Bidirectional DC-DC Converter Using Resonant PWM Technique

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Abstract— A new soft-switched bidirectional buck and boost converter suitable for high-power applications such as hybrid electric vehicles , power factor correction, and fuel cell power conversion systems is investigated in this work. The converter attains Zero Voltage Switched (ZVS) turn on of the active switches which reduces switching losses. The voltage ratings of components and energy volumes of passive components of the converter are reduced compared to the conventional zero voltage transition converters. The proposed converter has also achieved voltage conversion ratio almost double compared to the conventional boost converter. The performance of the converter is analyzed using MATLAB/Simulink R2010a.

Keywords— Resonant PWM, Soft switching, DC-DC converter, Zero Voltage Switching, Bidirectional Converter, High Power Applications, Electric Vehicles

INTRODUCTION

Continuous Conduction Mode (CCM) boost converters have been widely used as the front-end converter for active input current shaping [3]. CCM boost converters are increasingly used in high power applications such as uninterrupted power supplies, hybrid electric vehicles, fuel cell power conversion systems etc. High power density and high efficiency are major concerns in the high power CCM boost converters [8].

The hard switched CCM boost converter has severe diode reverse recovery problems in high current high power applications [7] [9]. That is, when the main switch is turned on, a shoot-through of the output capacitor to ground due to the diode reverse recovery causes a large current spike across the diode and main switch. Thus it increases turn-off losses of the diode and turn on loss of the main switch, but also causes severe electromagnetic interference (EMI) emissions [5].

The effect of the reverse recovery problems [2] become more significant at high switching frequency and at higher power levels. Therefore, the hard switched CCM boost converter is not capable of achieving high efficiency and high power density at high power levels [1] [6] [10]. Many techniques on soft switching CCM boost converters have been proposed. This work analyses a new soft switched CCM boost converter suitable for high power applications [4] [11]. The converter has Zero Voltage Switching turn-on of the main switches in CCM and negligible diode reverse recovery due to Zero Current Switching turn-off of the diode. Voltage conversion ratio is also almost doubled compared to the conventional boost converters [12]. It has significantly reduced components voltage ratings and energy volumes of most passive components. The operating principles and features of the proposed converter has been described. The performance of the converter is analyzed in detail using MATLAB/Simulink Ra2010. The simulated waveforms are found to be similar to the theoretical waveforms and is clear that the performance of the converter has improved.

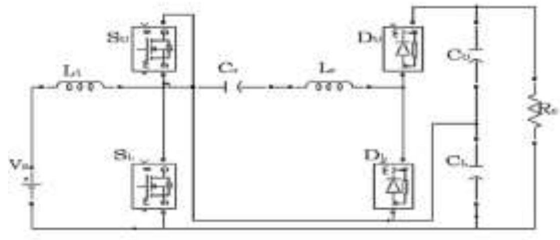

Fig.1 ZVZCS resonant PWM DC-DC converter

Fig. 1 shows the circuit diagram of the proposed CCM boost converter, and Figure 3.3 shows key waveforms illustrating the operating principle of the proposed converter.

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Upper switch S_U in the ZVZCS resonant PWM DC-DC converter replaces the rectifier diode in the conventional boost converter. Lower switch S_L and upper switch S_U are operated with asymmetrical complementary switching in order to regulate the output voltage as shown in Figure. An auxiliary circuit that consists of a capacitor C_r, an inductor L_r, two diodes D_L and D_U, and a capacitor C_U is connected on top of the output capacitor C_L to form the output voltage of the converter. The auxiliary circuit not only increases the output voltage, but also helps ZVS turn-on of active switches S_L and S_U in CCM.

Applying the soft switching techniques to switched mode converters would eliminate the need for bulky snubbers and heat sinks and can considerably improve the converter efficiency. In addition to that, the soft switching technique will reduce the converter electromagnetic interference. A new non-isolated bidirectional ZVS DC-DC converter for high power applications using resonant PWM technique is investigated in this work. The switches in the resonant DC-DC converter is fully soft switched, thus reducing the switch stresses and losses. Thus, the converter has an acceptable efficiency as compared to other conventional switching converters.

