BIDIRECTIONAL DC-DC CONVERTER FOR ENERGY STORAGE SYSTEMS

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Abstract: A bidirectional DC-DC converter with a high step-up/step-down voltage gain is presented. In low voltage side it adopts an interleaved structure this is to reduce the low voltage side current ripples. In order to obtain high step-up/step-down gain series connected structure is adopted in the high voltage side. The efficiency of the converter is improved by synchronous rectification without the use of any extra hardware unit. The converter is able to operate in wide ranges of input voltage in low voltage side .The converter was able to attain a high voltage gain of 400V when the input voltage varies between 50V to 120V.This converter can be used efficiently to interface an energy storage systems to a DC bus. The converter can be used to compensate the power fluctuations of the load. Whenever the load demand more power the converter takes input from the battery and operates in step up mode or while there is an extra power coming from the input source and load demand lower power it operates in step-down mode and charges the battery.. The validity and effectiveness of the converter and when connected to the battery are verified by MATLAB simulink software.

Keywords: Renewable energy systems (RES), Hybrid electric vehicles(HEV), Bidirectional converter (BDC).

I. INTRODUCTION

With the increase in the demand for the renewable energy systems, researchers pay more attention to interfacing converters. There are several types of renewable energy systems including photovoltaic systems, wind power generating systems, hydro power generating systems and other types .Renewable energy systems usually depends on the environmental specifications and has a low dynamic response [1][2]. Renewable energy systems was unable to give stable power, also they cannot provide instantaneous power when the power demand of the load suddenly increases. So, there comes the importance of energy storage systems. In order to compensate the power fluctuations between the power generation side and the load side energy storage systems are being used [1]. In order to interface an energy storage element to a DC bus, there is a need of a bidirectional DC-DC converter. The bidirectional DC-DC converter is used in order to charge and discharge the battery The bidirectional converters transfer the energy in both directions between two sources [2][4].
Besides traditional applications in dc motor, it found its application of energy storage in uninterruptible power supplies (UPS), hybrid electric vehicles (HEV), fuel cell energy systems, renewable energy systems. The fluctuating nature of most renewable energy resources, like, solar, wind makes them unsuitable for standalone operation as a sole source of power [2]. A common solution to maintain a smooth and continuous power flow to the load, to compensate these fluctuations energy storage system with a bidirectional converter is used. The economical energy storage devices are batteries, super capacitors for medium power range.[6]

Bidirectional converters are primarily classified into isolated converters and non isolated converters. The isolated converters include the Fly back converters, the Forward converters, the Forward-Fly back, the half-bridge and full bridge converter. . By adjusting the turns ratio of the transformer, high voltage gain is obtained. Leakage inductance is the main problem faced by isolated type of converters. High voltage spikes appear across semiconductor device due to the leakage inductance. In order to overcome this problem a full bridge bidirectional DC-DC converter with a fly back snubber circuit[7] and a bidirectional converter with an active clamp circuit[8] was introduced. Here more additional components are required and switching losses increases.

The non isolated components include conventional Buck- Boost converter, Cuk converter, Sepic/Zeta converter, Multi level converters. Conversion efficiencies of Cuk and Sepic/Zeta will be lower due to the cascaded configurations of two power stages [9][10]. Coupled-inductor converters can achieve a high voltage gain by adjusting the turns ratio of the coupled inductor [11], but the problem associated with the leakage inductor is still difficult. The converters mentioned in the references suffer many other problems like limited voltage gain, the converter require more complicated control scheme, EMI problems, maintenance issue etc. The advantage of the proposed converter includes low current ripple, low voltage-stress of power semiconductors and high voltage-gain. In addition, the connection between the low-voltage and the high-voltage side grounds of the proposed converter is a capacitor instead of a power semiconductor. In order to achieve a high step-up gain in step up mode, the capacitors are charged in parallel and discharged in series and vice versa for step down mode. Also, the capacitor voltage of the proposed converter is half of the high-voltage side voltage, efficiency is improved by synchronous rectification .Analysis of converter were done and discussed with the help of MATLAB simulation.

