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High Gain Zero Voltage Switching Bidirectional Converter with Reduced Number of Switches

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Abstract: A non-isolated bidirectional DC-DC Converter has been proposed in this paper for charging and discharging the battery bank through single circuit in applications of Uninterruptible Power Supplies (UPS) and the hybrid electric vehicles. The proposed bidirectional converter operates under zero voltage switching (ZVS) condition and provides large voltage diversity in both the modes of operation. This enables the circuit to step up the low battery bank voltage to high DC link voltage and vice versa. The bidirectional operation of the converter is achieved by employing only three active switches, a coupled inductor and an additional voltage clamped circuit. Complete description of the operation principle of the circuit is explained and design procedure of the converter has been discussed. The experimental results of a 300W prototype of the proposed converter confirmed the validity of the circuit. The maximum efficiency of 96% is obtained at half load for boost operation mode, and 92% for buck mode of operation.
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Keywords: Bidirectional DC-DC Converter, Zero voltage switching (ZVS), Coupled inductor.

I. INTRODUCTION

Bidirectional DC-DC Converters are widely used in many industrial applications such as hybrid vehicles, auxiliary supplies, and in battery charging/discharging DC converters in UPS system. Usually battery bank are the backup energy source which provides very low voltage at the input of the bidirectional converter. Although, a string of batteries connected in series can provide a high input voltage, but still it has some disadvantages. A larger battery bank increases the size and cost of the system. Also if there is a slight mismatch in the batteries voltage or difference in the batteries temperature within the string, it will cause charge imbalance in the battery bank [1]. This study therefore focuses on the analysis and design of a high efficiency bidirectional converter with high voltage conversion ratio, which helps in reducing the number of batteries in order to elude a larger battery bank. The bidirectional converter may be transformer isolated [2] or non-isolated [3-10]. Isolated bridge-type bidirectional converters are probably the most popular topology in high power applications. However, the major concerns of this topology are high switching losses, excessive voltage and Current stresses, and significant conduction losses because of the increased in the number of switches [6]. Hence, their practical implementation is quite complex.

With incorporation of coupled inductor and zero voltage switching (ZVS), Non-isolated bidirectional converters has attracted special interest due to high conversion ratio, reduced switching losses, and simplicity in design. These types of topologies are highly cost effective and acceptable due to high efficiency improvement, and considerable reduction in the weight and volume of the system. Several topologies of the non-isolated converters have been proposed so far [3-6]. A ZVS bidirectional converter with single auxiliary switch has been proposed in [3]. Although the main switches operate under ZVS which increase the efficiency of the system, but the auxiliary switch still performs hard switching and the converter offers very limited voltage diversity [7]. Other high voltage gain bidirectional converters have been proposed in [8-11]. These converters provide high voltage gain in both the boost and buck mode of operation but at the cost of high number of active switches and extra auxiliary circuit components used in the circuit. This adds more complexity in the control circuitry, with high size and cost. According to the analysis of the drawbacks related to the aforementioned topologies, this paper proposes a new non-isolated bidirectional DC-DC converter with coupled inductor. The proposed converter has following advantages.

1. High Voltage Gain in both the buck and boost mode
2. Only three active switches are used to perform bidirectional operation.
3. Less number of passive components is used in the circuit
4. Zero voltage switching (ZVS), synchronous rectification, and voltage clamping circuit are used which reduces the Switching and conduction losses.

This paper is organized as follows: the operation of proposed topology is explained in section II. Design considerations are presented in section III, followed by experimental results in section IV and conclusion in Section V.

II. OVERVIEW OF BLDC MOTOR

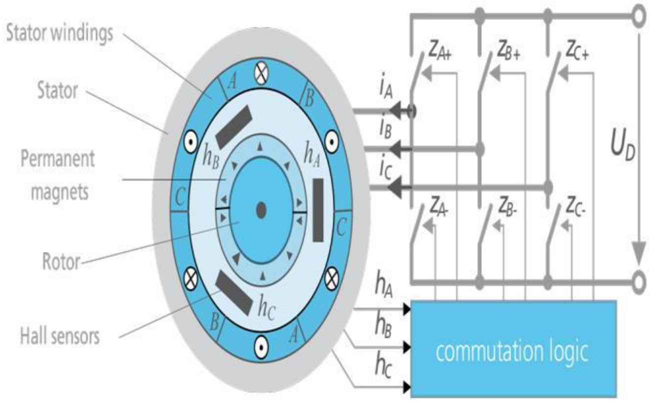

Fig.1. Input inverting stage of BLDC motor.

