

A non isolated bidirectional DC-DC converter with LCD snubber

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Abstract: This paper proposes a non isolated Bidirectional DC-DC Converter with LCD (Inductance Capacitance Diode) snubber achieves high efficiency. In this paper non dissipative LCD clamp circuit is introduced not only achieves high efficiency, reduces cost, simple structure and also reduces current spike in the conventional NBDC, reduces switching losses and applicable for higher power conversion. The proposed non dissipative LCD snubber recycle the energy absorbed from either input or output side and it circulate through throughout the switching period. The proposed topology is simulated using MATLAB/SIMULINK software and its operation modes for both boost and buck conversion has been investigated throughout the paper. The simulated results of the proposed converter are compared with the conventional NBDC's topologies to verify its effectiveness. The proposed NBDC topology is experimentally verified for a 0.5 KW prototype.

Key words: LCD Snubber, Non isolated bidirectional dc-dc converter (NBDC), soft switching, current spike.

1. INTRODUCTION

The Bidirectional DC-DC Converter topologies has raised lot of attention in recent years for the application of many power related system including fuel cell, hybrid electric vehicle ,renewable energy system, Uninterruptable power supplies and so on which needs high efficiency and high power density. The Bidirectional DC-DC Converter transfer power between its input and output power sources by step up or step down the voltage levels depending upon the requirements. Basically bidirectional DC-DC converters can be classified in to Non Isolated bidirectional DC-DC converters and isolated bidirectional DC-DC converters.

In Isolated bidirectional DC-DC converters galvanic isolation is needed between current fed and voltage fed bridges. High frequency isolation transformer provided in the full bridge topologies increases cost and number of switching devices (Inoue.S et al.,2007, Lizhi Zhu ,2006, and T.Reimann et al.,1997).Dual active bridge isolated bidirectional are proposed to raise the power level with different phase shift control (Huiqing Wen et al.,2015,Krismer F et al.,2009,Mi.C et al.,2008, and R.W. De Doncker et al.,2007).Isolated bidirectional dc-dc converter with RCD snubber,flyback, active clamp and passive clamp methods are also described to improve the conversion ratio ,reduction of voltage spike, limiting voltage and current stresses through the active switches and soft switching achieved (Mohammadjavad Baei et al.,2014,R.Watson et al., 1996, Tsai-Fu-Wu et al.,2010, Tsai-Fu Wu et al.,2011,and Yanbo Che et al.,2014). Sometimes bidirectional power flow between grid and battery is possible (Ho-Sung Kim et al., 2013, and Hua Han et al., 2014).

Due to weight, size, high number of semiconductor devices and power transformer associated in the isolated bidirectional dc-dc converter ,the interest is focused to transformer less non-isolated bidirectional DC-DC converter which is attractive converter topology for improving the efficiency .The basic transformer less non-isolated bidirectional DC-DC converter is the combination of boost and buck converter connected in antiparallel.The comparative evaluation of various NBDC based on their efficiencies and cost consideration have done in (Baburaja.C et al.,2013,and Taewon Kang et al.,2012).In the high power converters to achieve maximum efficiency MOSFETS can be applied instead of IGBT with bidirectional power flow legs which suppress the switching loss occurs due to reverse recovery of the body diode (Hyung-Min Ryu ,2014).

To improve the power rating as well as clamp the diode oscillations of the converter RC-RCD clamp circuit is introduced (Milanovic.M et al.,2006).Optimal design of DC-DC converter employed with genetic algorithm and taguchi method are proposed for spike voltage reduction (Chuan-Kuei Huang et al.,2010).To reduce the ripple current shown in the conventional NBDC multiphase interleaved half bridge topology is introduced (Yanbo Che et al.,2014).Due to the low ripple current and reverse recovery problem in the conventional NBDC, series resonance, parallel resonance, and quasi-resonance methods have progressed to alleviate the above problem (K. H. Liu et al.,1987,and R. Redl et al.,1986).Due to high circulating energy conduction losses are occur in the resonant converter, the zero voltage transition (ZVT) and zero current transition (ZCT) methods are introduced to overcome the problems in the resonant converter (G. Hua et al.,1994).

The ZVT and ZCT methods are that switches turning ON and turning OFF under zero voltage and zero current condition using resonance. Sometimes auxiliary switches are used in addition with main switches to operate the NBDC without switching loss (D.-Y. Lee et al.,2003).Zero Voltage transition PWM NBDC are implemented with coupled inductor to achieve high efficiency at both step up and step down conversion (Ju-Kyoung Eom et al.,2012).Leakage inductance is fully utilized and voltage stress in the switches reduced by providing tapped inductor topology(Amin Mirzaei et al.,2012,and Jeong-il Kang et al.,2014).

Modified PWM based NBDCs with coupled inductor is presented to reduce the converter volume (A.Amalin Rishma et al.,2012).Further soft switching NBDC with LC Series resonant circuit is also proposed to achieve maximum efficiency at all load conditions (Doo-Yong Jung et al.,2013).Soft-switching dc-dc converter

with auxiliary switch control is proposed to improve the efficiency of non isolated bidirectional converter with look up table reference (Jung-Hyo Lee et al.,2013) this method brings the more efficient control in both step up and step down mode operation.

In this paper non dissipative LCD clamp circuit is introduced to achieve high efficiency, reduces switching losses and applicable for higher power conversion. This Non dissipative LCD snubber recycle the energy absorbed from either input or output side and it circulate through throughout the switching period. The advantages of the proposed converter are high reliability, simple structure, low cost and high efficiency.

2. PROPOSED TOPOLOGY

The proposed non isolated bidirectional dc–dc converter with LCD snubber is shown in Fig.1. The proposed LCD snubber circuit consists of Resonant inductor L_r , Resonant Capacitors C_{r1} and C_{r2} , and two Diodes D_1 and D_2 in addition with basic bidirectional converter topology. RCD snubber is a dissipative one which dissipate large amount of energy stored in the capacitor through the snubber resistance. Hence it increases the component sizes and creates a heat transfer problems. The proposed non dissipative LCD clamp with passive components eliminates the above problems by storing the leakage energy in to a capacitor even the semiconductor device is in OFF conditions. The proposed converter reduces switching losses with the help of soft switching. The proposed converter is categorized in to two modes: boost mode conversion (step up) and buck mode conversion (step down) based on the current flowing through each component in a proposed circuit and voltage across the switches.