II. PROPOSED CONVERTER

The bidirectional DC-DC converter circuit is shown below in Fig. 1, which consists of a low voltage side V_{low} and a high voltage side V_{high}.In LV side it consists of a filter/storage capacitor .The interleaved structure is used in the low voltage side, $L_{l,}$- $S_{l,}$, L_2- S_2 form the parallel structure of the low-voltage side to reduce the LV side ripple current. The switched capacitor network, includes switched-capacitor units $C_{l,}$- S_3 , C_2- S_4 and ,C_3- S_5 for high gain of the converter. Bidirectional DC-DC converter form the structure of the low-voltage-side in parallel and the high-voltage-side in series. The switching frequency is 20khz .

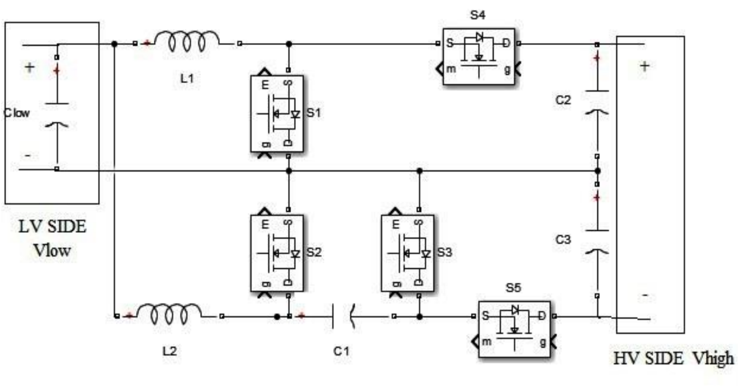

Fig.1: Bidirectional DC-DC Converter

A. *Voltage gain in step up mode:*

From the voltage second balance principle on $L_{l,}$ and L_2. $V_{c1,}$ $V_{c2,}$ V_{c3} are the voltages across C_l ,C_2 ,C_3

$$d_{boost} \times V_{low}=(1-d_{boost}) \times (V_{c2}- V_{low})$$

$$d_{boost}\times V_{low}=(1-d_{boost}) \times (V_{c1}- V_{low})$$

$$V_{c1}= V_{c3}$$

$V_{c1}=V_{c2}=V_{c3}=\frac{1}{(1-d_{boost})}V_{low}$

$V_{high}=\frac{2}{(1-d_{boost})}V_{low}$

B. Voltage gain in step down mode:

From the voltage second balance principle on $L_{l,}$ and L_2

$d_{buck}\times(V_{c2}-V_{low})=(1-d_{buck})\times(V_{low})$

$d_{buck}\times(V_{c1}-V_{low})=(1-d_{buck})\times(V_{low})$

$V_{c1}=V_{c2}=V_{c3}=\frac{1}{(2)}V_{high}$

$V_{low}=\frac{d_{buck}}{2}V_{low}$

C. Voltage stress:

The voltage stress across the power semiconductor switch is found to be half of the V_{high} . V_{S1} , V_{S2} , V_{S3} , V_{S4} , V_{S5} are the voltage across the switch, S_1 , S_2, S_3 , S_4 , S_5

$V_{S1}=V_{S4}=V_{c2}=\frac{1}{2}V_{high}$

$V_{S2}=V_{S3}=V_{S5}=V_{c3}=V_{c1}=V_{high}\frac{1}{2}$

III. OPERATING PRINCIPLE

A. Step-up mode:

Figure 2 shows the modes of operation of the converter operating in step up mode. By controlling the power semiconductors of $S_{l,}$ and S_2, and the anti-parallel diodes of switches S_3,S_4 and $S_{5,}$ the energy flows from the low-voltage side to the high-voltage side, the output voltage V_{high} is stepped up from V_{low} .

MODES	S1	S2	S3	S4	S5
Mode 1	1	0	1	0	0
Mode 2	0	0	1	1	0
Mode 3	0	1	0	1	1
Mode 4	1	1	0	0	1

Fig.2 Modes in step up operation

MODE:1

The output voltage V_{high} is stepped up from V_{low} ,When the energy flows from the low-voltage side to the high-voltage side by controlling the power semiconductors switches S_1,S_2 and the anti-parallel diodes of switches S_3,S_4,$S_{5.}$

The phase shift between gating signals are 180 degree The energy is transferred from the DC source V_{low} to the inductor L_1,at the same time C_1 is being charged by inductor L_2, while C_2 and C_3 are discharging. C_2 and C_3 are connected in series to provide energy for the load in the high voltage side.

