# A Novel High Conversion Ratio Bi-Directional DC-DC Converter

**Sarun S S[1], Anil J Thomas[2]**

[1]PG Student [PEPS], Department of EEE, FISAT, Angamaly, Kerala, India

[2]Assistant professor, Department of EEE, FISAT, Angamaly, Kerala, India

**Abstract:** ***This paper presents a high-conversion ratio bi-directional dc-dc converter with coupled inductor. In the boost mode, two capacitors are parallel charged and series discharged by the coupled inductor. Thus, high step-up voltage gain can be achieved with an appropriate duty ratio. The voltage stress on the main switches reduced by a passive clamp circuit. Therefore, the low resistance $R_{DS}(ON)$ of the main switch can be adopted to reduce conduction loss. In the buck mode, two capacitors are series charged and parallel discharged by the coupled inductor. The bi-directional converter can have high step-down gain. Aside from that, all of the switches achieve zero voltage-switching turn-on, and the switching loss can be reduced. Due to two active clamp circuits, the energy of the leakage inductor of the coupled inductor is recycled. The efficiency can be further improved. Simulation of open loop and closed loop control of novel high-conversion-ratio bi-directional dc-dc converter with coupled inductor is done in MATLAB and output is obtained. Hardware implementation of the open loop is being done and the output is obtained.***

**Keywords:** DC-DC Converter, Boost Mode, BuckMode ,Zero Voltage Switching, MATLAB/SIMULINK

## 1. Introduction

Renewable energy sources such as wind and solar are widely used nowadays. The output voltage of these sources is very low. Also sudden load changes cannot met by these sources. Therefore battery with bi-directional DC-DC converter is needed [1] - [3]. Isolated bidirectional dc-dc converters such as half and full bridge types, can provide high step-up and step-down voltage gains by adjusting the turns ratio of the transformer. The high step-up gain and the high step-down voltage gain can be achieved. The leakage inductor of the transformer leads to the HV spike on the main switch during switching transition. A novel soft commutating isolated boost full-bridge zero-voltage-switching (ZVS) pulse width modulation dc-dc converter is introduced [4]. The energy of the leakage inductor is recycled and not dissipated. However, the number of switches is increased. To achieve a high conversion ratio, two inductors charged in parallel and discharged in series are proposed [5].Based on above topologies, the novel bidirectional converter combines all advantages such as high conversion ratio, recycling of the inductor energy, soft switching and high efficiency etc.in this converter a mutually coupled inductor and two capacitors are used to achieve the high conversion ratio. The inductor energy is also recycled by using another capacitor. Soft switching is also obtainedin the converter. So that switching losses are minimized. Therefore converter has got high efficiency.

## 2. Operating Principle of the Novel High Conversion Ratio Bi-Directional DC-DC Converter

The switched-capacitor technique in [5] and [6] has proposed that parallel-chargedand series-discharged capacitors can achieve high step-up gain. Also, series charged and parallel-discharged capacitors can achieve high step-down gain.Thecharacter of the coupled inductor is that the secondary side can have oppositepolarity when the switch is on and off. In the boost-state operation, this character is combined with the switched capacitor technique. Two capacitors $C_2$ and$C_3$ are parallel charged when the switch is on and series discharged when theswitch is off. In the buck-state operation, the coupled inductor is used as atransformer. Thus, two capacitors $C_2$ and $C_3$ can be series charged by HV sideand parallel discharged through the secondary side. In addition, the problem ofthe energy of the leakage inductor is also solved. In the boost-state operation,$S_1$ is the main switch, and capacitor $C_1$ recycles the energy. The voltage acrossswitch $S_1$ can be clamped. Since switch $S_1$ has an LV level, the low conductingresistance $R_{DS}(ON)$ of the switch is used to reduce the conduction loss. In thebuck-state operation, the main switches are $S_2$ and $S_5$. Two capacitors $C_2$ and$C_3$ with switches $S_3$ and $S_4$ are used as active clamp circuits, recycling the energyof the leakage inductor on the secondary side of the coupled inductor. Capacitor$C_1$ with switch $S_2$ is another active clamp circuit that recycled the energy ofthe leakage inductor on the primary side.

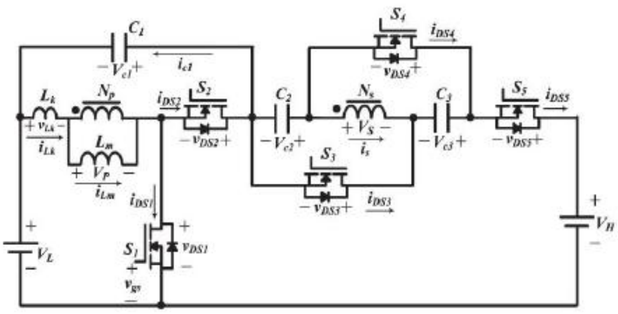


**Figure 1:** Circuit configuration of the bidirectional converter

Thus, four switches are ZVS turned on. The switching loss is improved; the efficiency can be increased. It is because that the high step-up converter needs a large input current, which results that the conduction loss is larger than the switching loss. Thus, reducing the switch voltage stress for alleviating the conduction loss and the elimination of reverse-recovery current is the key point to improve efficiency. Similarly, the main switch of the high step-up and step-down converters suffers HV stress and low conducting current. The switching loss should be reduced to improve efficiency.

