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BIDIRECTIONAL DC-DC CONVERTER WITH WIDE RANGE ZVS FOR LOW AND MEDIUM POWER APPLICATIONS

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ABSTRACT

This paper introduces a new three level bidirectional dc-dc converter which operates with wide range ZVS. Compared to traditional full and half bridge bidirectional dc-dc converter for similar application, the new topology uses soft switching without any additional devices and it is capable of providing bidirectional power flow which gives the functionality of two uni-directional converter in a single converter unit. The proposed bidirectional dc-dc converter operates with zero voltage switching from no load to full load condition. Since the converter has very less amount of circulating current and its switches are exposed to half of input voltage, it has high efficiency under light loads. This topology has both buck and boost mode of operation in same converter and is suitable for low and medium power applications. This converter has half bridge on primary side and current fed push pull on secondary side. It operates in buck mode to provide power to upstream converters. On other hand it operates in boost mode and delivers power to downstream converters. In this project the bidirectional DC-DC converter with wide range ZVS has been simulated using MATLAB software.

Index Terms— zero voltage switching (ZVS), Bidirectional dc-dc converter, Phase-shifted modulation converter.

1. INTRODUCTION

Many papers in the area of power electronics and drives proposes the use of different type of DC-DC converters especially isolated converters. The selection of these converters is strictly based on the area of application and power levels. Any way almost all power electronics papers encourages the use of isolated DC-DC converters because of safety considerations. Among these converters half bridge converter has significant role in power electronics and drives application. The majority of power converters are unidirectional with the power being supplied from the source to load. But, a number of application like motor drives, space system require the additional exchange of energy from the load to source. These application utilize power converter with bidirectional transfer properties.

Bi directional dc–dc converters allow transfer of power between two dc sources, in either direction [1]–[4]..Due to their ability to reverse the direction of flow of current, and thereby power, while maintaining the voltage polarity at either end unchanged, they are being increasingly used in applications like dc uninterruptable power supplies, battery charger circuits, telecom power supplies and computer power systems. Possible implementation of bidirectional converters using resonant [4], soft switching [5]-[6] and hard switching PWM [7] has been reported in literature. But, these topologies may often lead to an increase in component ratings, circuit complexity and conduction losses in resonant mode implementations, high output current ripple and loss of soft switching at light loads for soft switched circuits, and lack of galvanic isolation in integrated topologies. In some paper bidirectional dc-dc converter with full bridge topology in both sides is presented [8]-[9]. The advantages of these converters are symmetric configuration and ZVS due to PWM and they have no extra reactive components. But in such converters the output voltage is proportional to load however they can transmit more power in comparison with half bridge topology. In some literatures converters are consist of half bridge in both side [10]-[13]. These converters can be controlled easily and they have not neglecting current that is major problem in dual full bridge dc-dc converters. Another bidirectional converter have half bridge or full bridge in high voltage side and center tapped rectifier in low voltage side [14]-[15].These configurations have advantages of simple circuit and easy implementation but they have a low current output due having only one self in their output. A dc-dc converter with a novel current Tripler rectifier is presented in [16]. But, only power flow in one direction is inspected. In this proposed paper the unidirectional converter presented in [17] is modified to handle bidirectional power flow. For this purpose Diode Bridge on rectifier secondary side is replaced with inverter. In this paper the converter operate in two modes and has reduced circulating current.

2. POWER STAGE DESCRIPTION AND OPERATING PRINCIPLE

The proposed isolated bidirectional dc-dc converter for low power application is shown in fig.1. The circuit consists of two HB converters in series which is mounted one on the top of another in primary side. It has inductor such that (L_r =L_{r1}=L_{r2}), clamping diodes and current doubler circuit. Inductor stores extra energy to extend ZVS range while clamping diodes minimize the voltage ringing that may appear on either side of transformer.Each HB operates with 50% duty cycle and it can be phase shifted from 0° to 180°.

