HIGHLY EFFICIENT NATURALLY CLAMPED BIDIRECTIONAL PUSH-PULL DC/DC CONVERTER

Deepak Kumar Nayak[1] , S. Sheik Aalam[2] , R. Murugan[3] , K. Selvakumarasamy[4], and B. Nadheer Ahmed[5]

[1]Department of Electronics and Communication Engineering, Dhanalakshmi college of Engineering, Tambaram,Chennai, Tamilnadu, India
[2,3,4,5]Department of Electronics and Communication Engineering, Aalim Muhammed Salegh College of Engineering,Chennai,Tamilnadu, India

Abstract: *This paper proposes a secondary modulation based zero current switching (ZCS) current fed push-pull DC/DC converter. Due to the secondary modulation method, the proposed circuit achieves ZCS of the primary switches and ZVS of the secondary switches. The converter has advantages like (a) clamp circuits or snubber circuits are not required. (b) Soft switching of the converter is load independent (c) reduced switching stress (d) high efficiency. Steady state analysis, design, and implementation in MATLAB are presented for 20 kHz switching frequency and 19 W output power. Using the proposed converter 48 V DC is reduced to 12 V DC and the performance of the converter is compared with a conventional push-pull converter.*

Key words: *Current fed converter, Voltage fed converter, DC/DC converter, Zero voltage switching, Zero current switching, Soft switching.*

1. Introduction

Bidirectional DC/DC converters allow transfer of power in forward and reverse directions. These converters are beneficial in applications like DC uninterruptable power supplies, telecom power supplies, battery charger circuits and computer power system [1]. High frequency transformer isolated converters are preferred to non-isolated converters due to the galvanic isolation and flexible of system configuration [2].

The transformer isolated bidirectional DC/DC converters could be either voltage fed [3-6] or current fed [7-11]. In voltage fed converters, the switches are turned-on at zero voltage. So, conduction losses of the primary side switches are reduced but some of the disadvantages of the voltage fed converters are (a) high pulsating current at the input (b) Rectifier diode ringing (c) Duty cycle loss if inductive output filter is used (d) High circulating current through the devices.

Current fed converters give smaller input current ripple, small diode ringing, and no duty cycle loss. For high voltage converters, current fed converters are very useful. In [12], current fed bidirectional full bridge DC/DC converter for high power application is proposed. But RCD passive snubber is used to absorb the surge voltage for soft switching of the switches. Due to the RCD snubber, energy absorbed by the clamping capacitor is dissipated in the resistor, which results in low efficiency.

In [13], current fed bidirectional half bridge DC/DC converter is analyzed. Active clamp circuit is used to absorb the serge voltage. In [14], current fed bidirectional push-pull DC/DC converter is analyzed. The leakage inductance and the parasitic capacitance are utilized to achieve ZCS but resonant current is much higher than the input current which increases the current stress of the devices.

The above literature does not deal with secondary modulation based natural clamped soft switching bidirectional DC/DC converter. In this paper, a soft switching push-pull bidirectional DC/DC converter is proposed with secondary modulation based natural voltage clamping, ZCS of the primary switches and ZVS of the secondary switches. The proposed converter can work in forward mode (current fed mode) as well as backward mode (voltage fed mode). In the forward mode (current fed mode), the converter acts as a current fed push-pull DC/DC converter. In the backward mode (voltage fed mode), the converter acts as a voltage fed full bridge DC/DC converter with inductive filter. Due to the space limitation of this paper, only forward mode (current fed mode) operation is described in detail. The simulation results using MATLAB are presented for 19 W/12 V output in current fed mode. The proposed converter is very simple to implement and provides soft switching in a wide range with high efficiency. Although the converter can work in both directions, only forward mode is discussed here.

2. Operation of forward mode (current fed mode) of the proposed converter.

The proposed basic power circuit topology is shown in Fig.1 by using push-pull DC/DC converter. The following assumptions are made during the analysis of the converter:

(a) Inductor L is assumed large so that the current through it can be considered as constant.

(b)The magnetizing inductance of the transformer is assumed to be very large.

(c) The series inductors L1 and L2 include leakage inductance of the transformer.

The operating waveforms of the current fed mode are shown in Fig. 2.

