Design of Two stage Isolated BidirectionalConverter for Plug-in Electric Vehicles

Dwaipayan Mazumdar*[1], Barnali Kundu[2], Debmalya Das[3], Sujoy Ghati[4], Arnab Dutta[5]

[1,2,3,4,5]*Department of Electrical Engineering,*
Guru Nanak Institute of Technology, Kolkata, India
[1]dwaipayan.mazumdar07@gmail.com, [2]barnali.kundu@gnit.ac.in,
[3]debmalyad700@gmail.com, [4]ghatisujoy2000@gmail.com,
[5]arnab7035@gmail.com

Abstract

Nowadays, in smart grid environment, Electric Vehicles are contributing a decisive role to flow power in bidirectional mode through connected distribution grid. The present research has shown the mathematical modelling of two stage isolated bidirectional converter. Design of all passive circuit elements for the proposed topology has been accomplished with the considerations of a DC/DC buck-boost converter for the application in Plug in hybrid electric vehicles. The proposed model shows the bidirectional power flow from grid to vehicle and vice versa. The proposed circuit operates in two ways: Charging and Discharging of the battery where each mode has two stages. During Charging mode, the DC source supplies dc power to the bridge inverter then the inverted square wave AC is transferred using a transformer then that rectified to DC power and power supply to the battery through the Buck switch. While during the discharging mode, the power of the battery is through the boost switch is fed to the bridge rectifier then it is fed to the transformer then the AC power is rectified to DC and fed to the Load. The switching frequency of the switches is 250 kHz while the presence of the transformer enables us to transfer a power of 10kW. The projected topology is comprehended in MATLAB/Simulink and the found he satisfactory results which establish that the topology will be perfectly suitable for different V2G applications.

.

Keywords: *Bi-Directional Converter, Buck Converter, Boost Converter, Battery, Plug in electric Vehicles*

1. Introduction

Since few centuries, vehicles are playing an important role to modernize the human life. The conventional vehicles are depleting day by day to reduce carbon di-oxide (CO_2) mixing in the atmospheric air. To stop the green hose gas emission, Electric Vehicles (EVs) are coming as a boon to protect the all living beings in the earth. The advancement in automotive technology brings different types of hybrid vehicle like plug-in hybrid electric vehicle, (PHEV), battery electric vehicle (BEV), and fuel cell electric vehicle, (FCEV) in the market. EVs, especially PHEVs, require a high energy and power density energy storage device, a bidirectional converter as presented in Figure 1 so as to run efficiently with a high state battery charging. Presently, technology allows PHEV to run with a battery capacity to cover10 to 60 miles of driving [1]. Two modes of operation of the battery i.e., charging and discharging consecutively happens and energy returned backto the connected grid or used as local source of electricity. Therefore, a bidirectional ac-dc converter is needed to design for the specific battery considering its chemistry. Fuel cells are alternatively used as a storage unit for the renewable resources. When the generation are at their peak, then the EVs can be charged using that energy and then during the peak load hours, if necessary, the stored energy of the fuel cell will supply energy to the Grid. Thus, the battery needs a device to make the bidirectional flow of power possible. So, the Bidirectional converters have a huge role in these types of operation [2], [3], [4]. Bidirectional converter is a type of DC-DC converter. The proposed research work has been focused on design of the circuit components essential for Bidirectional Converter to operate in a ripple free condition. This paper also presents a comparative study of the operation of the proposed bidirectional converter in changing frequency.

2. Theory of Bidirectional Converter

The proposed system is a hybrid circuit designed by combining the full bridge and the buck boost converter to maximize the output and efficiency of the system. It is composed of full bridge converter, high frequency transformer and a buck boost converter [5]. Figure 1 represents the charging mechanism of Plug-in Electric Vehicles The high frequency transformer is present in the circuit for the following reasons:

- It provides isolation between grid and battery.
- It provides the ease of high-power transfer betweengrid and battery.

The bidirectional Buck Boost converter has twomodes of operation, during charging the 230 V supply is converted into 200 V DC and then fed to the battery while during discharging, the battery supplies the 200 V power through the transformer to the load of 230 V. To design the converter for high voltage and high frequency operations, IGBTs are chosen as switches. The parts of the system are as follows:

2.1 **Full Bridge Converter:** In the first step, pulse width modulated full bridge converter is presented, which acts as a phase shifted full bridge inverter when battery will take charge and a full bridge rectifier when battery will discharge through primary side and vice versa the secondary side.

2.2 High Frequency Transformer: In designing the bidirectional converter with high power density, low noise, reduced weight, better reliability and less cost, high frequency transformer is fed with high frequency square waves. The basic purpose of the transformer is to transfer high power and provide isolation between the converters on either side of it. During charging and discharging mode, it acts as step-down and step-up respectively.

2.3 Buck Boost Converter: To obtain step-up or step-down DC-DC voltage and enable the power flow bidirectionally, the converters have to be operated in two mode Buck and Boost separately.

Buck Mode: In this mode of operation, the buck switch is turned on and boost switch is turned off, thus, it operates as diode. Battery is supplied from the input supply via the filter circuit. When the buck switch is turned off , the inductor release it’s energy via the diode in boost circuit. So, the charging mode voltage is given by:

$$V_{ch} \propto N * D * V_{battery} \quad (1)$$

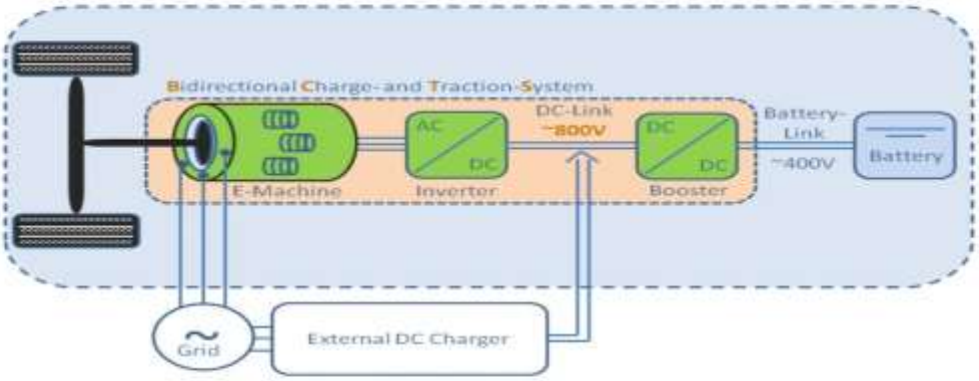

Figure 1. Charging mechanism of Plug-in Electric Vehicles

Boost Mode: In this mode, the IGBT switch is turned on while the buck switch is off, acts as a diode. The inductor receives energy via the battery and when boost switchis off, the inductor fed energy to the load via the buck diode. So, the discharging voltage is given by:

$$V_{disch} \propto \frac{V_{battery}}{N*(1-D)} \qquad (2)$$

Where N is the transformer's turns ratio and D is duty cycle of the switch in that mode of operation. Here an LC filter is used to reduce ac components in the output

2.4 Battery Charging and Discharging: In Electric Vehicles, charging and discharging process of battery connected traction system needs delicate handling with an appropriate designof converters. In this research paper, a two-stage isolated Bidirectional converter has been proposed to overcome an interval by designing the converter at high-frequency. The battery's charging and discharging operation can be calculated using the following formulas:

State of Charge (Soc) denotes the charge level relative to batteries rated capacity. The state of charge can be calculated by:

$$\% SOC = \frac{I*T}{C_{battery}} * 100 \qquad (3)$$

While the depth of discharge (DOD) is the capacitydischarged from a fully charged battery relative to its rated capacity. The depth of discharge can be calculated by:

$$\% \text{DOD} = \frac{\text{I}*\text{T}}{\text{C}_{\text{battery}}} * 100 \qquad (4)$$

Where T is time taken in hours and C_{bat} is battery capacity.

3. Proposed Methodology

The working principle of the circuit is described below. The topology is presented in Figure. 2 has two full bridge converts connected on either side of the high frequency transformer which is further connected to a buck boost converter which is then fed to the battery. The proposed circuit shown in has four modes of operation for charging and discharging.

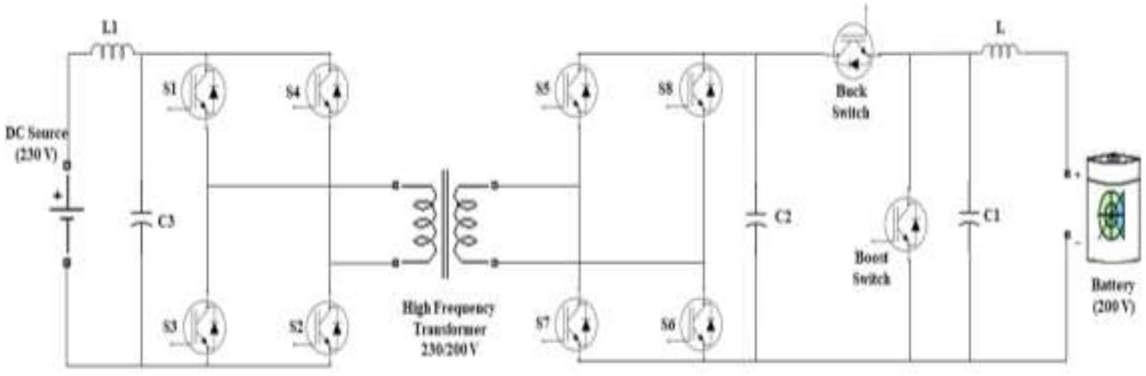

Figure 2. Basic circuit Diagram of converter

Mode 1 (Buck Mode positive half cycle): When switch in the buck circuit is turned on and boost switch is off, the energy supplied by the source is inverted by the IGBTs , for the positive half cycle , S1 and S2 are ON, shown in Figure 3(a). Then the inverted DC is stepped down by the transformer then fed to the rectifier switches S5and S6 on the other side of the transformer. Then the rectified ac through the buck switch and the filtered DC is fed to the battery. When the switch in the buck circuit is turned off, the inductor releases energy via the boost diode,providing a constant DC voltage of 200 V to the battery.

$$V_{battery} = V_{SOC} - V_2 - V_{C1} - V_L \quad (5)$$

Mode 2 (Buck Mode negative half cycle): The inverter switches S3 and S4 areturned on while on the rectifier side, the switches S7 and S8 are turned on during the negative half cycle and the same operation as Mode 1 is followed as shown in Figure 3(b).

Mode 3 (Boost Mode positive half cycle): When the boost switch is turned on and buck switch is off, the energy stored in the battery charges the inductor. When the boost switch isturned off, the energy stored in the inductor is supplied to theload via the phase shifted inverter switches S5 and S6 and then it is stepped up by the transformer as shown in Figure 3(c). The rectifier on the other side via switches S1 and S2 rectifies the input square wave AC and feds it to the 230 V load.

$$V_{DC\ supply} = V_{sec} - V_{C3} - V_{L1} \quad (6)$$

Mode 4 (Boost Mode negative half cycle): During the negative half cycle, the inverter switches S7 and S8 areturned on and the rectifier side, the switches S3 and S4 are turned on while the rest of the operations remain same as Mode 3 as shown in Figure 3(d).