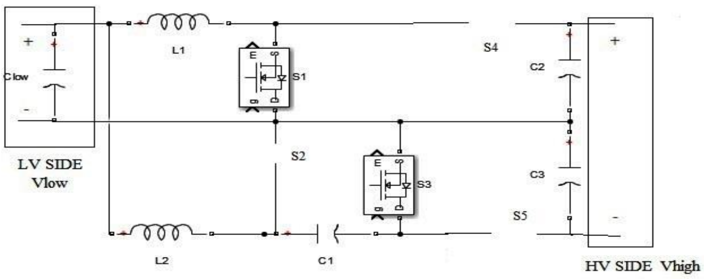

Fig. 3 Mode 1

MODE:2

Here the power semiconductors $S_1$and S_2 are turned off. The anti-parallel diodes of the switches S_3 and S_4 are turned on, while the anti-parallel diode of the switch S_5 is turned off. At this time, C_1 will be charging from the inductor L_2 also $C_3$is in the discharging state. The DC source V_{low} , L_1 and C_3 provides output energy to the load.

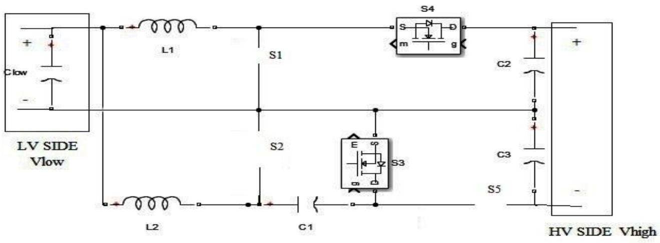

Fig.4 Mode 2

MODE:3

Here the power semiconductor S_1 is turned off and S_2 is turned on also the anti-parallel diode of switch S_3 is turned off, while the anti-parallel diodes of the switches S_4 and S_5 are turned on. In this mode the inductor L_1 will be discharging, while the inductor L_2 will be charged by the DC source. At the same time, C_3 will be charged by $C_{1,}$while C_2 is charged by inductor L_1.The DC source V_{low}, $L_1$and C_1 provides output energy to the load.

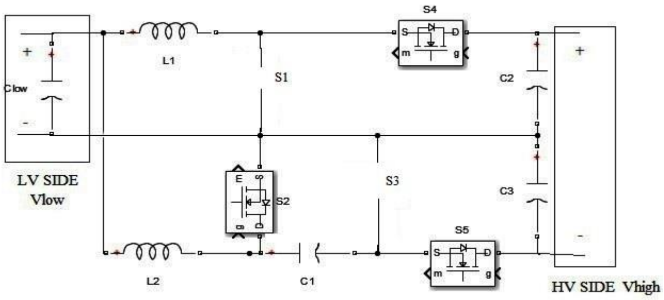

Fig.5 Mode 3

MODE:4

Here power semiconductors S_1 and S_2 are turned on, while the anti-parallel diodes of switches S_3 and S_4 are turned off, while the anti-parallel diode of switch S_5 is turned on. The inductors L_1 and L_2 are charged by the DC source V_{low} that is in parallel. At the same time, $C_1$and C_2 will be discharging in series to provide energy for the load.