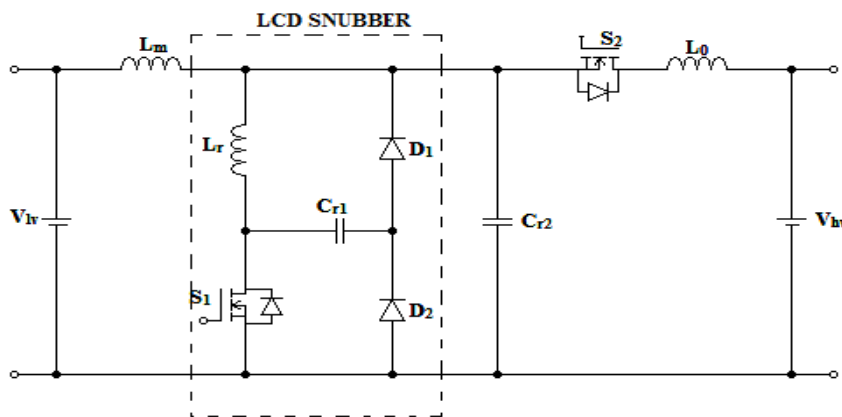


Fig.1.The proposed non isolated bidirectional dc–dc converter with LCD snubber

Fig.1 consists of main inductor L_m , two main switches S_1 and S_2 are operated under soft switching. The output inductor L_0 perform filtering when energy flows from the input side (low voltage side) to the batteries (high voltage side), which is denoted as a boost mode and vice versa operation takes place in buck mode when power flows from the batteries (high voltage side) to the low voltage side. The resonance of the proposed converter is caused by the main inductor L_m and snubber capacitors C_{r1} and C_{r2} . The proposed LCD clamp recycle the energy absorbed from either input or output side and it circulate through throughout the switching period and soft switching can be achieved .

A non isolated bidirectional dc-dc converter with LCD clamp has two types of conversion: boost mode conversion (step up) and buck mode conversion (step down).In boost mode switch S_1 controlled and body diode of S_2 provide a current path to the load. In buck mode switch S_2 controlled and body diode of S_1 provide a current path to the load. To intend the converter design, theoretical investigation must be indomitable. The main aim of the steady state analysis is to obtain derivations and equations for various devices used in the proposed bidirectional LCD clamp circuit.The assumptions are

- 1) Main inductor L_m is considered large enough
- 2) All devices are ideal
- 3) All the elements have zero voltage drops.

In boost mode switch S_1 is operated, body diode of switch S_2 will conduct to transfer power from low voltage side to high voltage side. In this mode snubber capacitor C_s makes the switch S_1 to turn OFF under ZVS.The operation mode of proposed topology in boost mode is divided in to eight modes. Fig. 2 shows the various operation mode of the proposed converter in step up conversion during a switching period.

Mode 1 [$t_0 \leq t < t_1$]: At time t_0 switches S_1 and S_2 are in off state .The input dc voltage is directly connected to the load through main inductor current i_{L_m} and antiparallel diode of switch S_2 . Here the voltage across L_m is negative. Hence i_{L_m} decreases linearly.

$$iL_m(t_0) = \frac{V_{iv}-V_{hv}}{L_m}(t - t_0) + I_0 \quad (1)$$

$$iL_m(t_1) = I_1 = I_{min} \quad (2)$$

$$iL_r(t_0) = 0 \quad (3)$$

$$VC_{r1}(t) = 0 \quad (4)$$

$$VC_{r2}(t) = V_{hv} = V_{co} \quad (5)$$

Mode 2 [$t_1 \leq t < t_2$]: Mode 1 starts when the switch S_1 is turned ON by ZCS because of L_r .output voltage is supplied via resonant inductor, thus iL_r starts increasing. The current through the antiparallel diode of switch S_2 becomes zero when $iL_r = iL_m$

$$iL_m(t) = \frac{V_{iv}-V_{hv}}{L_m}(t) + I_{min} \quad (6)$$

$$iL_m(t_2) = I_1 = I_{min} \quad (7)$$

$$iL_r(t_2) = I_1 \quad (8)$$

$$VC_{r1}(t) = 0 \quad (9)$$

$$VC_{r2}(t) = V_{hv} = V_{co} \quad (10)$$

Mode 3 [$t_2 \leq t < t_3$]: This mode is started when current through the antiparallel diode of switch S_2 becomes zero. In this mode main inductor current iL_m flows through L_r and switch S_1 .the resonant inductor L_r and the resonant capacitor C_{r2} starts resonate, therefore VC_{r2} starts decreases from output voltage to zero.

$$iL_m(t_3) = I_1 = I_{min} \quad (11)$$

$$iL_r(t) = I_1 + \frac{V_{hv}}{L_r}(t) \quad (12)$$

$$iL_r(t_3) = I_2 \quad (13)$$

$$VC_{r1}(t) = 0 \quad (14)$$

$$VC_{r2}(t) = V_{co} \cos \omega_r t \quad (15)$$

$$\omega_r = \frac{1}{\sqrt{C_r L_r}} \quad (16)$$

$$C_r = C_{r1} + C_{r2} \quad (17)$$

$$VC_{r2}(t_3) = 0 \quad (18)$$

Mode 4 [$t_3 \leq t < t_4$]: This mode begins at $VC_{r2}=0$ and the snubber diodes D_1 and D_2 are turned on.

$$iL_m(t) = \frac{V_{iv}}{L_m}(t) + I_2 \quad (19)$$

$$iL_m(t_4) = \frac{V_{iv}}{L_m}(t) + I_2 \quad (20)$$

$$iL_r(t_4) = I_{min} + \frac{VC_0}{Z_r} \quad (21)$$

$$VC_{r1}(t) = 0 \quad (22)$$

$$VC_{r2}(t) = 0 \quad (23)$$

Mode 5 [$t_4 \leq t < t_5$]: At time t_4 ,the switch S_1 is turned OFF with ZVS condition because of resonant capacitor V_{cr1} .the proposed circuit serves two current loops in this mode .