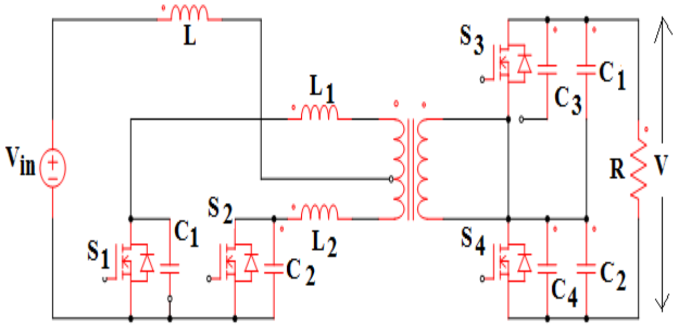


Fig.1. Proposed bidirectional DC/DC converter

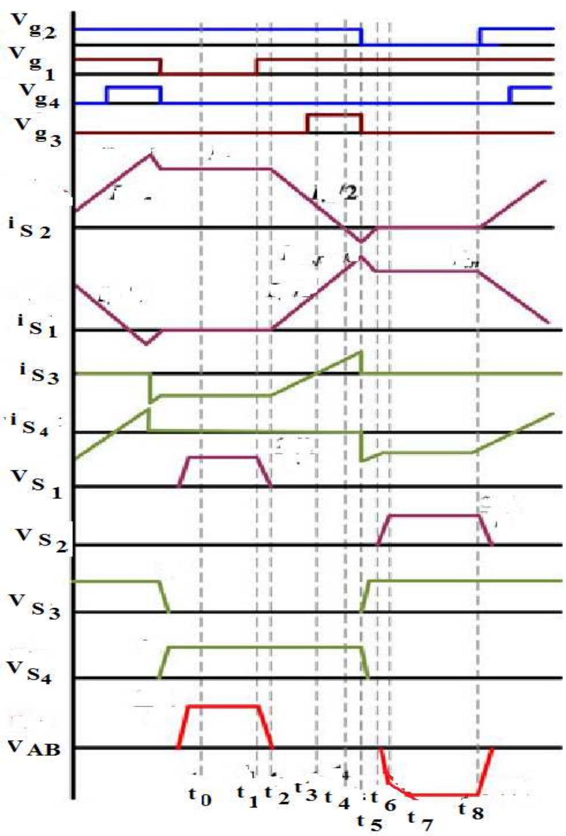


Fig.2.Waveforms of the proposed bidirectional DC/DC converter

Interval 1 (t_0 to t_1)

In this interval, primary side switches S_2 and secondary body diodes of S_3 (D_3) are conducting. So, positive power transfer happens in this interval. Voltage across non conducting switch S_1 at the primary side is 2V/n. Where n is the turns ratio of the transformer. At the end of this interval at t=t_1,

$$i_{L_1}(t_1) = i_{S_1}(t_1) = 0\,,\; i_{S_2}(t_1) = I\,,$$

$$i_{D_3}(t_1) = \frac{I}{n}\,,\; V_{S_4}(t_1) = V$$

Interval 2 (t_1 to t_2)

At t=t_1, S_1 is turned-on. So, the snubber capacitor of S_1, i.e., C_1 discharges in a very short period of time.

Interval 3 (t_2 to t_3)

In this interval, both the primary switches S_1 and S_2 are conducting. Current through S_1 decreases and that through S_2 increases linearly.

$$i_{L_1} = i_{S_1} = \frac{2V}{n(L_1 + L_2)}(t - t_2) \qquad (1)$$

Where V is the output voltage and I is the input current of the converter.

$$i_{L_2} = i_{S_2} = I - \frac{2V}{n(L_1 + L_2)}(t - t_2) \quad (2)$$

(2)

$$i_{D_3} = \frac{I}{n} - \frac{4V}{n^2(L_1 + L_2)}(t - t_2) \qquad (3)$$

At t=t_3, D_3 and D_4 are conducting and start commutating naturally. So, S_3 and S_4 are gated at ZVS turn-on. At t=t_3,

$$i_{L_1}(t_3) = i_{L_2}(t_3) = \frac{I}{2}\,,\; i_{S_1}(t_3) = i_{S_2}(t_3) = \frac{I}{2}\,,$$

$$i_{D_3}(t_3) = 0$$

Interval 4 (t_3 to t_4)

In this interval, S_3 is turned-on with ZVS. At t_4, S_2 commutates naturally with ZCS. At t=t_4,

$$i_{L_1}(t_4) = i_{S_1}(t_4) = I\,,\; i_{L_2}(t_4) = i_{S_2}(t_4) = 0\,,$$

$$I_{S_3}(t_4) = \frac{I}{n}$$

Interval 5 (t_4 to t_5)

Body diode of D_2 starts conducting. The secondary devices S_3 and S_4 are turned-off. At the end of this interval, S_3 is turned-off.