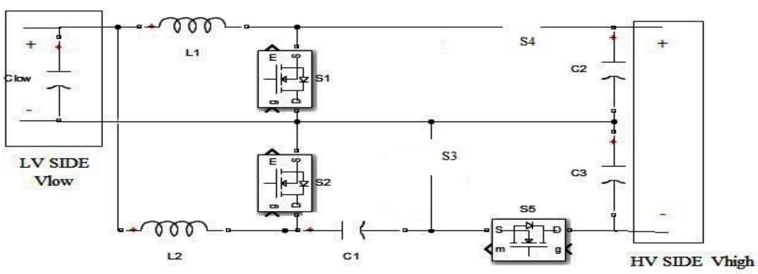

Fig.6 Mode 4

B. Step-down mode:

Figure 7 shows the modes of operation of the converter operating in step up mode. When energy flows from the high-voltage side to the low-voltage side, the output voltage V_{low} is stepped down from V_{high} by controlling the power semiconductors S_3, S_4 and S_5, and the anti-parallel diodes of switches S_l and S_2

MODES	S1	S2	S3	S4	S5
Mode 1	1	0	1	0	0
Mode 2	0	0	1	1	0
Mode 3	0	1	0	1	1
Mode 4	1	1	0	0	1

Fig.7 Modes in step up operation

MODE:1

Here, the power semiconductor S_3 is turned on, while $S_4$and S_5 are turned off. The anti-parallel diode of switch S_1 is turned on, also and the anti-parallel diode of switch S_2 is turned off. C_2 and C_3 will be charged by the DC source V_{high} in series. At the same time, inductors L_1 , L_2 and C_1 are discharging to provide energy for the load in the low voltage side.

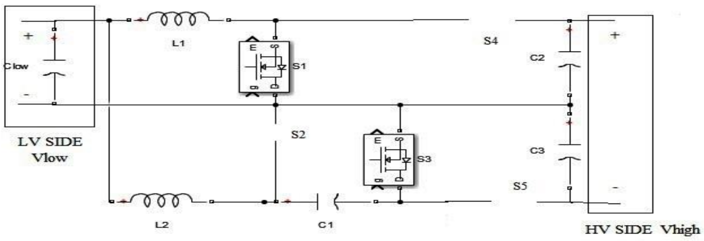

Fig. 8 Mode 1

MODE:2

Here, the power semiconductors S_3 and S_4 are turned on,while $S_5$is turned off. The anti-parallel diodes of switches $S_1$and S_2 are turned off.. C_1 is discharging to transfer energy to inductor L_2 and simultaneously outputting energy to the load. Meantime, the DC source V_{high} charges L_1 and C_3 ,and simultaneously outputs energy to the load. In addition, C_2 is discharging to supply energy to L_1 and the load.

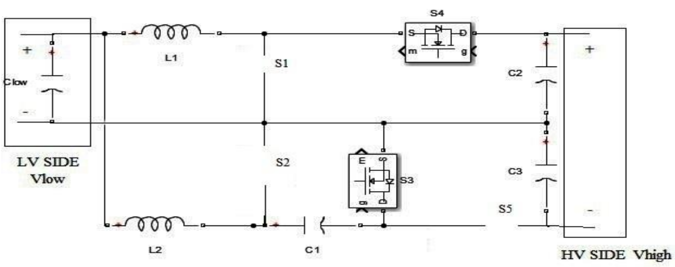

Fig. 9 Mode 2

MODE:3

Here, the power semiconductor S_3 is turned off, while the switch S_4 and S_5 are turned on. The anti-parallel diode of switch S_1 is turned off, and the anti-parallel diode of switch S_2 is turned on. The Inductor L_2 is discharging to provide energy for the load. At the same time, the DC source V_{high} charges the inductor L_1 and capacitor C_1 and simultaneously provide energy for the load. In addition, C_2 is discharging to supply energy to L_1 and the load, and C_3 is discharging to provide output energy to C_1 .

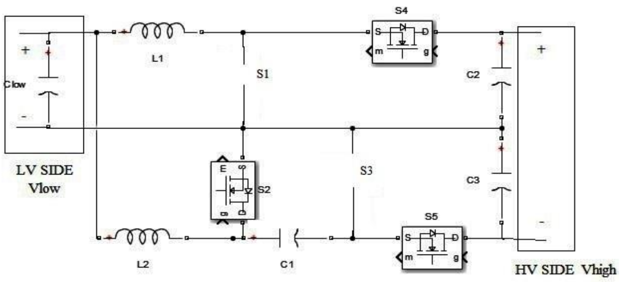

Fig. 10 Mode 3

MODE:4

Here, the power semiconductors S_3 and S_4 are turned off, while $S_5$is turned on. The anti-parallel diodes of switch S_1 and S_2 are turned on. L_1 and L_2 will be discharging to provide energy for the load in parallel. At the same time, the DC source V_{high} charges C_1 and C_2 in series, and C_3 discharges to provide energy to C_1

