Performance Improvement and Reliability of a Bidirectional DC-DC Converter

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Abstract: **In this paper a bidirectional converter operating in buck and boost modes of operation is observed for various operating conditions. It consists of power switches and coupled inductor with same number of turns in the primary and secondary windings. From the simulation and experimental results it is observed that this configuration has higher efficiency at high power gain level when compared with conventional bidirectional buck/boost converter and also its reliability for various operating conditions is presented.**

Key words: **Bidirectional converter, Reliability, Coupled inductor**

[1]. INTRODUCTION

High power dc/dc converters playing a crucial role in today's emerging vehicular technologies, such as hybrid-electric, battery-electric, and fuel-cell vehicles. The development of bidirectional dc–dc converters has become urgent for clean-energy vehicle applications, because battery-based energy storage systems are required to cold start and battery recharge. However, back-up power from the battery is supplied using a bidirectional converter, which is employed in many uninterrupted power supplies (UPS), aerospace power systems and industrial applications. The dc back-up energy system normally consists of numerous typical low-voltage-type batteries. Although series strings of storage batteries can provide a high voltage, slight mismatches or temperature differences cause charge imbalance if the series string is charged as a unit [1]. Charge equalization cycles must be used in an attempt to correct imbalance, but conventional approaches to this process stress the batteries, shorten their life, and are not always effectiveness. In the recent past, the extensive operation of batteries in parallel strings stems from the desire of enhancing the redundancy of the power supply from the battery, and the problems induced by series strings of storage batteries could be alleviated [2]. However, the output voltage remains low by this parallel connection way. Therefore, a high-efficiency bidirectional dc–dc converter with high voltage diversity is a key component of batteries connected in parallel. Bidirectional dc–dc converters with transformer-based structures are probably the most popular topologies [3]–[12], and soft-switching techniques are usually applied to reduce the corresponding switching losses. These mechanisms with isolated transformers have high conduction losses because the usual number of power switches is between four and nine. Accordingly, practical implementation is complicated and expensive. Switched-capacitor dc–dc converters [13], [14] have attracted much attention as an alternative means of providing bidirectional power flow control. However, increased switching loss and current stress are the critical drawbacks, and the major challenge is to design a circuit with few switching devices and capacitors. Moreover, bidirectional dc–dc converters with transformer- based structures are not suitable for use in power sources with wide voltage variations because magnetizing currents are difficult to manage, large copper losses occur on the low-voltage side, and all energy is transferred from the large core. Therefore, the number of devices must be minimized and good transformer performance ensures in a high-efficiency bidirectional converter. This study presents a bidirectional converter with a coupled inductor, which uses only three switches to achieve the high step-up and step-down properties along with that converter efficiency and voltage regulation also improved which will be shown.

[2]. BIDIRECTIONAL CONVERTER

The basic non-isolated bidirectional dc-dc converter is shown in Fig.1. It is a combination of a step-up stage and a step-down stage connected in anti-parallel.

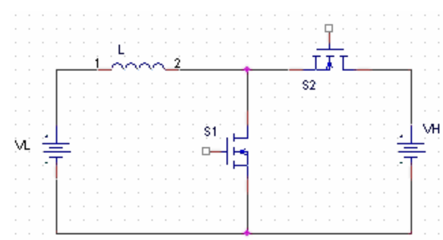


Fig.1 Conventional converter

The conventional Bidirectional Boost/Buck converter is modified and a new Bidirectional boost/buck is proposed [15]. The circuit diagram of the bidirectional converter is as shown in Fig.2.

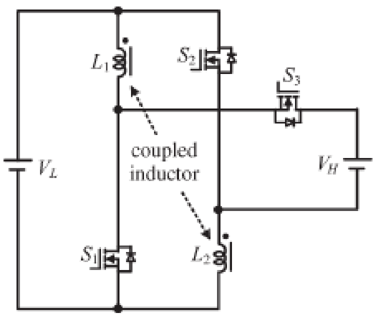


Fig.2. Bidirectional converter [15]

This converter employs a coupled inductor with same winding turns in primary and secondary winding. In step-up mode, the primary and secondary windings of the coupled inductor are operated in parallel charge and series discharge to achieve high step-up voltage gain. In step-down mode, the primary and secondary windings of the coupled inductor are operated in series charge and parallel discharge to achieve high step-down voltage gain. This converter has higher step-up and step-down voltage gains than the conventional bidirectional dc–dc boost/buck converter. Under same electric specifications for the proposed converter and the conventional bidirectional boost/buck converter, the average value of the switch current in the proposed converter is less than the conventional bidirectional boost/buck converter. This converter has higher step-up and step-down voltage gains, lower average value of the switch current under same electric specifications and higher efficiency.