### A. Boost Mode Operation

The typical waveforms in the boost state at the CCM is shown in fig.2.There are five operating modes in one switching period of the novel converter in theCCM. Switches $S_2$, $S_3$, $S_4$, and $S_5$are synchronous rectifiers. The main switchis $S_1$ for each modes.

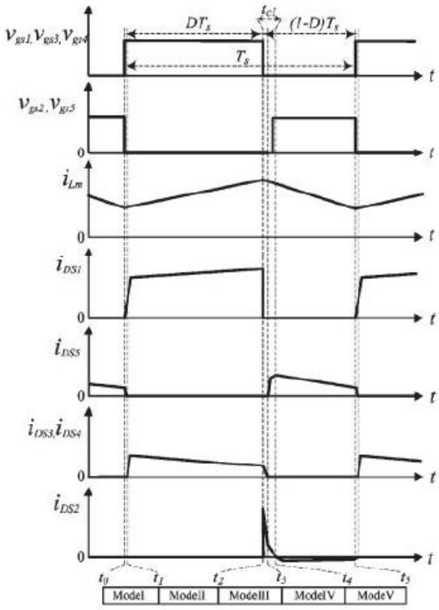


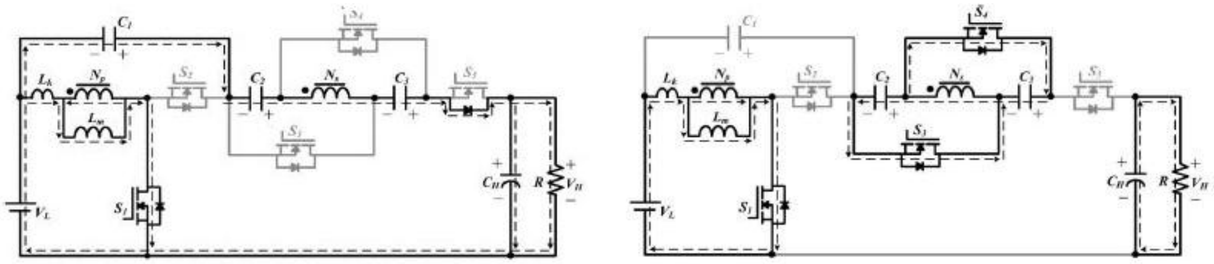

**Figure 2:** Waveforms of the bidirectional converter in the boost state at the CCM

- **Modes of Operation**

The operating modes at the CCM are described below.

**MODE 1:** At t =$t_0$, $S_1$ is turned on. $S_2$, $S_3$, and $S_4$are off, and $S_5$ is on.The current flow path is shown in Fig.3(a) The voltage of the primary side is $V_L$ =$V_{Lk}$ +$V_p$. Thus, the leakage inductor $L_k$ and the magnetizing inductor $L_m$are charged by the dc source $V_L$. Due to the leakage inductor $L_k$, the secondary side current is linearly decreases. The reverse-recovery problem of the diode is alleviated. When current $i_{DS5}$ becomes zero at t= $t_1$, this operating mode is ended.

**MODE 2:**$S_1$ is still on. $S_2$ and $S_5$are off, &$S_3$ and $S_4$are turned on at t = t-1. The current flow path is shown in Fig.3(b) The dc source $V_L$charges the magnetizing inductor $L_m$, as well as the charging capacitors $C_2$and $C_3$ via the coupled inductor. Voltages $V_{c2}$ and $V_{c3}$are approximately equal to nVL. Two capacitors are charged in parallel.The output capacitor $C_H$provides energy to load R. This operating mode ends when switch $S_1$ is turned off at t = $t_2$.

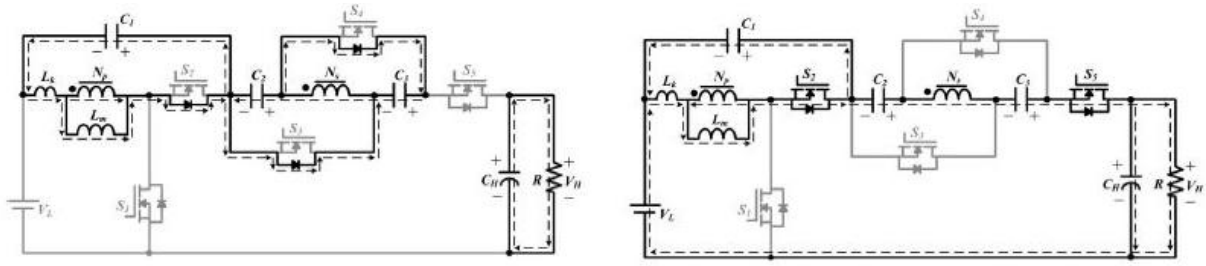


(a) (b)

**Figure 3:** (a)Current flow path during mode 1 in the boost state at the CCM(b)Current flow path during mode 2 in the boost state at the CCM

**MODE 3:**At t = $t_2$, $S_1$ is turned off, and diode $S_2$ is turned on. Diodes $S_3$and $S_4$ are still on, and $S_5$ is still off. The current flow path is shown in Fig.4(a).The output capacitor $C_H$ still provides energy to load R.The leakage inductor $L_k$ energy and the magnetizing inductor $L_m$ energy charge the clamp capacitor $C_1$. Due to the leakage inductor of the secondary side of the coupled inductor, currents $i_{DS3}$ and $i_{DS4}$ are linearly decreased. The reverse-recovery problem of the diode is alleviated. As $S_3$ and $S_4$are cut off at t = $t_3$, this operating mode ends.