BIDIRECTIONAL DC-DC CONVERTER USING RESONANT PWM TECHNIQUE

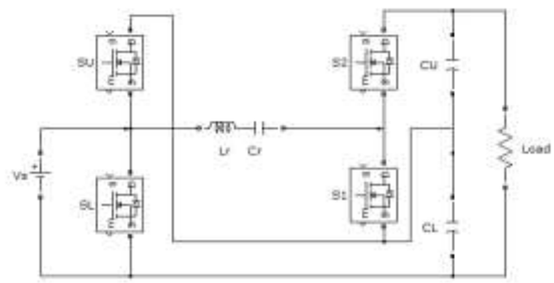

Fig.2 Bidirectional DC-DC converter using resonant PWM

BOOST MODE

Mode I: This mode begins with turning off of S_U and S_1. Then the body diodes of S_L and S_1 are turned on. The gating signal for S_1 is applied with appropriate dead time during this mode, and then S_1 could be turned on at ZVS condition.

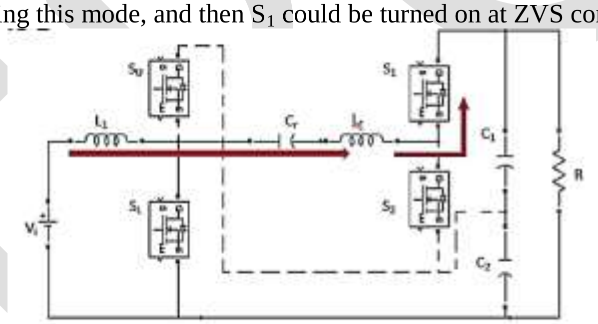

Fig.3 Mode I operation

Mode II: When the increasing current i_{L1} becomes greater than the decreasing current i_{Lr}, current flowing through S_L is reversed, and main channel of S_L conducts. This mode ends when i_{Lr} reaches 0A. Switch S_1 is turned off under zero current condition.

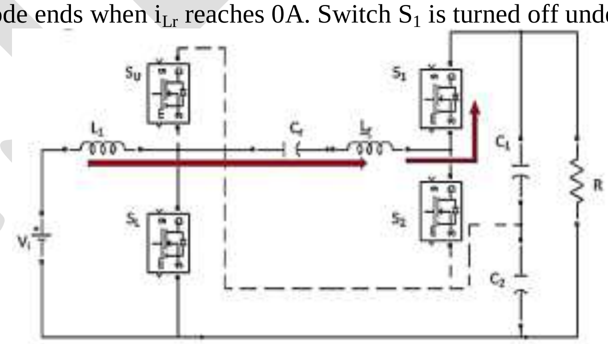

Fig.4 Mode II operation

Mode III: i_{Lr} is reversed and body diode of S_2 is turned on. Gating signal for S_2 can be applied during this mode.S_2 is turned on under ZVS condition.

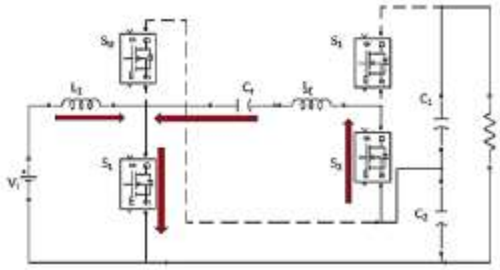

Fig.5 Mode III operation

Mode IV: S_L and S_2 are turned off and then body diodes of S_U and S_2 are turned on. The gating signal for S_U is applied during this mode. Then S_U could be turned on under ZVS condition. This mode ends when i_{Lr} reaches 0A. S_2 is turned off under ZCS condition.