The control of PMBLDC motors can be accomplished by various control techniques using conventional six pulse inverters which can be classified in two broad categories as voltage source inverter (VSI) and current source inverter (CSI) based topologies. The controllers can further be divided on the basis of solid state switches and control strategies. The BLDCM needs rotor-position sensing only at the commutation points, e.g., every 60°electrical in the three-phases; therefore, a comparatively simple controller is required for commutation and current control. The commutation sequence is generated by the controller according to the rotor position which is sensed using Hall sensors, resolvers or optical encoders. These sensors increase the cost and the size of the motor and a special mechanical arrangement is required for mounting the sensors. The components are DC-AC inverter, DC-DC converter, battery, and electric BLDC motor. DC-AC inverters supply voltage to the electric motor from the battery and also supply utility loads such as air conditioning and AC power outlet.

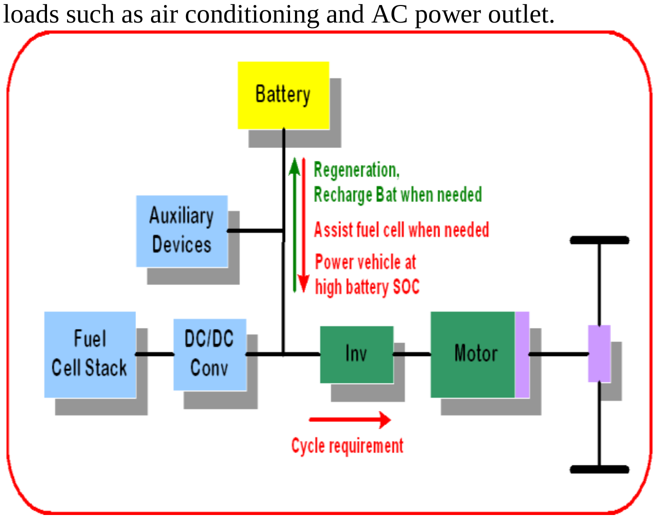

Fig.2. Driving process of high voltage BLDC motor.

DC-DC converters supply voltage to various vehicular loads set to operate at different voltages. In the near future, high power DC-DC converters will be needed for EVs since the vehicular power requirements are continuously increasing due to which the present day 12- V/14-V electrical system will be replaced by 42-V/300-V architecture. DC-DC converters are well developed for low and medium power applications, whereas development of highly efficient and cost effective high power DC-DC converters for vehicular applications is in continuous progress. This is partly due to the stringent Electromagnetic Interference (EMI) standards and also due to temperature related issues. The boost dc voltage is the input of the BLDC motor.

III. HARD SWITCHING VS SOFT SWITCHING

Recently, switch-mode power supplies have become smaller and lighter due to higher switching frequency. However, higher switching frequency causes lots of periodic losses at turn ON and turn OFF, resulting in increasing losses of whole system. Semiconductors utilised in Static Power Converters operate in the switching mode to maximise efficiency. Switching frequencies vary from 50 Hz in a SCR based AC-DC Phase Angle Controller to over 1.0 MHz in a MOSFET based power supply. The switching or dynamic behaviour of Power Semiconductor devices thus attracts attention specially for the faster ones for a number of reasons: optimum drive, power dissipation, EMI/RFI issues and switching-aid- networks. Present day fast converters operate at much higher switching frequencies chiefly to reduce weight and size of the filter components. As a consequence, switching losses now tend to predominate, causing the junction temperatures to rise. Special techniques are employed to obtain clean turn-on and turn-off of the devices. This, along with optimal control strategies and improved evacuation of the heat generated, permit utilisation of the devices with a minimum of deration.