- i) $L_m-C_{r2}-V_{LV}$, VC_{r2} increases from zero to output voltage
- ii) $L_r-C_{r1}-D_1$, loop for second resonance,energy stored in resonant inductor shifts to C_{r1} ,therefore iL_r starts decreasing and VC_{r1} becomes high value.

$$iL_m(t_5) = I_3 \quad (24)$$

$$iL_r(t_5) = I_2 \cos \omega_r t \quad (25)$$

$$VC_{r1}(t) = \left(\sqrt{\frac{L_r}{C_r}} \right) I_2 \sin \omega_{r1} t \quad (26)$$

$$\omega_{r1} = \frac{1}{\sqrt{C_{r1} L_r}} \quad (27)$$

$$VC_{r2}(t) = \frac{I_3}{C_{r1}} \quad (28)$$

$$VC_{r2}(t_5) = V_{hv} = V_{co} \quad (29)$$

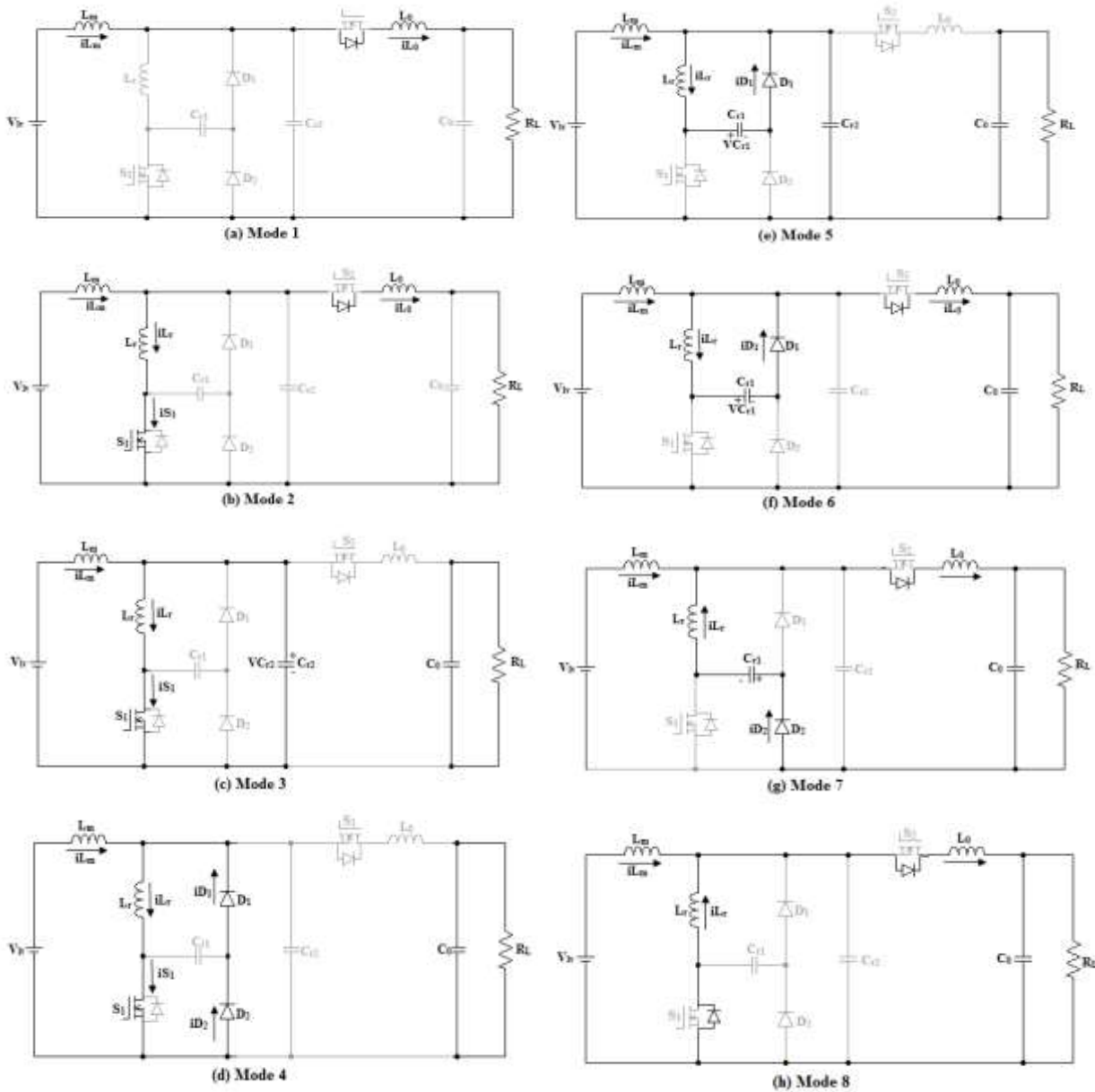


Fig.2.Operation modes of boost mode conversion (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4 (e) Mode 5 (f) Mode 6 (g) Mode 7 (h) Mode 8.

