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Bidirectional Converter and Energy Storage System

Abhay Kumar[1], N. Neogi[2]
[1]M.E. Student, Department of Electrical and Electronics Engineering, Birla institute of technology, Mesra, Ranchi
[2]Assistant Professor, Department of Electrical and Electronics Engineering, Birla institute of technology, Mesra, Ranchi

Abstract: An isolated bidirectional buck-boost converter with bidirectional inverter is present in this paper. It can be design for supply power to consumer during the peak load. For this operational principle of the proposed converter is describe and then design equation is derived. A 100W prototype with low-side voltage of 24 V and high-side voltage of 230 V has been design, from design experimental results have verified its feasibility.

Keywords: Bidirectional buck-boost converter, Bidirectional switch, Bidirectional inverter.

1. Introduction

Since the use of fossil fuel and coal power plant cause undesirable effect on the environment, the environment friendly energy become very important in today time. Also demand for electrical (environment friendly) energy will continue to increase as world population increases. Renewable energy is not immediate solution to the problem. Renewable energy faces several drawbacks on its path to become the sole source of electric power generation. One main drawback is its dependency on geographic location. Example, the locations for solar energy lie in the desert regions of earth's surface and best available wind energy in the United States lies in the Midwestern and Great Plains states.[1]-[4] Wind energy has been known to cause major brown-outs because of unexpected drops in wind speed. Therefore, an energy storage system is needed. Another issue that the electric power grid faces is peak demand loading periods.

These periods of time are when energy demand is at its highest and generally happen during the hours of 5 PM to 8 PM. During these hours, power plants must ramp up generation in order to keep up with demand. Energy is expensive for the power utility to produce during these hours because the increased generation may come from high cost processes and increased prices of power generation. Most residential customers currently pay a flat rate; however, improved metering technologies will allow utility companies to start charging different rates at different time periods. Energy demand drops well below the baseline power generation during the late night and early morning. Energy during these hours is cheap to generate for the power utility and also cheap for purchase. The way to eliminate the peaks and troughs of the power consumption trend is needed in order to help make energy more economical. [5]

The circuit diagram for the complete grid-tied system is shown in fig. 1.The purpose of the design is to demonstrate that a bi-directional system can be achieved using minimal components this design project was focused on building a scaled down battery energy storage system. The design was required to utilize power electronics to interface a battery bank with the grid. The system was required to operate in two different modes, main aim to focus on the "discharge mode" (**B2G)** in which power is drawn from the batteries and injected into the grid. The design was required to recharge the battery bank from the grid without making any hardware changes during a "charge mode" **(G2B)** of operation.

The intent of the design was to provide a proof of concept for the system to allow later development in capacity and complexity. Although the entire B2G system is presented, due to given time restraints, the main focus on the design of the bi-directional DC-DC converter and inverter power stages, as well as the inverter output filter. The two power stages are required to operate in both charging and discharging modes using the same hardware. These systems were designed and verified using MATLB simulation dSPACE. The two designs along with control circuitry will be used in later development for a complete B2G system. Furthermore, an analysis on the effects of B2G will be conducted.

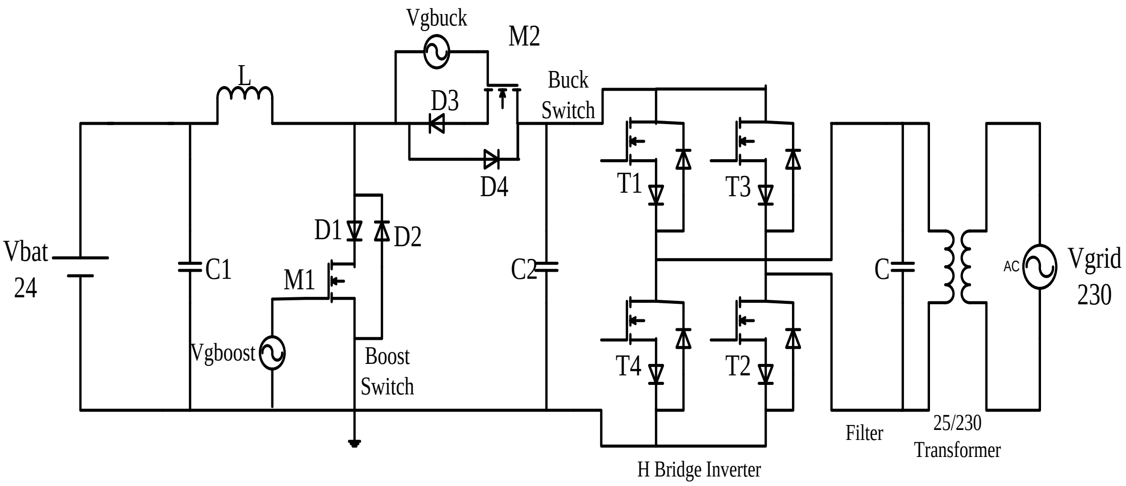


Fig.1: Conventional and propose Bi-directional DC to Ac converter

2. Operation Principal of Converter

Its operation principal is classified in two mode of operation:-
a)Forward mode (BtoG):-In forward mode of operation it is divided in two stage of power flow and two stage of control.

a) Step-up mode of the converter

In the step-up mode, the equivalent circuit of the converter is shown in Fig. 2. The continues pulse technique is used to control the switches M1.In this mode of operation MOSFET M1 is gating gate pulse for triggering the switch. When MOSFET is trigger at the same time diode D1 also conducting and inductor L storage energy during this time capacitor C2 is discharging. When switch not conducting then whole power from battery and energy storage by inductor L will supply the power at input side of inverter, at the same time diode D4 is conducting. Equivalent circuit for mode of operation and waveform is shown in fig. 3.