This phase shifting will affect the voltage that is delivered to current doubler filter nodes F_1 and F_2 , V_{F1} and V_{F2} . The output voltage can be regulated by means of phase shift control of converter switches from full load to light load conditions. The capacitor across the switches (C_1=C_2=C_3=C_4) is lossless snubber for soft switching. The transformer is for isolation and voltage matching purpose. It is advantageous to operate the switches with 50% duty cycle and transformer inductors operate in such a way to maintain ZVS over wide range across the switches. Converter secondary act as two interleaved converter and has inductors (L_{01} & L_{02}). When power flow from high voltage side to low voltage side the circuit operate in buck mode. Similarly, when power flow from low voltage side to high voltage side the circuit work in boost mode. Boost function is achieved by inductor L_{01} & L_{02} and low voltage side converter. The operating principle of the proposed converter is explained below with simulation results.

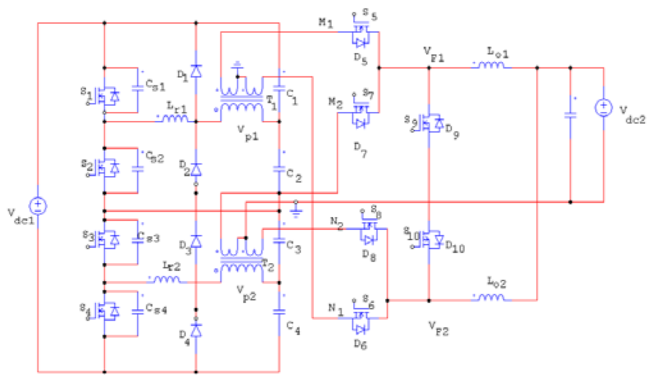


Fig. 1. Proposed bidirectional dc-dc converter with wide range ZVS for low and medium power applications.

3. CONVERTER OPERATION

The proposed converter is divided into two modes of operation (ie) buck and boost mode of operation. In buck mode of operation if the transfomer turns ratio is N:1:1 , the converter input and output voltage relationship is described as

$$V_O = \frac{V_{dc}}{4} * \left(\frac{0.5 + (\Phi / 360)}{N} \right) \tag{1}$$

And the converter's duty cycle is

$$D = 0.5 + \frac{\Phi}{360} \tag{2}$$

It should be noted that this converter actually transfers power from the primary to the secondary during both D and $1 - D$ periods. It is because of the fact that the converter has two HB converts in such a way that they always transfer energy from input to output.

Mode 1 ($t_1 \leq t \leq t_2$)

During this mode, switches S_1 and S_4 are ON. The voltage across the primary of T_1 is positive and the voltage across the primary of T_2 is negative and diodes D_5 and D_8 conduct Energy is transferred from the primary side to the secondary side of both T_1 and T_2 . In this mode, each HB separately transfers energy to the output. The voltage across the output inductors L_{01} and L_{02} are the same and equal to (V_{dc}/4N)-$V_0$and inductor currents i_{l01} and i_{l02} are increasing. The duration of this mode depends on the phase-shift degree φ.

Mode 2 ($t_2 \leq t \leq t_3$)

At t_2, S_4 turned OFF and capacitor C_{s4} is charged and C_{s3} is discharged in resonant fashion. The primary current of T_2 also starts resonating down to zero. To be able to achieve ZVS during this transition, the resonant peak of the capacitor C_{s4} has to be higher than $V_{dc}/2$.

In order to achieve ZVS for S_3 , it needs to have a delay time t_d before S_3 turns ON, for the primary current of T_2 to discharge completely the body capacitor of S_3 and conduct the body diodeof S_3. t_d Can be expressed by

$$t_d = \sin^{-1}\left(\frac{V_{dc}/(2*I_p*Z_r)}{\omega_r}\right)$$

$$t_d \le \Pi/2\omega_r$$

(3)

Where, I_p Is the maximum transformer current

$$\omega_r = \frac{1}{\sqrt{L_{r2}*(C_{s3}+C_{s4})}}$$

$$Z_r = \sqrt{\frac{L_{r2}}{C_{s3}+C_{s4}}}$$

(4)

During this mode, the primary voltage across T_2 reverses its polarity and becomes positive, which causes dioe D_{10} to conduct and take over current $i_{lo2}$from D8 . The top HB maintains its previous state and continues to apply a voltage to F_1 through diode D_5.