**MODE 4:**$S_1$ is still off, and diode Ds2 is still on. At t = $t_3$, diodes $S_3$ and$S_4$ are turned off, and $S_5$ is turned on. The current flow path is shown in Fig.4(b). The energies of the leakage inductor $L_k$ and the magnetizing inductor $L_m$are released to the clamp capacitor $C_1$. Some of the magnetic energy is released bythe secondary side of the coupled inductor. Voltage $V_s$of the secondary side is build. At t = $t_4$, the energy of the leakage inductor is totally recycled bycapacitor $C_1$; $S_2$ is cut off. This mode is ended.



(a) (b)

**Figure 4:** (a)Current flow path during mode 3 in the boost state at the CCM (b) Current flow path during mode 4 in the boost state at the CCM

**<u>MODE 5</u>:**$S_1$ is still off and $S_2$ is on, diodes $S_3$ and $S_4$are still off, and $S_5$is still on. The current flow path is shown in Fig. The coupled inductor, dc source $V_L$, and capacitors $C_2$ and $C_3$ are connected in series to charge the output capacitor $C_H$ and load R. The HV gain is achieved. This operating mode endsat t = $t_5$ when switch $S_2$ is turned off and $S_1$ is turned on at the beginning of the next switching period.

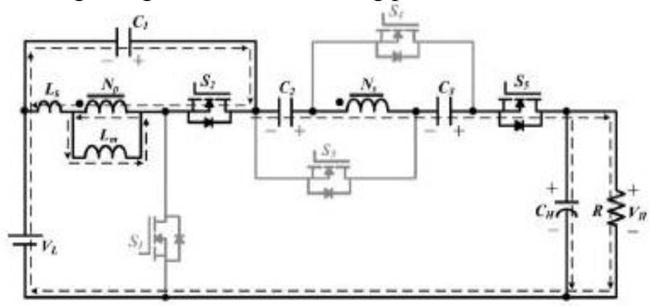


**Figure 5:** Current flow path during mode 5 in the boost state at the CCM

**B. Buck Mode Operation**

In buck mode, there are six operating modes in one switching period. The main switch is $S_5$. Switches $S_2$,$S_3$ and $S_4$ are auxiliary switches for achieving ZVS turn-on. The typical waveforms in the boost state at the CCM is shown in Fig.6.

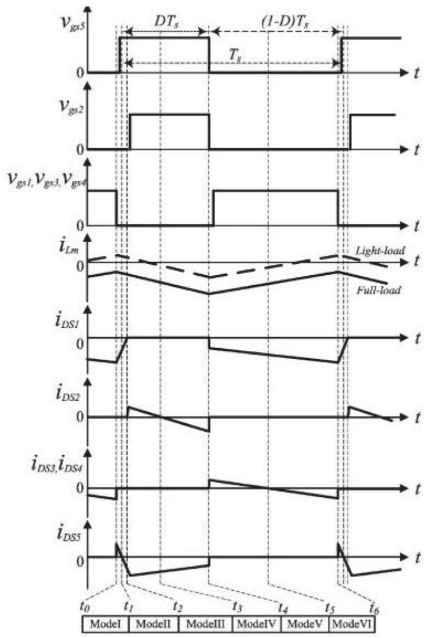



**Figure 6:** Waveforms of the bidirectional converter in the buck state at the CCM

- **Modes of Operation**

**<u>MODE 1</u>:**The switch $S_2$ is turned on at t = $t_0$. The current flow path is shownin Fig.7(a). Due to the leakage inductor $L_k$, the current of the secondary side of the coupled inductor flows through diode $D_{s5}$. Capacitors $C_1$, $C_2$, and $C_3$are also discharged to $V_H$. Then, switch $S_5$ is turned on, and ZVS is achieved. Because of the HV side $V_H$, current $i_{DS1}$ and $i_{DS5}$ linearly decrease. Meanwhile, the output capacitor $C_L$ is charged by the magnetizing energy. At t=$t_{1,}$ this mode is ended. $i_{DS5}$ become zero.

**<u>MODE 2</u>:**The switch $S_5$ is turned on. The output capacitor $C_L$ provides energy to load R. Capacitors $C_1$, $C_2$, and $C_3$, and the secondary side coil $N_s$ are charged in series by HV side $V_H$. Thus, the induced voltage $V_p$ on the primary-side coil $N_p$ makes current $i_{DS1}$ decrease and charge the magnetizing inductor $L_m$. The magnetizing current $i_{Lm}$ is increased. At t = $t_2$,this mode is ended. the current $i_{DS1}$ become equal to zero.