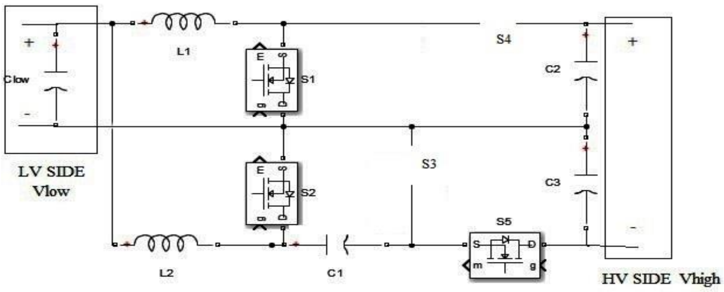

Fig.11 Mode 4

IV. SIMULATION RESULTS

The simulation results of the BDC were shown below. These are the parameters used for simulation in matlab.

PARAMETERS	VALUES
Rated Power	1 KW
Storage/Filter Capacitor *Clow*	520μF
Capacitor *C*1, *C*2 and *C*3	520μF
Storage/Filter Inductor *L*1	353μH
Storage/Filter Inductor *L*2	357μH
High voltage side *V*high	400V
Low voltage side *V*low	50-120 V
Switching frequency *fs*	20 KHZ

Fig.12 Simulation Parameters

A. Converter operating in Step-up mode:

In closed loop simulation the converter is able to provide stable output voltage of 400V for the wide range of input voltages that is from 50 to 120V. Energy flows from the low-voltage side to the high-voltage side, the output voltage V_{high} is stepped up from V_{low} by controlling switches S_l, and S_2 .