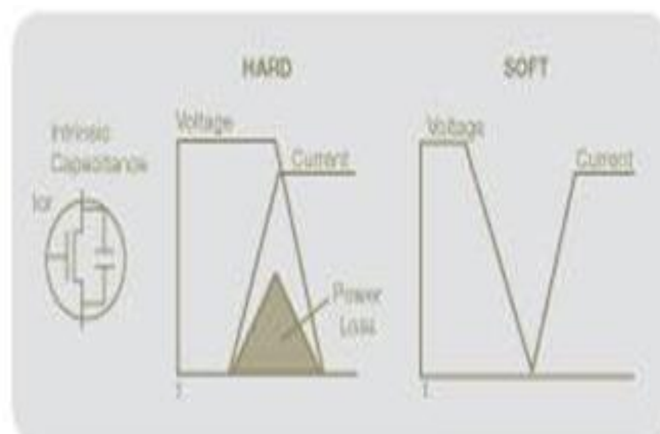

Fig.3. Hard and Soft Switching Waveform.

IV. METHODS OF SOFT SWITCHING.

A. Design a High Frequency PWM Subsystem.

The carrier waveform used is Saw tooth waveform instead of Triangular waveform. When the reference value is more than the carrier waveform the output PWM signal is HIGH. The switching turn ON points is determined by the saw tooth waveform used.

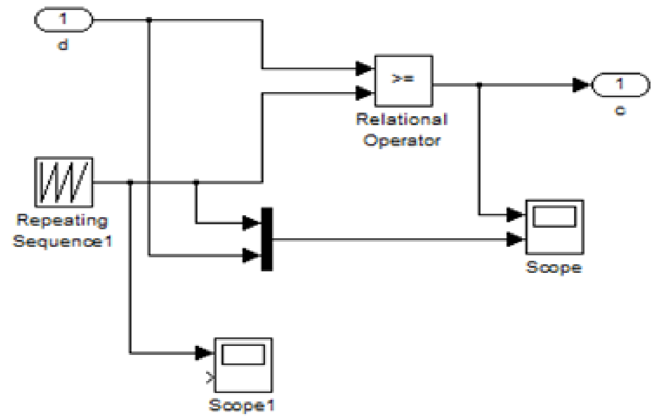

Fig.4. PWM subsystem.

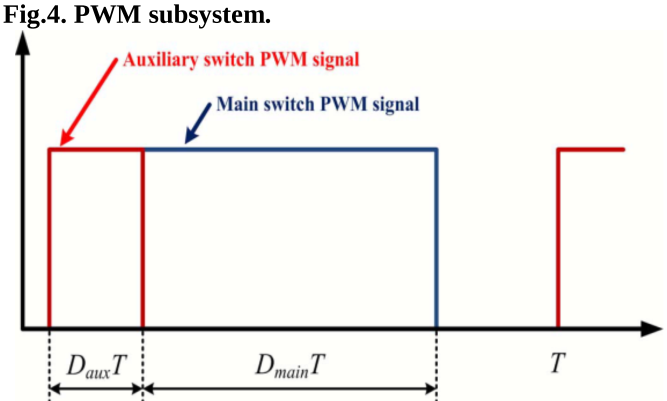

Fig.5. PWM signals of the main and auxiliary switch

The proposed Boost Converter has two switches namely main switch and auxiliary switch. The main switch has a duty ratio of 0.61 while that of auxiliary switch is 0.21. The main switch duty ratio determines the average output voltage. The function of auxiliary switch is to enable the main switch to operate soft switching. First the auxiliary switch is turned ON then the main switch in turned ON after some time delay. The resonant loop of the resonant inductor (Lr) and resonant capacitor (Cr) is completed by the turning ON of the auxiliary switch. By the help of resonance the auxiliary switch is made to operate at ZCS. As the snubber capacitor is discharged the current of the resonant loop flows through the anti-parallel diode of the main switch. By turning ON the main switch the ZVS is assured. As the resonant capacitor is fully discharged the auxiliary switch is turned OFF. The PWM signal of the main switch is given some delay compared to auxiliary switch. The phase difference is obtained by delaying the carrier waveform. The main switch is turned ON while the auxiliary switch is still in the ON state.

B. Configuration of the proposed HI-Bridge Boost conve-rter.

The proposed converter is shown in Fig. 6. The main switch (IGBT) and the auxiliary switch (IGBT1) of the proposed circuit enable soft switching through an auxiliary switching block, consisting of an auxiliary switch, two resonant capacitors (Cr and Cr2), a resonant inductor (Lr), and two diodes (D1 and D2). The following assumptions are made

1. All switching devices and passive elements are ideal.
2. The input voltage (Vin) is constant.
3. The output voltage(Vo) is constant. (Output capacitor
4. Co is large enough).
5. The recovery time of all diodes is ignored.