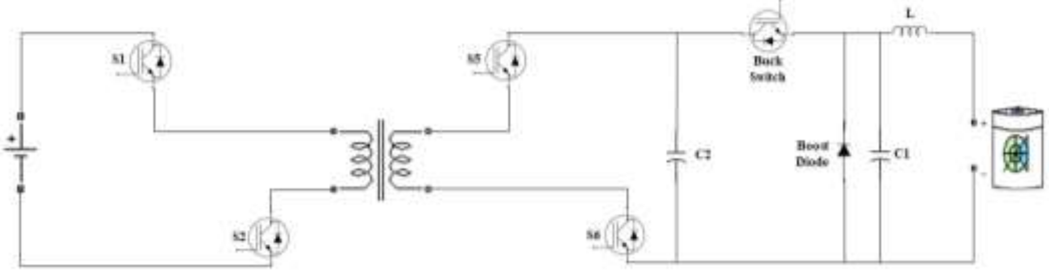

Figure 3(a): Buck Mode Operation for positive half cycle

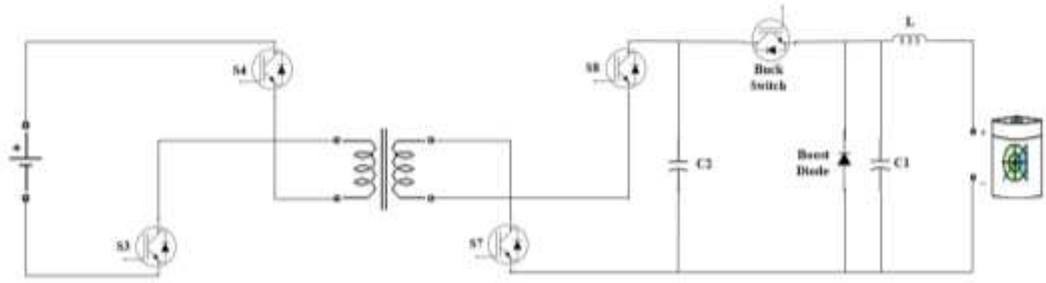

Figure 3(b): Buck Mode Operation for negative half cycle

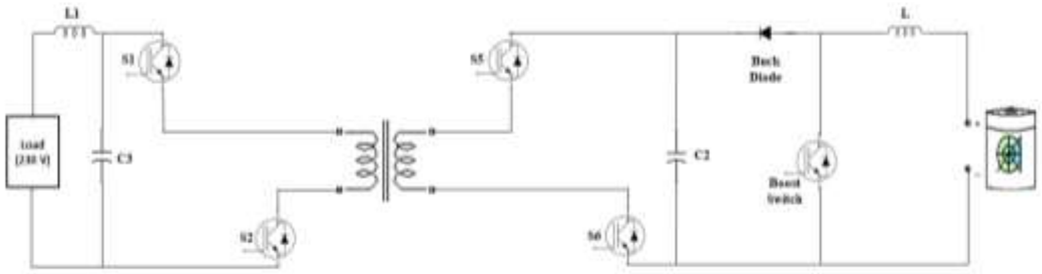

Figure 3(c): Boost Mode Operation for positive half cycle

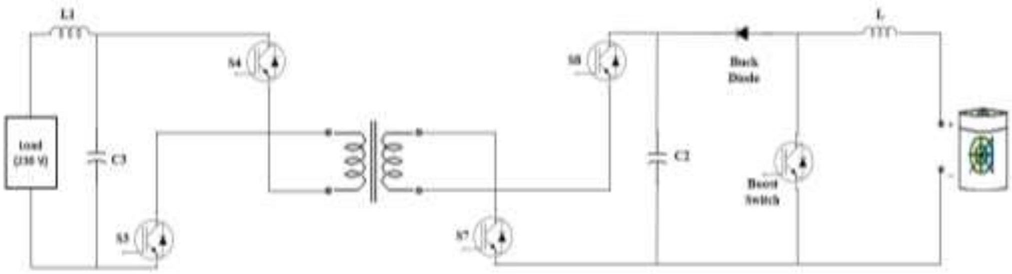

Figure 3(d): Boost Mode Operation for negative half cycle

4. Mathematical Modelling

From the simulated circuit we get to know about the operations of the circuit, thus the following equations (7) to (13) gives the variables in the circuit. In Figure 3(a) and 3 (b) the operation of the circuit in buck mode i.e., the battery charges via the buck switch. Thus, the Buck Mode variables are [15, 16],

$$\frac{d}{dt}v_{bat}(t) = L\frac{d}{dt}(i_1 + i_2) + v_{C_1}(t) + i_2(t)R + v_{sec}(t) \tag{7}$$

$$\frac{d}{dt}i_L(t) = \frac{1}{L}(v_{C_1}(t) + i(t)R + v_{bat}(t) + v_{sec}(t)) \tag{8}$$

$$\frac{d}{dt}v_{C_1}(t) = \frac{1}{C_1}(L\frac{d}{dt}i_1 + \big(i_1(t) + i_2(t)\big)R + v_{bat}(t) + v_{sec}(t)) \tag{9}$$

In Figure 3(c) and 3(d) the operation of the circuit is in Boost mode i.e., the battery discharges via the boost switch and supplies power to the load. Thus, the Boost Mode variables are,

$$\frac{d}{dt}v_z(t) = L_1\frac{d}{dt}(i_1 + i_2) + v_{C_3}(t) + i_2(t)R_2 + v_{sec}(t) \quad (10)$$

$$\frac{d}{dt}i_{L_1}(t) = \frac{1}{L_1}(v_{C_3}(t) + i_2(t)R_2 + \big(i_1(t) + i_2(t)\big)Z + v_{sec}(t)) \quad (11)$$

$$\frac{d}{dt}v_{C_3}(t) = \frac{1}{C_3}(L_1\frac{d}{dt}i_2 + i_2(t)Z + \big(i_1(t) + i_2(t)\big)R_2 + v_{sec}(t)) \quad (12)$$

$$\frac{d}{dt}v_{ph}(t) = L\frac{d}{dt}i_1 + v_1(t) + i_2(t)R + v_{bat}(t) \quad (13)$$

4.1. Design of Passive Elements

The above given circuit is designed by the following mathematical modelling of the P and I of the PID controller.