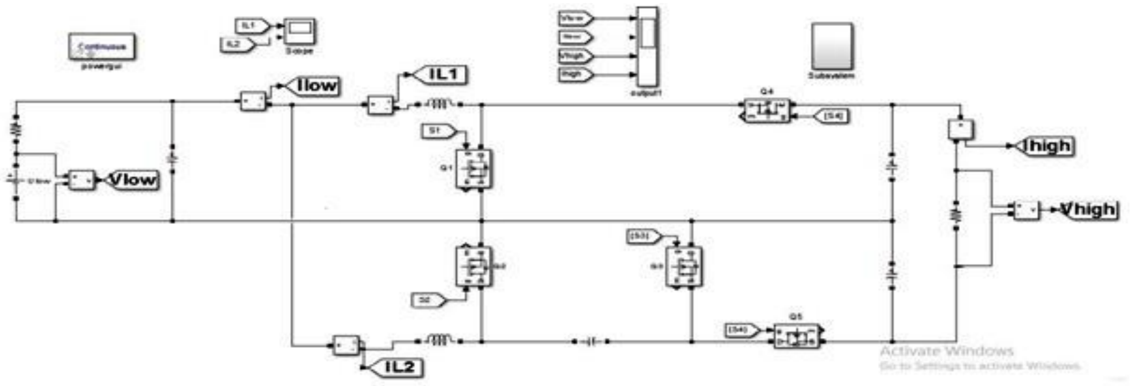

Fig.13 Simulink diagram for step up mode

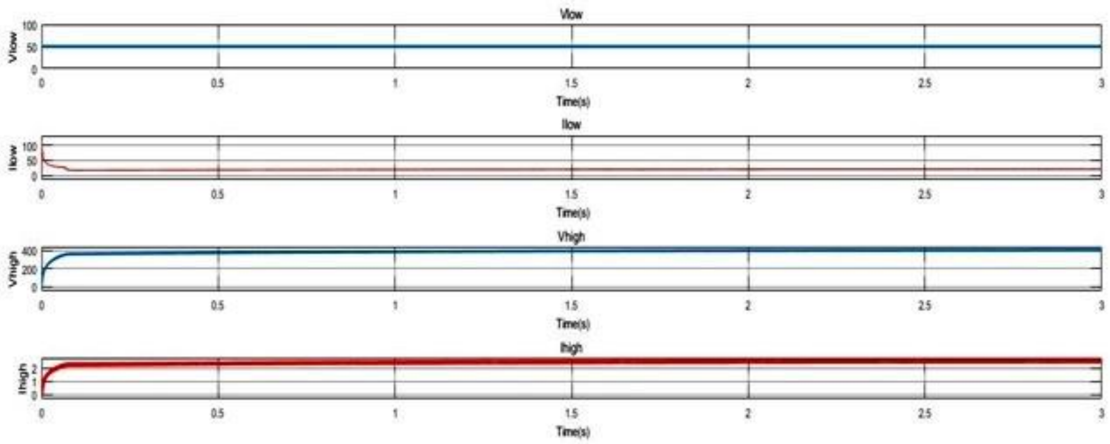

Fig 14 Step up waveforms

B. Converter operating in Step-down mode:

Energy flows from the high-voltage side to the low-voltage side, the output voltage V_{low} is stepped down from V_{high} by controlling the power semiconductors S_3, S_4 and S_5,that is from 400V to 50V.

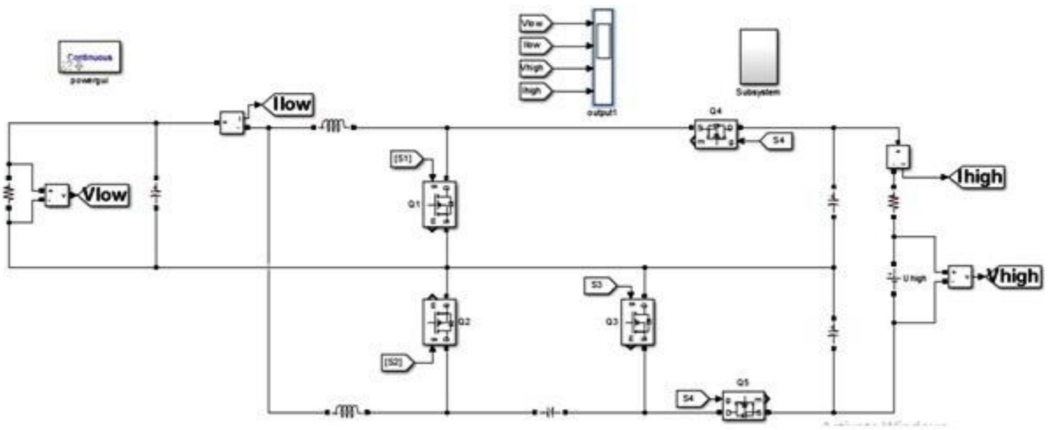

Fig 15 Simulink diagram for step down mode

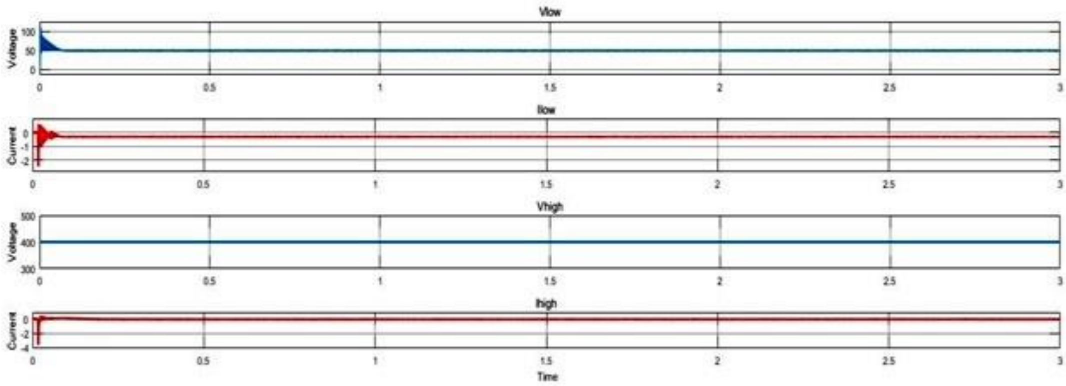

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Fig 16 Step down waveforms

C. Converter operating for battery charging and discharging :

Renewable energy systems were not able to meet the load fluctuations, so whenever the load demand increases the BDC operates to meet the load demand. The input to the BDC is battery. So by taking the input from the battery the BDC operates in step-up mode and meets the power demand, at that time the battery will be discharging. Also, whenever the load demand decreases the BDC operates in step-down mode and charges the battery. Here for simulation work two cases are being considered.