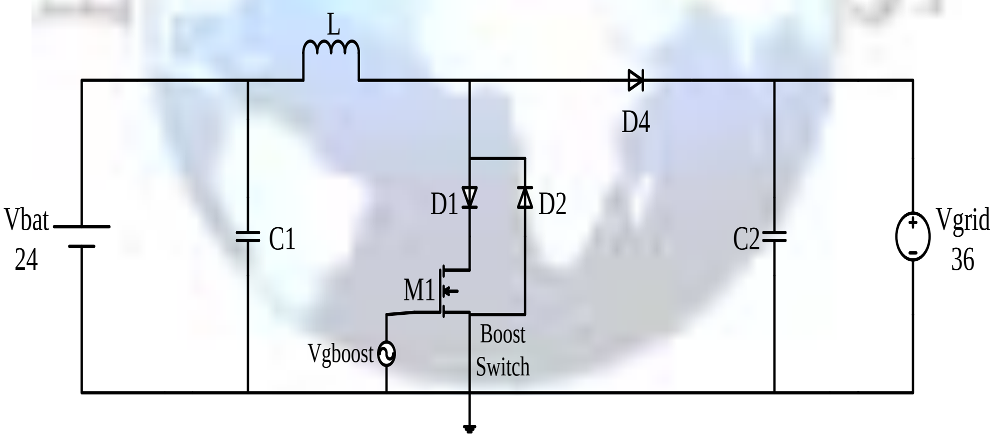


Fig. 2: Equivalent circuit of step up converter

In continuous conduction mode inductor current $I_L(t)$ remain greater than zero. Steady state operation of the circuit can be explained with two states energy storing state or energy pumping state shown in Figure 3(a).When the switch M1 is ON and Figure 3(b).When switch M1 is off and diode D1 is conduct respectively. Consider the switching period is T and switch M1 is ON for T_{ON} period and OFF for T_{OFF} period. During ON period of switch M1 current through the inductor increases from minimum value $I_{L,\min}$ to $I_{L,\max}$ and storing energy into inductor. During off period of switch M1, energy store in inductor and source energy get transfer to load connecting in parallel with output capacitor. During this period inductor current falls down from $I_{L,\max}$ to $I_{L,\min}$ and boost capacitor voltage increases from $V_{C,\min}$ to $V_{C,\max}$. Inductor current waveform is shown in Fig.3(c). If we consider that inductor, capacitor and switch are ideal and no loss takes place during complete process. So "average energy store in the inductor during ON interval of switch M1 will be equal to energy transfer to capacitor during OFF interval of switch M1.

