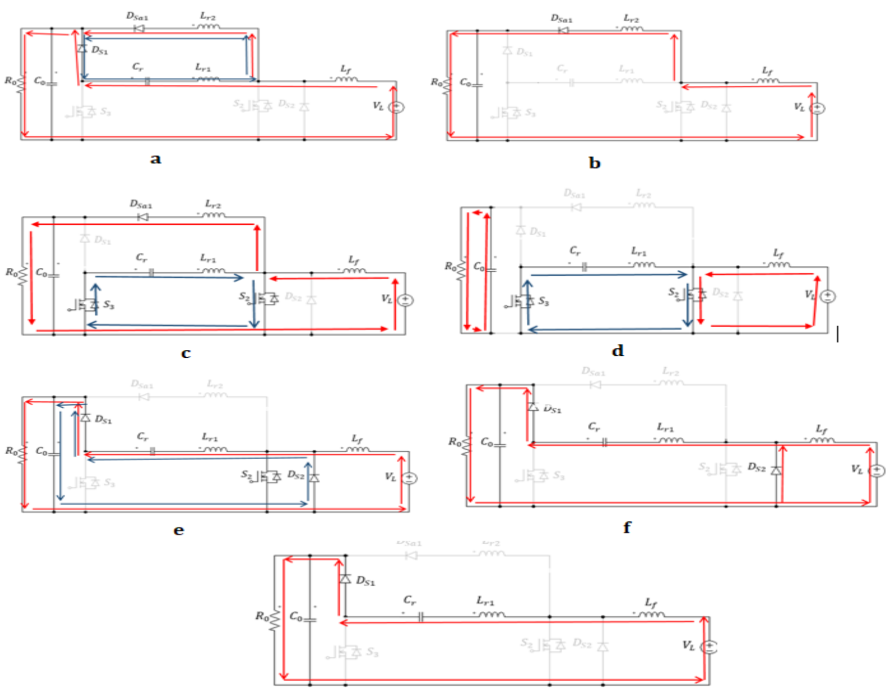


Figure.7. Modes of operation in Boost mode

Mode 2: (t1-t2) [refer Figure. 7 (b)]: This mode starts when ILr1 reaches to zero. So, the diode DS1 is turned off under ZCS condition and the total current I0 flows through Lr2 and DSa1. The resonant capacitor voltage is constant during this mode. Moreover, the energy is transferred from the input source to the output in this mode.

Mode 3: (t2-t3) [refer Figure. 7 (c)]: This mode starts when the switch S2 and S3 is turned on. Since, the value of ILr2 is equal to ILf and the value of ILr1 is equal to zero, so the switch S2 is turned on under ZCS condition. A resonance starts between Lr1 and Cr through S2 and S3 during this mode. Thus, the resonant inductor current (ILr1) increases and the resonant capacitor voltage (VCr) decreases in a resonance manner. Moreover, the switch S3 is turned on under ZCS condition due to the series connection with Lr1. Since, the negative output voltage is applied

across the resonant inductor Lr2 , its current decreases linearly. At the end of this mode, ILr2 reaches to zero and the diode DSa1 is turned off under ZCS condition.
Mode 4: (t3-t4) [refer Figure. 7 (d)]: The resonance between Lr1 and Cr through S2 and S3 still continues, even when the diode DSa1 is turned off. At the end of this mode, ILr1 reaches to zero and the resonant capacitor voltage (VCr) reaches to its maximum value in the reverse direction. Consequently, the switch S3 is turned off under ZCS condition. The capacitor C0 supplies the output load during this mode. Furthermore, the inductor current ILf is still increasing during this mode.
Mode 5: (t4-t5) [refer Figure. 7 (e)]: Another resonance starts between Lr1 and Cr through DS2 and DS1 when the diode Dr is turned off. The diodes DS1 and DS2 are turned on under ZCS condition because of the series resonant inductor Lr1. The current ILr1 increases from zero and the capacitor starts to charge. When the current ILr1 is equal to ILf, the switch S2 is turned off under ZVZCS condition.
Mode 6: (t5-t6) [refer Figure. 7 (f)]: This mode starts when the switch S2 is turned off at t5. During this mode, the resonance between Cr and Lr1 continues through DS1 and DS2. Moreover, the current ILr1 is bigger than ILf. Besides, the resonant capacitor Cr is charged during this mode. On the other hand, the difference between the currents (ILr1- ILf) flows through the diode DS2. At the end of this mode, the current ILr1 is equal to ILf again and the diode DS2 is turned off under ZCS condition.
Mode 7: (t6-t7) [refer Figure. 7 (g)]: This mode starts when the switch S2 is turned off at t5. During this mode, the resonance between Cr and Lr1 continues through DS1 and DS2. Moreover, the current ILr1 is bigger than ILf. Besides, the resonant capacitor Cr is charged during this mode. On the other hand, the difference between the currents (ILr1-ILf) flows through the diode DS2. At the end of this mode, the current ILr1 is equal to ILf again and the diode DS2 is turned off under ZCS condition.