Mode 3 ($t_3 \le t \le t_4$)

This mode starts when S_3 turns ON with ZVS. The polarity of T_1 and T_2 are both positive and diodes D_5 and D_7 both conduct and share output current i_{lo1}, since the two transformer outputs, V_{M1} and V_{M2} , have almost the same voltage. In the meantime, D_{10} continues to conduct current i_{lo1} and i_{lo2} starts to decrease as $-V_o$ is applied to L_{02} . The decrease of i_{lo2} and the increase of i_{lo1} lead to current ripple cancellation and output current ripple minimization.

Mode 4 ($t_4 \le t \le t_5$)

At t_4 , S_1 is turned OFF and C_{s2} is discharged and C_{s1} is charged in resonant fashion. The primary current of T_1 also starts resonating down to zero. To be able to achieve ZVS during this transition, the resonant peak of the capacitor C_{s1} has to be higher than $V_{dc}/2$. In this mode, the delay time should be the same as for mode 2.

$$t_d = \sin^{-1}\left(\frac{V_{dc}/(2*I_p*Z_r)}{\omega_r}\right)$$

$$t_d \le \Pi/2\omega_r \qquad (5)$$

Where

$$\omega_r = \frac{1}{\sqrt{L_{r1}*(C_{s1}+C_{s2})}}$$

$$Z_r = \sqrt{\frac{L_{r2}}{C_{s3}+C_{s4}}} \qquad (6)$$

To achieve ZVS for S_2 . The body-diode of S_1 starts to conduct and continues. The voltage across T_1 starts to decrease and eventually reverses its polarity. Output inductor current i_{lo1} still continues to flow through D_{10} until D_6 starts to conduct.

Mode 5 ($t_5 \le t \le t_6$)

After S_2 is turned ON with ZVS at t_5 , inductor current i_{lr2} decreases to zero quickly and then starts to build up in the opposite direction. When the current i_{lr2} reflected to the secondary becomes greater than i_{lo2} then current is transferred from D_{10} to D_6 . In this mode, each HB separately transfers energy to the output. The voltage across the output inductors L_{01} and L_{02} are the same and equal to $(V_{dc}/4N)-V_0$and inductor currents i_{l01} and i_{l02} are increasing.

The proposed converter has the following feature during boost mode of operation,

1) It can operate with ZVS from full-load to near no-load conditions. This is because each converter switch is part of an HB converter that operates with 50% duty cycle. Since an HB converter with 50% duty cycle does not operate with any freewheeling modes of operation as does a FB converter, there will always be sufficient energy to discharge the output switch capacitances.

2) In addition to the fact that each converter switch is in an HB converter, it is exposed to only half the input voltage as the converter has two HB converter arranged in a multilevel structure. As a result, less energy is needed to discharge the output capacitor of each converter switch, which further extends the load range over which the converter can operate with ZVS to near no-load conditions

The proposed converter has the following modes of operation during boost mode of operation. In the *boost mode*,

inductor current is assumed to be continuous. The time intervals between t_1 to t_4 describe the converter operation, which is repetitive over a switching cycle Ts .

Mode 1($t_1 \le t \le t_2$)

Switch S_9 is turned ON at time t_1 while S_5 remains in the ON state from the previous interval. The transformer secondary Ts, , is subject to an effective short circuit, which causes the inductor L_{01} , to store energy as the total voltage appears across it. The inductor current, i_{l01} ramps up linearly and is shared equally by both switches . During this interval, the bulk capacitors provide the output load power load.

Mode 2($t_2 \leq t \leq t_3$)

S_5 is turned OFF at instant while S_9 continues to remain ON. Now S_8 is turned on.The energy stored in the inductor, L_{01} & L_{02} during this interval is now transferred to the load through the body diode and the diode . Voltage across the auxiliary winding and the primary winding Tp is identical due to their series phasing and equal number of turns.This allows simultaneous and equal charging of both diodes and capacitors respectively.