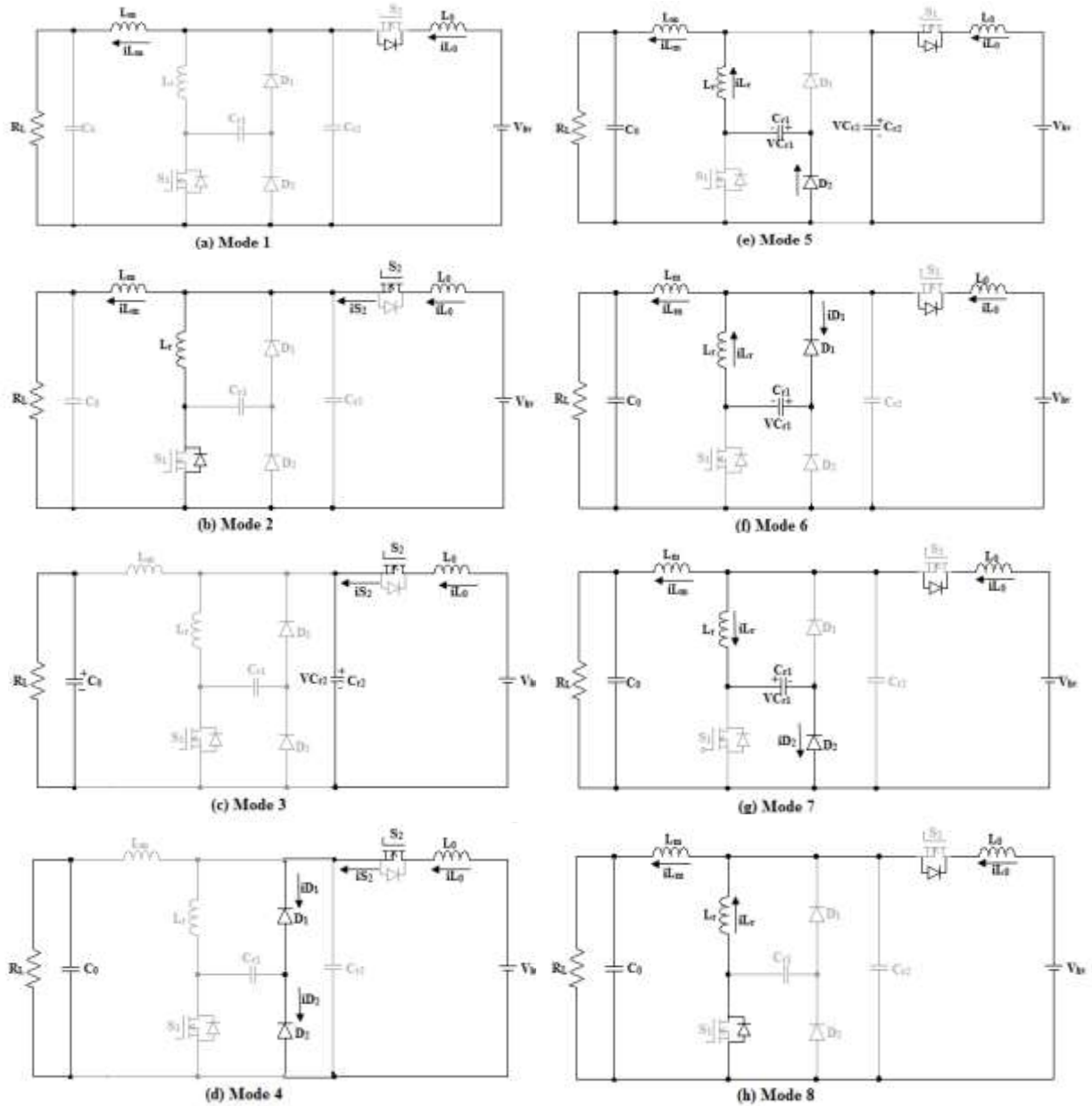


Fig.3.Operation modes of buck mode conversion (a) Mode 1 (b) Mode 2 (c) Mode 3 (d) Mode 4 (e) Mode 5 (f) Mode 6 (g) Mode 7 (h) Mode 8.

Mode 6 [$t_5 \leq t < t_6$]: This mode starts at $VC_{r1} = V_0$ and $iL_r = 0$ because of energy stored in resonant inductor is totally discharged to VC_{r1} .

$$iL_m(t_5) = I_4 = I_{max} \quad (30)$$

$$iL_r(t_6) = 0 \quad (31)$$

$$VC_{r1}(t) = \left(\sqrt{\frac{L_r}{C_r}} \right) I_2 \cos \omega_{r1} t \quad (32)$$

$$VC_{r1}(t_6) = 0 \quad (33)$$

$$VC_{r2}(t) = V_{hv} = V_{c0} \quad (34)$$

Mode 7 [$t_6 \leq t < t_7$]: In this mode VC_{r1} starts resonate and decreases through $D_2 - C_{r1} - L_r - D_{s2} - C_0$ until $VC_{r1} = 0$, the energy absorbed in C_{r1} discharges to resonant inductor L_r . when $VC_{r1} = 0$, iL_r changes its current direction, then antiparallel diode of switch S_2 turns on.

$$iL_m(t) = \frac{V_{iv} - V_{hv}}{L_m}(t) + I_4 \quad (35)$$

$$iL_m(t_7) = I_5 \tag{36}$$

$$iL_r(t) = I_2 \sin \omega_r t \tag{37}$$

$$iL_r(t_7) = 0 \tag{38}$$

$$VC_{r1}(t) = \left(V_{c0} - \sqrt{\frac{L_r}{C_r}} I_2 \right) \cos \omega_{r1} t \tag{39}$$

$$VC_{r1}(t_7) = 0 \tag{40}$$

$$VC_{r2}(t) = V_{c0} \tag{41}$$

Mode 8 [$t_7 \leq t < t_8$]: This mode begins at $VC_{r1}=0$. It has two current paths. The main inductor current flows to the load through antiparallel diode of switch S_2 as well as resonant inductor current shifts to the load through D_{s1} and D_{s2} . This mode ends at iL_r reaches to zero.