CASE:1

Load power requirement is 650W, Load voltage is 400V,therefore load current and load impedance will be

,$I_{load}=\frac{P_{load}}{V_{load}}=\frac{650}{400}=1.626A$, $R_L=\frac{V_{load}}{I_{load}}=\frac{400}{1.626}=246\Omega$

Since the load demand is high and pv power is low, the PV panel will not be able to meet the power demand. So the BDC converter comes to action. It takes input from the battery and will meet the load demand .In this case the battery state of charge will get reduced, that is battery discharging.

CASE:1

Load power requirement is 400W, Load voltage is 400V,therefore load current and load impedance will be

$I_{load}=\frac{P_{load}}{V_{load}}=\frac{400}{400}=1A$,$R_L=\frac{V_{load}}{I_{load}}=\frac{400}{1}=400\Omega$

when the load demand is low and the PV panel power is high, the BDC converter comes to action. It operates in stepdown mode and the battery state of charge will get increased ,that is battery charging thereby meets load demand.

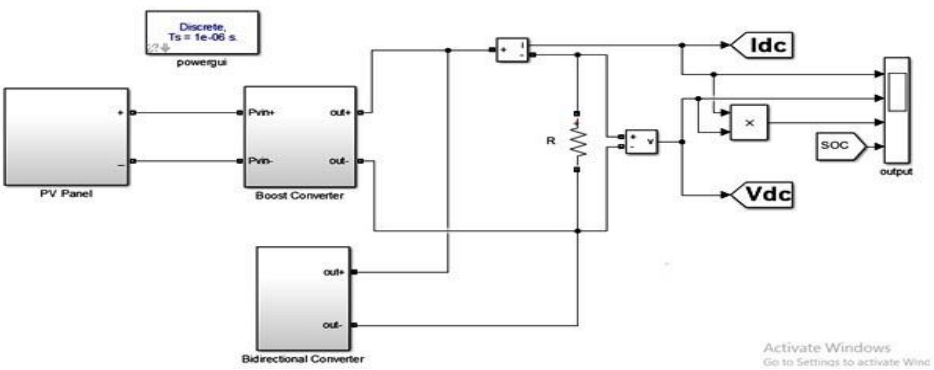

Fig 17 :Simulink diagram for the proposed system

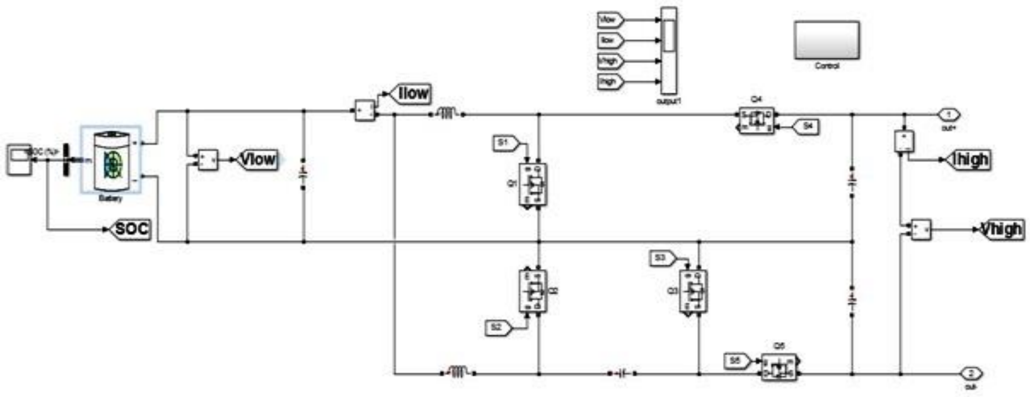

Fig 18:Bidirectional converter with battery

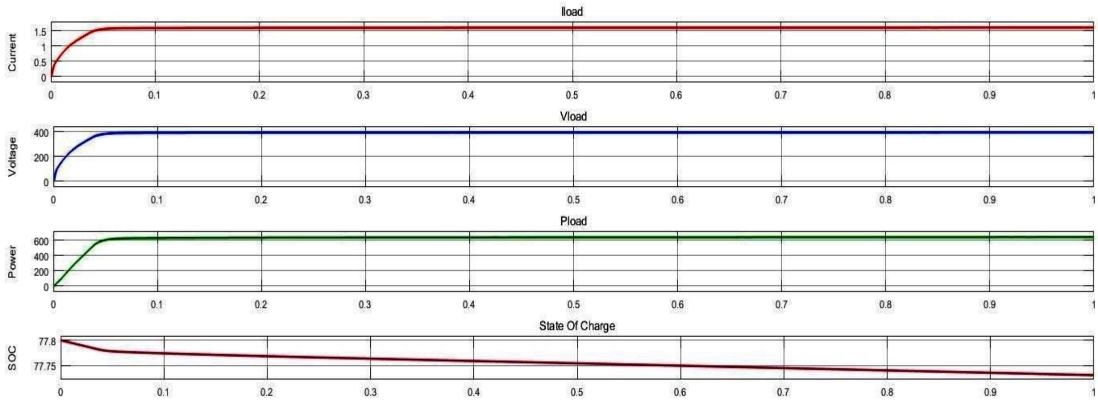