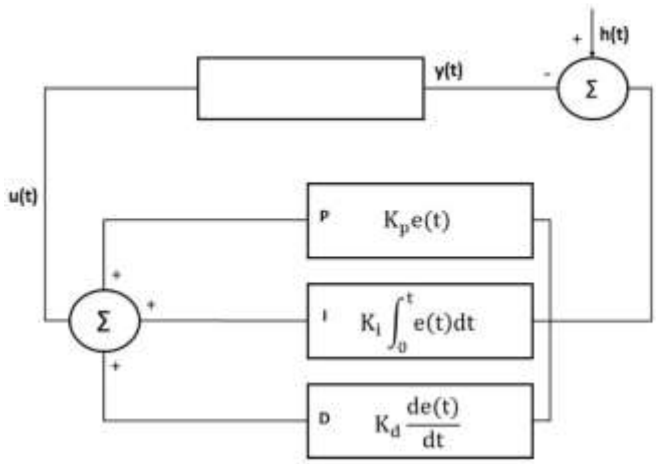

Fig. 7: Block diagram of the feedback control circuit.

The output of the PID controller is given by the following equation:

$$u(t) = K_p + K_i \int_0^t e(t)\,dt + K_d\frac{de(t)}{dt} \quad (14)$$

The transfer function of the PID controller is given by the equation below:

$$G(s) = K_p + \frac{K_i}{s} + K_d s = \frac{K_d s^2 + K_p s + K_i}{s} \quad (15)$$

The passive filter circuit is designed by the following Equations:

$$V_l = V_{in} * \frac{N_s}{N_p} - V_o \quad (16)$$

From the equations (14) to (16) we have designed the values of the of the filters used in the circuit to reduce the ripple. Firstly, the ripple criterion is set to limit the amount of ripple in the output current and voltage respectively. Then by calculating the amount of ripple to be reduced, the value of inductor and capacitor is calculated by the given equation 19.

Ripple current in the Inductor is given by the following equation:

$$\Delta I_L = \frac{1}{2}\frac{V_{in}}{L} D * T_s \quad (17)$$

Ripple Voltage in the Capacitor is given by the following equation:

$$\Delta V_C = \frac{1}{2}\frac{V_{in}}{C} D * T_s \quad (18)$$

Thus, the value of inductor and capacitor are hereby calculated respectively,

$$L = \frac{D * T_s}{I_{ripple}} \quad \& \quad C = I_{ripple} * \frac{D * T_s}{V_{ripple}} \quad (19)$$

5. Simulation of proposed methodology

The circuit consists of a DC voltage source that acts as the gird that supplies power to the battery during charging mode. The DC source is connected to a to a full bridge converter that has a high switching frequency of 250 kHz [12]. The converters invert the DC supply to AC then feds it to the primary side of a high frequency transformer that hasa turns ratio of 1:0.87. The secondary side of the transformeris connected to a full bridge converter that again rectifies theAC power into DC and it is fed to the Buck or Boost switches that further turns on or off to supply the power to the battery. Three pulse generators are used in the circuitone of which is used as the gate pulse of the 8 IGBT switches, used for a full bridge converter, and the other two are used for the buck and boost switch respectively. The voltage measurement block is connected to the primary and secondary of the transformer that is connected to the RMS block that is then connected to a display block that showsthe rms value of the primary and secondary voltages of the transformer. A voltage and current measurement block are connected to the secondary side full bridge converter, that is connected to a scope that shows the output voltage andcurrent of the full bridge converter. The battery is connectedto a bus selector that measures the voltage, current and the %soc of the battery. An inductor is connected in series with the battery as a filter to minimize the ripple in the battery current. There are two modes of operation of the circuit:

Charging Mode: As in Figure 3. the switches S1 and S2 are turned on and similarly switches S3 and S4 are turned on simultaneously. In this simulation, never the switch pair S1 , S2 and S3 , S4 are never turned on and turned off simultaneously. The switches S5 and S6 are turnedon simultaneously and similarly switches S7 and S8 areturned on simultaneously. In this simulation, whenever switches S5 and S6 are turned on, switches S7 and S8 are turned off and vice versa. The converter operates as a buck mode while battery is taking energy to be charged, while the DC sourceis powering the downstream load converters to supply power to the battery. During charging mode, the duty cycle of the buck switch was 0.2, the current flows through the buck switch through the inductor to the battery, thus supplying power to it.

Discharging Mode**:** When the DC-main is unable to supply the power, the battery regulates the bus voltage and thereby powers the downstream converters and the converter operates as a boost converter. For the discharging mode as shown in Figure 4., a series RLC load replaced the primary side voltage source. For an input battery voltage, the duty cycle of boost switch was 0.1, hence the power flows from the secondary side to the primary side of transformer, supplyingpower to the load [13].

5.1. Control Algorithm

The control algorithm of bidirectional converter is designed to control the gate pulse of the full bridge inverters. The control logic is shown in Figure 4. A pulse generator of 250 kHz is connected to two switches while the other two switches are connected via a NOT gate. The control scheme is as follows:

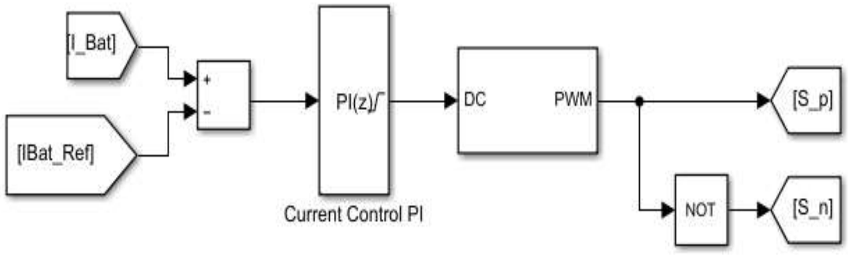

Figure 4. Current Controlled PWM Control

This control is used to control the battery current to protect it from overcurrent faults during charging or discharging. The reference battery current that was obtained from the on/off control acts as an error signal. The error signal is compared to the nominal battery current (i.e., 65.2A) and their difference is fed to the PID controller. The output from PID controller is fed to a DC to PWM generator, that generates the necessary PWM signal. The generated PWM signal is fed to one of the switches.