$$iL_m(t_8) = I_6 \tag{42}$$

$$iL_r(t) = I_5 - \frac{V_{c0}}{L_r}(t) \tag{43}$$

$$iL_r(t_8) = 0 \tag{44}$$

$$VC_{r1}(t) = 0 \tag{45}$$

$$VC_{r2}(t) = V_{hv} = V_{c0} \tag{46}$$

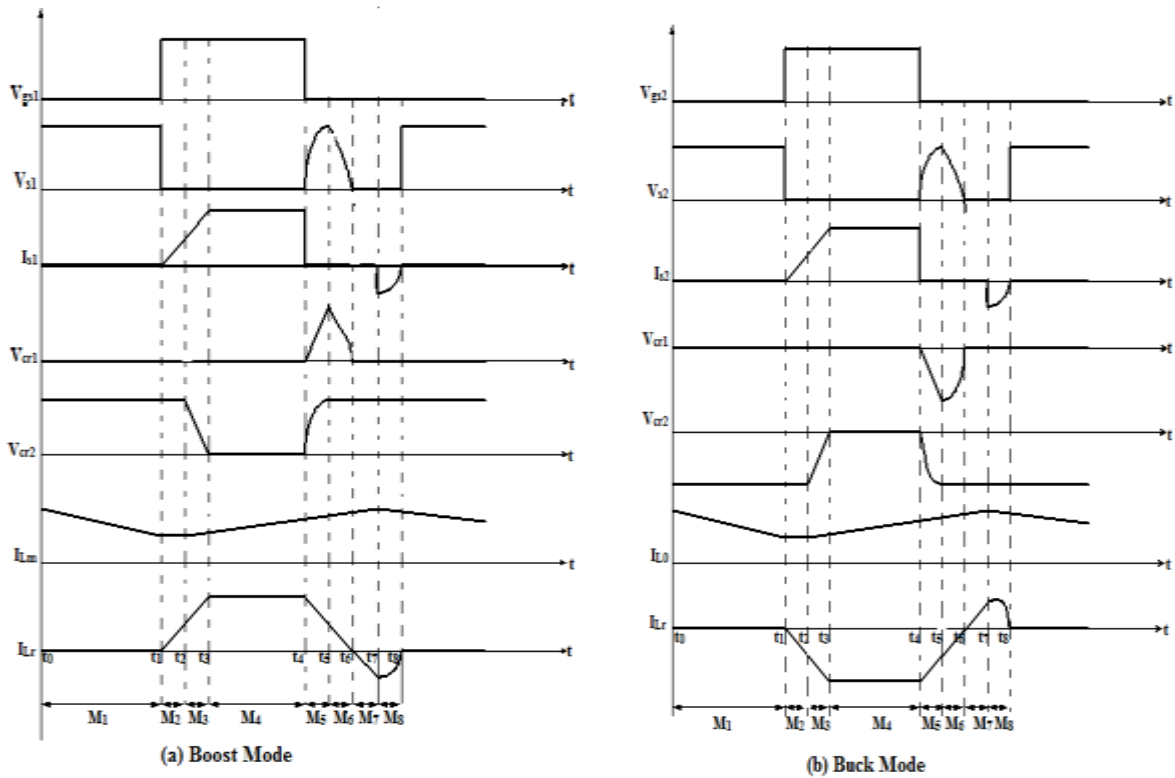


Fig.4.Key waveforms (a) Boost Mode (b) Buck Mode

Fig.3 shows the operation mode of the proposed converter in step down conversion during a switching period. Key waveforms for boost mode and buck mode is described in Fig.4. In buck mode switch S_2 is operated and body diode of switch S_1 will conduct to transfer power from high voltage side to batteries (low voltage side). In this mode snubber capacitor C_s makes the switch S_2 to turn OFF under ZVS. The operation mode of proposed topology in buck mode is analogous to the boost mode and also divided in to eight modes as indicated in fig 3 because it operates in inverse with boost mode.

3. RESULTS AND DISCUSSIONS

In order to verify the feasibility of the proposed LCD snubber topology. A 0.5 KW converter prototype was built and implemented. MATLAB/SIMULINK software is used to simulate the proposed non isolated bidirectional dc-dc converter with LCD clamp circuit to verify its effectiveness for both buck and boost modes. The switching current and voltages waveforms are measured to ensure the converter is operated in soft switching condition. Fig.5 shows the 0.5 KW prototype of the proposed NBDC with LCD clamp, it should be

capable of work in both boost and buck modes as explained in section 2 and table I illustrated the parameters used in the practical and simulation set up.

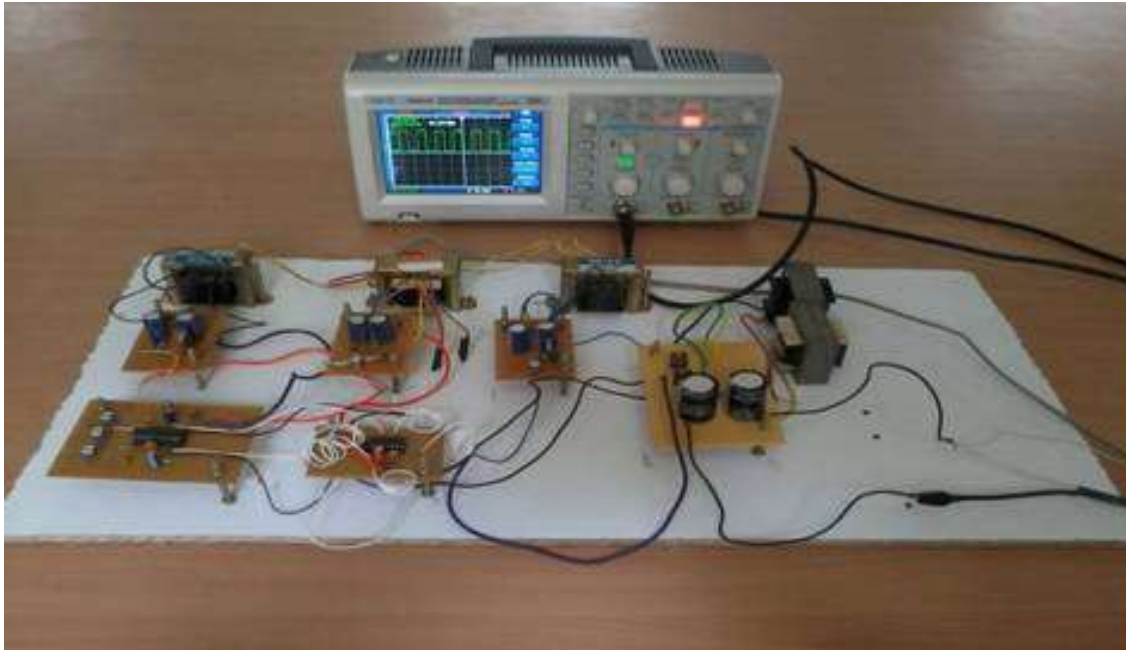


Fig.5.Experimental prototype

Table I. Experimental and Simulation Parameters

Parameter	Value
Rated Low Voltage	100 V
Rated high Voltage	200 V
Rated Power	0.5 KW
Main inductor	470 μ H
Resonant Inductor	4 mH
Resonant Capacitor	18 nF
Output Capacitor	47 mF
Switching Frequency	50 HZ