III. DESIGN OF COMPONENTS

The bidirectional Buck and Boost converter is designed at 36V (low voltage) VL and 84V (high voltage) VH. The converter operates at 100 kHz and an output power of 250W.

3.1. Duty Ratio D in Buck and Boost Modes

The duty ratio D in Buck mode is calculated as follows;

$$D = \frac{V_L}{V_H} = \frac{36}{84} = 0.42 \tag{1}$$

and the duty ratio D in Boost mode is obtained as below;

$$\frac{V_H}{V_L} = \frac{1}{1-D}; \frac{84}{36} = \frac{1}{1-D}; D = 0.57 \tag{2}$$

3.2 Resonant Elements Lf, Lr1, Lr2 and Cr

From mode 2 of Boost mode,

$$Z_{r1} = \sqrt{\frac{L_{r1}}{C_r}} = \frac{V_H}{1.5 * I_{in}} = \frac{84}{1.5 * 6.94}; \sqrt{L_{r1}} = 8.115 * \sqrt{C_r} \tag{3}$$

Due to the converter operation, the resonant period should be higher than the switching period. So,

$$T_{res} = 2\pi\sqrt{L_{r1}C_r} \geq T_{sw} \tag{4}$$

Choose Cr = 220nF and Lr1 = 13 µ H.

$$Z_{r1} = \sqrt{\frac{L_m}{C_r}} = \sqrt{\frac{L_{r1}+L_{r2}}{C_r}} = \frac{V_H}{1.5 * I_{in}} = \frac{84}{1.5 * 2.97} = 18.855\Omega \tag{5}$$

$$\sqrt{L_{r2}} = (18.855 * \sqrt{C_r}) - \sqrt{L_{r1}} \tag{6}$$

Choose Lr2=30µH

In Boost mode, the rated input current is 6.94 A. The input current is equal to the inductor current ILf. Moreover, 20% of the full load inductor current i.e., 1.38 A is chosen as peak to peak ripple current.

$$L_f = \frac{V_{in}D}{f * \Delta I_{Lf}} = \frac{36 * 0.57}{100 * 10^3 * 1.38} = 148\mu H \tag{7}$$

In Buck mode, the rated output current is 6.94 A. 20% of the rated output current i.e., 1.38 A is chosen as peak to peak ripple current. From Fig 4.a. of the Buck mode, the output filter inductor (Lf) is computed as follows;

$$L_f = \frac{V_L}{\Delta I_0}(t_1 - t_0) = \frac{V_L}{\Delta I_0} * \frac{L_{r2} * I_0}{V_H} \tag{8}$$

Therefore, the value of bigger inductor is selected for the BDC. Choose Lf = 132 µH.

3.3 Output Capacitor C0

The purpose of the filter capacitor is to decrease output voltage ripple. Considering the output voltage ripple to be 0.002, the minimum value of the filter capacitor is given by the following in Boost mode;

$$C_{o,min} = \frac{D * V_0}{(\Delta V_o * R_o * f_s)} = 95\mu F \tag{9}$$

Choose C0 = 102 µF for better filtered output. The value of filter capacitor is common in both Buck and Boost modes.

IV. SIMULATION OF THE PROPOSED CONVERTER WITH RESULTS

Simulation parameters for the bidirectional DC-DC converter is given in Table 1.