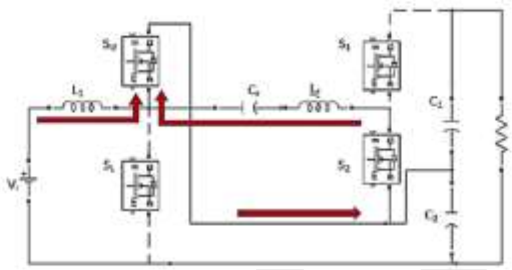

Fig.6 Mode IV operation

Mode V: This mode begins when i_{Lr} is reversed and body diode of S_L is turned on. Gating signal for S_1 can be applied during this mode. S_1 is turned on under ZVS condition.

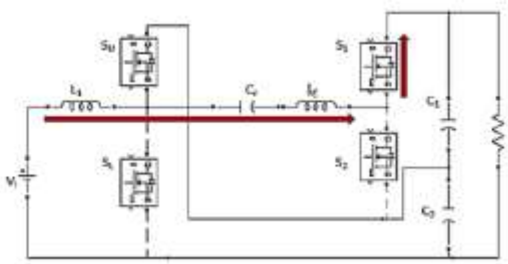

Fig.7 Mode V operation

This is the end of one complete cycle.

BUCK MODE

The same converter can be used for buck operation in the reverse direction. In the buck mode operation, the output load is replaced by dc source and input voltage source is replaced by output load with capacitor filter. The only difference is the power flow through the converter will be reversed. In the buck mode also, ZVS turn on of the switches are ensured. Buck and boost operation of the bidirectional converter is analysed using MATLAB/Simulink model.

DESIGN

The resonant frequency of the circuit is given by,

$$f_r = \frac{1}{2\pi\sqrt{LrCr}}$$

The output voltage is obtained as,

$$V_{out} = V_{CL} + V_{CU}$$

where, voltage across lower capacitor is,

$V_{CL} = \frac{1}{1-D} V_{in}$ and,

Voltage across upper capacitor is,

$V_{CU} = \frac{1}{1-D} V_{in} - \Delta V$

The input filter inductor,

$L_1 = \frac{1}{2} \frac{D\, Vin}{\Delta I1\, fs}$

$= 60\ \mu H$

The resonant frequency obtained is, $f_r = 40kHz$

Resonant elements are,

$L_r = 6\mu H$

$C_r = 2.7\mu F$

Normally, below resonance operation is found to be more efficient than the above resonance operation. For below resonance operation, switching frequency is selected to be greater than the resonance frequency. Switching frequency is selected as 70kHz.

MATLAB/SIMULINK MODEL

This section depicts the performance of the bidirectional converter in MATLAB/Simulink environment. The MATLAB/Simulink model is operated in buck mode and boost mode. And, the simulation results of both operations are analysed.