$$i_{S_1} = i_{L_1} = I + \frac{2V}{n(L_1 + L_2)}(t - t_4) \qquad (4)$$

$$i_{D_2} = \frac{2V}{n(L_1 + L_2)}(t - t_4) \qquad (5)$$

$$i_{S_3} = \frac{I}{n} + \frac{4V}{n^2(L_1 + L_2)}(t - t_4) \quad (6)$$

Interval 6 (t_5 to t_6)

At this interval, the secondary switch S3 is turned-off. At the end of this interval, current through D2 is reduced to zero and D2 is commutated automatically. At the end of this interval,

$$i_{L_1}(t_6) = i_{S_1}(t_6) = I \,,\; i_{L_2}(t_6) = i_{D_2}(t_6) = 0 \,,$$

$$i_{D_4}(t_6) = \frac{I}{n}$$

Interval 7 (t_6 to t_7)

At this interval, snubber capacitor of switch S_2, i.e., C_2 charges to 2V/n.

Interval 8 (t_7 to t_8)

At this interval, current through S_1 is constant. At the end of this interval,

$$i_{L_1}(t_8) = i_{S_1}(t_8) = I \,,\; i_{L_2}(t_8) = i_{S_2}(t_8) = 0 \,,$$

$$i_{D_4}(t_8) = \frac{I}{n} \,,\; V_{S_2} = \frac{2V}{n}$$

For the other half cycle, the same intervals are repeated.

3. Results and discussions

The proposed converter is simulated using MATLAB simulink. The component values and specifications of the desired converter are shown in Table 1.

Table 1 Component values and specifications

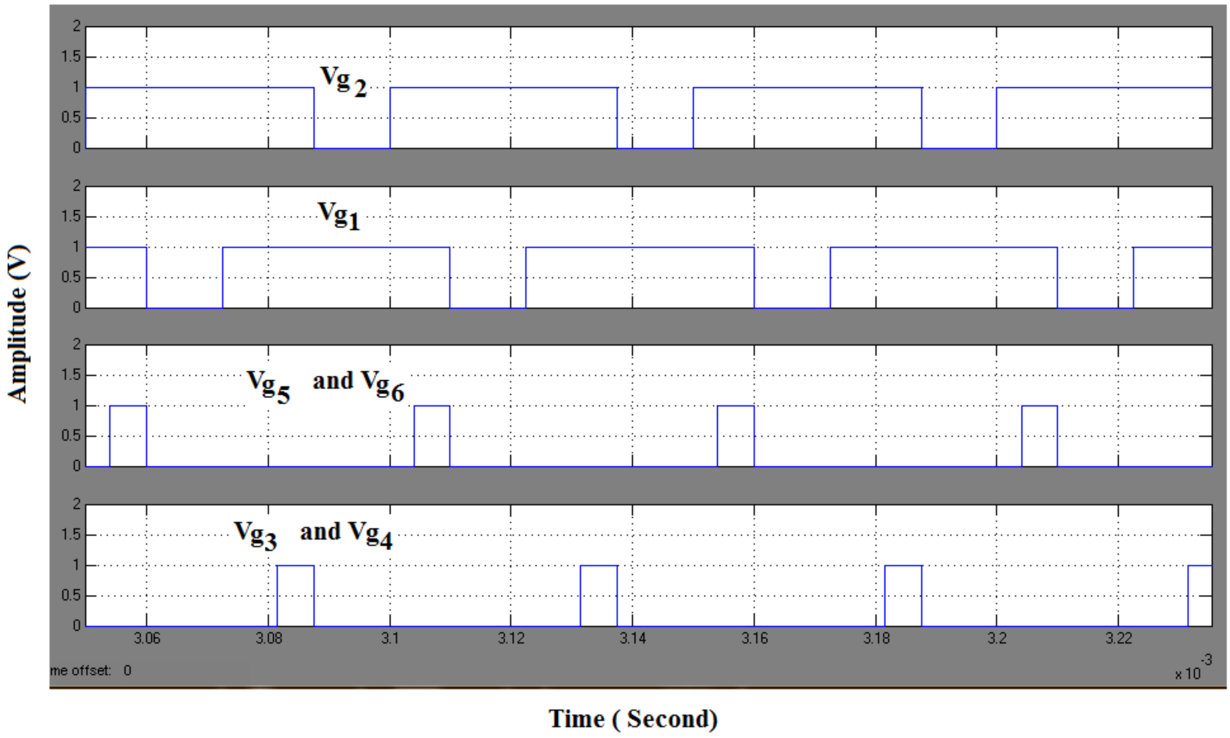
Specification	Component value
Input voltage V_{in} =48 V	Input inductance L=15 µH
Output voltage V=12 V	Primary inductance L_1= 0.11 µH
Switching frequency f= 20 KHz.	Primary inductance L_2= 0.11 µH
Power P= 19 W	Filter capacitance C= 500 µF