In order to analyze the steady-state characteristics of the proposed converter, ON-state resistance $R_{DS}(ON)$ of the switches and the equivalent series resistances of the coupled inductor and capacitors are ignored and the capacitance is assume to be sufficiently large. Since the primary and secondary winding turns of the coupled inductor is same, the inductance of the coupled inductor in the primary and secondary sides are expressed as

$$L = L_1 = L_2$$

Thus, the mutual inductance M of the coupled inductor is given by

$$M = k\sqrt{L_1 L_2} = kL$$

Where k is the coupling coefficient of the coupled inductor.

The voltages across the primary and secondary windings of the coupled inductor are as follows:

$$v_{L1} = L_1 \frac{di_{L1}}{dt} + M \frac{di_{L2}}{dt} = L \frac{di_{L1}}{dt} + kL \frac{di_{L2}}{dt}$$

$$v_{L2} = L_2 \frac{di_{L2}}{dt} + M \frac{di_{L1}}{dt} = L \frac{di_{L2}}{dt} + kL \frac{di_{L1}}{dt}$$

……(1)

Buck mode: In this supply is given on high voltage side and load is connected at low voltage side.

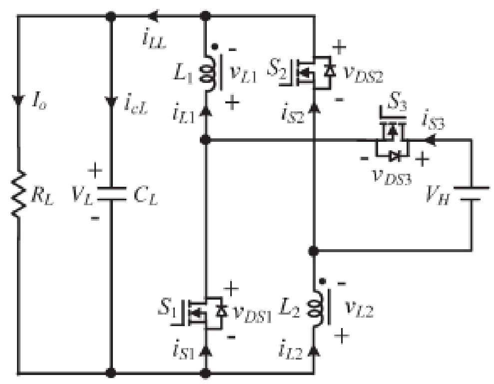


Fig.3 Bidirectional converter in buck mode

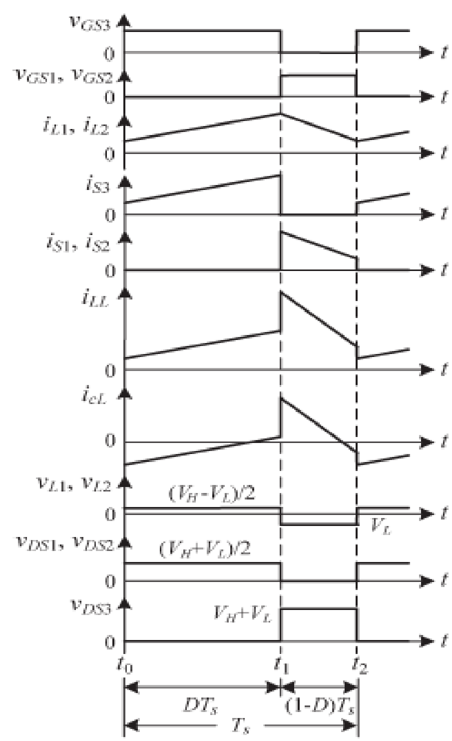


Fig.4. Theoretical waveforms of Bidirectional converter in Buck mode [15]

Boost Mode or Step up Mode:

During this time interval [t_0, t_1], S_1 and S_2 are turned on and S_3 is turned off. The energy of the low voltage side V_L is transferred to the coupled inductor. Meanwhile, the primary and secondary windings of the coupled inductor are in parallel. The energy stored in the capacitor C_H is discharged to the load. Thus, the voltages across L_1 and L_2 are obtained as

$$v_{L1} = v_{L2} = V_L \qquad \text{.......(2)}$$

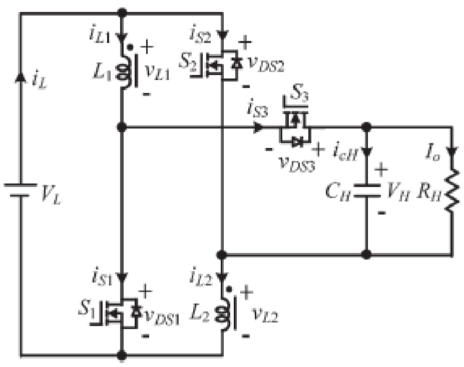


Fig.5 Bidirectional converter in boost mode [15]