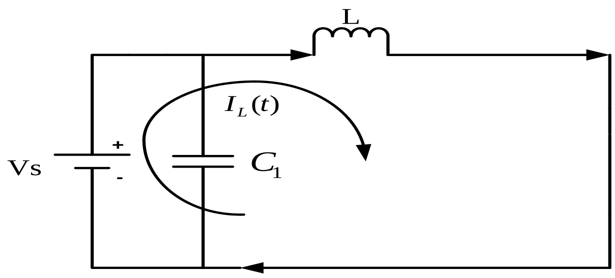


Fig 3 (a): Energy storing state

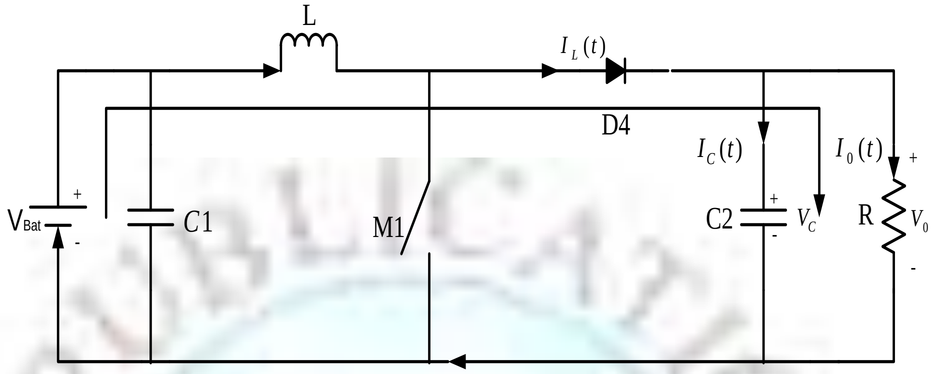


Fig 3(b): Energy pumping state

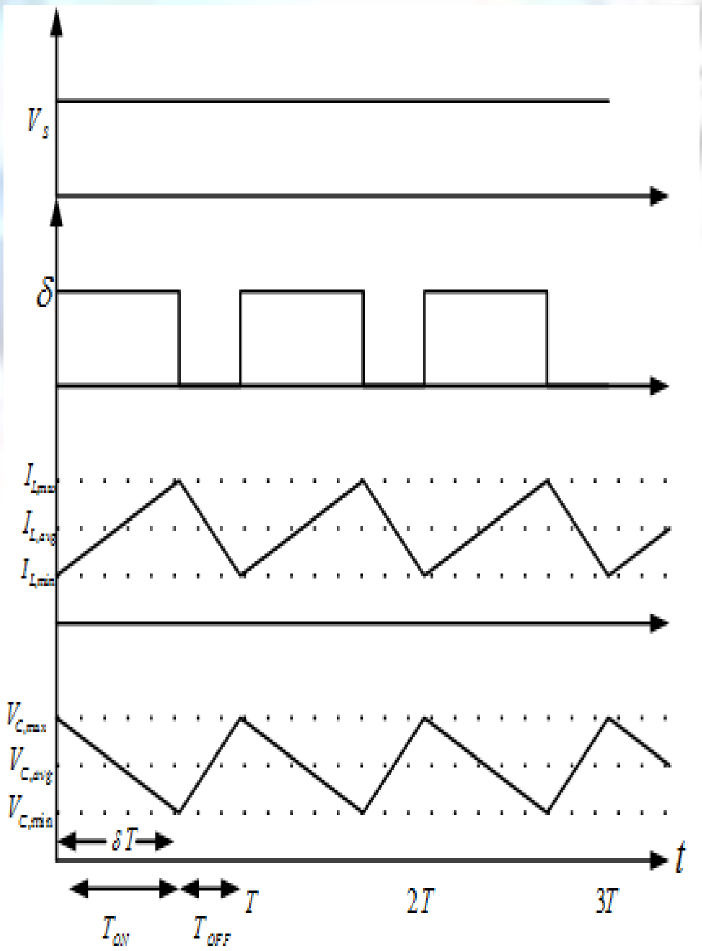


Fig. 3 (c): Inductor current and capacitor voltage waveform

We know that

$$\delta = \frac{T_{ON}}{T} \quad (1) \qquad W_{in} = W_{out} \quad (2)$$

So voltage ratio is given by

$$\frac{V_0}{V_S} = \frac{T}{T_{OFF}} = \frac{1}{1-\delta} \quad (3)$$

For an Ideal case for current ratio input power is equal to the output power so

$$\frac{I_{L,avg}}{I_{0,avg}} = \frac{V_0}{V_S} = \frac{T}{T_{OFF}} = \frac{1}{1-\delta} \quad (4)$$

Therefore we have at the boundary average value of the inductor current is

$$I_{LB} = \frac{1}{2}\frac{V_o(1-\delta)}{L}\delta T \quad (5)$$

So output current I_{OB} at the boundary is can be derived with the help of equation.

$$I_{OB} = I_{LB}(1-\delta)$$

$$= \frac{V_0 T}{2L}\delta(1-\delta)^2 \quad (6)$$

b) Inverter mode of the converter:

A device that converts dc power into ac power at desired output voltage and frequency is called an inverter Fig 4 shows the proposed bidirectional inverter using H-bridge

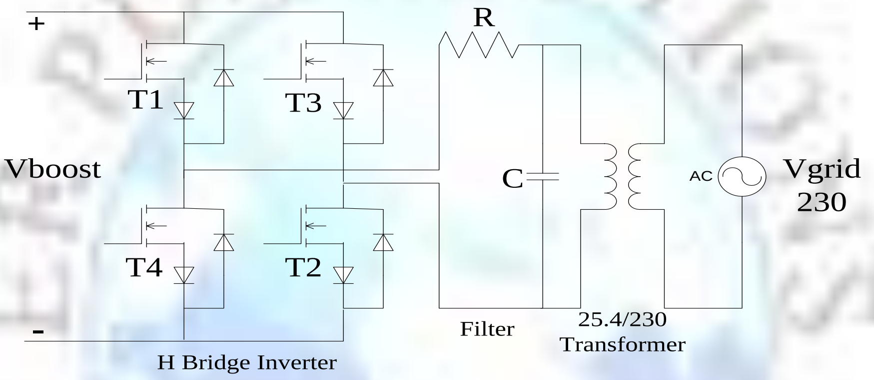
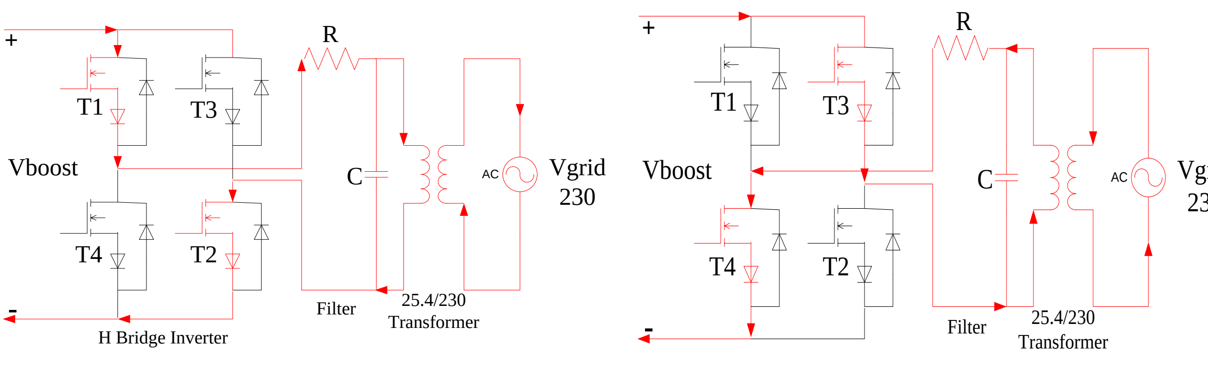