Fig. 3 shows the simulation output in the forward mode (current fed mode) operation. Gating signals for S_1, S_2, (S_5&S_6), and (S_3&S_4) are shown in Fig. 3 (a). It is observed that conduction of main switches S_1, and S2 are identical with the phase shift being 180^0 with each other. The duty cycle of both the switches is more than 50%. The conduction times of S_5&S_6 are same same. Similarly the conduction times of secondary diagonal switches S_3&S_4 are the same. The duty cycle of S_3,S_4,S_5, and S_6, are less than 50%. Fig.3 (b) shows current through the input inductor and voltage V_{AB}. It is observed that voltage across the primary switch is naturally clamped at voltage 2V/n.

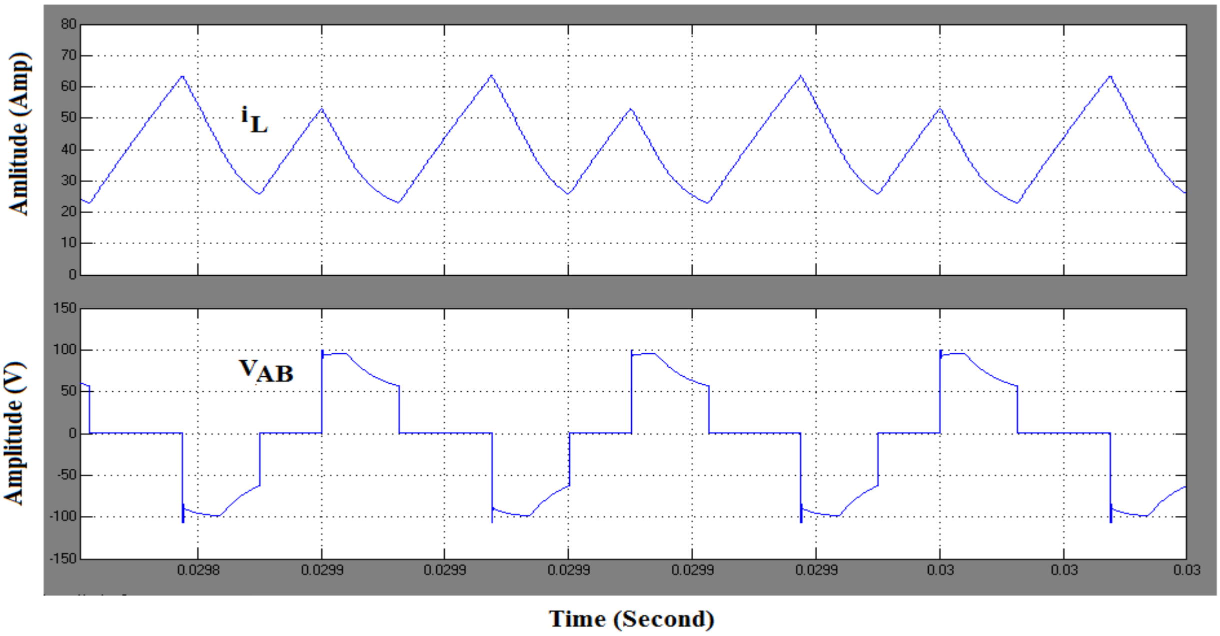
Fig. 3 (c) shows current waveforms of the primary switches S_1 and S_2. We observe that primary switch currents are diverted from one switch S_1 to the other switch S2 and vice versa, i.e., when the current through one switch is increasing, the current through the other switch is decreasing. The negative primary currents imply that before the switches are turned-off, body diodes of the switches conduct which ensures ZCS turn-off of the primary switches. Fig. 3 (d) shows the secondary voltage of the transformer. Fig. 3 (e) shows gate voltage of the switch S_6,(V_{g6}), drain voltage of the switch S_6, (V_{d6}), and current across the switch S_6.We observe that gate voltage of the switch S_6 ,(V_{g6}) is applied when drain voltage of the switch S_6, (V_{d6}) is already zero. So, it provides ZVS turn-on for the secondary switch S_6.In secondary switches, body diode conducts prior to switch conduction for providing ZVS turn-on. Fig. 3 (f) shows the output voltage and current at a load resistance of 5 Ω.

Table 2 shows the performance of the proposed DC/DC converter. As shown in Fig.4, one conventional converter is taken for comparison of the proposed converter with the conventional converter. It has been found that the proposed converter's efficiency is higher than that of the conventional converter. We observe from Fig. 4 that although the efficiency curve decreases at higher load but over a wide load current range, it remains high and flat.