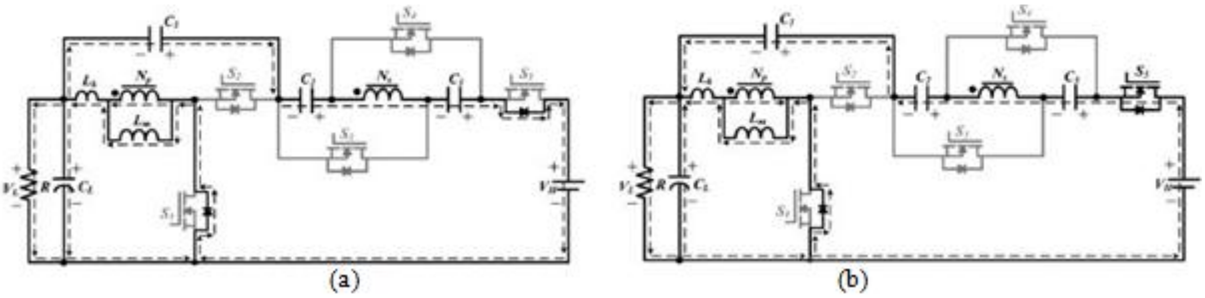


**Figure 7:** (a) Currentflow path during mode 1 in the buck state at the CCM(b)Current flow path during mode 2 in the buck state at the CCM

**MODE 3:** The switch $S_5$ is on. The leakage inductor $L_k$ is charged by the primary-side coil $N_p$. The charge current flows through the antiparallel diode $D_{s2}$ of switch $S_2$. Then, $S_2$ is turned on, and ZVS is achieved. Capacitors $C_1$, $C_2$, and $C_3$ , and the secondary side coil $N_s$ are still charged in series by HV side $V_H$, and the magnetizing inductor $L_m$ is also charged. The output capacitor $C_L$ provides the energy to load R.At t = $t_3$, $i_{DS2}$ is equal to zero. This mode is ended.

**MODE 4:** The switches $S_2$ and $S_5$ are on. At t = $t_3$, capacitor $C_1$ starts to charge the magnetizing inductor Lm. The output capacitor CL discharges to load R. Because two capacitors $C_2$ and $C_3$, and the coupled inductor are charged in series by the HV side $V_H$, the high step-down voltage gain can be achieved. At t = $t_4$, switches $S_2$ and $S_5$are turned off. This mode is ended.

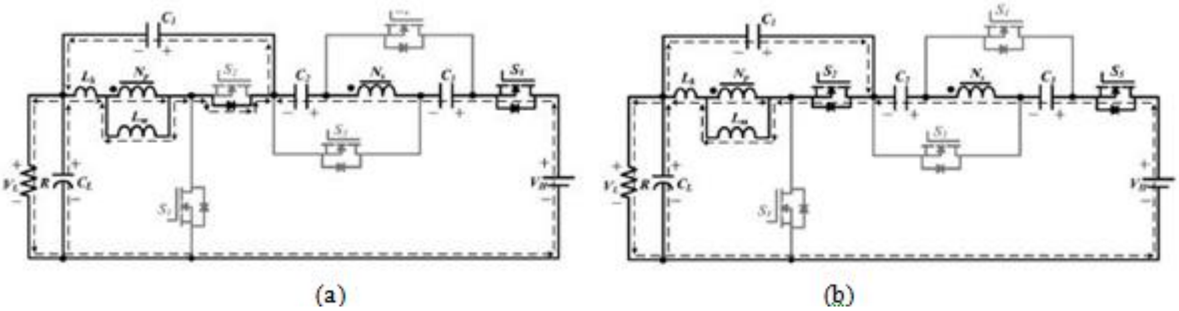


**Figure 8:** (a) Current flow path during mode 3 in the buck state at the CCM (b)Current flow path during mode 4 in the buck state at the CCM

**MODE 5:**The switches $S_2$ and $S_5$ are turned off at t=$t_4$. The current ofthe leakage inductor flows through the antiparallel diodes $D_{s1}$, $D_{s3}$, and $D_{s4}$of switches. Then, switches $S_3$ and $S_4$ are turned on, and ZVS turn on is achieved. The energy of the magnetizing inductor $L_m$ discharges to capacitor $C_L$ and loadR. At t = $t_5$, currents $i_{DS3}$ and $i_{DS4}$ are zero. This mode is ended.

**MODE 6:**The switches $S_3$ and $S_4$ are on. At t = $t_5$, the energy of capacitors$C_2$ and $C_3$ discharges to the output capacitor $C_L$and load R through the coupled inductor. The magnetizing inductor $L_m$ also discharges to the output. This mode is ended at t = $t_6$ when $S_3$ and $S_4$ are off.

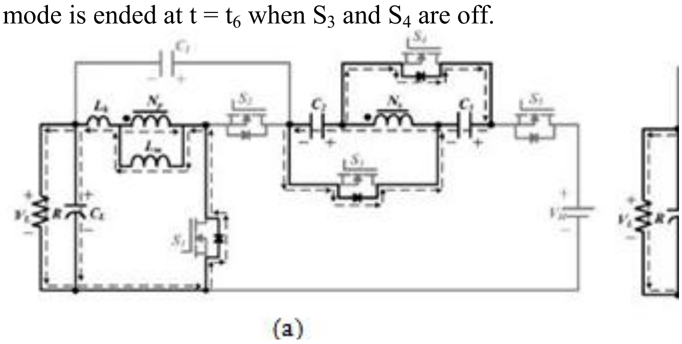


**Figure 9:** (a) Currentflow path during mode 5 in the buck state at the CCM (b)Current flow path during mode 6 in the buck state at the CCM