BOOST OPERATION OF OPERATION

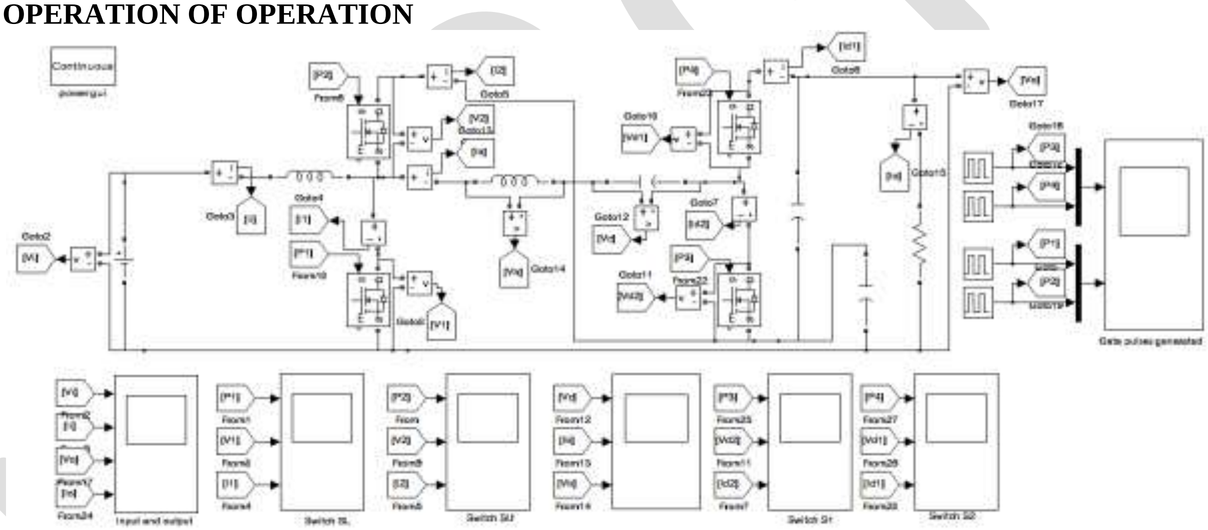

Fig.8 MATLAB/Simulink model of bidirectional converter in boost mode

The study parameters and conditions for the MATLAB/Simulink model are given by,

TABLE XII
SIMULATION PARAMETERS

COMPONENTS	PARAMETER
Input voltage	80V
L_1	60µH
C_r	3µF
Switching frequency	70kHz
R_0	30Ω
f_r	40kHz
L_r	6µH

The bidirectional operation of the converter finds applications in hybrid electric vehicles. Fig. 8 depict the study results for the boost mode of operation.

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BUCK MODE OF OPERATION

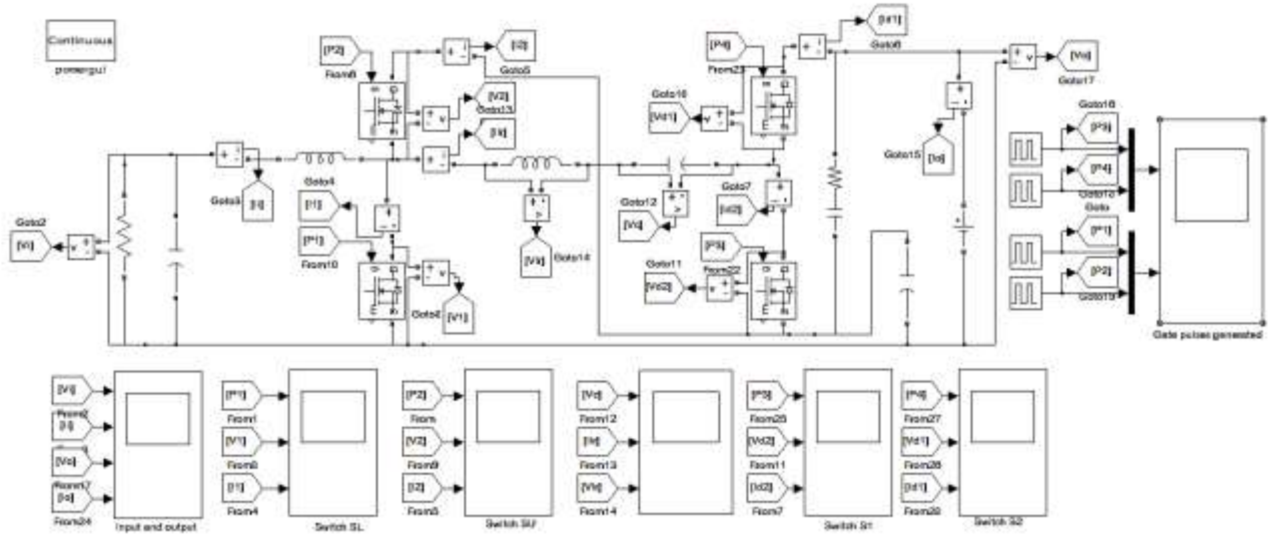

Fig.9 MATLAB/Simulink model of bidirectional converter in buck mode

When the converter is used in buck mode, the direction of power flow is reversed.