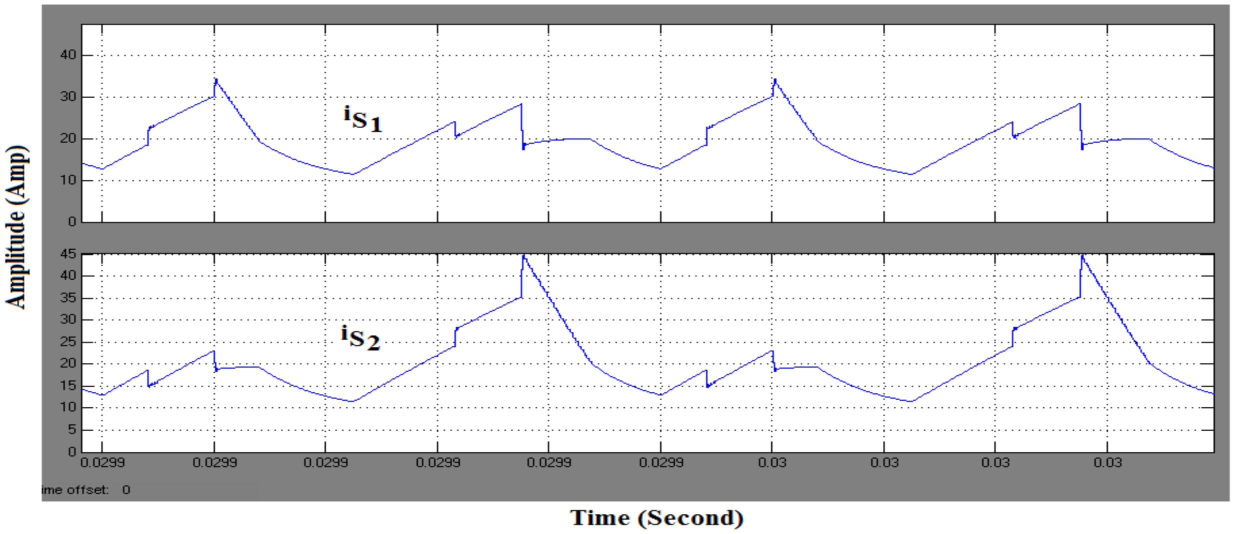
Table 3 shows the cost analysis comparison of the proposed converter with the conventional converter (8). The cost of the proposed system is less than existing system due to the presence of low cost PIC Microcontroller and reduced number of switches. However, the operating frequency of FPGA is higher than that of PIC Microcontroller.


Vg2
Vg1
Vg5 and Vg6
Vg3 and Vg4
Amplitude (V)
Time (Second)
x 10^-3

(a)

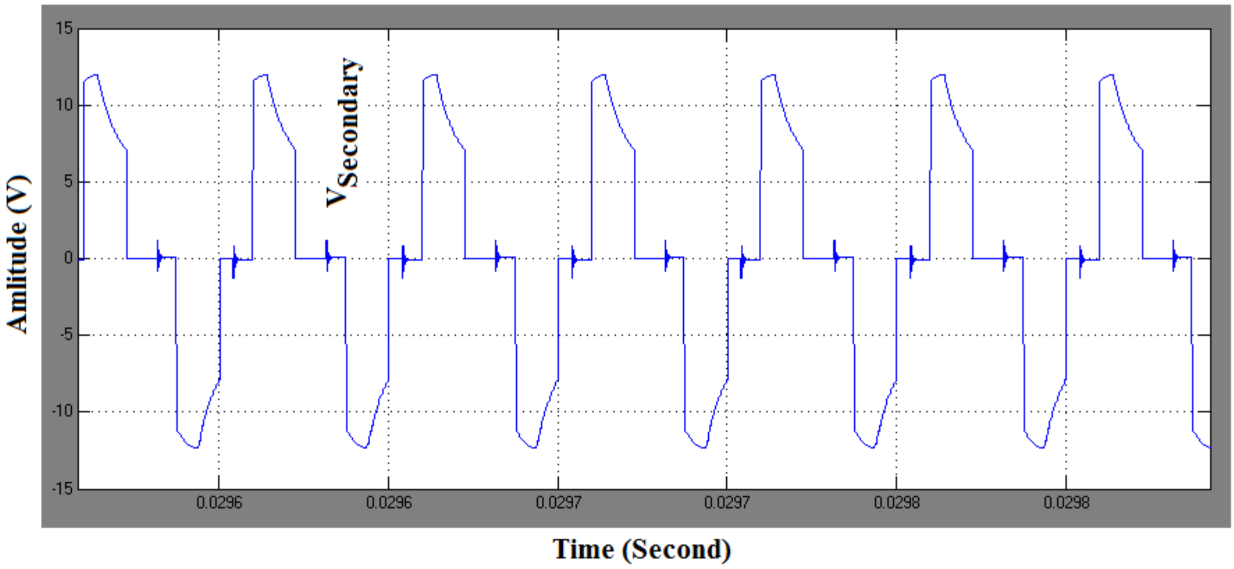

iL
VAB
Amlitude (Amp)
Amplitude (V)
Time (Second)