## 3. Steady State Analysis of the Novel Converter

According to the assumptions before the steady state analysis, the equations of the turn ratio and the coupling coeffcients k of the coupled inductor are defined as,

$$n = \frac{N_s}{N_p}$$

$$k = \frac{L_m}{L_m + L_k}$$

The voltage gain of the boost-state operation is obtained as,

$$M_{boost} = \frac{V_H}{V_L} = \frac{1+n}{1-D} + n$$

The voltage gain of the buck-state operation is obtained as,

$$M_{buck} = \frac{V_L}{V_H} = \frac{D}{1+n+Dn}$$

The value of the magnetic inductor can be decided by,

$$L_m = \frac{D(1-D)^2 R_H}{2(1+n)(1+2n-nD)f_s}$$

where $R_H$ is the load, D is the duty ratio and $f_s$ is the switching frequency. Here$L_m$ is 60µH and $L_k$ is 0.16 µH.The capacitor $C_1$ is 47 µF and $C_2$ and $C_3$ are of23.5 µF. The value of capacitors $C_2$ and $C_3$ are obtained as,

$$C_2 = C_3 > \frac{((1-D)T^2}{\pi^2 n^2 L_k}$$

## 4. Simulink Model and Results

### A. Open Loop Control of Boost Mode Operation

The simulation diagram of bi-directional dc-dc boost converter is shown below.

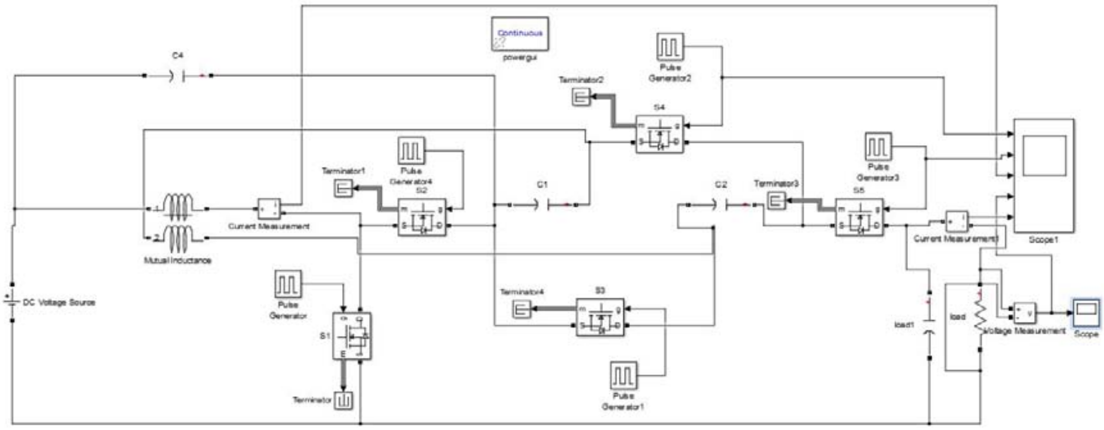



**Figure 10:** Simulation diagram of bi-directional dc-dc boost converter in MATLAB

The input voltage and output voltage waveforms obtained in MATLAB Simulink are shown in the Fig.11 and Fig .12.