Fig 4: Proposed Bidirectional Inverter using H-Bridge Topology

For full bridge inverter, when switch T1,T2 conduct for period 0≤t≤T/2 load voltage is Vs and when T3,T4 conduct for period T/2 <t≤T load voltage is –Vs. Frequency of output voltage can be controlled by varying the periodic time T. In fig 4, switch T1,T2,T3,T4 are in series across the sources. During inverting operation, it should be ensured that two switches in the same branch. Such as T1,T2 do not conducting simultaneously as this would lead to a direct short circuit of the source. In fig 5(A),(B) shows the current flow direction for the time period 0≤t≤T/2 and T/2 <t≤T. And respectively out voltage across RC low pass filter is Vs , -Vs. Switching control and to reduce the amount of harmonic content, which ultimately reduces the number output filtering elements, a unipolar PWM is implemented into the design. The two inputs (sine wave & triangle wave) will be adjusted according to measure the desired output voltage. The more pulses impacted in one area will assist on filtering the signal. By increasing the carrier frequency, there will be very minimal total harmonic distortion (THD) output waveform.



(A) (B)

Fig 5: Direction of Current Flow in H-Bridge Inverter Circuit

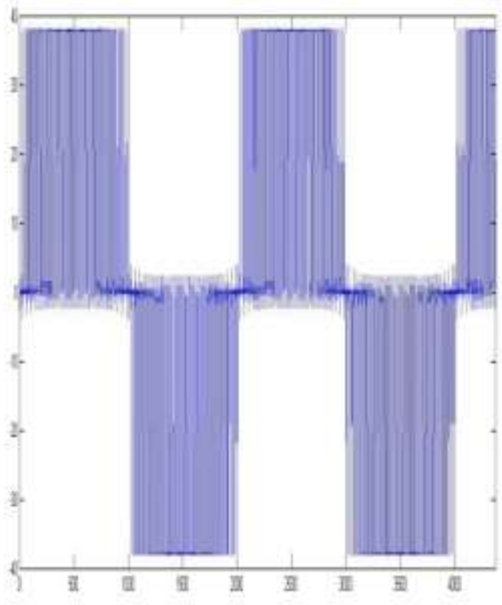


Fig 6: Inverter output

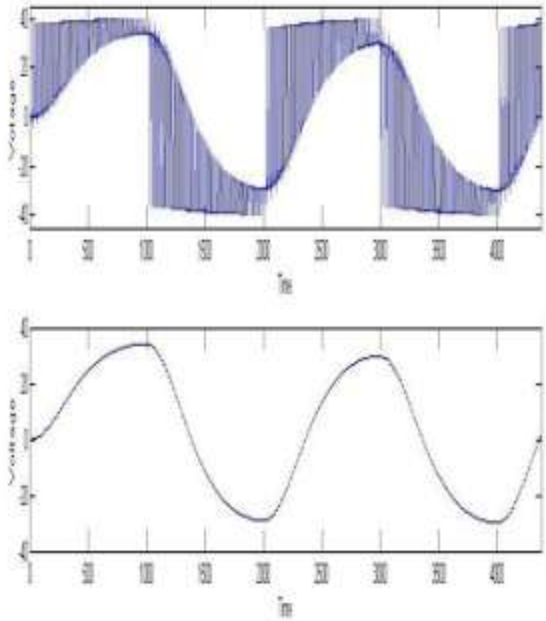


Fig 7: Inverter output before or after filter

Inverter output fed into to the RC low pass filter so the result of inverter out with the effect of RC low pass filter, before the filter and after the filter is shown in fig 7. Result of RC low pass filter is approximating sinusoidal. And the out of filter is fed into the transformer which can give the output voltage is 230 volt.

b) Reversal mode (GtoB):-In reverse mode of operation it is divided in two stage of power flow and two stage of control.

I) Rectifier mode of the converter:

In this mode of operation power supply come from the grid side which can step down voltage up to 25.4 volt rms . After this step rectification mode is work. A single phase full wave bridge rectifier employing diode anti parallel of the MOSFET switch is shown in fig 8. When anti parallel of switches T1 and T2 are conduct together so output voltage is Vs. Each of anti parallel diodes T3 and T4 is reverse voltage of Vs when other anti parallel diode is conduct. When anti parallel of switches T3 and T4 are conduct together so output voltage is Vs. Each of anti parallel diodes T1 and T2 is reverse voltage of Vs when other anti parallel diode is conduct. In fig 7 (A),(B) shows the current flow direction in bridge rectifier.