SIMULATION RESULTS

The simulation results for the buck mode of operation are given by,

Fig. 10 Input voltage

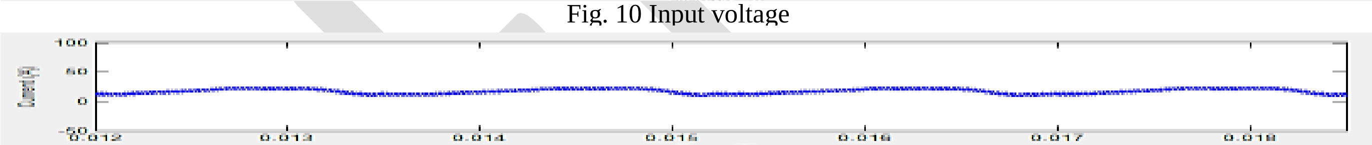

Fig. 11 Input current

In the MATLAB/SIMULINK environment, the input voltage 80V is given and the input current is of the order of 20A.

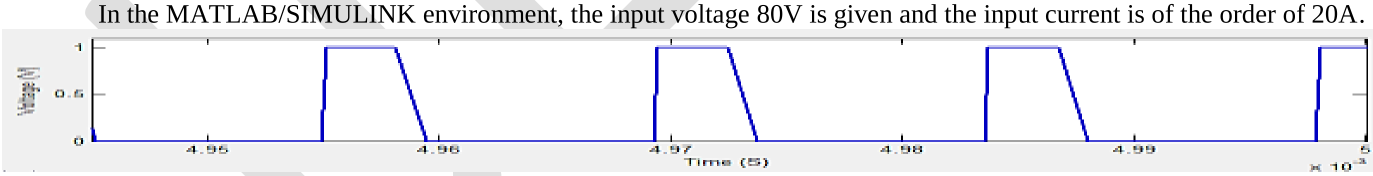

Fig. 12 Gate pulse given to S_L

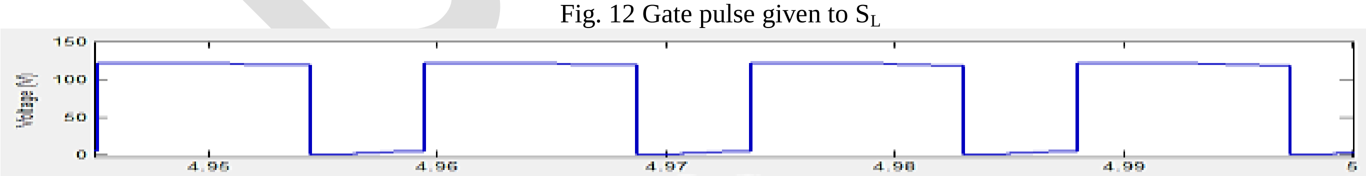

Fig. 13 Voltage across S_L

From Fig.12 and Fig.13, it is clear that the lower switch S_L is turned on under ZVS condition.

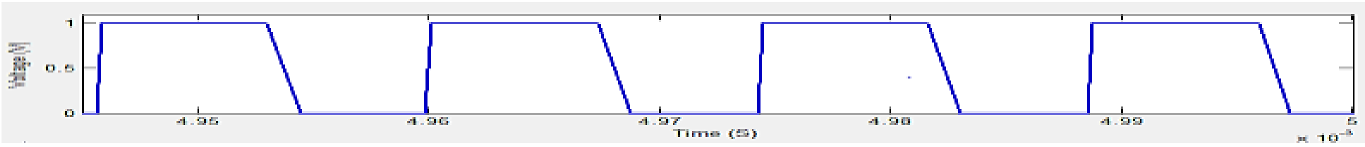

Fig. 14 Gate pulse given to S_U

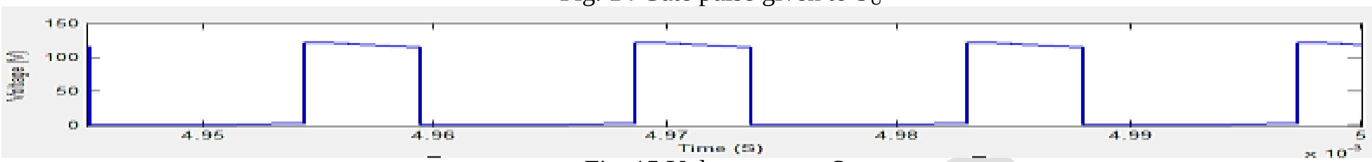

Fig. 15 Voltage across S_U

From Fig.14 and Fig.15, it is clear that the lower switch S_U is turned on under ZVS condition.