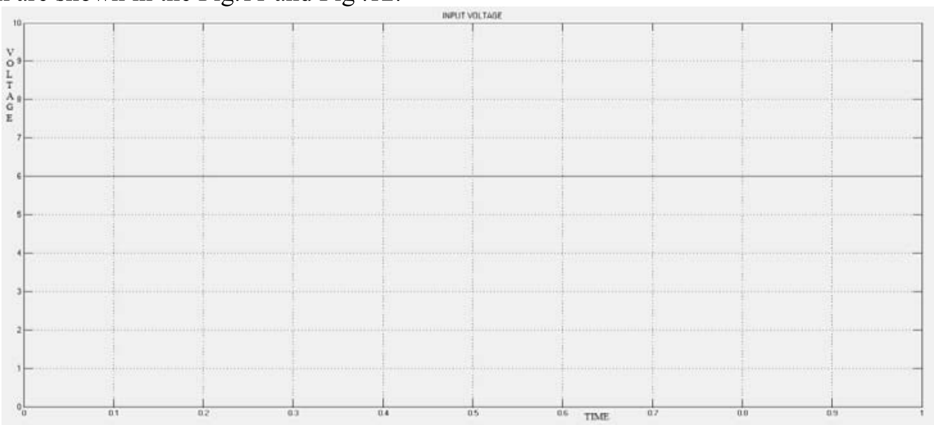



**Figure 11:** Input voltage (6V) waveform of bi-directional dc-dc boost converter

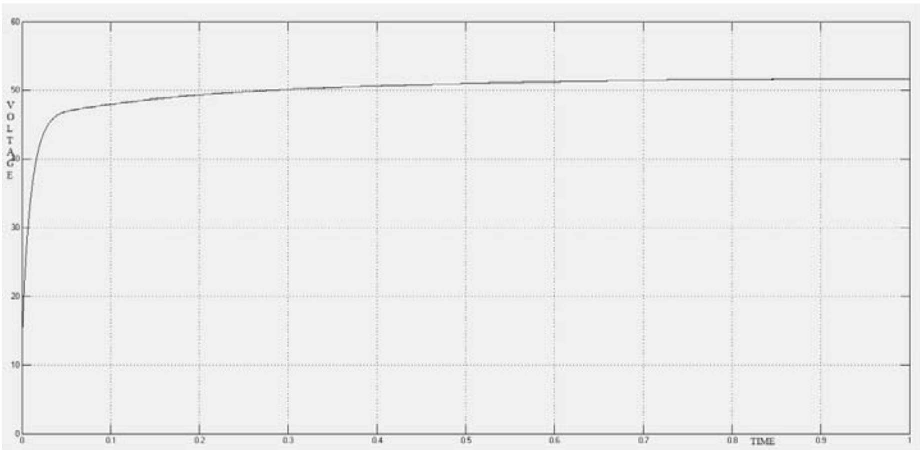



**Figure 12:** Output voltage (52V) waveform of bi-directional dc-dc boost converter

The input voltage is 6V. The output voltage obtained after simulation is 52V.

### B. Open Loop Control of Buck Mode Operation

The simulation diagram of bi-directional dc-dc buck converter is shown below.

International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
Index Copernicus Value (2013): 6.14 | Impact Factor (2015): 6.391

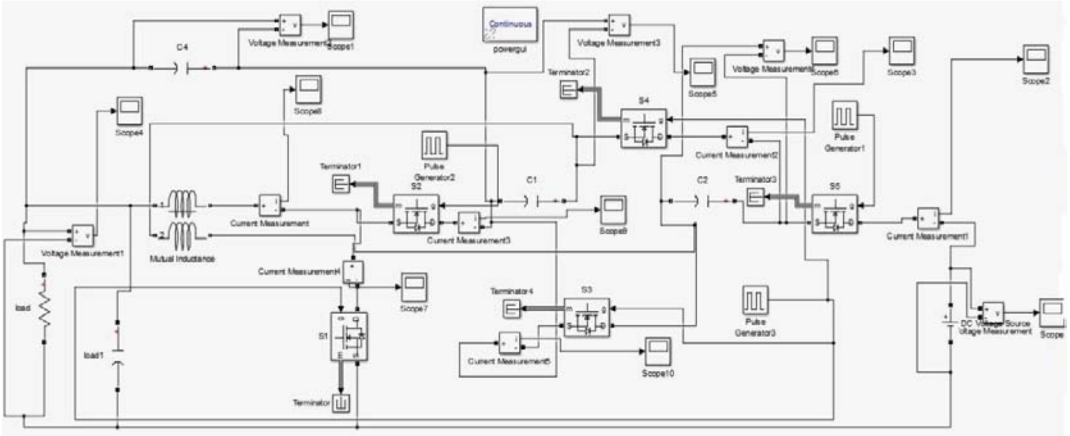


**Figure 13:** Simulation diagram of bi-directional dc-dc buck converter in MATLAB

The input voltage and output voltage waveforms obtained in MATLAB Simulink are shown in the Fig.14 and Fig .15