(b)



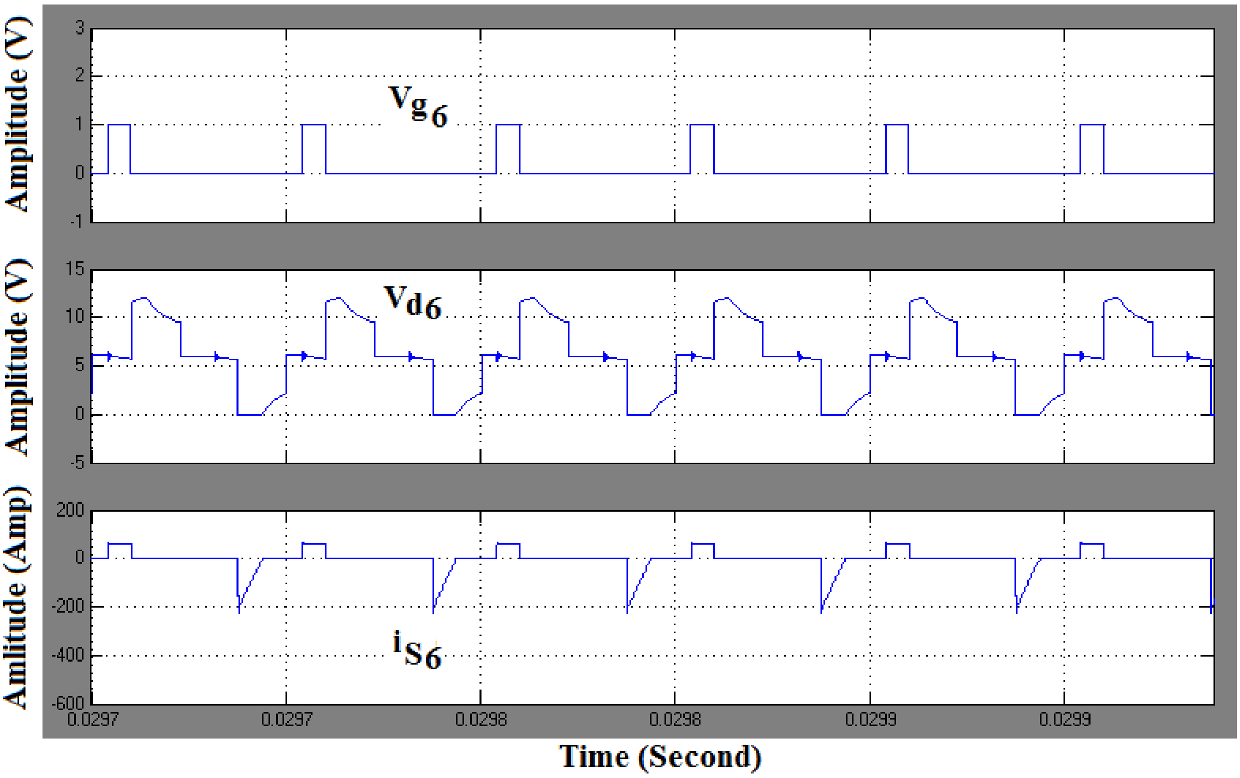
Amplitude (Amp)
i_{S1}
i_{S2}
Time (Second)

(c)