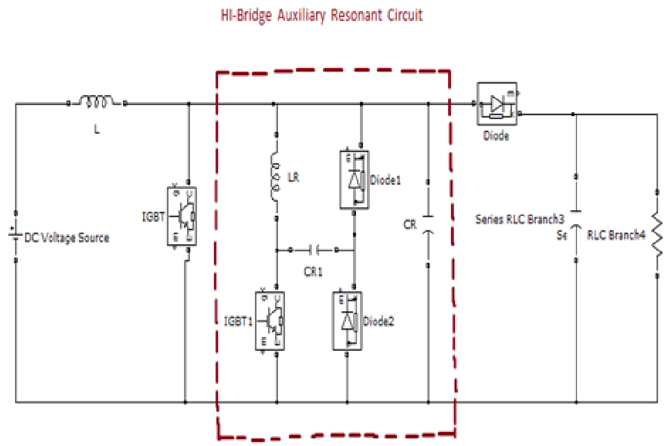

Fig.6. Schematic of the proposed soft-switching boost converter

C. The main switch and auxiliary switch.

There are two switches in this paper. One is the main switch deal with a duty ratio and the other one is the auxiliary switch enables the main switch to operate with a soft switching. The carrier, reference and pulse width modulation(PWM) waveforms of the main switch and auxiliary switch are illustrated in Fig. 4. After the auxiliary switch is turned on, the main switch is turned on. If the auxiliary switch is turned on, the resonant loop of the resonant inductor(Lr) and resonant capacitor(Cr) is made. The auxiliary switch operates with ZCS using the resonance. The current of the resonant loop flows across the anti-parallel diode of the main switch after the snubber capacitor is discharged. Thus, ZVS area is guaranteed by turning on the auxiliary switch. A point the auxiliary switch is turned off is the time the energy of the resonant capacitor(Cr) is fully discharged. The main switch set a voltage gain. A transfer function of the proposed soft switching boost converter is same to the conventional boost converter and that is given by the equation (1) .

$$Gv = (Vout/Vin) = 1/(1-D) \quad (1)$$

Where Gv is a voltage gain and D is a duty ratio. The PWM has to be made with a delay between the main switch and auxiliary switch. A phase difference can be obtained by delaying the carrier waveform. The main switch always has to be turned on during the auxiliary switch turns on. Points which switches turn on at have to be fixed to realize a soft switching without resonance failure. A Sawtooth waveform is used as a carrier waveform instead of a triangular one. If a reference value is upper than a carrier one, the PWM output signal becomes high. Thus, switching turn on points can be fixed by using the sawtooth waveform.

V. SIMULATION AND OUTPUT

A. PWM Subsystem output waveform.

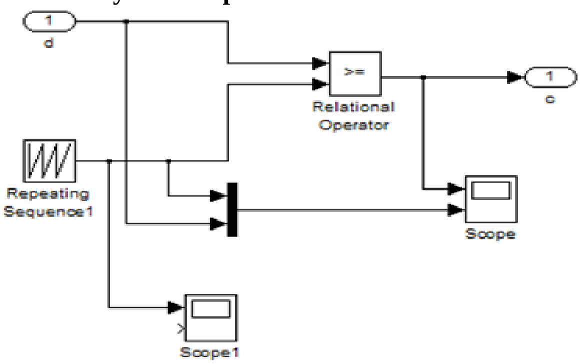

Fig.7. PWM Subsystem.

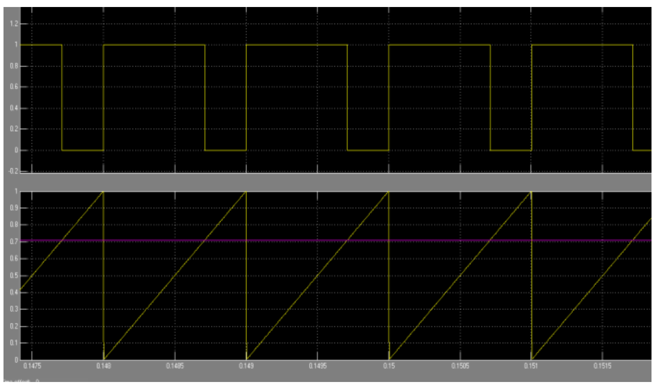

Fig.8.PWM subsystem and output waveform in MATLAB.