Table 1: Simulation Parameter

Parameters	Specification
Low voltage ,V_L	36V
High voltage ,V_H	84V
Switching frequency, f_{sw}	100kHz
Duty Ratio (Buck/Boost)	0.42/0.57
Inductor L_{r1} ,L_{r2} ,L_f	13µH, 30µH , 132 µH
Resonant Capacitor, C_r	220nF
Filter Capacitor ,C_0	102µF
Load Resistor, R_0 (Buck/Boost)	5Ω/30Ω

The simulation results of the converter in Buck mode are shown in the following figures.

Figure 8. shows the output voltage (Vout) and output current (Iout) and its zoom version for the BDC on Buck mode of operation. Output voltage (Vout) is about 34V and has a ripple of 0.4V. Output current (Iout) is about 6.606A and output current ripple is in the range of 0.008A.

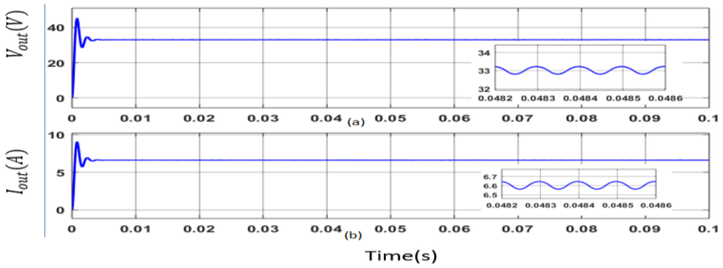


Figure 8: (a) Output Voltage (Vout) and (b) Output Current (Iout)

The switching frequency is chosen to be 100 kHz. Figure 9. and Figure 10. shows the gate pulses, voltage across the switches and the current through the switches S1 and Sa1. Comparing with the conventional Buck converter, the voltage stress of the main switch S1 reduced about 5V. In Buck mode, the switches S1 and Sa1 have an important role to transfer the power. Based on mode 3 in Buck operation, the main switch S1 is turned on under ZVZCS condition. Also, the main switch S1 is turned off under ZCS. Based on mode 1 in buck operation, the auxiliary switch Sa1 is turned on under ZCS condition and based on mode 4, it is turned off under ZCS condition.

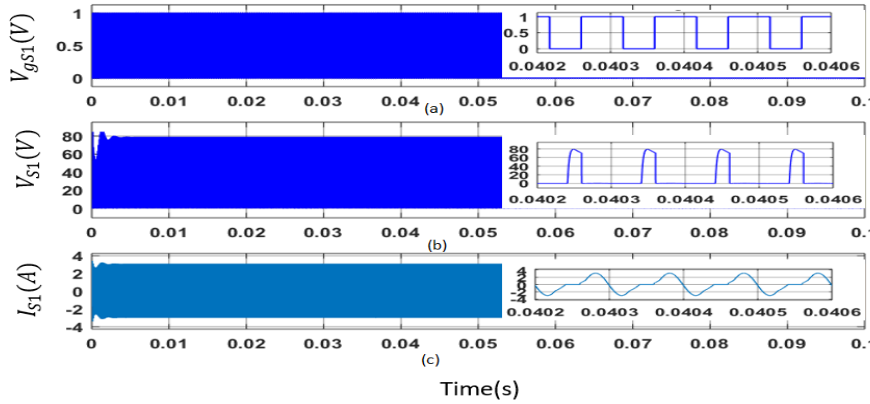


Figure 9. (a)Gate pulse (VgS1), (b) Voltage across switch (VS1) ,and (c)Current through switch (IS1)