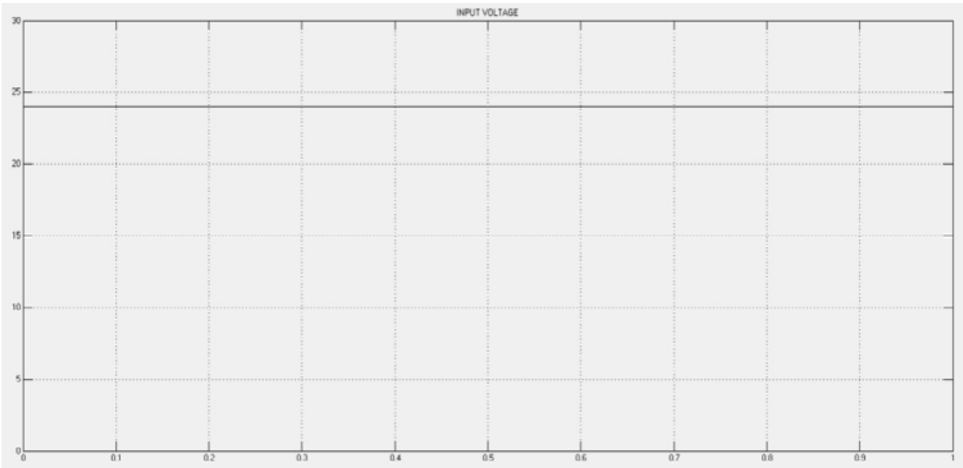



**Figure 14:** Input Voltage (24V) waveform of bi-directional dc-dc buck converter

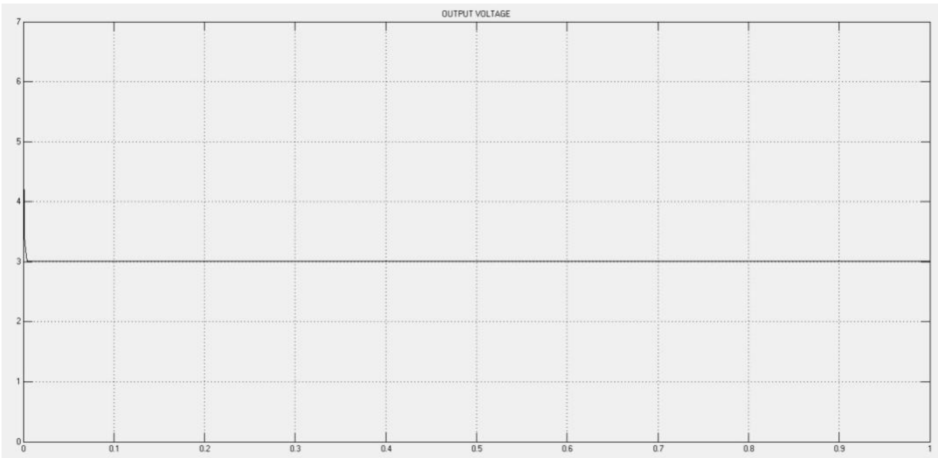



**Figure 15:** Input Voltage (3V) waveform of bi-directional dc-dc buck converter

The input voltage is 24 V. The output voltage obtained after simulation is 3V.

**C. Closed Loop Control of Boost Mode Operation**

The simulation of the closed loop bi-directional converter is done and the resultis obtained. The reference output voltage is set to 35 V. The initial input voltage is set as 5 V and final input voltage is set as 10 V. Closed loop is obtained usingpi controller. The simulation results are shown below.

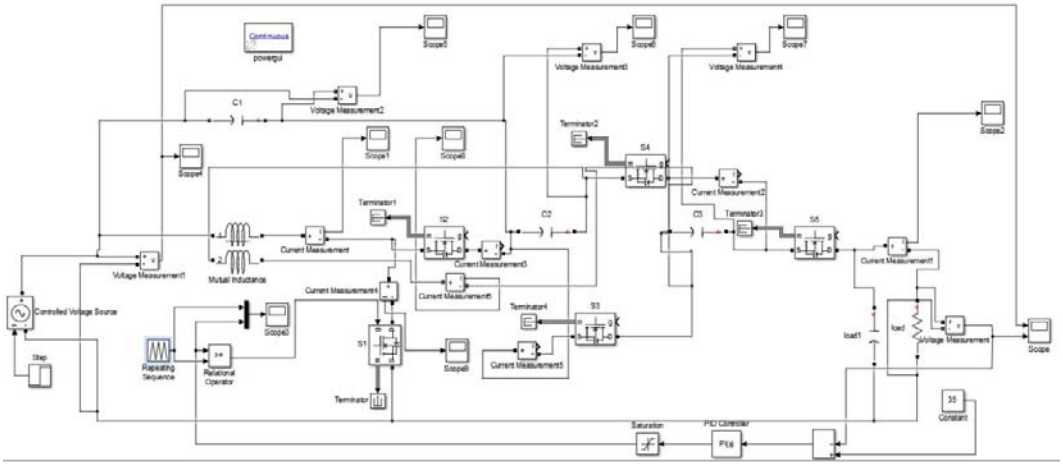


**Figure 16:** Closed loop simulation diagram of bi-directional dc-dc boost converter

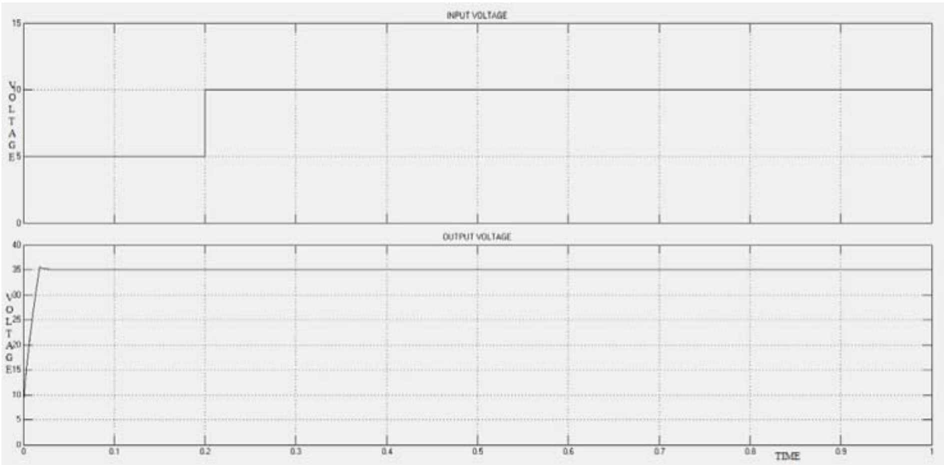



**Figure 17:** Closed loop input and output voltage of bi-directional dc-dc boost converter

## 5. Hardware Implementation

The simulation is done by using MATLAB software and practical prototypeis made in the experimental environment. Hardware implementation of the bi-directional dc-dc boost converter with coupled inductor is done. Figure below shows the experimental set up. The switching pulses are generated using Arduino .And TLP250 is used as optocoupler and IRF350 is used as the switch. For an input voltage of 6V, an output voltage of 24 V is obtained here.