B. Simulation of HI-bridge soft-switching boost converter output waveform.

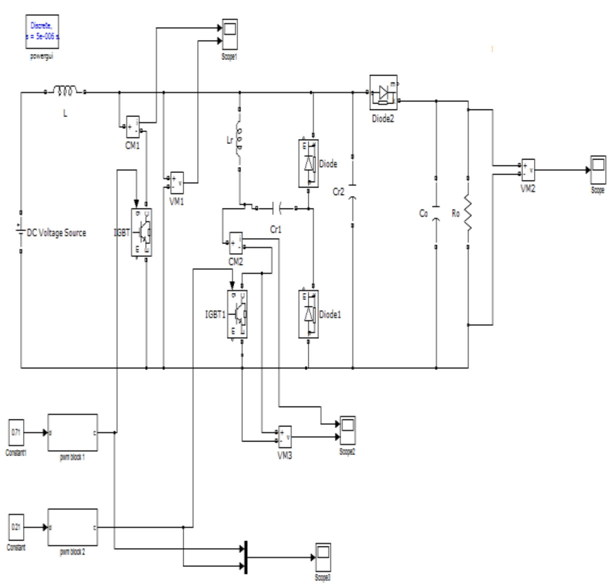

Fig.9. Simulink model of HI-bridge boost converter using auxiliary boost converter.

The above proposed boost converter with auxiliary resonant circuit is simulated in MATLAB-SIMULINK. The values of the circuit parameters are given below:

Table1. Key Data

Parameters	Values
Input voltage (Vin)	130-170[V]
Output voltage (Vo)	400[V]
Switching Freq.(fsw)	30[]KHz]
Resonant Cap. (Cr)	3.3[nF]
Resonant Cap. (Cr2)	30[nF]
Resonant Ind. (Lr)	20[µH]
Main Inductor (L1)	560[µH]

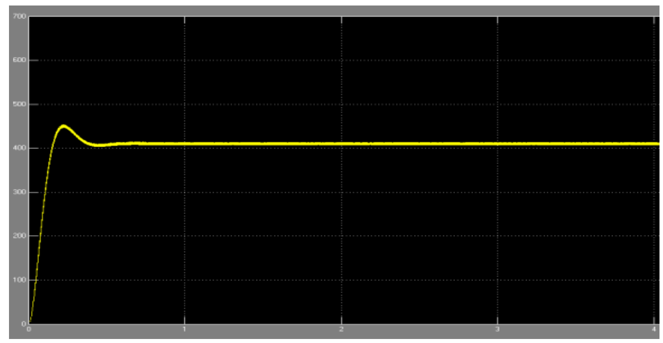

Fig.10. Output Voltage Vs Time Waveform.

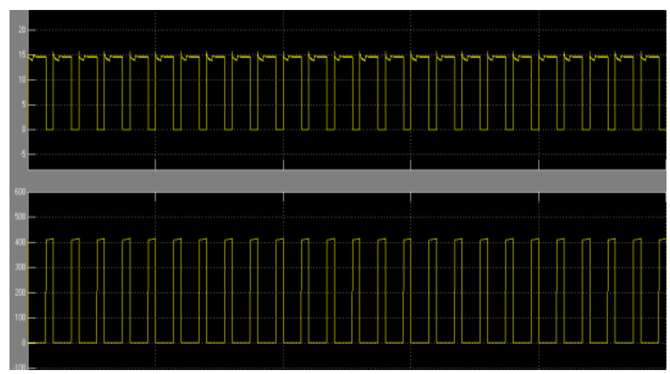

Fig.11. Main switch Current and Voltage.