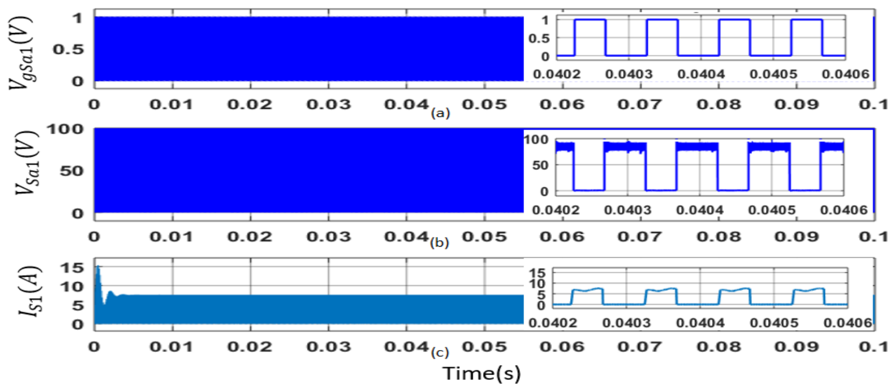


Figure 10: (a) Gate pulse (VgSa1), (b) Voltage across switch (VSa1) and (c) Current through switch (ISa1)

The simulation results of the bidirectional DC-DC converter in Boost mode are shown in the following figures.

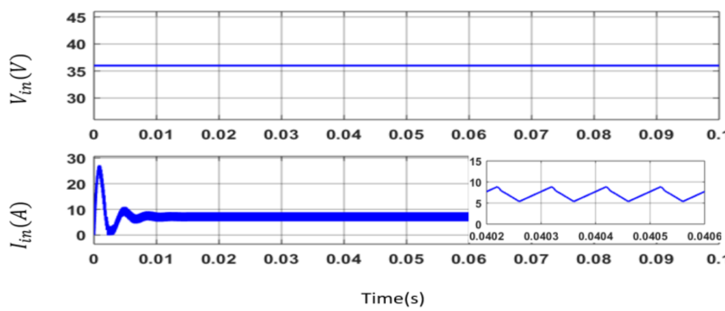


Figure 11: (a) Input Voltage (Vin), (b) Input Current (Iin)

Figure 11. shows the input voltage (Vin) and input current (Iin) and its zoom version for the BDC on Boost mode of operation. Input voltage Vin is 36V and input current Iin is about 7.056A. Input current has a ripple of 3.46A.

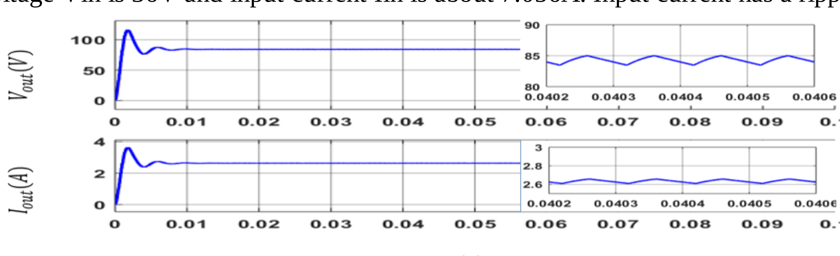


Figure 12: (a) Output Voltage (Vout) and (b) Output Current (Iout)

Figure 12. shows the output voltage (Vout) and output current (Iout) and its zoom version for the BDC on Boost mode of operation. Output voltage (Vout) is about 84.45V and has a ripple of 1.5V. Output current Iout is about 2.798A and output current ripple is in the range of 0.144A.

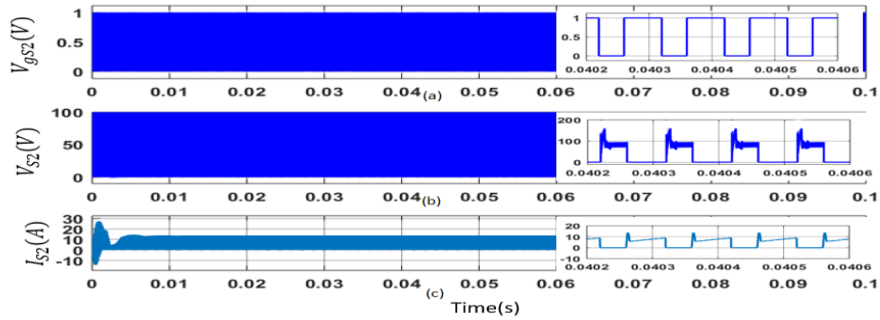


Figure 13: (a)Gate pulse (VgS2), (b) Voltage across switch (VS2) ,and (c)Current through switch (IS2)