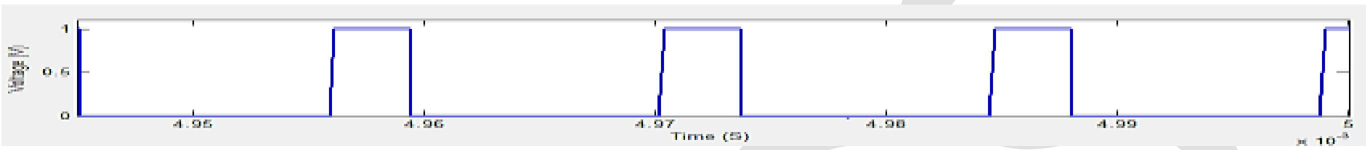

Fig. 16 Gate pulse given to S_2

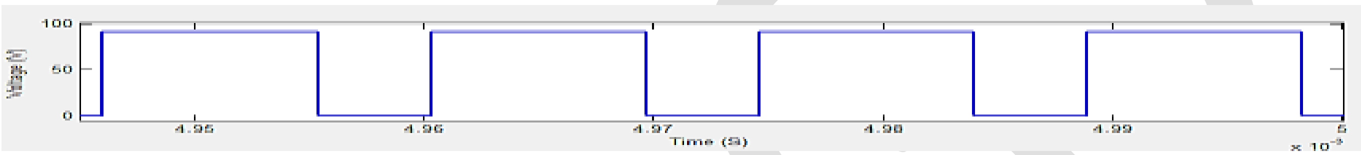

Fig. 17 Voltage across S_2

From Fig.16 and Fig.17, it is clear that the lower switch S_2 is turned on under ZVS condition.

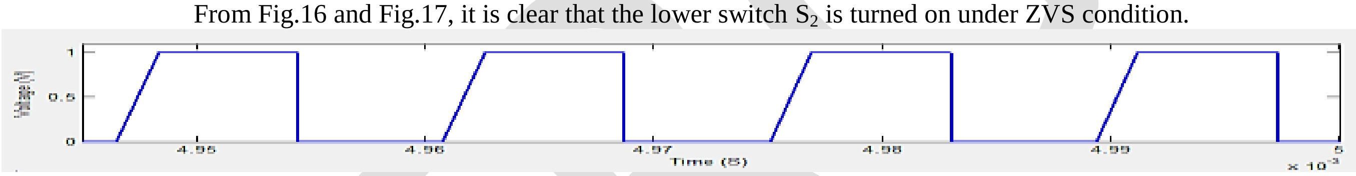

Fig. 18 Voltage across S_1

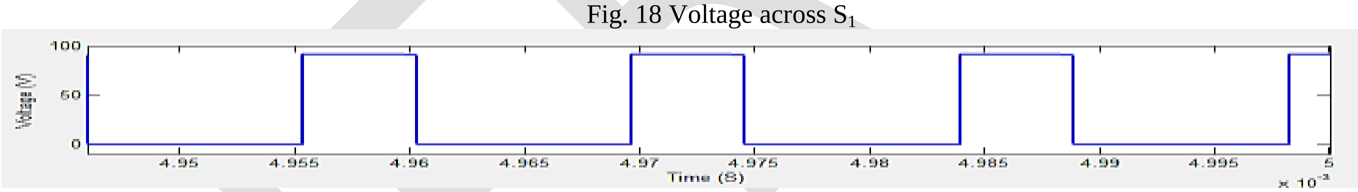

Fig. 19 Voltage across S_1

From Fig.18 and Fig.19, it is clear that the lower switch S_1 is turned on under ZVS condition.