Mode 3($t_3 \leq t \leq t_4$)

During this interval Switch S_{10} & S_6 remains ON and is also turned ON at time t_3 .The duty ratio for is therefore greater than 0.5. With both switches turned ON, the transformer secondary is effectively shorted and the inductor stores energy, resulting in a linear rise in its current, .Voltage across both primary is zero, so load power is supplied by the discharge of the bulk capacitors.

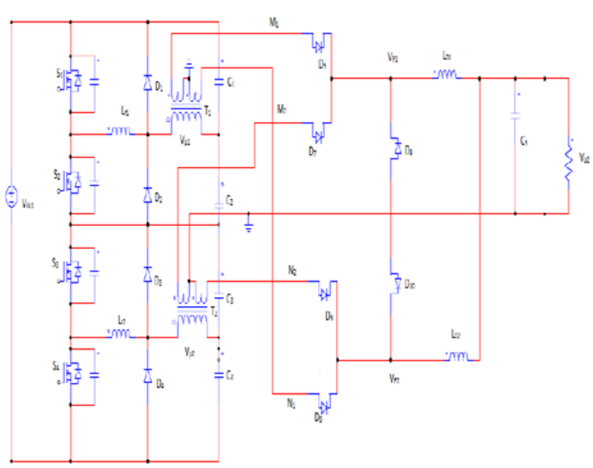
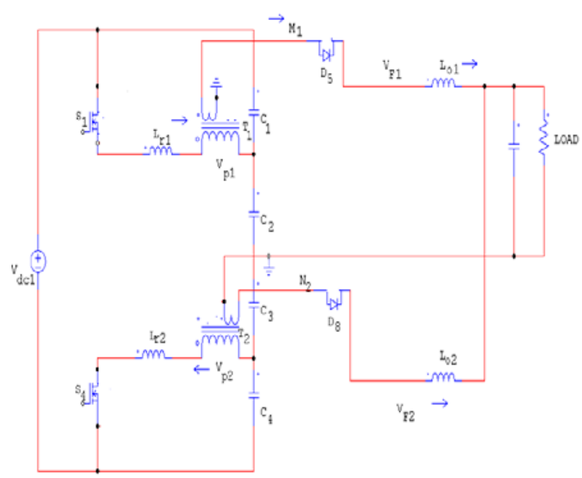


Fig.3. Proposed converter during forward mode



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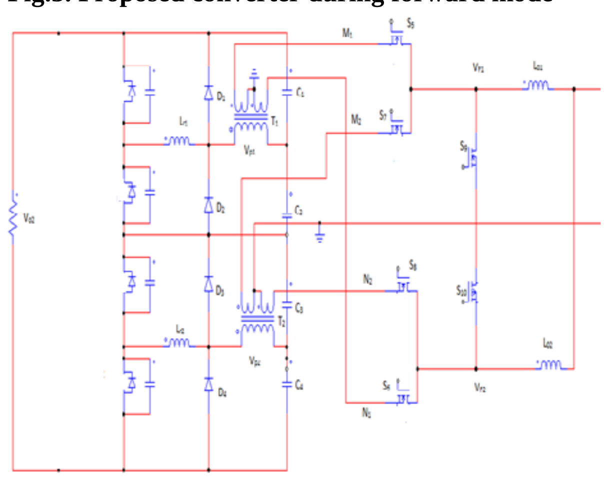
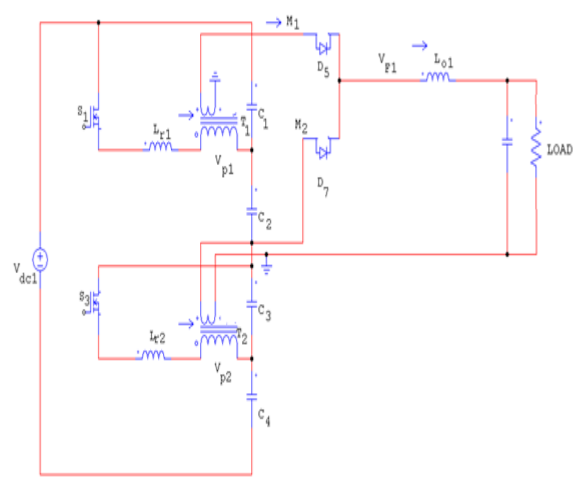