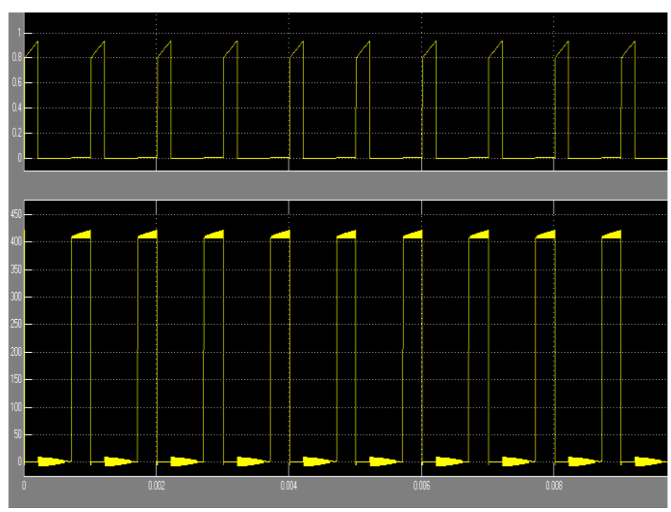

Fig.12. Auxiliary switch Current and Voltage.

VI. DESIGN PROCEDURE

The following design procedure is based on the soft-switching turn-ON and turn-OFF requirements of the main switch, the main diode, and the auxiliary switch.

A. Resonant Capacitor (Cr)

The resonant capacitor (Cr) is selected to allow ZVS of the main switch. The charging time of the resonant capacitor (Cr) must be longer for ZVS of the main switch. Thus, for the resonant capacitor (Cr), it is more than ten times the output capacitance of the main switch. Assume that the maximum current of the resonant inductor is IL max, and the sum of the two inductor currents is the charging current of the resonant capacitor (Cr). In this case, the minimum resonant capacitor (Cr) is equal to 20 times the output capacitance of the main switch.

B. Parameters Design

D = 1- (Vin (min) * η)/ Vout
D= Duty Cycle.
Vin (min) = Minimum input voltage.
Vout = Desired output voltage.
Ƞ = Efficiency of Converter

$$L = (Vin/\Delta IL) * (Vout - Vin) * (1/Vout) * (1/fs)$$

L = Inductance of main Inductor.
fs = Switching frequency.
ΔIL = Estimated Inductor ripple current.
ΔIL = (0.2 - 0.4) * Iout (max) * (Vout/Vin).
Iout (max) = Maximum output current.
Cout (min) = (Iout (max)/fs) * D/ΔVout.
Cout (min) = Minimum output Capacitance.

VII. EXPERIMENTAL RESULTS

A 300W protype has been built to confirm the feasibility of the proposed circuit. The circuit operated between LVS voltage VL = 24V, and HVS voltage VH =200V. The switching frequency is 20 KHz. The Switches S1-S3 used in the circuit are IPW60R045CP MOSFETs. Coupled inductor is designed using PQ40-40 with magnitising inductance of 24uH, and turns ratio N = 2.5. An inductor L1 has 80uH inductance, so the size is very small. Besides C1 and C2 consist of 4.4uF ceramic capacitors. The diodes D1~D3 used are ultrafast recovery diodes UF5408. Thus all the axilary components are not adding considerable in the size of the circuit. A low cost PWM controller TL494 is employed for controlling the switches of the bidirectional converter. The dead time between the switching PWM is 5us which helps in ZVS of the circuit. An experimental prototype was built to confirm its feasibility. Fig 8 and Fig. 9 shows the experimental waveform during buck and boost mode of the proposed circuit respectively.The voltage stress across both the switches S1 and S2 is about 50V which is quite small as compare to HVS (200V). The voltage across the Switch S2 is quite low, and conduction current in the coupled inductor is smoothened as shown in the Fig.8. Fig.7 shows the Zero voltage switching in switch S1 during buck mode of operation. Fig. 10 gives the experimental results which shows maximum efficiency of about 96% during boost mode and 92% during buck mode of operation Thus utilizing synchronous rectification and soft switching reduces the switch losses and increases the efficiency of the system. The

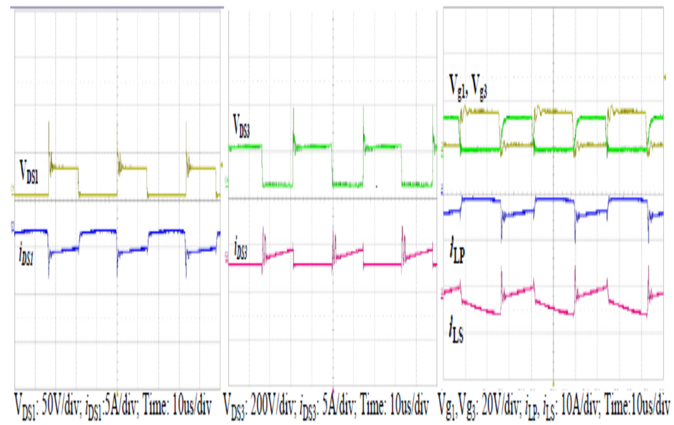

Fig.13. Experimental Waveform of Drain to Source Switch voltages and Inductor current during Buck Mode