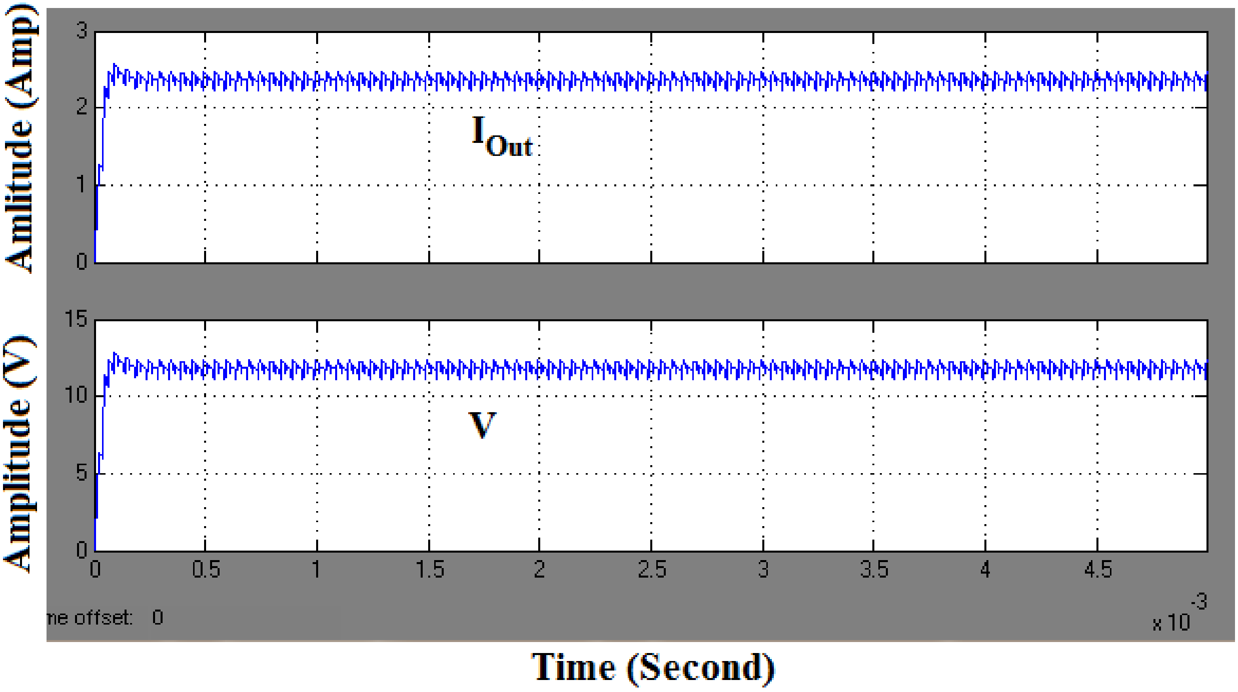


Amlitude (V)
$V_{Secondary}$
Time (Second)

(d)



(e)



(f)

Fig.3. Simulation waveforms (a) Driving pulses of S_1, S_2, (S_5&S_6) and (S_3&S_4) (b) Current through input inductor L, (i_L) and voltage across primary side V_{AB}. (C) Current through primary switches S_1 and S_2 (d) Secondary voltage of the transformer. (e) Gate to source voltage, drain to source voltage and drain to source current of secondary switch S_6 (f) DC output voltage (V) and DC output current (I_{Out}) Table 2: Performance of the proposed bidirectional DC/DC converter from simulation

Table 2: Performance of the proposed bidirectional DC/DC converter from simulation

% load	Output voltage (V)	Output current (A)	Output power (W)	Input power (W)	Efficiency (%)
42	12.41	0.65	8.07	8.77	92.02
56	12.39	0.87	10.78	11.59	93.15
67	12.38	1.05	13	13.83	94.01
76	12.35	1.19	14.7	15.64	93.72
86	12.34	1.34	16.54	17.78	93.07
100	12.32	1.56	19.22	10.67	92.66

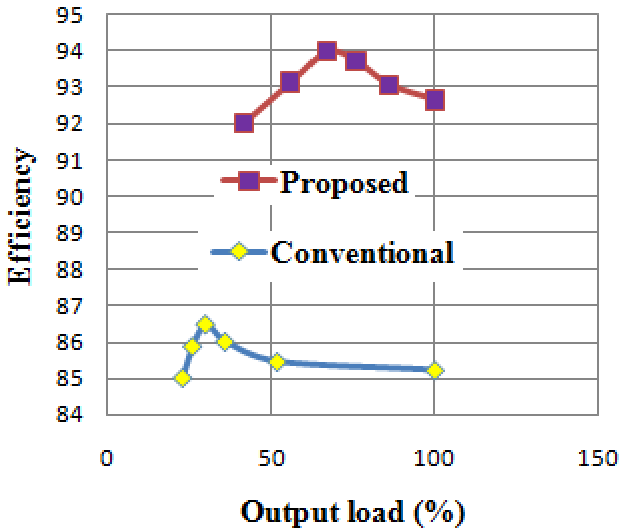


Fig.4. Efficiency versus load current

Table 3: Cost Analysis

Topology	Conventional current fed bidirectional push-pull DC/DC converter(8)	Cost	Proposed current fed bidirectional push-pull DC/DC converter	Cost
Number of switches	6	150	4	100
Number of input inductor	1	65	1	65
Number of primary inductor	2	130	2	130
Output capacitors	1	25	2	50
HF transformer	1	850	1	850
PIC Microcontroller			1	180
Xilinx Spartan-6 FPGA	1	4100		
Regulators			2	90
Driver			1	80
Top botton sheels	1	500	1	500
PCB	1	45	1	45