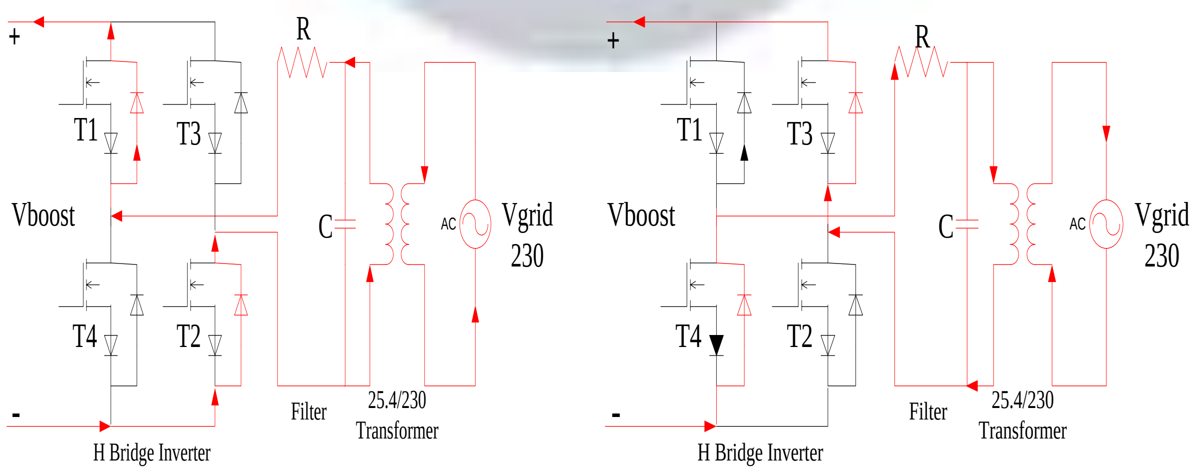


Figure 7: Direction of Current Flow in H-Bridge Rectifier Circuit

II Step-down mode of the converter:-

Circuit diagram of buck converter using MOSFET is shown in fig 8. The direction of current flow from the high voltage 36V DC to the low voltage 24V DC sources is called "buck" or charging mode.

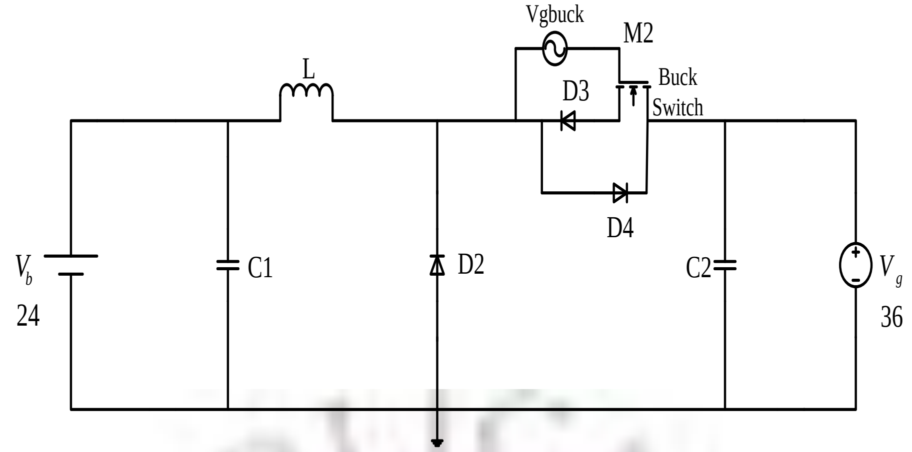


Fig 8: Buck Equivalent Model

Its operation is divided into two modes. Mode1:- It begin when MOSFET (M2) is switch on at t=0. The input current $I_S(t)$ witch rise flows through inductor L, capacitor C, and battery.Mode2:- It begins when MOSFET (M2) is switch off at t=t1. The freewheeling diode D2 conducting due to energy stored in the inductor; and the inductor current continues to flow through L, C1, battery and diode D2. The inductor current fall until MOSFET (M2) is switch on again in the next cycle. The equivalent circuits for the modes of operation are shown in fig 9(a) or 9(b). The wave form for the voltage and current are shown in fig 10 for a continuous current flow in the inductor L. It is assumed that the current rise and falls linearly. In practical circuits, the switch has a finite, nonlinear resistance. Its effect can generally be negligible in most application. Depending on the switching frequency, filter inductance, and capacitance, the inductor current could be discontinuous.