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Fig 19: Step up Waveforms-Battery Discharging

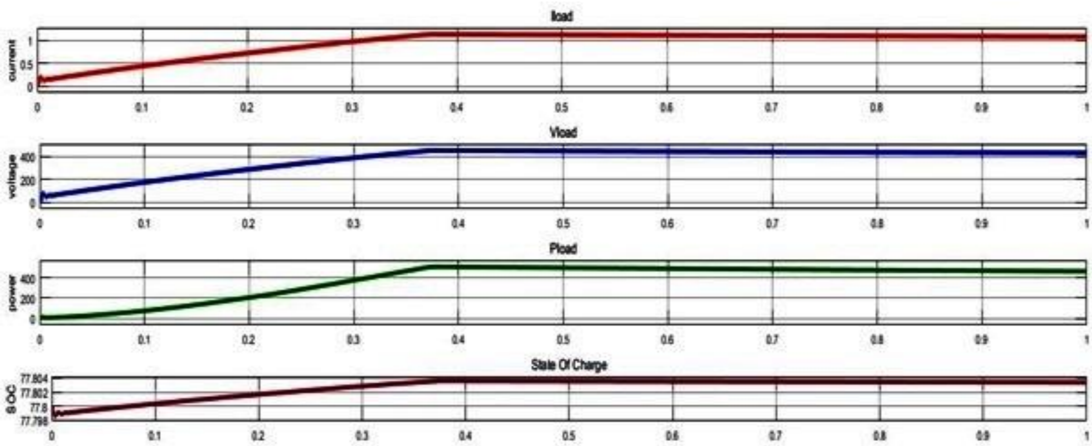

Fig 20: Step down Waveforms-Battery charging

V. CONCLUSION

The converter was analysed by simulation using MATLAB simulink software. The bidirectional DC-DC converter can operate in high step-up/step-down ratio, a wide voltage-gain range can be achieved without the need of and extreme duty cycles. In addition, this converter has the advantages of the low voltage stress of power semiconductors and capacitors, and low current ripples in the low-voltage side. Also, the slave active power semiconductors allow ZVS turn-on and turn-off, and the efficiency of the converter is improved. Due to the self balance function the capacitor voltages and the inductor currents can be easily balanced. The bidirectional DC-DC converter has good dynamic and steady-state performance and is suitable for the power interface between the low-voltage battery pack and the high-voltage DC bus. It founds its application in hybrid electric vehicles, hybrid renewable energy systems, uninterruptable power supplies, for its charging and discharging operation from an energy storage device.

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