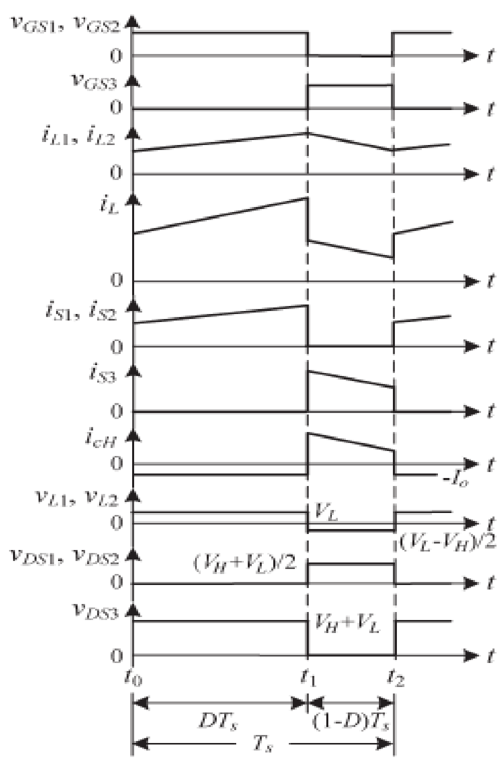


Fig.6.Theoretical Waveforms of proposed Bidirectional converter in Boost mode [15]

Gain

Gain is the ratio of output voltage to the given input voltage. The gains of the two converters are compared in both modes i.e. boost and buck.

Table - I

Mode of operation	Gain
Conventional Buck	D
Bidirectional Buck	D/2-D
Conventional Boost	1/1-D
Bidirectional Boost	1+D/1-D

When graphs are drawn between duty cycle and gain, with D on x-axis and gain on y-axis, they are as shown.

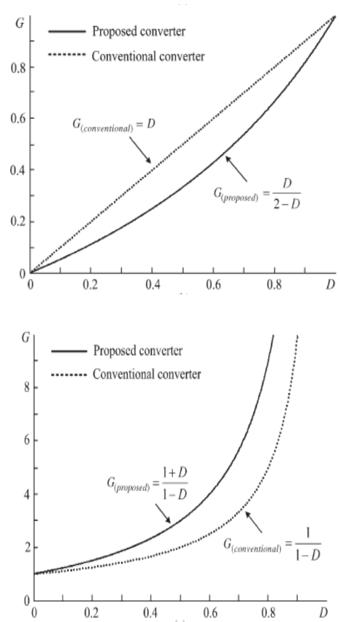
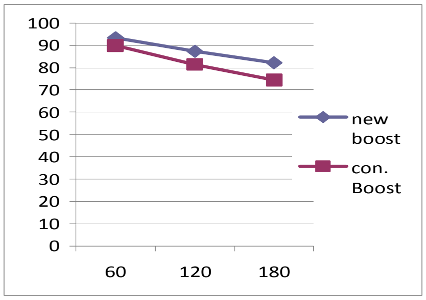
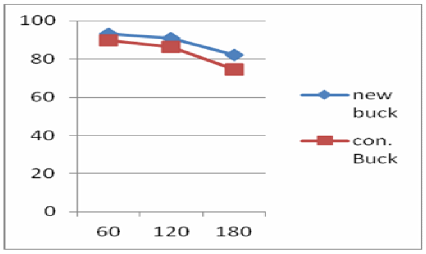


Fig.7.Graph between Duty cycle and gain for conventional and proposed converter [15]

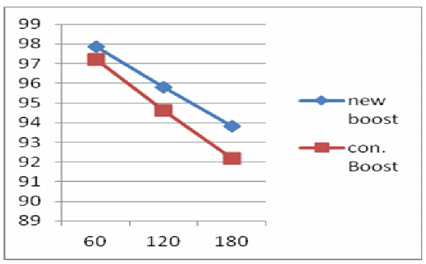
The power vs efficiency of the Bidirectional converter for boost and buck operation is calculated and compared with conventional buck and boost converter for the following two cases and results are shown in Fig.7.

Case1: V_L=10v,V_H=40,r_{L1}=r_{L2}=0.01Ω, r_{s1}=r_{s2}=r_{s3}=0.18Ω





Case2: V_L=20v,V_H=40,$r_{L1}=r_{L2}=0.01\Omega$, $r_{s1}=r_{s2}=r_{s3}=0.18\Omega$



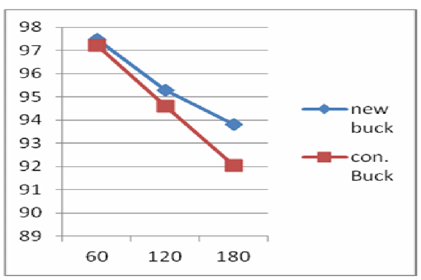


Fig.8. Efficiency vs output power

Efficiency and regulation are calculated for various values of loads.