3.1 Step-up conversion (Boost mode)

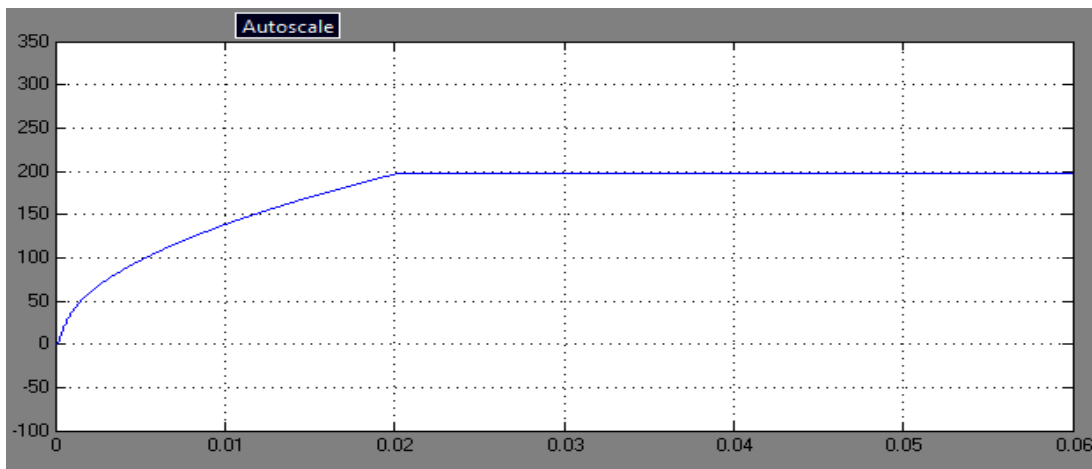


Fig.6.Output Voltage for Boost Mode

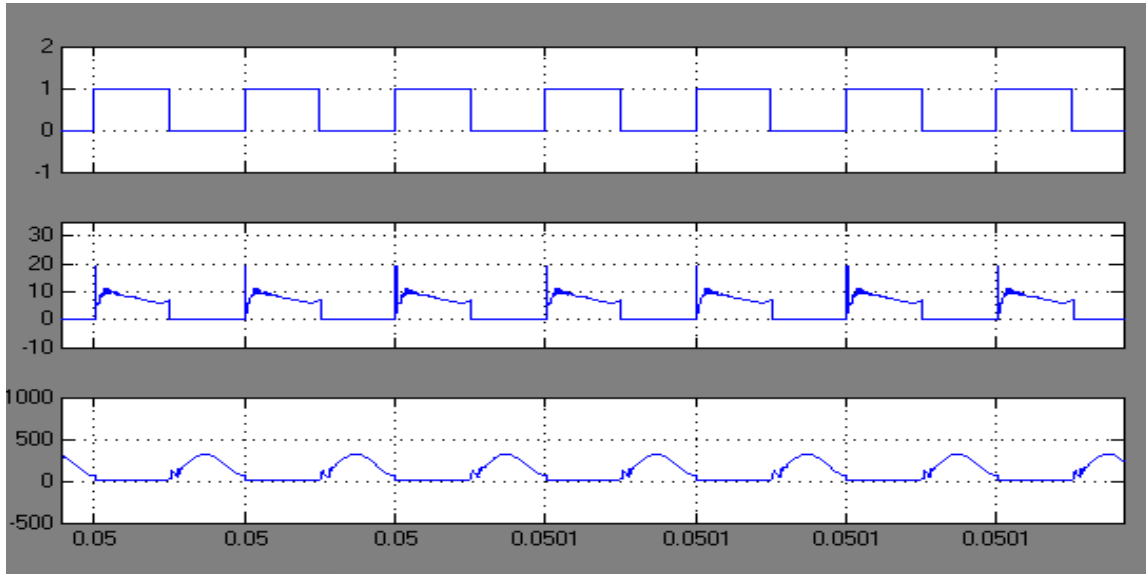


Fig.7.Triggering pulse, current through and voltage across switch S_1

Fig.6 shows the simulated output voltage for boost (200 V) mode with the dc input voltage of 100 V. The gate pulse, current flowing through and voltage across the terminals for switch S_1 of the proposed topology is obtained in Fig.7 for step up and 200 V dc for step down conversion. From the above waveforms it is clearly states the switch S_1 is operated under zero voltage condition, it is turned ON and OFF at zero voltage ripple current also reduces, and therefore current through the inductor is continuous.