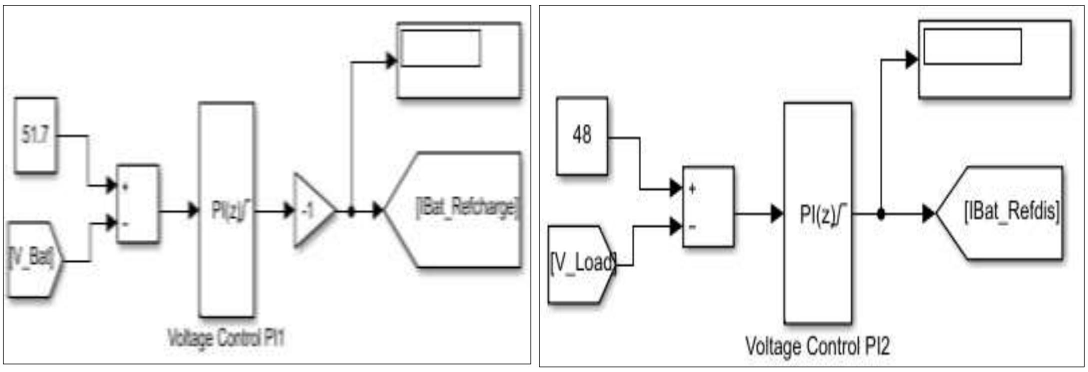

Figure 5. Voltage Control for (a) Charging (b) discharging.

This is the PID control algorithm for voltage control while discharging the battery. This is used to control the voltage level to ensure that the battery isn't in undervoltage fault whole during discharging. The battery voltage is measured and compared with the rated voltage of the battery (i.e., 48V) and an error signal is generated. The error signal is then fed to the PID controller which in turn generates a gain signal. That gain signal is then fed to the on/off control switch which again generates a new reference battery current signal. Now, that new error signal generates a PWM signal to drive the switches $\mathbf{S_1}$ and $\mathbf{S_2}$.

6. Simulation Result

The proposed topology has been simulated in MATLAB/SIMULINK and the results of each mode of operation is shown below:

6.1. Charging Mode

During charging mode of the proposed topology, a square wave voltage 230 V fed to the primary side of the transformer by the bridge inverter which is shown in the Figure 6 (a) while Figure 6(b) shows the voltage at secondary side of the transformer is 200 V .

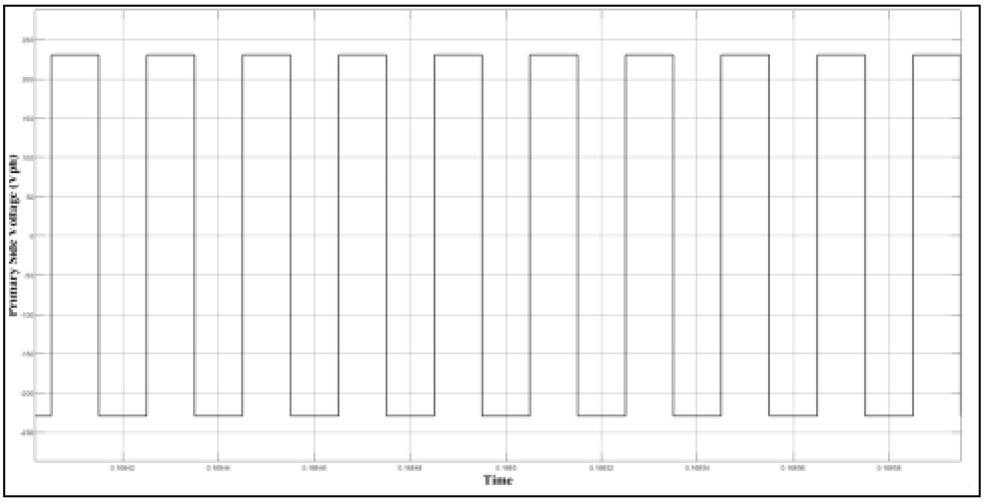

Figure 6 (a). Transformer primary voltage (V) in Buck Mode

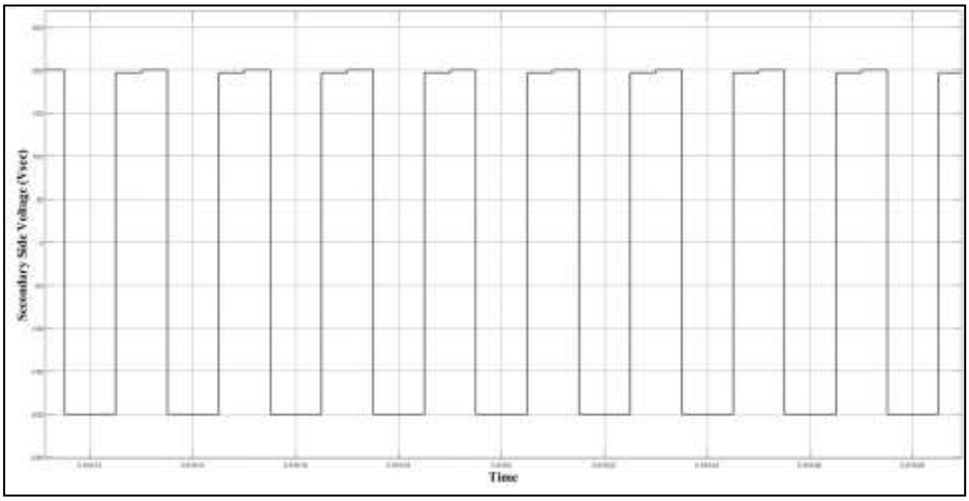

Figure 6 (b). Transformer secondary voltage (V) in Buck Mode

The Figure 7 states the voltage across the battery reaches at 200.23 V and the DC current flowing through the battery has reached at nearly 4.5 A at steady state nearly after 0.04s. Figure 9 shows the State of charge of the battery during charging operation. In this proposed topology, the SoC of the battery gains 80% charge during its charging operation.