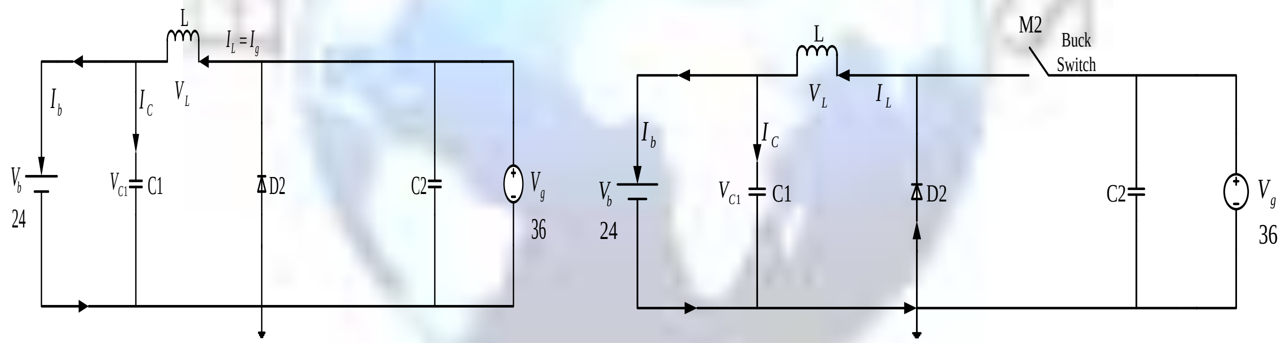
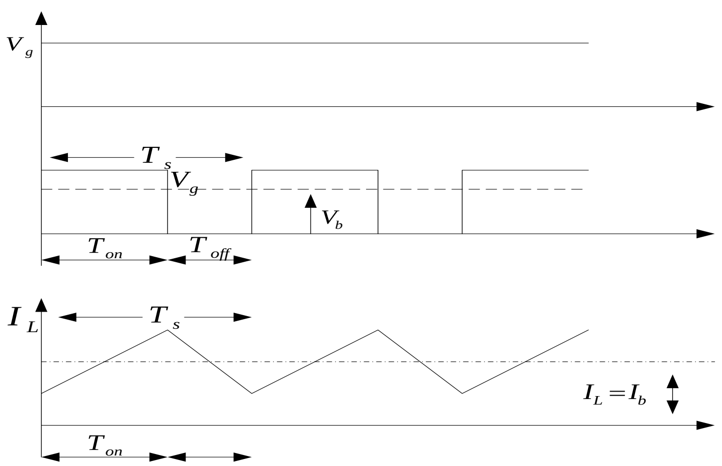


Fig 9 (a) Mode1 **Fig 9(b) Mode2**

Fig 9: Equivalent Circuit diagram of buck convertor



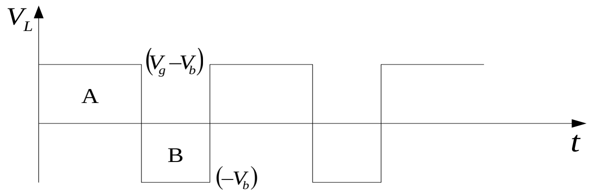


Fig 10: wave form for the voltage and current

Fig10 shows the waveform for the continuous conduction mode of operation where the inductor current flow continuously [$I_L > 0$]. When switch is on for a time duration T_{ON}, the switch conducts the induct current and the diode become reverse biased. This result is positive voltage $V_L = V_g - V_b$ across the inductor in figure 9 a. This voltage causes a linear increase in the inductor current I_L. When the switch is turned off, because of the inductive energy storage I_L continues to flow. This current now flows through the diode, and $V_L = -V_b$ in fig 9 b.

In fig10, the forgoing equation implies that the area A and B must be equal. Therefore,

$$(V_g - V_b)T_{ON} = V_b(T_S - T_{on}) \quad (7) \qquad \frac{V_b}{V_g} = \frac{T_{ON}}{T_S} = \delta \quad (8)$$

Neglecting power losses associated with all the elements, the input power P_g equals the output power P_b :

$$P_g = P_b \quad (9)$$

Therefore,

$$V_g I_g = V_b I_b \quad (10) \qquad \frac{I_b}{I_g} = \frac{V_g}{V_b} = \frac{1}{\delta} \quad (11)$$

The average inductor current, where the subscript B refers to the boundary, is

$$I_{LB} = \frac{1}{2} i_{L,Peck} = \frac{t_{on}}{2L}(V_b - V_g) = \frac{\delta T_S}{2L}(V_b - V_g) = I_{OB} \quad (12)$$

3. Hardware and result

A block diagram of bidirectional converter with proposes buck boost converter is shown in fig.11, describing the linking between power stage and controller. Note that the picture of 100-W experiment setup with propose configuration is shown in fig.12. As we know this convertor is operated in both of the direction (power will flow in forward and reverse direction). So battery model side is taken as he low voltage side is employ as the energy storage model whose voltage decide as 24 V DC. The high voltage side is ie. grid 230 V AC. Equation (13) and (14) shows the inductor of boost and buck converter respectively. And equation (15) and (16) shows the capacitor of boost and buck converter respectively. By help of equation (13) and (14) we can find the inductor value and choose one of them as suitable for system.

$$L_{Boost} = \frac{V_o}{I_{o,avg} f} \frac{\delta(1-\delta)^2}{\left(\frac{\Delta I_L}{I_{L,avg}}\right)} \quad (13) \qquad L_{Buck} = \frac{V_o}{I_{o,avg} f \delta} \frac{(1-\delta)}{\left(\frac{\Delta I_L}{I_{L,avg}}\right)} \quad (14)$$

Calculated inductor value for boost converter is 3.839mH and for buck converter is 3.557mH. As we design this converter we can chose the higher value inductor is 3.839mH. By help of equation (15) and (16) we can find the capacitor value. And we chose the two capacitor value for boost and buck converter as C1 and C2 are 470 μF and 330 μF respectively.