Fig.4. Proposed converter during reverse mode



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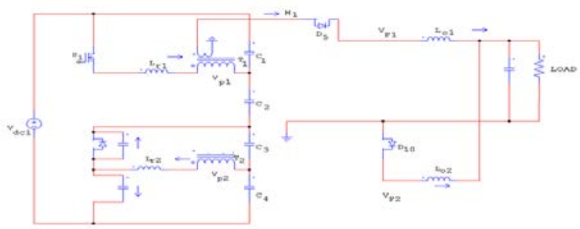

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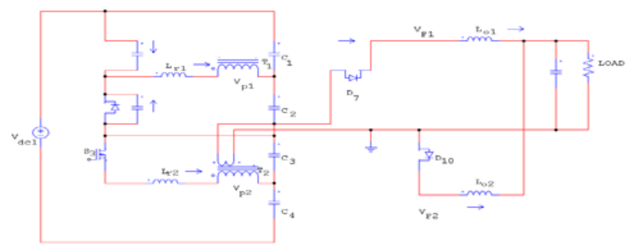

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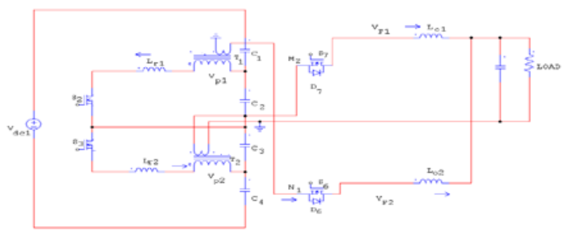
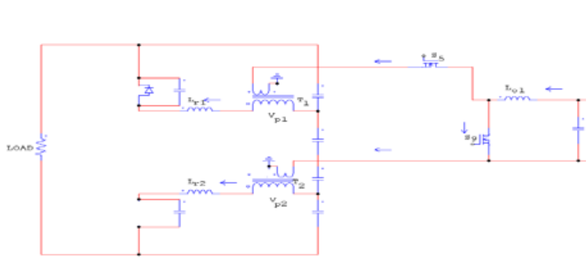


(e)

Fig. 4. Buck Modes of operation. (a) Mode 1 ($t_1 \leq t \leq t_2$) . (b) Mode 2 ($t_2 \leq t \leq t_3$). (c) Mode 3 ($t_3 \leq t \leq t_4$). (d) Mode 4 ($t_4 \leq t \leq t_5$). (e) Mode 5 ($t_5 \leq t \leq t_6$).



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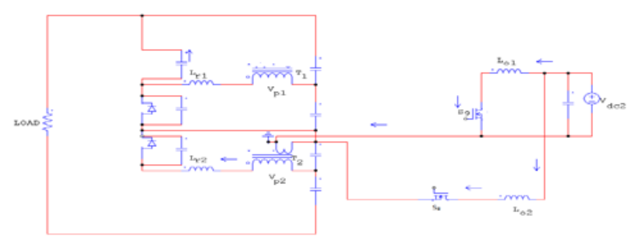

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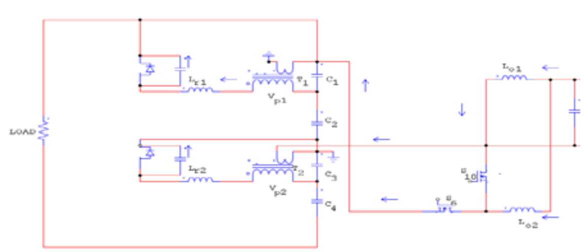

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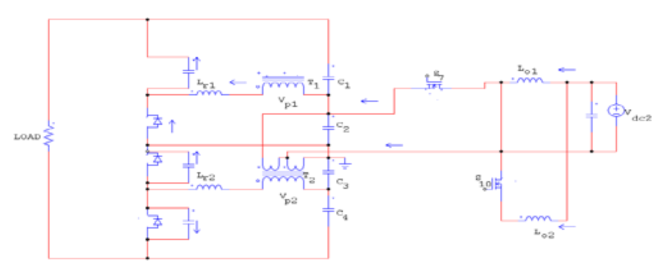

(d)

Fig. 5. Boost Modes of operation. (a) Mode 1 ($t_1 \leq t \leq t_2$) . (b) Mode 2 ($t_2 \leq t \leq t_3$). (c) Mode 3 ($t_3 \leq t \leq t_4$). (d) Mode 4 ($t_4 \leq t \leq t_5$).