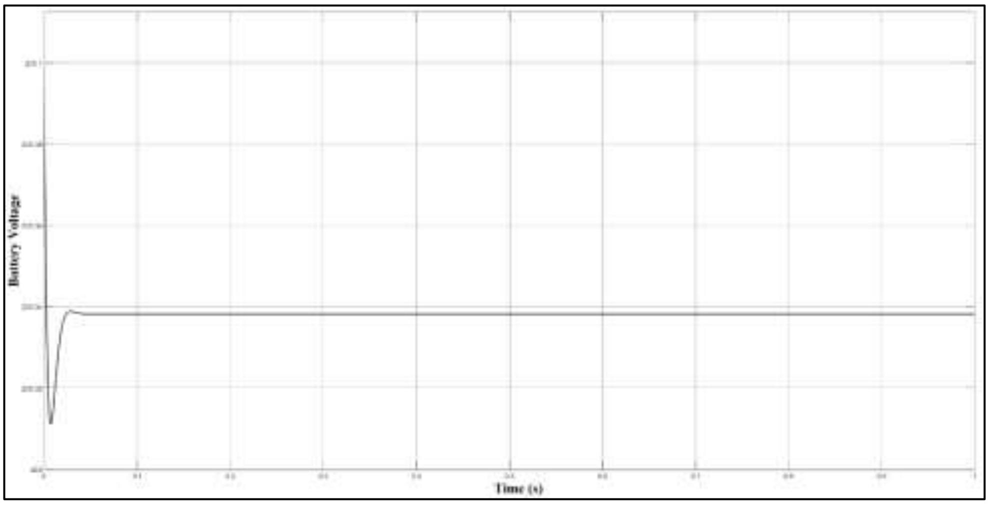

Figure 7. Voltage of Battery in operation during charging operation

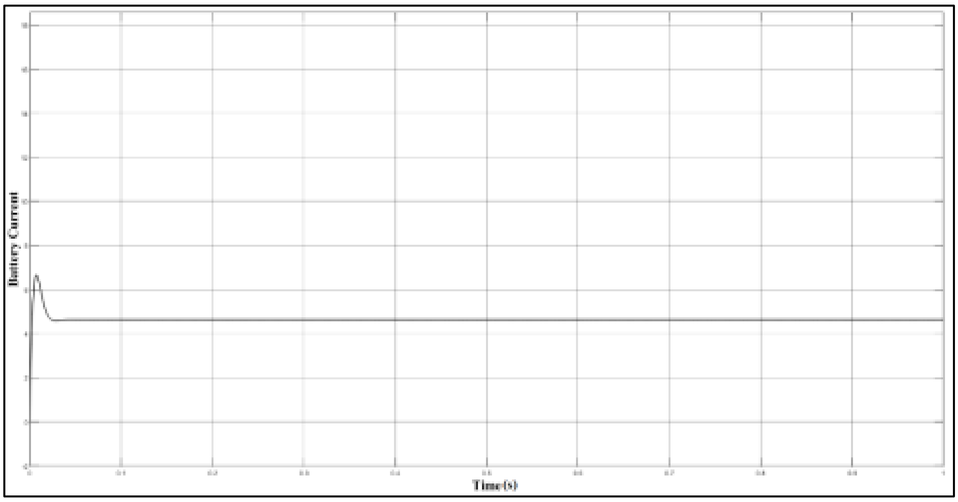

Figure 8. Current through Battery during charging operation

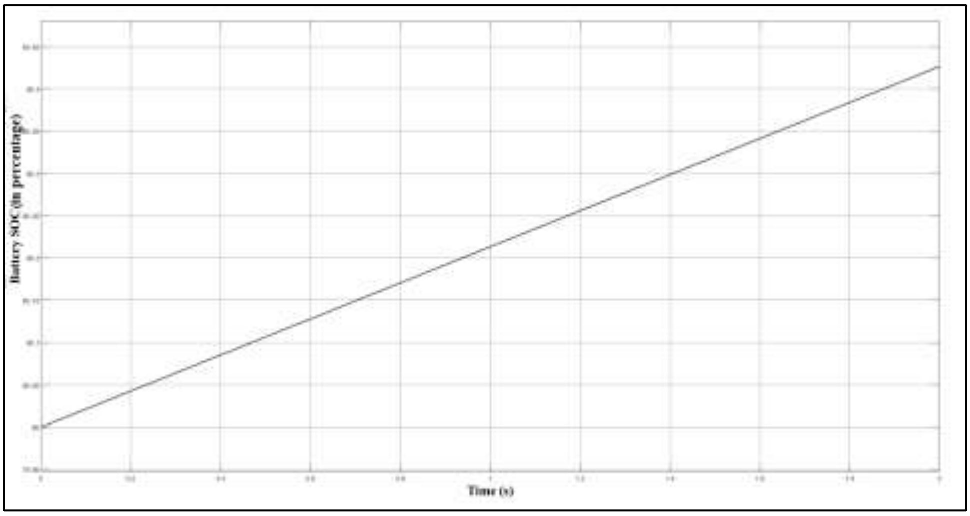

Figure 9. State of Charge (Soc) of Battery

6.2 Discharging Mode

From the Figure 10 (a) , it interprets that 220V voltage is fed to the primary side of the transformer by the bridge inverter, while in Figure 10(b) shows the 230 V secondary side of the transformer.