$$C_{Boost} = \frac{\delta}{R\left(\frac{\Delta V_o}{V_o}\right) f} \quad (15) \qquad C_{Buck} = \frac{1-\delta}{R\left(\frac{\Delta V_o}{V_o}\right) f} \quad (16)$$

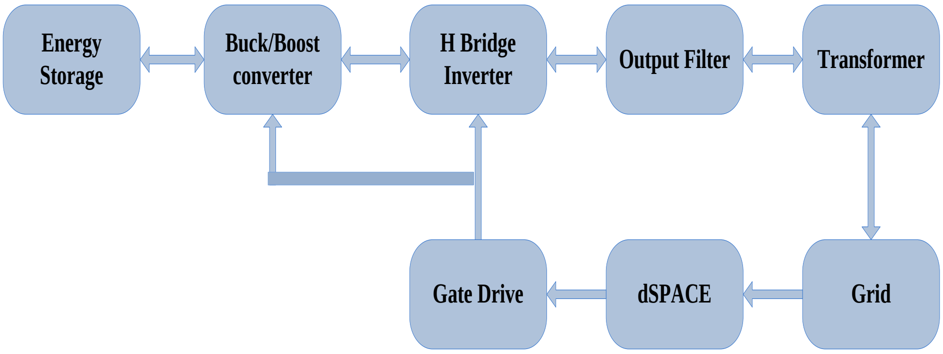
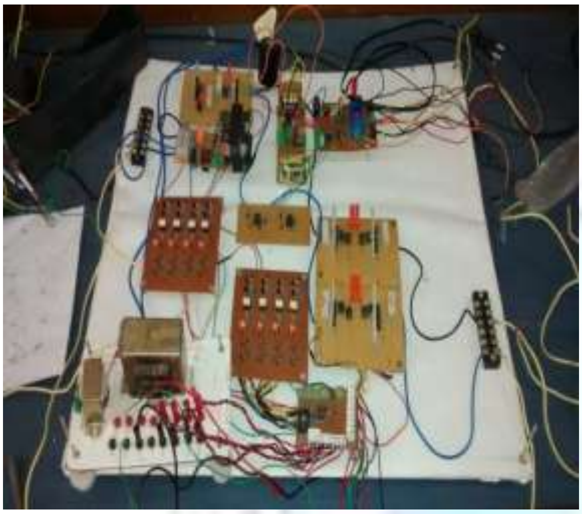


Fig 11: Block diagram of Bi-directional converter



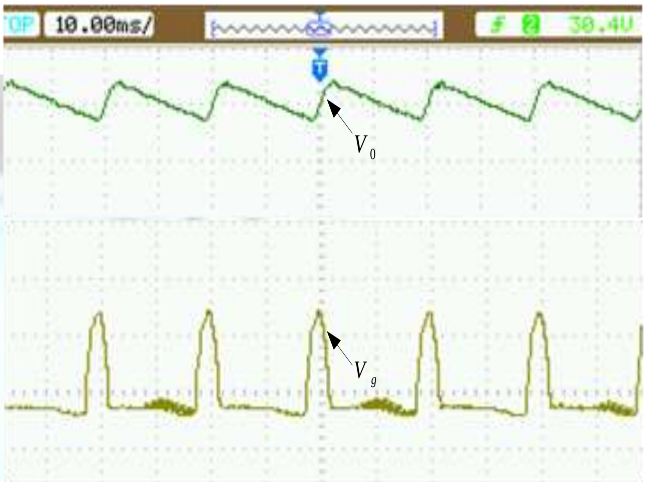
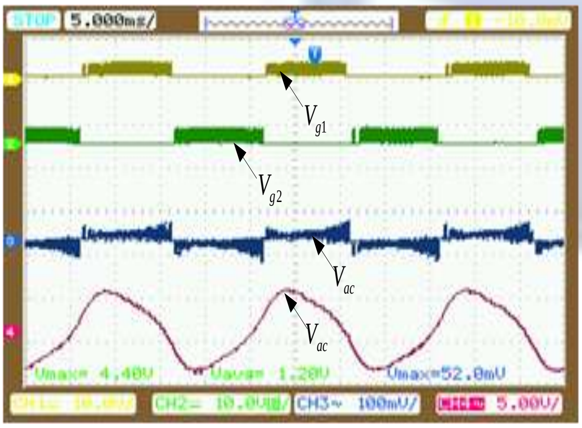


Fig 12: Photograph of Bi-directional converter from low voltage to high voltage side

Fig 13: For measured voltage of Boost converter (24→ 230)



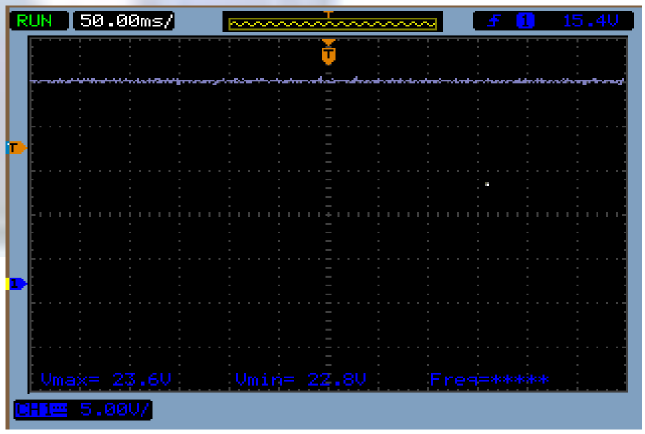


Fig 14: For measured voltage inverter output with or without filter converter from high voltage to low voltage