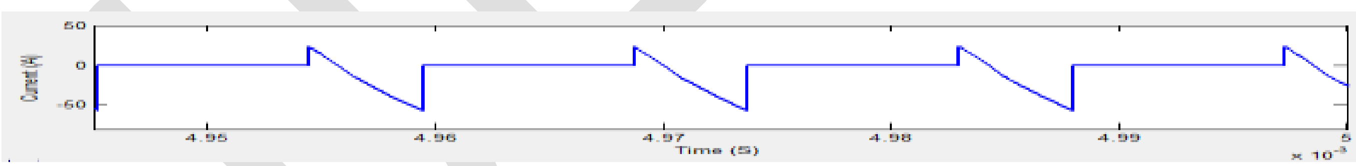

Fig. 20 Current through S_L

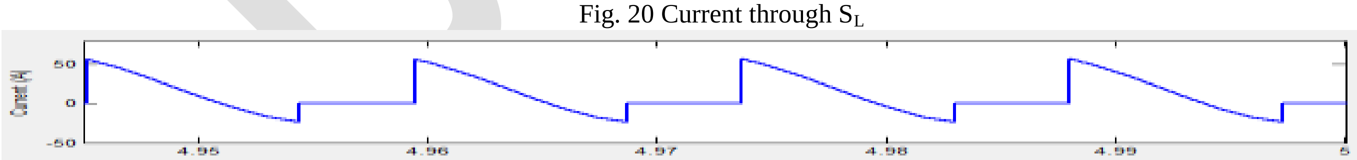

Fig. 21 Current through S_U

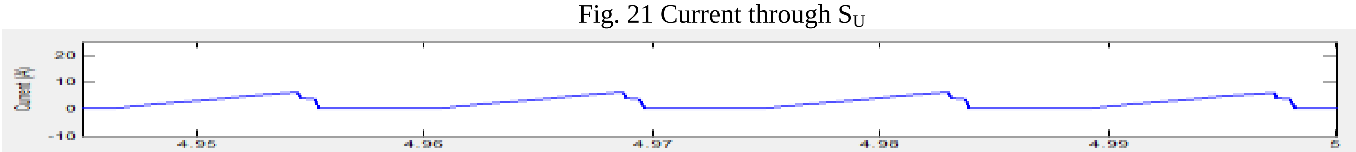

Fig. 22 Current through S_2

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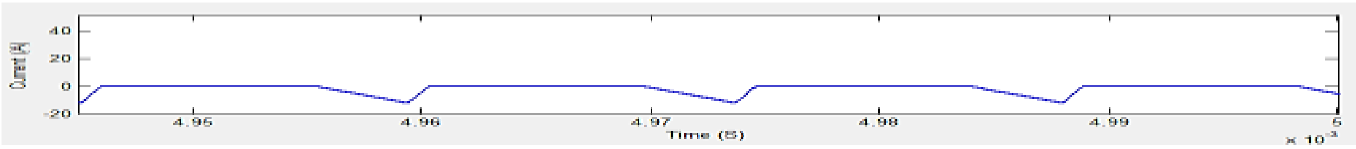

Fig. 23 Current through S_1

Current through the switches are shown in the above figures.