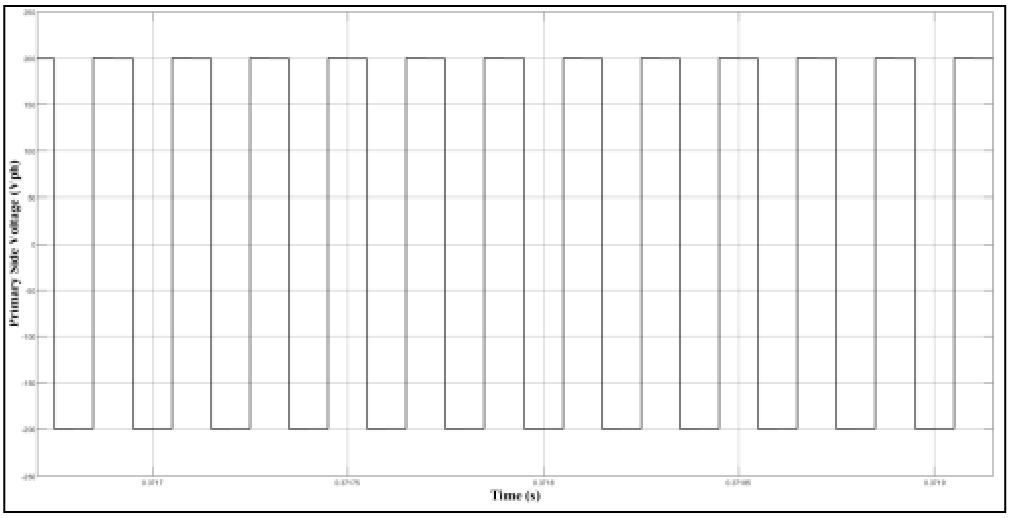

Figure 10 (a): Transformer primary voltage (V) in Boost Mode

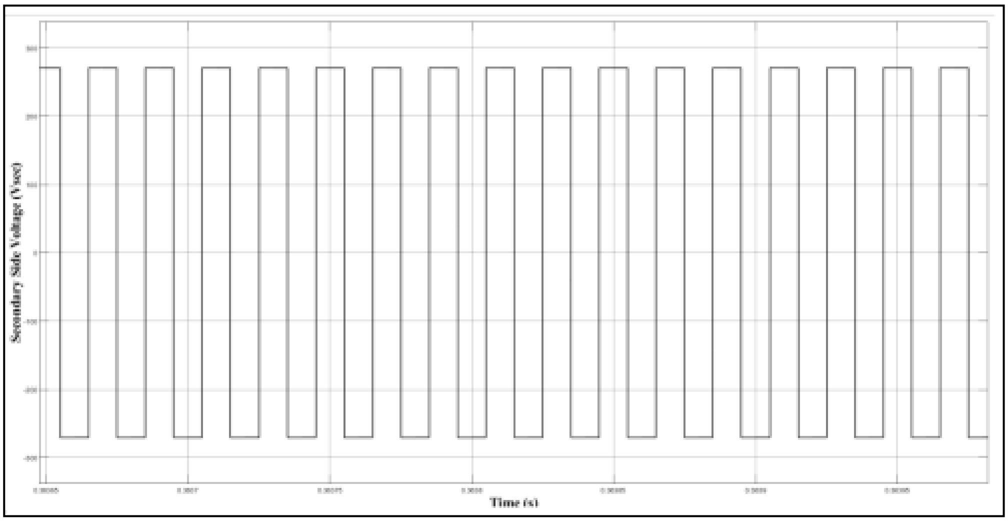

Figure 10 (b): Transformer secondary voltage (V) in Boost Mode

The Figure 11 shows the DC voltage of nearly 120 V, that reaches a steady state nearly after 4s and DC current of nearly 2.5 A fed to the load, that reaches a steady state nearly after 2s. While Figure 12 shows the Depth of discharge of the battery during discharging operation. As per proposed topology and control algorithms, the simulation has been done and have obtained the specification for the components to complete the design part. Table 1 shows the designed values of the passive components as well as the parameters.

Table 1. **Designed Model parameters for the proposed topology**

Parameters	Designation	Values
Input Voltage	V_{in}	230 V
Output Voltage	V_{out}	200 V
Switching Frequency	f_s	250 kHz
Transformation ratio	N	1:0.87
Input ripple current	ΔI_L	0.00329 A
Inductor	L	31.7 mH
Inductor	L_1	28 mH
Capacitor	$C_1 = C_2$	51.9 pF
Capacitor	C_3	37.8 pF
Damping Resistance	$R_d = R = R_1$	22.7 Ω
Damping Resistance	$R_d = R_2$	53.3 Ω