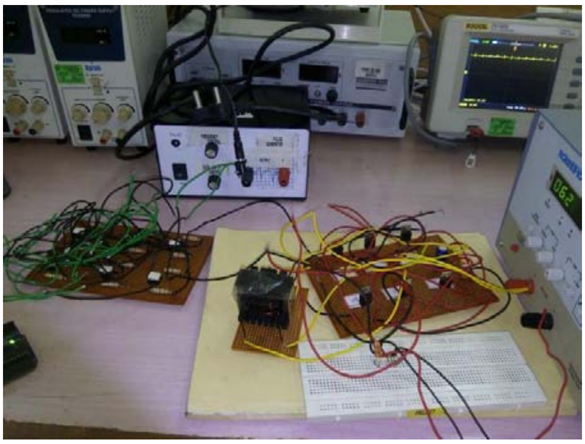


**Figure 18:** Hardware Setup

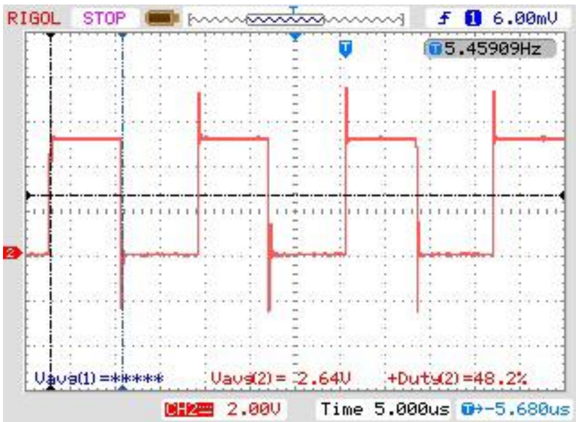



**Figure 19:** Gating Signal generated from Arduino

Input and output voltage waveform is shown below.

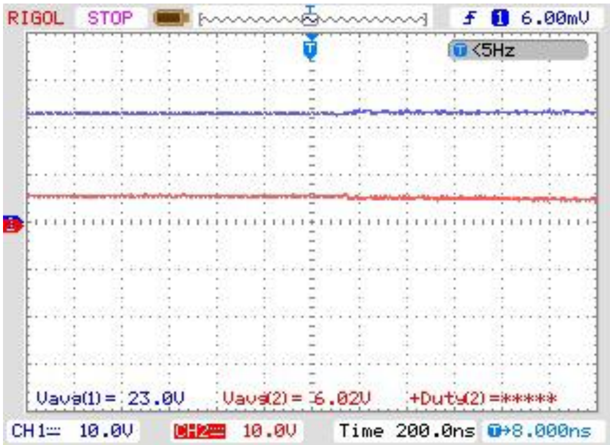



**Figure 20:** Input and output voltage waveform

## 6. Conclusion

A novel, high efficiency, and high step-up/step-down bidirectional dc-dc converter has been introduced here. By using the capacitor charged in parallel and discharged in series by the coupled inductor, proposed converter have been discussed. The voltage gain and the utility rate of the magnetic core have been increased by using a coupled inductor with a low turn ratio. The energy of the leakage inductor has been recycled with the clamp circuit. The simulation of the converter for open loop and closed loop is done in MATLAB and results are obtained. And also the hardware implementation of the bi-directional boost converter is done and boost output is regulated using the pi controller.

## References

[1] Yi-Ping Hsieh, Jiann-Fuh Chen, Lung-Sheng Yang, Chang-Ying Wu, andWei-Shih Liu, “High Conversion Ratio Bidirectional DC-DC Converter WithCoupled Inductor",IEEE Trans. in Power Electronics, vol. 61, NO.1, Jan.2014.

[2] Roger Gules, Juliano De Pellegrin Pacheco, Hlio Lees Hey and JohninsonImho,“A Maximum Power Point Tracking System With Parallel Connectionfor PV Stand-Alone Applications",IEEE Trans. Ind. Electron.,vol. 55, NO.7, July. 2008.

[3] Rong-Wai and Rou-Yong Duan,“High-Efficiency Bidirectional Converter forPower Sources With Great Voltage Diversity",,IEEE Trans. Ind. Electron.,vol. 22, NO. 5, Sept. 2007.

[4] [4] T. F. Wu, Y. C. Chen, J. G. Yang, and C. L. kuo, “Isolated bidirectional full bridge dc-dc converter with a ybacksnubber", IEEE Trans. Power Electron.,vol. 25, no. 7, pp. 1915-1922, Jul. 2010.

[5] L. S. Yang and T. J. Liang, “Analysis and implementation of a novel bidirectional dc-dc converter", IEEE Trans. Ind. Electron., vol. 59, no. 1, pp.422-434, Jan. 2012.

[6] Fanghua Zhang and Yangguang Yan, “Novel Forward Flyback Hybrid Bidirectional DC-DC Converter,"IEEE Trans. Ind. Electron.,vol.56, NO. 5, May2009.

[7] Mohammad Reza Mohammadi and HoseinFarzanehfard,“New Family of Zero-Voltage-Transition PWM Bidirectional Converters With Coupled Inductors,”IEEE Trans. Ind. Electron.,vol.59, NO. 2, Feb. 2012.

[8] Pritam Das, S. Ahmad Mousavi, and Gerry Moschopoulos, “Analysis and Design of a Nonisolated Bidirectional ZVS-PWM DC-DC Converter With Coupled Inductors,"IEEE Trans. in Power Electronics,vol.25,NO.10,Oct.2010..