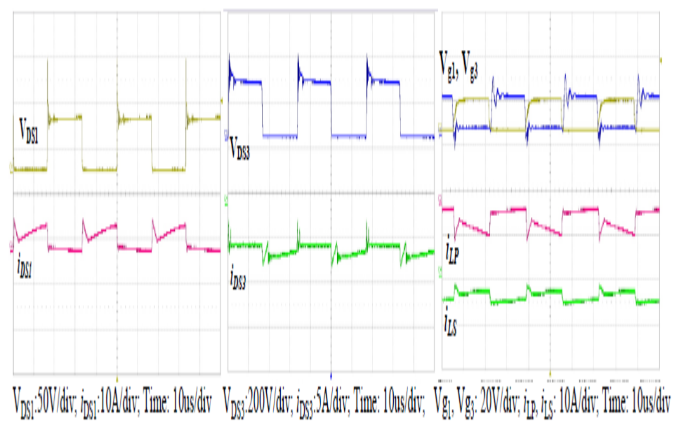

Fig.14. Experimental Waveform of Drain to source voltages and Inductor current during Boost mode

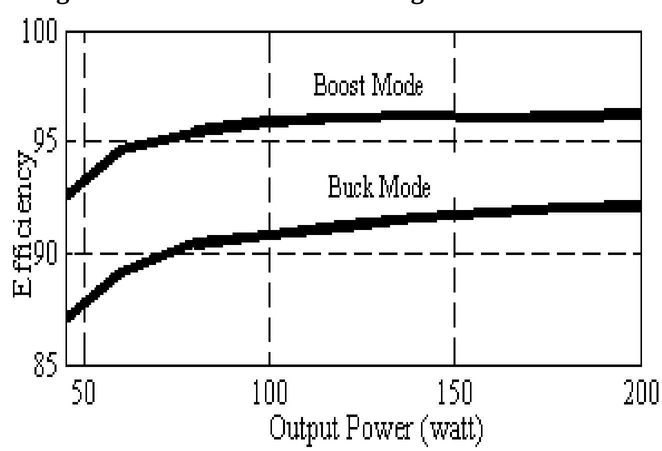

Fig.15. Experimental Efficiency Graphs.

Efficiency during buck mode is less than boost mode due to utilization of an additional switch S2 which is not used in the boost mode. Table. I shows the comparison of different bidirectional converters recently published. The voltage conversion ratio of the proposed converter shows more diversity as compared to [9] and [10], with less no of switches. [11] shows high gain ratio but with five switches which increases the size and cost of the circuit. The size of the proposed circuit is considerable small with small heat sink for the given power rating, and only few passive auxiliary components help in operation under ZVS.

VIII. CONCLUSION

This paper presents a non-isolated ZVS bidirectional DC-DC converter. The most promising features of the converter are high voltage conversion ratio in both modes of operation, with less number of active switches, and low voltage & current stresses on the switches. The operation principle of each mode has been explained and the design steps of the converter are discussed. The experimental results of the proposed converter shows exemplary results with high efficiency of about 96% and 92% in boost and buck modes of operation respectively.

TABLE I. Comparison of Different Topologies

Topology Features	Conv.	[11]	[9]	[10]	Proposed Topology
Switches	2	5	4	4	3
M_{BOOST}	1/(1-D)	$\frac{1+N}{(1-D)}+N$	$\frac{2+N}{D}$	$\frac{2}{1-D}$	$\frac{2+ND}{1-D}$
M_{BUCK}	D	$\frac{D}{1+N+DN}$	$\frac{D}{N+2}$	$\frac{D}{2}$	$\frac{D(1-D)}{2N(1-D)^2+1}$
Efficiency (%)	90	96	95	94	96
Size	Small	Large	Medium	Medium	Small
Estimated Cost(US $)	-	~172	~118	~136	~116

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