Bidirectional converter in Boost mode:

When $r_{L1}=r_{L2}=0.01\Omega, r_{s1}=r_{s2}=r_{s3}=0.18\Omega, V_L=10v, R_H=100\ \Omega$

Table - II

D	P_o(w)	Gain	η_{calc}	η_{sim}	reg_{calc}	reg_{sim}
0.4	5.44	2.33	99.25	96.090	0.762	0.591
0.6	16	4.00	98.13	93.614	1.864	1.443
0.8	81	9.00	92.92	93.918	7.070	6.250

Conventional converter in Boost mode:

When $r_{L1}=0.01\Omega$,$r_{s1}=r_s=0.18\Omega$, V_L=10v,R_H=100 Ω
$r_{s1}=r_{s2}=r_{s3}=0.18\Omega$,

Table – III

D	P_o(w)	gain	η_{calc}	η_{sim}	reg_{calc}	reg_{sim}
0.571	5.44	2.33	98.97	95.713	1.03	0.9
0.750	16	4	97.193	92.712	2.81	2.30
0.888	81	9	86.66	74.95	13.34	12.80

Bidirectional converter in Buck mode:

When $r_{L1}=r_{L2}=0.01\Omega, r_{s1}=r_{s2}=r_{s3}=0.18\Omega, V_H=40v, R_L=10\Omega$

Table - IV

D	P_o(w)	Gain	η_{calc}	η_{sim}	reg_{calc}	reg_{sim}
0.311	5.44	0.184	99.88	98.22	0.20	0.88
0.480	16	0.316	98.87	98.87	1.13	1.096

Conventional converter in Buck mode:

When $r_{L1}=0.01\Omega$,$r_{s1}=r_{S2}=0.18\Omega$, V_H=40v,R_L=10 Ω

Table - V

D	P_o(w)	Gain	η_{calc}	η_{sim}	reg_{calc}	reg_{sim}
.5711	5.44	0.1843	98.13	98.20	1.87	1.55
.750	16	0.316	98.13	98.22	1.873	1.33
.888	81	0.7115	98.13	98.55	1.87	1.33

We can observe that the efficiency and voltage regulation of the bidirectional converter is higher than the Conventional converter in all conditions.

All the values of the two converters can be estimated at desired output power and can be tabulated as given with:

When $r_{L1}=r_{L2}=0.01\Omega$,

Table – VI

Buck mode	60 watts			120 watts		
	G=0.25	G=0.42857	G=0.666	G=0.25	G=0.42857	G=0.666
Conventional converter	D=0.25 η=89.89 reg=10.106	D=0.42857 η=96.264 reg=3.736	D=0.666 η=98.42 reg=1.58	D=0.25 η=81.46 reg=18.54	D=0.42857 η=92.798 reg=7.20	D=0.666 η=96.892 reg=3.108
Bidirectional converter	D=0.4 η=93.27 reg=6.72	D=0.6 η=97.185 reg=2.814	D=0.8 η=98.636 reg=1.363	D=0.4 η=87.405 reg=12.59	D=0.6 η=94.63 reg=5.569	D=0.8 η=94.842 reg=5.13

Table - VII

Boost Mode	60 watts			120 watts		
	G=2.33	G=4	G=9	G=2.33	G=4	G=9
Conventional converter	D=0.5713 η=89.70 reg=10.30	D=0.75 η=89.77 reg=10.2	D=0.8889 η=89.76 reg=10.235	D=0.57136 η=80.81 reg=19.91	D=0.75 η=81.432 reg=18.568	D=0.8889 η=81.40 reg=18.60
Bidirectional converter	D=0.4 η=92.39 reg=7.69	D=0.6 η=93.18 reg=6.82	D=0.8 η=94.01 reg=5.89	D=0.4 η=85.22 reg=14.78	D=0.6 η=87.51 reg=12.76	D=0.8 η=88.69 reg=11.30