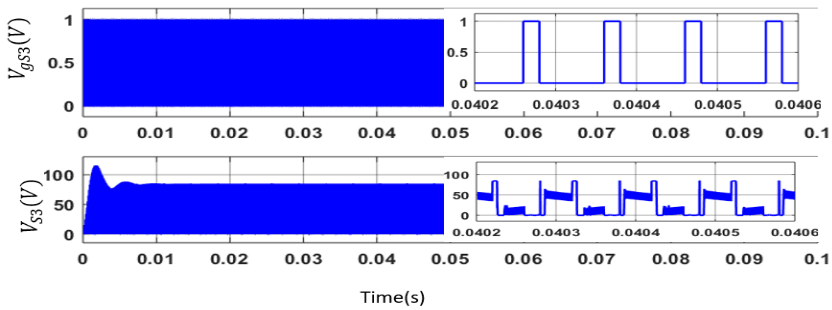


Figure 14: (a) Gate pulse (VgS3), (b) Voltage across switch (VS3)

The duty ratio of main switch S2 and S3 is equal to 0.57 and 0.2 respectively. Figure 13. shows the gate pulse, voltage across the switch and the current through the switch S2. During the Boost operation, only the switch S2 is on in the BDC and the switches S1 and Sa1 are off. Based on mode 3 in Boost operation, the switch S2 is turned on under ZCS condition. Fig 14. shows the gate pulse, voltage across the switch and the current through the switch S3. Moreover, based on mode 5 in Boost operation, the main switch S2 is turned off under ZVZCS condition.

V. ANALYSIS

A typical curve for the variation of efficiency as a function of output power is shown in Figure 15. The converter efficiency is around 98% for 250W output power for R load. The converter efficiency is around 91% for 250W output power for RL load. The efficiencies of the conventional converter is also compared.

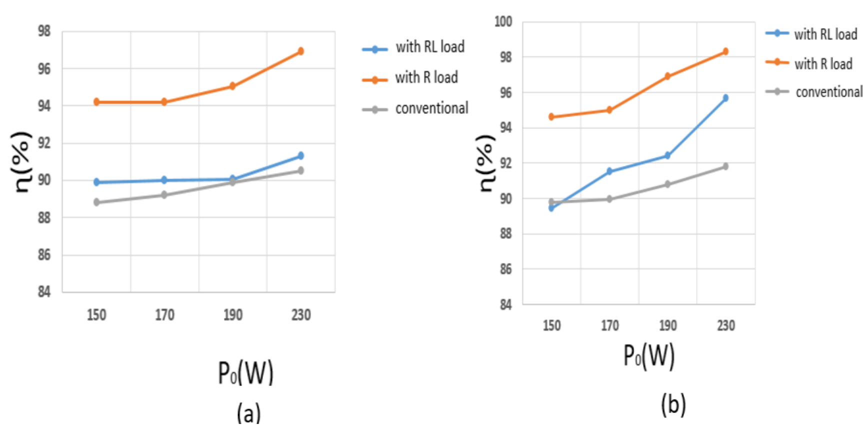


Figure 15: (a) Efficiency of the converter in Buck mode (b) Efficiency of the converter in Boost mode

The plot of voltage gain as a function of duty ratio is shown in Figure 16. According to this figure, the voltage gain is 0.4 when the duty cycle is equal to 42% in Buck mode and if duty ratio is smaller than 42% the gain reduces. Also, if the voltage gain is 2.3 when the duty cycle is equal to 57%.