BOOST MODE OPERATION

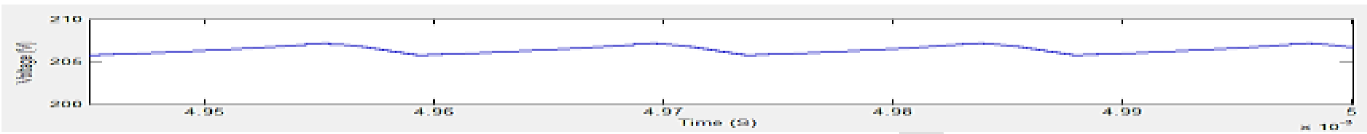

Fig. 24 Output voltage

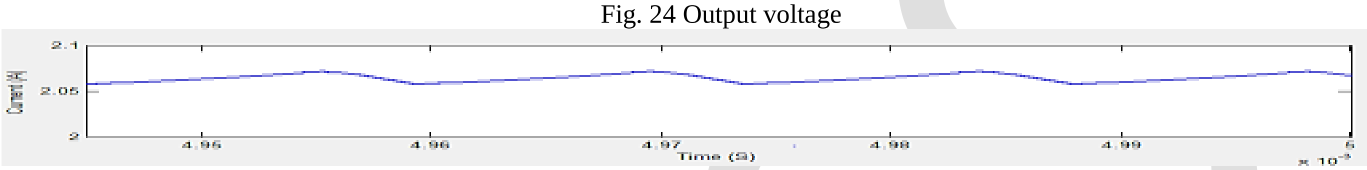

Fig. 25 Output current

In the boost mode, for an input voltage of 80V, an output voltage of 205V and current of 2.05A is produced at the output. As can be seen, the output ripple voltage is around 1V. For the same input parameters, buck operation of the converter is also analysed. All the waveforms are same excluding the output current and voltage. The same ZVS turn on of the switches is obtained in the buck mode operation also.

BUCK MODE OPERATION

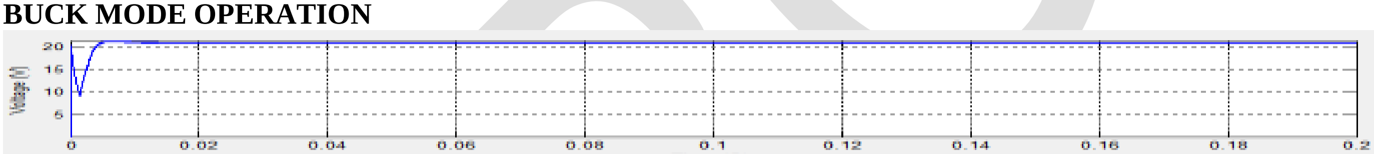

Fig. 26 Output voltage

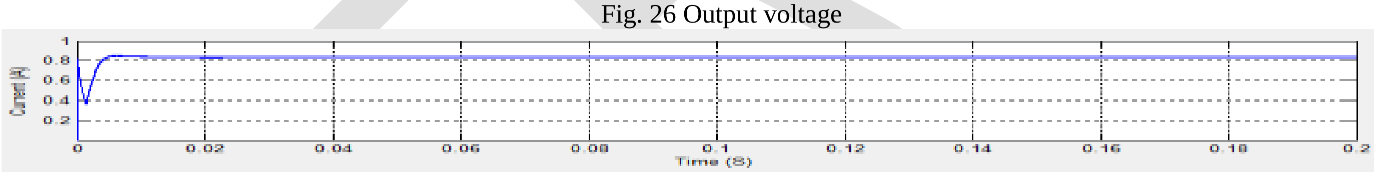

Fig. 27 Output current

In the buck mode, for an input voltage of 80V, an output voltage of 20V and current of 0.8A is produced at the output.

It is found that using this technique, we get improved soft switched bidirectional converter which finds applications in hybrid electric vehicles.

CONCLUSION

In this work, a new soft-switched CCM boost converter suitable for high voltage and high power application has been proposed. The proposed converter has ZVS turn-on of the active switches in CCM and negligible diode reverse recovery due to ZCS turn-off of the diodes. The voltage conversion ratio is almost doubled compared to the conventional boost converter. It greatly reduced components voltage ratings and energy volumes of most passive components.

The simulation of the ZVZCS DC-DC converter is done in MATLAB/SIMULINK R2010a. In the boost mode of operation, for an input voltage of 80V, an output voltage of 205V and current of 2.05A is produced at the output. In the buck mode operation, for an input voltage of 80V, an output voltage of 20V and current of 0.8A is produced at the output.

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