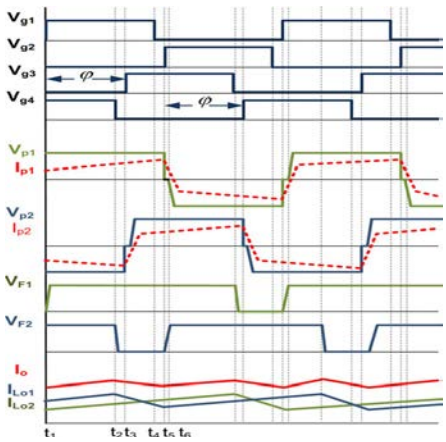

Fig.6.Typical waveform describing buck mode of operation.

Mode 4($t_4 \leq t \leq t_5$)

Converter operation during this interval resemble like t_2 to t_3. During the interval S_{10} & S_7 remains ON. The stored energy is transferred to the primary side of the converter through the switch conducting on the secondary side, and thus delivering power from load to source respectively.

4. DESIGN PROCEDURE

A.Transformer turns ratio and resonant inductor

The transformer turns N can be obtained as,

$$N = \frac{V_{dc} D + \sqrt{(V_{dc} D)^2 - 128 V_o f_s L_r I_o}}{8V_o} \tag{7}$$

This shows the relation between the transformers turns ratio and the resonant inductance of the transformers.

B. Delaytime for ZVS

Based on (5), to have ZVS the delay time, which is the amount of time between the turning OFF of one HB switch and the turning ON of another in the same HB is

$$t_{d1} < \frac{\Pi}{2} \sqrt{L_r (C_{Q1} + C_{Q2})} \tag{8}$$

$$t_{d2} < \frac{\Pi}{2} \sqrt{L_r (C_{Q3} + C_{Q4})} \tag{9}$$

This is based on a quarter of the resonant cycle interaction between L_r and the output capacitances of the switches.

5. SIMULATION RESULTS

The simulation result for buck mode of operation is given below:

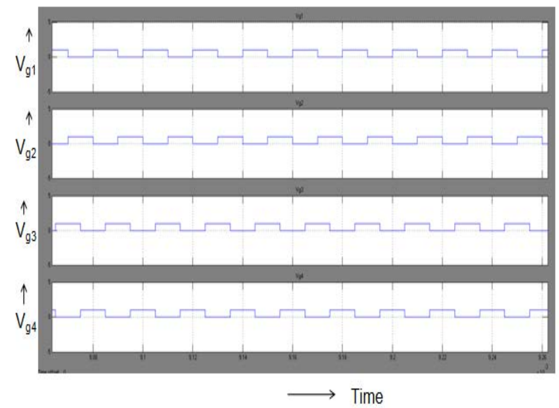

Fig. 7. Gate pulse for switches S_1, S_2 ,S_3 ,S_4 switches

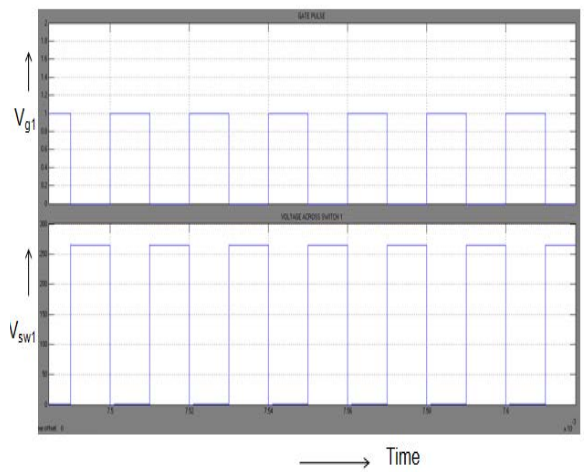

Fig. 8. ZVS switching waveform for switch S_1

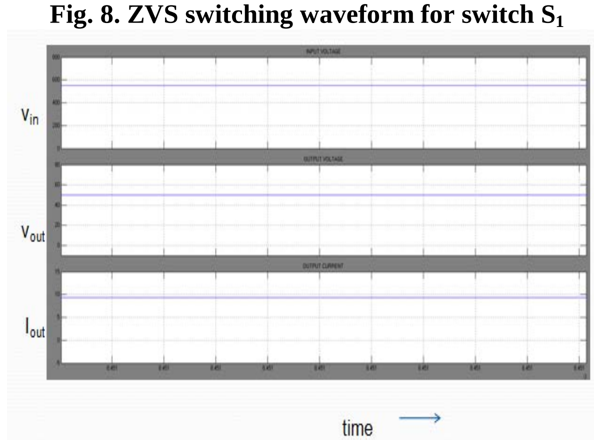

Fig. 9. Input voltage, output voltage and current waveform in buck mode operation (V_{in} = 550 V , V_{out} = 50 V ,I_{out} = 12 A)

The simulation result during boost mode of operation is given below:

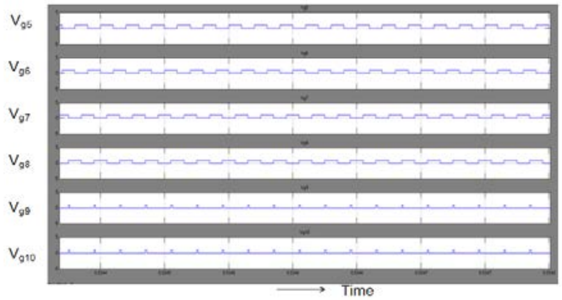

Fig. 10. Gate pulse for switches S_5, S_6 ,S_7 ,S_8 , S_9 ,S_{10} switches.

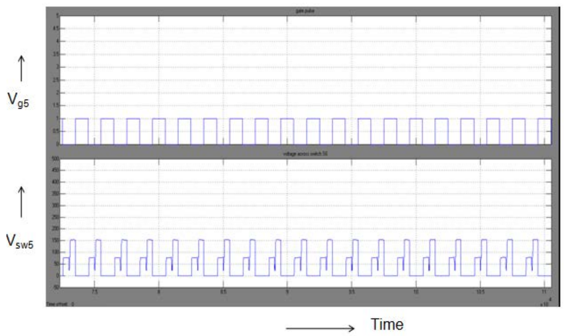

Fig. 11. ZVS switching waveform for switch S_6

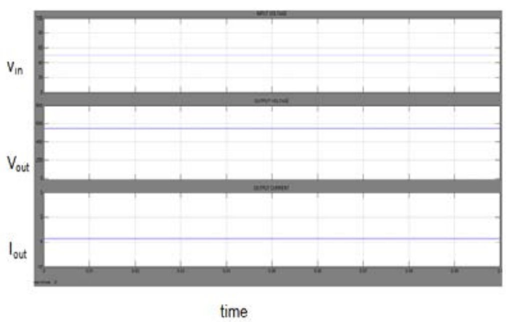

Fig.12.Input voltage, output voltage and current waveform in boost mode operation (V_{in} = 50 V , V_{out} =500-550 V ,I_{out} = 4.4 A)

6. CONCLUSION

A new three-level bidirectional dc/dc converter proposed in this paper which operates with zero-voltage-switching (ZVS) from full-load to near no-load conditions with hardly any circulating freewheeling primary current due to its novel structure when it is operating in buck mode. Since the converter has little primary circulating current and its switches are exposed to only half of the input voltage, it has high efficiency even under light loads and provides power transfer from source to load(To upstream converter). Similarly during boost mode we get reversible power from load to source(To downstream converter). This topology provides bidirectional power flow which is simple and efficient. In this project the bidirectional DC-DC converter with wide range ZVS has been simulated using MATLAB software and its feasibility is checked with the simulated results as shown. The prototype for this converter is yet to be developed.

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