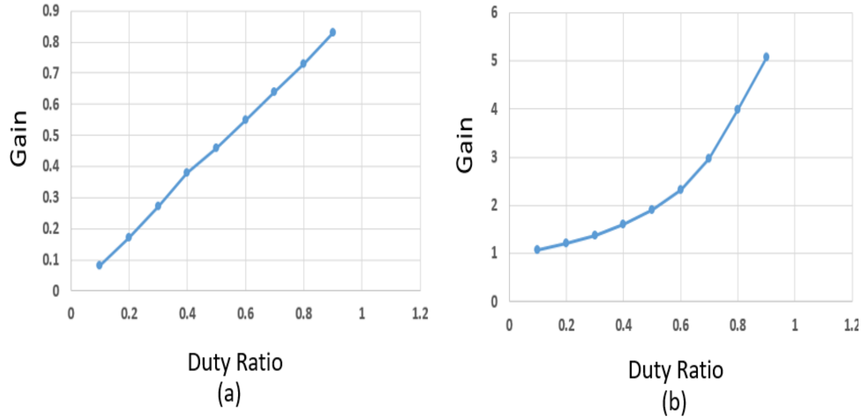
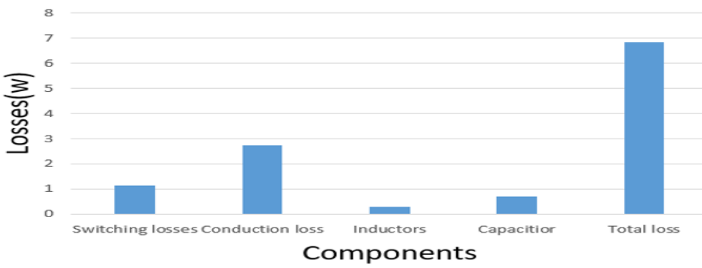


Figure 16: (a) Gain vs Duty ratio for Buck mode(b) Gain vs Duty ratio for Boost mode

The plot of losses in the discussed bidirectional DC-DC soft switched converter is shown in Figure 17. A total power loss of 6.8W is thus obtained.



Figre 17: Power Loss Distribution Of Components

The comparison between conventional converter, the bidirectioanl DC-DC converter and the modified converter is given in Table 2.

Table 2:Comparison of Conventional and Modified converter

Parameters	Conventional Converter	Soft Switched BDC	Modified Converter
Efficiency	90%	96%	97.5%
Voltage stress(S_1,S_2)	85V/84V	80V/82V	80V/82V
Voltage stress(S_{a1})	Nil	93V	93V
Current stress(S_1,S_2)	9A/8.5A	3.1A/12A	3.1A/12A
Current stress(S_{a1})	Nil	7.5A	7.5A
Output Voltage ripple(Buck/Boost)	0.3V/3.5V	0.4V/1.6V	0.4V/1.5V
Output Current ripple(Buck/Boost)	0.06A/0.11A	0.008A/0.054A	0.008A/0.144A

It is observed from the above discussions that in the modified bidirectional DC-DC converter ,the voltage stresses on the switches are reduced and the efficiency is improved to about 97% . Also, the output voltage and output current ripple is reduced to a desirable value.

A prototype of soft switched BDC with reduced losses with an input voltage of 12V for Buck mode and 30V for Boost mode is implemented. The topview of the experimental setup is shown in Figure.18. It consists of control circuit, driver circuit and power circuit.

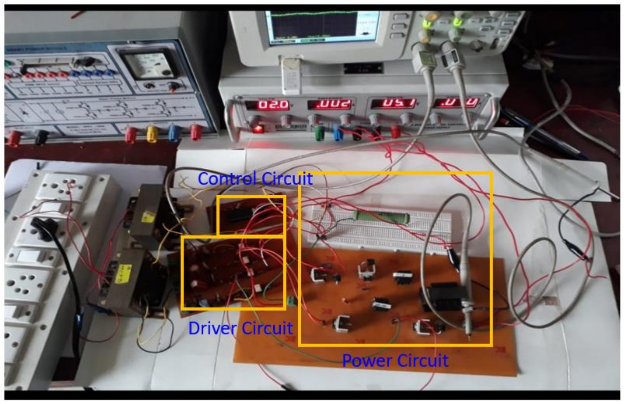


Fig 18: Top view of the experimental setup

VI. CONCLUSION

A fully soft switching bidirectional DC-DC converter which can be used as an interface circuit between renewable energy source and DC link is modified.The measured efficiency of the converter in both Buck and Boost modes is more than 96% with R load and more than 93% with RL load.The resonant elements provide soft switching condition for all semiconductor devices with only one auxiliary switch.The output voltage is about 36V at an input voltage of 84V in Buck mode and the viceversa in Boost mode.The switches have relatively low voltage stresses which enables an improved overall efficiency of the converter.

VII. REFERENCES

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