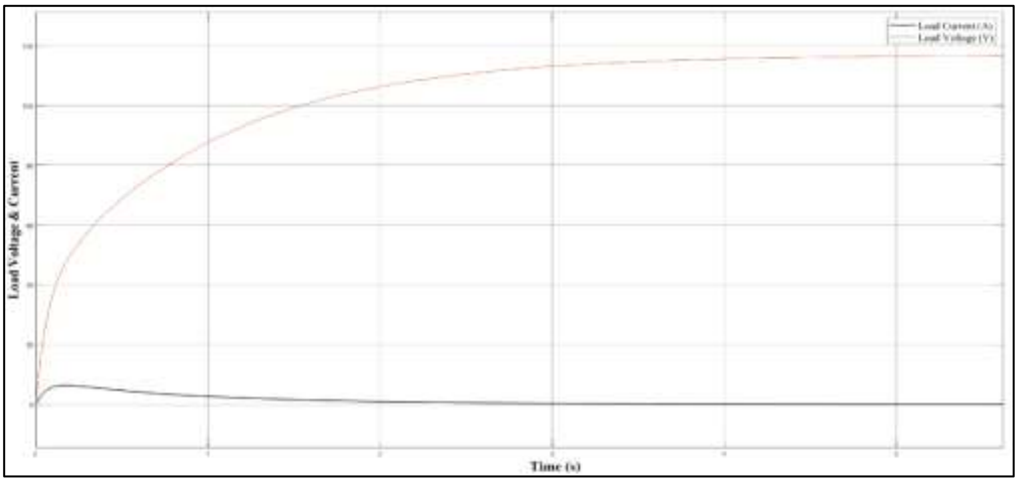

Figure 11. Load voltage and current

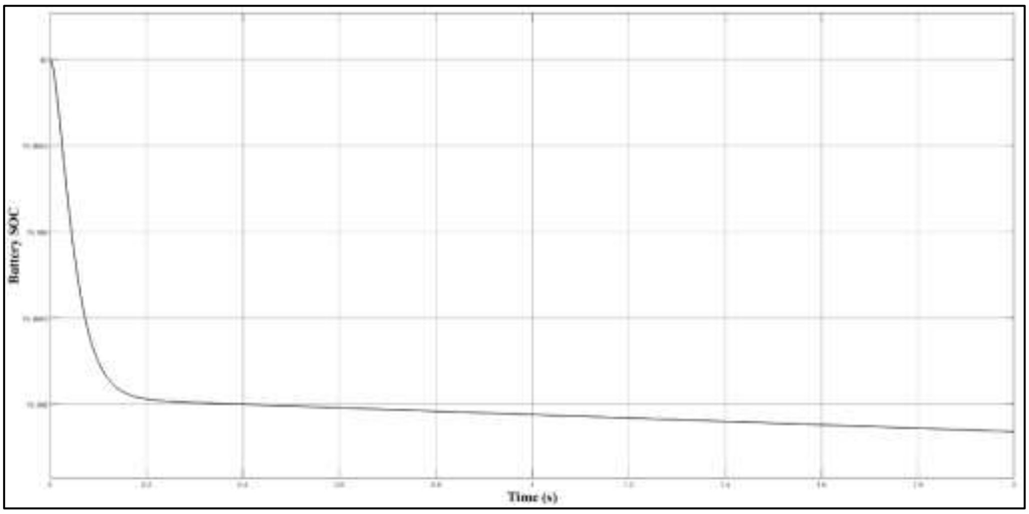

Figure 12. Depth of Discharge (DoD) of Battery

7. Conclusion

In this research, a bidirectional DC-DC converter has been designed for the t proposed wo stage topology where electrical isolation between the two sides for both battery charging and discharging applications has been achieved though the transformer. The designed parameters of the proposed circuit have been estimated. During charging and discharging mode of battery, the simulation provides the results in terms of various waveforms and therefore the proposed topology has been found to work in well manner. In present time, there are lots of advancement are going to implement in V2G applications of electric vehicles, so these converters will be effective. The proposed model is substantial in the examination of different driving cycles such as urban and suburban. The optimal control of bidirectional energyflows could be noticeably simple with the support of this study.

References

[1] S. Haghbin, S. Lundmark, M. Alakula and O. Carlson, "Grid Connected Integrated Battery Chargers in Vehicle Applications: Review and New Solution," in IEEE Transactions on Industrial Electronics, vol. 60, no. 2, (Feb, 2013), pp. 459-473.

[2] H. Lee and J. Yun, "High-Efficiency Bi-directional Buck–Boost Converter for Photovoltaic and Energy Storage Systems in a Smart Grid," IEEE Transactions on Power Electronics, vol. 34, no. 5, (May 2019), pp. 4316- 4328.

[3] K.V.Singh, H.O. Bansal, D.Singh “A comprehensive review on hybrid electric vehicles: architectures and components” Journal of Modern Transportation, vol. 27, (2019), pp. 77–107.

[4] K. Suresh, “A Multifunctional Non-Isolated Dual Input-Dual Output Converter for Electric Vehicle Applications,” IEEE Access, vol. 9, (2021) pp. 64445-64460,

[5] K. Jayasawal, Y. R. Purja, K. L. Rai, K Thapa, “A Novel Topology of Isolated Bidirectional Buck Boost DC-DC Converter” in proceedings of 8th IOE Graduate Conference, (2000), ISSN: 2350-8914.

[6] S. Liu, D. Xin and L. Yang, “A Novel Single-Phase Bidirectional Electric-Drive-Reconstructed Onboard Converter for Electric Vehicles,” in IEEE Access, vol. 8, (2020) pp. 44739-44747.

[7] G. VACHEVA, V. DIMITROV and N. HINOV, “Modelling and Control of Bidirectional Buck-Boost Converter for Electric Vehicles Applications” in XVI-th International Conference on Electrical Machines, Drives and Power Systems ELMA (2019).

[8] G. Lu, L. Zhang, Y. Bu, Y. Zhou, Study on front-end bidirectional dc/dc converter of photovoltaic grid-connected inverter, International Journal of Mechatronics and Applied Mechanics 1 (2017), pp. 45–52.

[9] L. Huang, X. Dong, C. Xie, S. Quan, Y. Gao, Research and modeling of the bidirectional half-bridge current-doubler DC/DC converter, International Journal of Rotating Machinery, (2017).

[10] Y. Zhang, Y. Gao, J. Li, M. Sumner, Interleaved switched- capacitor bidirectional DC-DC converter with wide voltage-gain range for energy storage systems, IEEE Transactions on Power Electronics 99 (2017), pp. 1–16.

[11] A. Chub, D. Vinnikov and E. Liivik, "Reverse power flow control possibilities of galvanically isolated impedance-source DC-DC converters," Proc. 11th IEEE Int. Conf. on Compatibility, Power Electron. and Power Eng., Cadiz, (2017), pp. 522-527.

[12] B. Zhao, Q. Song, W. Liu, and Y. Sun. Overview of dual-active-bridge isolated bidirectional dc–dc converter for high-frequency-link power-conversion system. IEEE Transactions on Power Electronics, 29(8), (2014), pp. 4091–4106.

[13] S. H. Hosseini, R. Ghazi and H. Heydari-Doostabad, “An Extendable Quadratic Bidirectional DC–DC Converter for V2G and G2V Applications,” in IEEE Transactions on Industrial Electronics, vol. 68, no. 6, (June 2021), pp. 4859-4869.

[14] A. Munsi, S. Chowdhuri and P. Pal, “An Efficient G2V and V2G Converter Systems for EV Application”, in Proceedings of 2020 IEEE Calcutta Conference (CALCON), (2020).