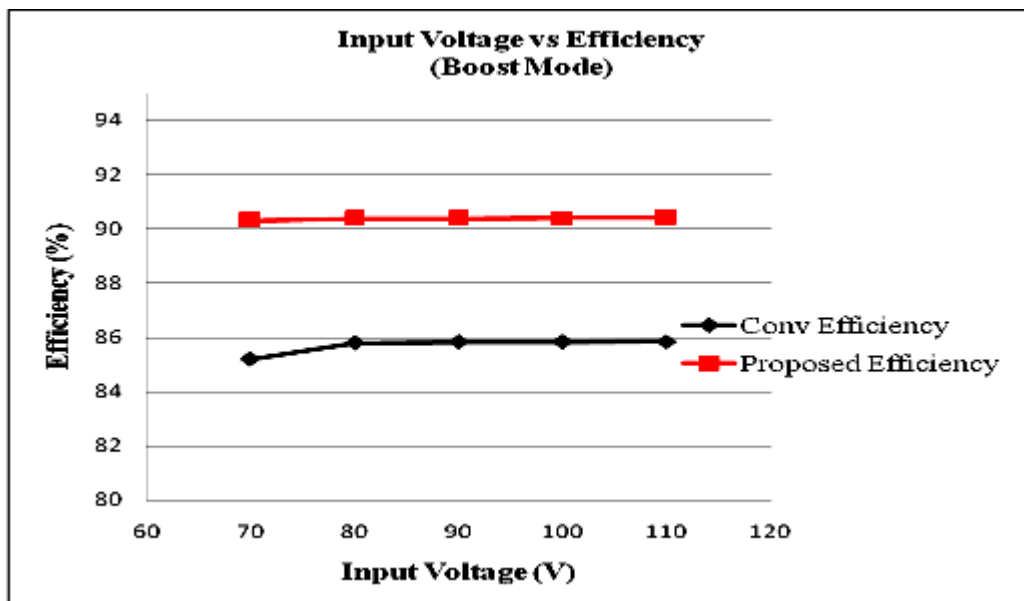


Fig.8.Efficiency Comparision of boost mode

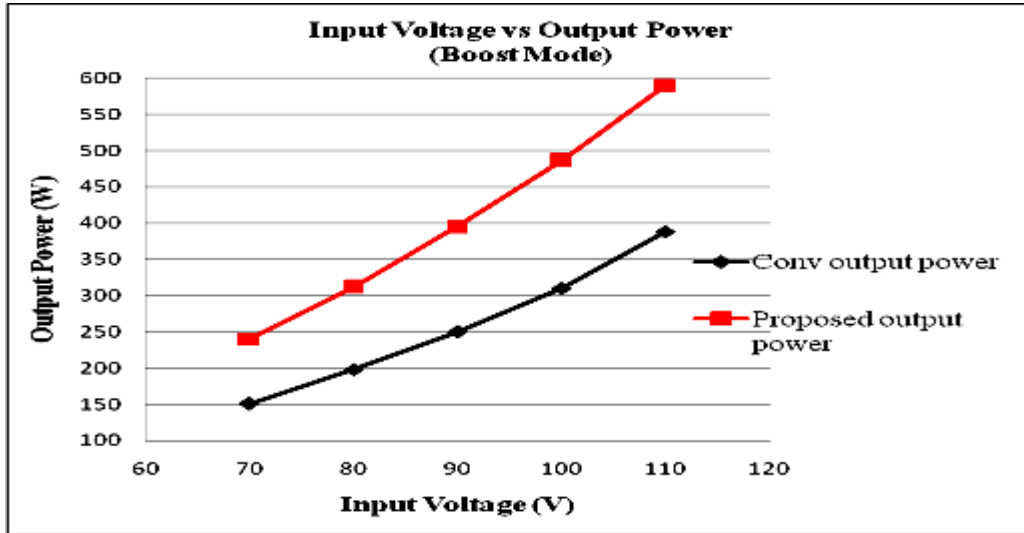


Fig.9. Output Power comparison of boost mode

Fig.8 and Fig.9 illustrate the efficiency and output power comparison of boost mode with conventional converter for various input voltages. Which implies the proposed topology achieves high efficiency about 4-5 % than conventional converter topologies.

3.2 Step-down conversion (Buck mode)

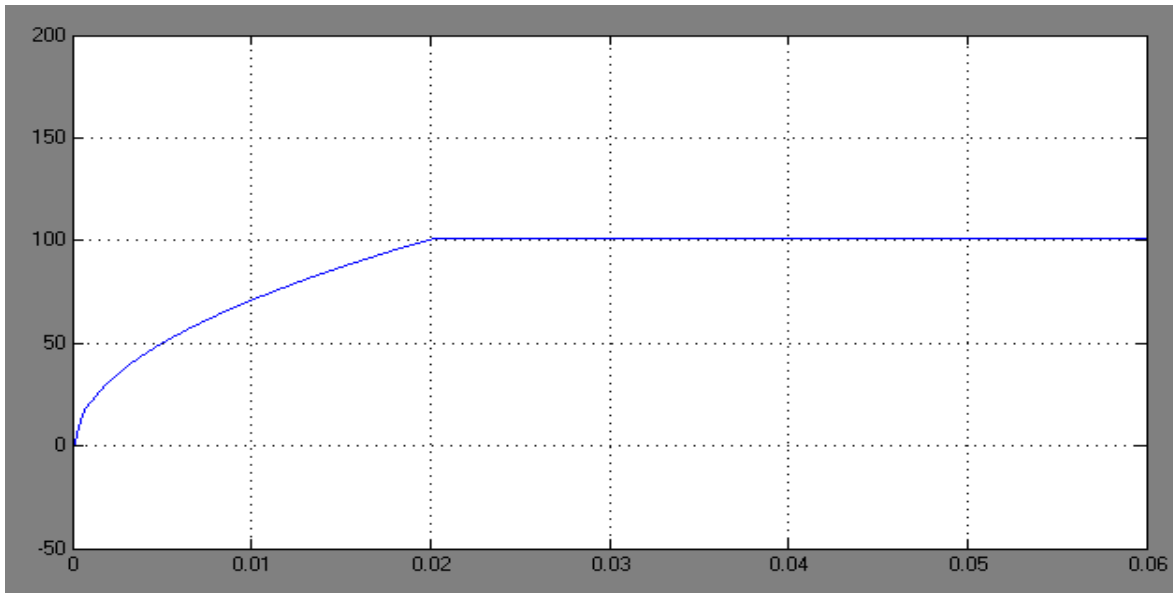


Fig.10. Output voltage for buck mode

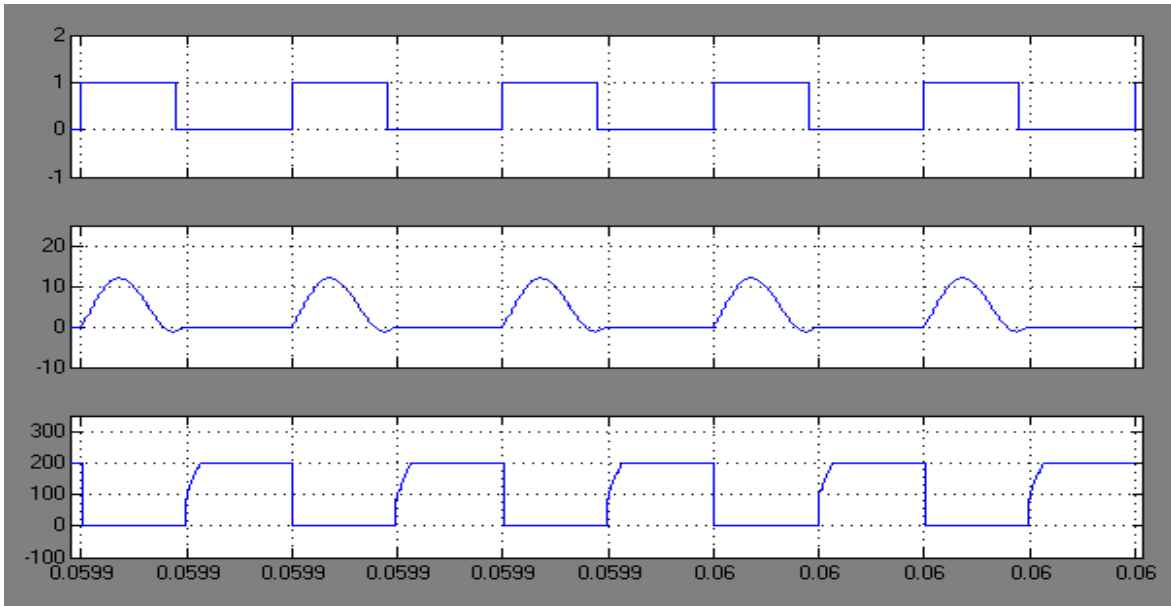


Fig.11.Triggering pulse, current through and voltage across switch S_2

Fig.10 shows the simulated output voltage for buck (100 V) mode. Fig.11 shows the gate pulse, current through and voltage across waveforms for switch S_2 of the proposed NBDC when the input voltage is 200 V dc for step down conversion. From the above waveforms it is obviously the switches are operated under zero voltage condition during buck mode, ripple current also reduces, and therefore current through the inductor is continuous as same as boost mode.