[3]. SIMULATION RESULTS

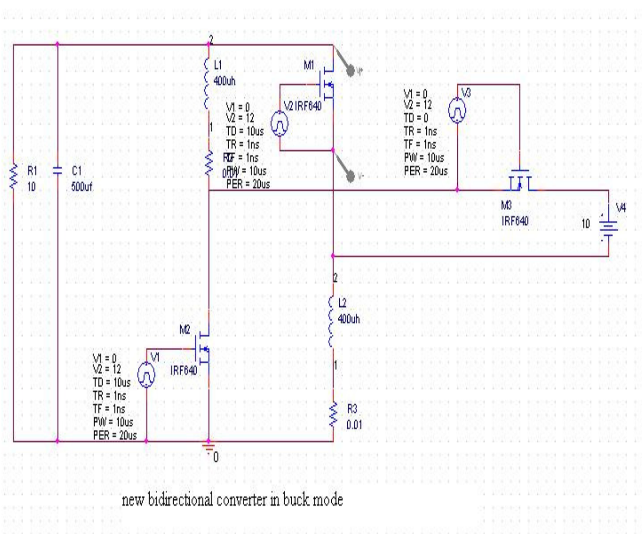


Fig.9. Simulation diagram of Bidirectional converter in Buck mode

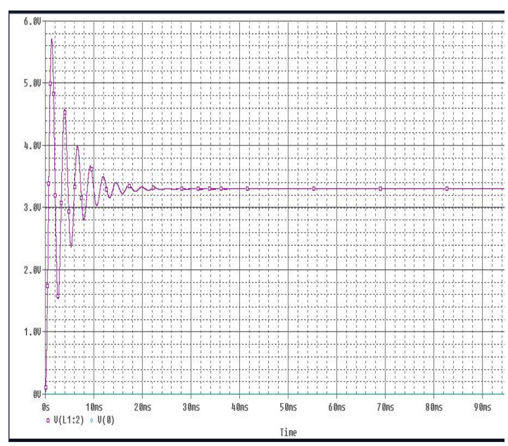


Fig.10 Output voltage for D=0.5,i/p=10v

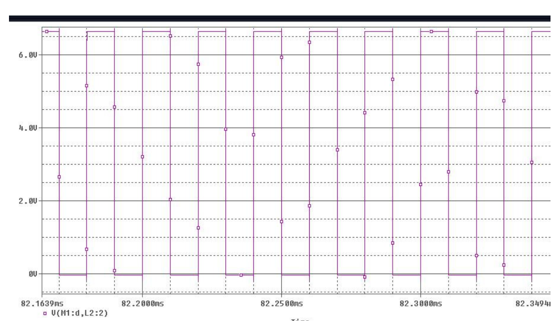


Fig. 11 Voltage across switch S_1 waveform

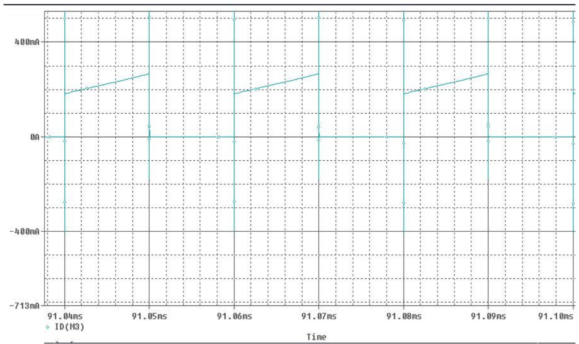


Fig. 12 Input current waveform

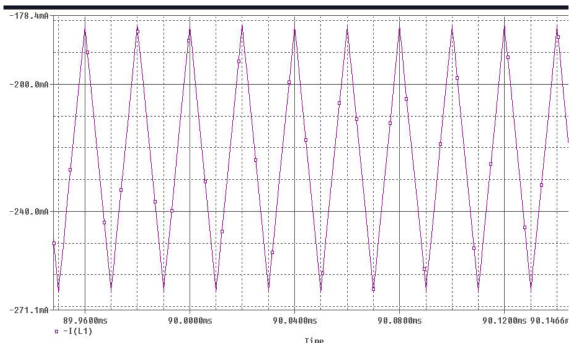


Fig.13 Inductor current waveform

Simulation results of boost mode:

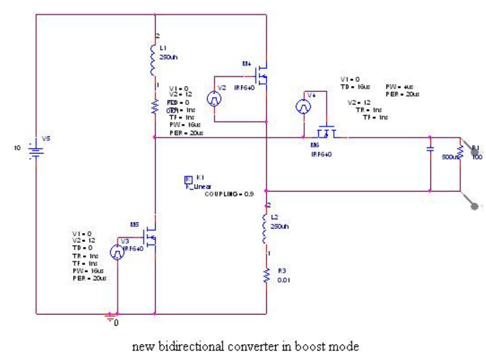


Fig.14 Bidirectional converter in boost mode

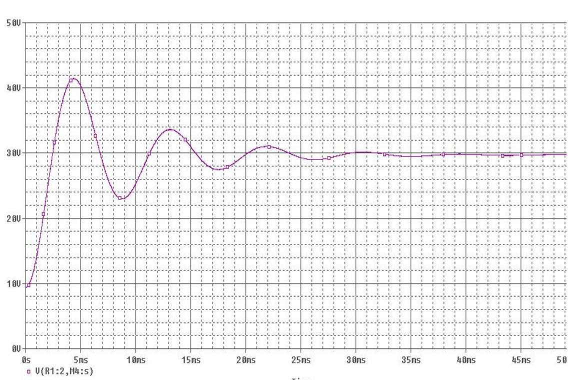


Fig.15 Output voltage for D=0.5,i/p=10v

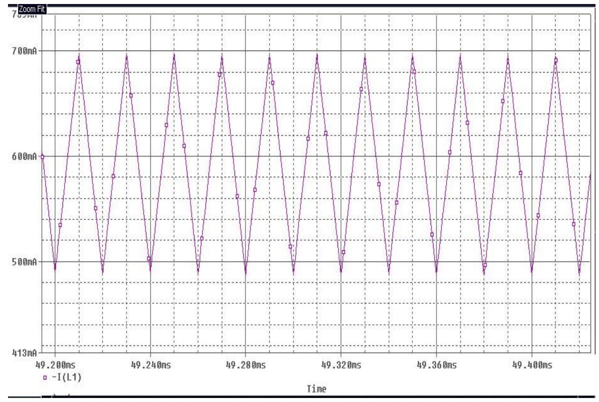


Fig.16 Inductor current waveform

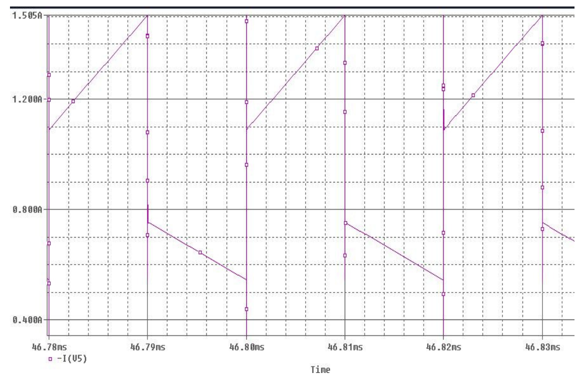


Fig.17 Input current waveform

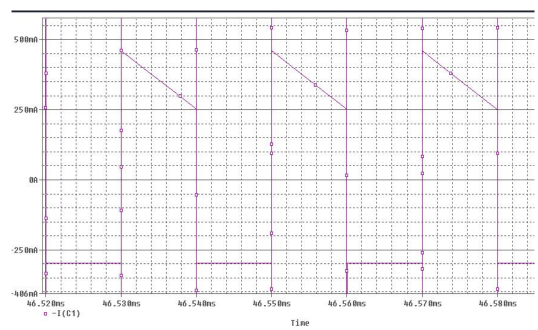


Fig.18 Capacitor current waveform

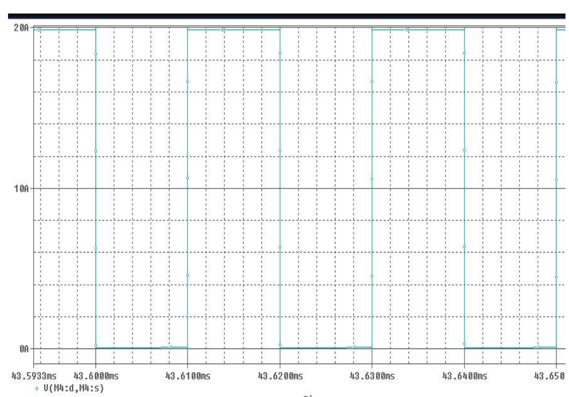


Fig.19 Voltage across switch S_1

[4]. EXPERIMENTAL RESULTS

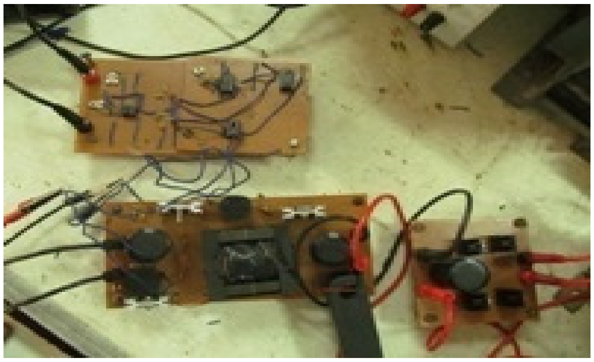


Fig.20. Experimental setup of bidirectional converter

Boost Mode