Load resistor	1	15	1	15
Total cost	5880		2105	

4. Conclusion and recommendations

A new soft switched bidirectional naturally clamped push-pull DC/DC converter has been proposed in this paper. The proposed converter employs secondary modulation based ZCS turn-off for the primary side switches and ZVS turn-on for the secondary side switches. The proposed converter can work in both the directions, namely forward and backward, and it is very easy to implement. The proposed circuit is suitable for any general step-up or step-down applications. Current fed converters are generally used for high step-up applications, but this work has been implemented for step-down applications using MATLAB simulink. The conversion of 48 V to 12 V has been done by using the proposed bidirectional DC/DC converter and the results have been compared with a conventional bidirectional converter. It has been found that the proposed converter has high efficiency and the efficiency is almost constant for a range of output current.

References:

1. Park T. and Kim T. Novel energy conversion system based on a multimode single-leg power converter. IEEE Trans. Power Electron. 2013, 28(1), 213-220.
2. Wu T. F., Chen Y. C., Yang J. G. and Kuo C. L. Isolated bidirectional full-bridge DC–DC converter with a flyback snubber. IEEE Trans. Power Electron. 2010, 25(7), 1915-1922.
3. Zhao B., Song Q., Liu W. and Sun Y. Overview of Dual-Active-Bridge Isolated Bidirectional DC-DC converter for high-frequency-link power-conversion system. IEEE Trans. Power Electron. 2014, 29(8), 4091-4106.
4. Corradini L., Seltzer D., Bloomquist D., Zane R. Marksimovic D. and Jacobson B. Zero voltage Switching Technique for Bidirectional DC/DC Converters. IEEE Trans. Power Electron. 2014, 29(4), 1585-1594.
5. Ding Z., Yang C., Zhang Z., Wang C . and Xie S. A Novel Soft-Switching Multiport Bidirectional DC-DC converter for hybrid energy storage system. IEEE Trans. Power Electron. 2014, 29(4), 1595-1608.
6. Kim Y., Lee I., Cho I. and Moon G. Hybrid dual full-bridge DC–DC converter with reduced circulating current, output filter, and conduction loss of rectifier stage for RF power generator application. IEEE Trans. Power Electron. 2014, 29(3), 1069-1081.
7. Rathore A. K. and Prasanna U. R. Analysis, Design, and Experimental Results of Novel Snubberless Bidirectional Naturally Clamped ZCS/ZVS Current-Fed Half-Bridge DC/DCConverter for Fuel Cell Vehicles. IEEE Trans. Power Electron. 2013, 60(10), 4482-4491.
8. Xuewei P. and Rathore A. K. Naturally Clamped Zero-Current Commutated Soft-Switching Current-Fed Push–Pull DC/DC Converter: Analysis, Design, and Experimental Results. IEEE Trans. Power Electron. 2015, 30(3), 1318-1327.
9. Yang J. W. and Do H. L. Soft-Switching Bidirectional DC-DC Converter Using a Lossless Active Snubber. IEEE Trans. Circuits and Systems. 2014, 61(5), 1588-1596.
10. Bal S., Rathore A. K. and Srinivasan D. Modular Snubberless Bidirectional Soft-Switching Current-Fed Dual 6-Pack (CFD6P) DC/DC Converter. IEEE Trans. Power Electron. 2015, 30(2), 519-523.
11. Jalbrzykowski S. and Citko T. Current-fed resonant full-bridge boost DC/AC/DC converter. IEEE Trans. Ind. Electron. 2008, 55(3), 1198-1205.
12. Zhu L. A novel soft-commutating isolated boost full-bridge ZVS-PWM DC–DC converter for bi-directional high power applications. IEEE Trans. Power Electron. 2006, 21(2), 422-429.
13. Jang S. J., Won C. Y., Lee B. K. and Hur J. Fuel cell generation system with a new active clamping current-fed half-bridge converter.

IEEE Trans. Energy Convers. 2007, 22(2), 332-340.

14. Chu C. L. and Li C. H. Analysis and design of a current-fed zero-voltage switching and zero-current-switching CL-resonant push-pull DC–DC converter IET Power Electron. 2009, 2(4), 456-465.