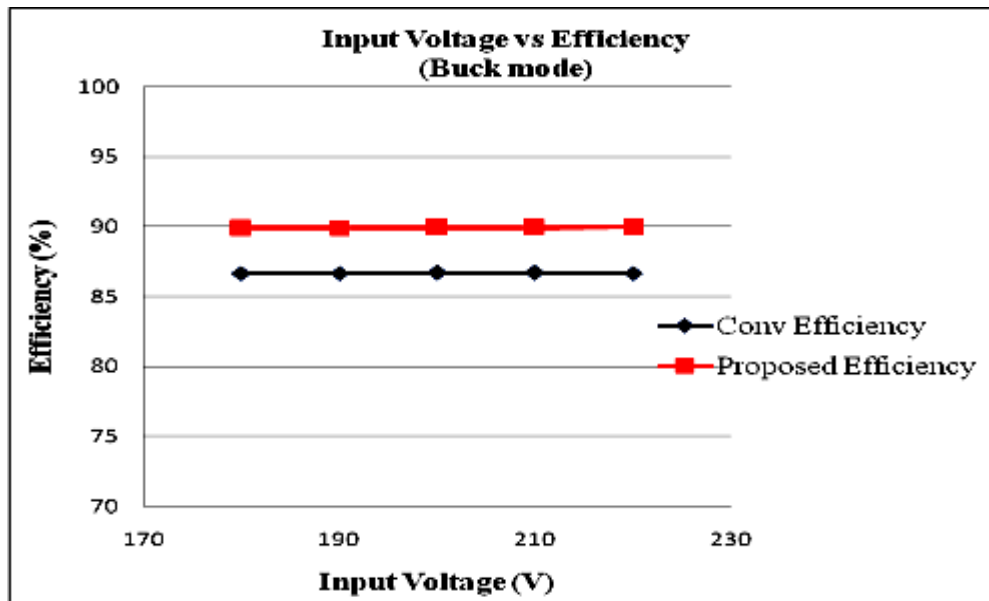


Fig.12.Efficiency Comparison of buck mode

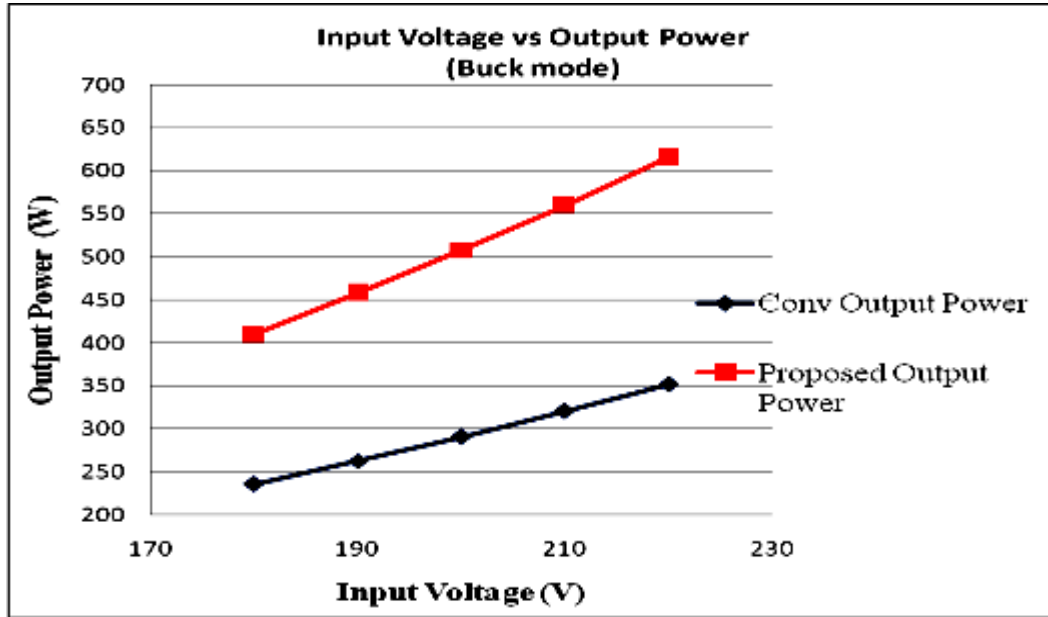


Fig.13. Output Power Comparison of buck mode

The efficiency and output power comparison of buck mode is done in Fig.12 and Fig.13, which also states that the proposed topology achieves high efficiency than conventional NBDC.

Table II. Efficiency comparison of the proposed converter operation

Switching	Boost mode			Buck mode		
	Input voltage(V)	Output power(W)	Efficiency (% η)	Input voltage(V)	Output power(W)	Efficiency (% η)
Hard	70	151	85.2	180	236	86.67
Soft		240	90.3		410	89.89
Hard	80	198	85.79	190	263	86.68
Soft		312	90.37		458	89.91
Hard	90	250	85.42	200	291	86.7
Soft		395	90.38		508	89.93
Hard	100	310	85.83	210	321	86.72
Soft		487	90.39		560	89.94
Hard	110	388	85.84	220	352	86.69
Soft		580	90.41		616	89.96

Table II indicates the output power and efficiency comparison of conventional hard switching NBDC and proposed NBDC with LCD clamp. The proposed circuit achieves high efficiency for the same input voltage applied at all modes.

4. CONCLUSIONS

This paper presents a non isolated bidirectional dc-dc converter with LCD clamp circuit that is specifically used for battery applications that require a maximum efficiency. It is proposed in this paper for step up and step down conversion. The proposed Non dissipative LCD snubber recycles the energy absorbed from either input or output side and it circulates throughout the switching period as well as reduces the current ripple and switching losses with proper operation of the switches. Soft switching capability is achieved at all operating modes. The validity of the proposed topology is experimentally verified.

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