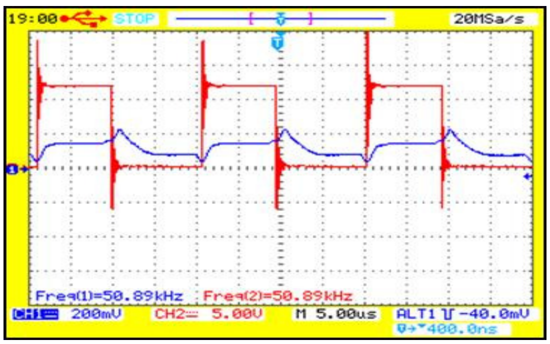


Fig.21. Input current waveform

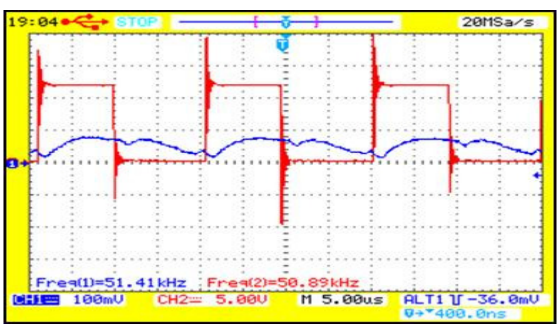


Fig.22. Inductor current waveform

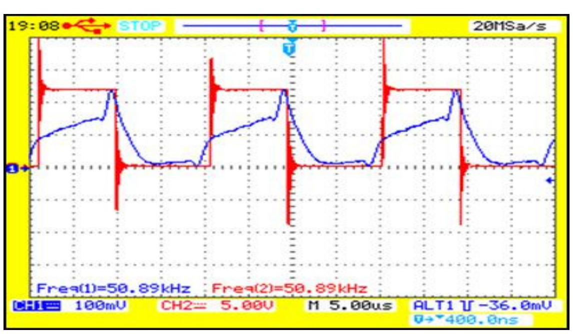


Fig.23. Current through switch S_1 waveform

Buck mode

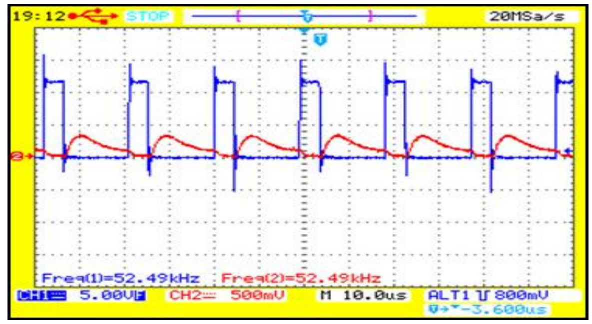


Fig.24. Current through switch S_1 waveform

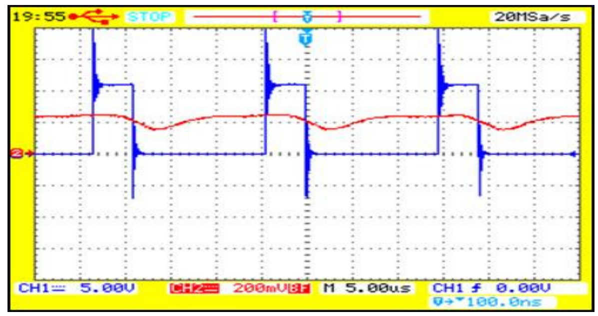


Fig.25. Inductor current waveform

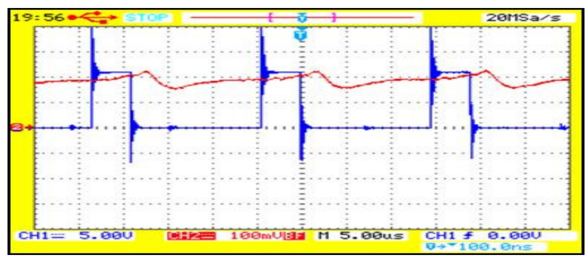


Fig.26. Output current waveform

Experiments are conducted for various values of duty cycle by keeping load constant and readings are tabulated below.