Fig 15: For measured voltage of Buck side (230→ 24)

Fig 12 shows the pictorial form of experimental prototype of converter. In fig 13 shows measured voltage V_o during the step up the voltage experiment result of boost converter on 33.3% of duty. After this part of experiment this voltage are fid in the inverter and low pass filter which is operated on the 5kHz frequency. Whose resulting sinusoidal wave form with or without filter is shown in fig 14.At last during the reversal mode the battery end voltage which can be use for charging the battery is shown in fig 15.

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5. Conclusion

This paper has proposed a high step up and step down bidirectional converter and energy storage system. The inverter is use to control the power flow between dc bus and the ac grid and regulate the dc voltage by buck boost converter. As we did the experiment on the design prototype, its working properly and we get the result as we expect from theoretically. Control part is done by the MATLAB simulation interface with the Dspace.

6. References

[1]. C.-C. Lin, L.-S. Yang, G.W. Wu "Study of a non-isolated bidirectional DC–DC converter" IET Power Electronics, Vol. 6,Iss.1, pp. 30–37, 29th October 2012.
[2]. Tsai-Fu Wu, Yung-Chu Chen, Jeng-Gung Yang, and Chia-Ling Kuo "Isolated Bidirectional Full-Bridge DC–DC Converter With a Flyback Snubber" IEEE Transactions On Power Electronics, Vol. 25, No. 7, July 2010.
[3]. Tsai-Fu Wu, Kun-Han Sun, Chia-Ling Kuo, and Chih-Hao Chang "Predictive Current Controlled 5-kW Single-Phase Bidirectional Inverter With Wide InductanceVariation for DC-Microgrid Applications" IEEE Transactions On Power Electronics, Vol. 25, No. 12, December 2010.
[4]. Honglin Zhou, Shuai Xiao, Geng Yang, HuaGeng "Modeling and Control for a Bidirectional Buck–Boost Cascade Inverter" IEEE Transactions On Power Electronics, Vol. 27, No. 3, March 2012.
[5]. R.-Y. Duan, J.-D. Lee "High-efficiency bidirectional DC-DC converter with coupled inductor" IET Power Electron., 2012, Vol. 5, Iss. 1, pp. 115–123, March 2011.
[6]. R.-J. Wai, R.-Y. Duan, K.-H. Jheng "High-efficiency bidirectional dc–dc converter with high-voltage gain" IET Power Electron., 2012, Vol. 5, Iss. 2, pp. 173–184, July 2011.
[7]. Biao Zhao, Qiang Song, and Wenhua Liu "Power Characterization of Isolated Bidirectional Dual-Active-Bridge DC–DC Converter With Dual-Phase-Shift Control" IEEE Transactions On Power Electronics, Vol. 27, No. 9, September 2012.
[8]. Dong Dong, FangLuo, Dushan Boroyevich, Paolo Mattavelli "Leakage Current Reduction in a Single-PhaseBidirectional AC–DC Full-Bridge Inverter" IEEE Transactions On Power Electronics, Vol. 27, No. 10, October 2012.
[9]. Omer C. Onar, Jonathan Kobayashi, Dylan C. Erb, Alireza Khaligh "A Bidirectional High-Power-Quality Grid Interface With Novel Bidirectional Noninverted Buck–Boost Converter for PHEVs" IEEE Transactions On Vehicular Technology, Vol. 61, No. 5, June 2012.
[10]. [10] Md. Nayeem Arafat, Sreeshailam Palle, Yilmaz Sozer, Iqbal Husain "Transition Control Strategy Between Standalone and Grid- Connected Operations of Voltage-Source Inverters" IEEE Transactions On Industry Applications, Vol. 48, No. 5, September/October 2012.
[11]. Yi-Ping Hsieh, Jiann-Fuh Chen, Lung-Sheng Yang, Chang-Ying Wu, and Wei-Shih Liu "High-Conversion-Ratio Bidirectional DC–DC Converter With Coupled Inductor" IEEE Transactions On Industrial Electronics, Vol. 61, No. 1, January 2014.
[12]. Tsai-Fu Wu, Chia-Ling Kuo, Kun-Han Sun, Yu-Kai Chen, Yung-Ruei Chang and Yih-Der Lee "Integration and Operation of a Single-Phase Bidirectional Inverter With Two Buck/Boost MPPTs for DC-Distribution Applications" IEEE Transactions On Power Electronics, Vol. 28, No. 11, November 2013.
[13]. Jung-Hyo Lee, Dong-Ho Yu, Jun-Gu Kim, Young-Ho Kim, Soo-Cheol Shin, Doo-Yong Jung, Yong-Chae Jung, and Chung-Yuen Won "Auxiliary Switch Control of a Bidirectional Soft-Switching DC/DC Converter" IEEE Transactions On Power Electronics, Vol. 28, No. 12, December 2013.