Buck mode R_L=10Ω,Vin=8V

Table - VIII

D	L_{in}	Vo	Io	% η
0.15	0.01	0.675	0.06	50.6
0.20	0.01	0.850	0.08	85.0
0.25	0.03	1.213	0.12	60.7
0.30	0.04	1.414	0.14	61.8
0.40	0.06	1.820	0.18	68.2

Boost mode R_H=100Ω, Vin=8V

Table - IX

D	L_{in}	Vo	Io	% η
0.15	0.01	0.675	0.06	50.6
0.20	0.01	0.850	0.08	85.0
0.25	0.03	1.213	0.12	60.6
0.30	0.04	1.314	0.13	53.3
0.40	0.06	1.820	0.18	68.2

[5]. RELIABILITY

The probability of proper function of a system after a time interval is referred to as its reliability, which is dependent on the type and quality of the parts and materials used in the device, the ambient conditions in which the device is working, etc [16-17]. The failure rate is represented by λ; the reliability is expressed by:

$$R(t) = e^{-\lambda t}$$

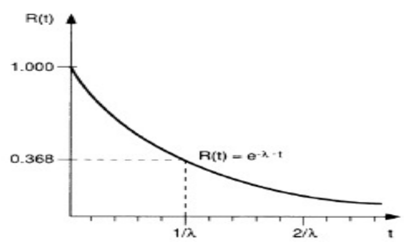


Fig.27. Reliability curve

The mathematical mean of R(t) occurs at: $t = \frac{1}{\lambda}$

Which is the amount of time that should elapse until the first failure occurs. This is called the Mean Time to Failure (MTTF). The mean time to repair (MTTR) of the system is negligible compared to MTTF, so the mean time between failures (MTBF) of a system is expressed as:

$$MTBF = MTTR + MTTF = \frac{1}{\lambda}$$

The total rate of the system failure is the sum of the failure rates of all parts of the system:

$$\lambda_{system} = \sum_{n=1}^{N} \lambda_{part}$$

Hence, the reliability of the system will be the product of all the system components' reliabilities:

$$R_{system} = \prod R_{part}$$

Every product has a failure rate, λ which is the number of units failing per unit time. This failure rate changes throughout the life of the product that gives us the familiar bathtub curve, shown in Fig.28.

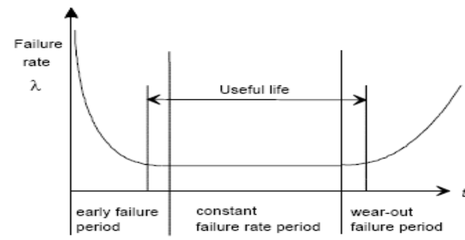


Fig.28. Failure rate vs time

To calculate the reliability, first the dynamic and static losses of MOSFET and Diodes should be calculated for different output powers. The important point that should be noted here is that if the converter is operating in DCM mode, then before further turn-on of the switch, the inductor current is reached to zero. So, there will not be the turn-on loss. Vise versa, in CCM operating mode, since in turn-on instant for the switch, the current should be transferred from diode to the switch, then the dynamic loss includes both turn-on/turn-off losses.

The peak of turn-on/turn-off loss is calculated by:

$$P = V_{avg} * I_{avg} * t_{ol} * f_S$$

Where V_{avg} and I_{avg} are the average voltage across the switch and the average current goes through the switch during turn-on/turn-off overlap times respectively. t_{ol} is the turn-on/turn off overlap duration and f_S is the switching frequency of the circuit.

Reliability calculations

The reliability of conventional buck/boost and bidirectional buck /boost converter are calculated for 60w and 120w for two environments i. e Ground movable environment, Ground fixed environment and results are tabulated.

Table - X

Ground movable environment	60 watts	120 watts
Conventional Boost Converter	76,312.9250	58,996.43756
Bidirectional Boost Converter	55,358.7245	50,244.14490
Conventional Buck Converter	82,783.9514	81,808.42430
Bidirectional Buck Converter	57,592.0550	56,872.92200

Table - XI

Ground fixed environment	60 watts	120 watts
Conventional Boost Converter	1,18,451.13300	90,872.0811
Bidirectional Boost Converter	85,162.23759	77,072.1225
Conventional Buck Converter	1,28,871.06120	1,27,298.558
Bidirectional Buck Converter	90,622.79800	87,501.4044

[5]. CONCLUSION

Bidirectional DC-DC Boost/Buck converter hardware was developed and tested for its performance. By comparing with conventional buck/boost converter this bidirectional converter has high gain is achieved and it has lower average value of the switch current. Efficiency and regulation also better than the conventional converter. If the lower voltage gain is required, the conventional converter can be selected for lower cost. If the higher voltage gain is required, the proposed converter can be chosen for higher efficiency From the Table – X & XI, the reliability of conventional converter is more than the bidirectional converter due to more number of components. It can also say that reliability of this converter is more in ground fixed environment than the ground movable converter.

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