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Bidirectional Charger for Electric Vehicle Applications

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Abstract
The rise in EV mobility has encouraged the growth of V2G technology. The vehicle-to-grid technology allows bidirectional power flow between the battery of the EV and the grid. In the G2V mode of operation, EV batteries are charged from the grid. Bidirectional buck-boost converters allow power flow control, load balancing, and distributed resource integration, contributing to grid stability and resilience. It also helps in the synchronization of renewable energy sources with the grid by stepping up or down the voltage to match the grid requirements. The proposed system consists of a bidirectional DC-DC converter, which is used to control the power flow in both directions. A MATLAB Simulink model for the converter has been simulated with a PI controller to operate in a closed-loop mode. In addition to the simulation, a prototype model of the converter has been developed.
Keywords: *Bidirectional DC-DC converter, G2V, V2G, electric vehicle applications.*

1. Introduction
Electric vehicles with bidirectional charging are useful to power a home, feed energy back into the electricity grid, and provide provisional power in a blackout or emergency. An EV has a large battery on the bus, so a bidirectional buck-boost converter can enable a vehicle to store cheap off-peak electricity or solar power to reduce electricity costs [1]. This rising technology known as vehicle-to-grid (V2G), could revolutionize how our power grids operate, with the eventuality of avoiding blackouts due to thousands of electric vehicles supplying power contemporaneously during peak electricity demand [2]. A bidirectional converter is an advanced EV that can work in two-way charging; this might sound fairly simple, but it's a complex power conversion process from AC (alternating current) to DC (direct current) instead of regular unidirectional EVs that Charge using AC. Unlike standard EVs, bidirectional EVs operate like a converter, convert AC to DC during charging, and operate like an inverter and convert DC to AC during discharging [3]. Bidirectional power flow can only work with vehicles that are compatible with two-way charging and discharging. Due to bidirectional buck-boost converters being far more sophisticated, they're also much more precious than regular EVs since they incorporate advanced power electronics conversion to manage the energy flow from the V2G and from G2V [4]. To supply power to a home, bidirectional converters also incorporate outfits to manage the loads and provide a proper solution during a power outage in the grid. The introductory operating principle of a bidirectional converter is veritably analogous to the bidirectional inverter, which has been used for provisory power in home battery storehouse

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systems for over a decade. The charging of electric vehicles (EVs) can have an impact on the power grid's stability and dependability. This is due to the growing number of EVs on the road, which boosts electricity demand. EV charging can burden the grid, adding a significant load, particularly during peak hours [5]. This can result in power outages and voltage swings. Some of the negative effects of EV charging on electrical grids are voltage instabilities and phase imbalances, overloading distribution network components, distortion in harmonics, outages of electricity, imbalanced demand and supply, shortened transformer lifespans, and over-heating in the distribution transformer and cable [6]. To overcome these effects, a bidirectional charger is a wise solution for protecting the grid from the impact of EVs [7]. Bidirectional converters can be used for two different operations. The first is about vehicle-to-grid, or V2G, which is used to feed energy into the electricity grid when demand is high. [8] EVs have large batteries, so the combined power of thousands of vehicles with V2G could be enormous. Also, V2X is a term that's occasionally used to describe all variations, such as vehicle-to-grid (V2G) and vehicle-to-home (V2H) [9]. The paper is organized as follows: Section II provides detailed information about the bidirectional DC/DC converter with the two modes of operation, such as vehicle-to-grid and grid-to-vehicle. Section III deals with the design of the converter circuit with parameters for the hardware of the proposed model with a control circuit for each mode individually. Section IV deals with the simulation and results for the proposed system for both buck and boost modes of operation and the output results for various load values and waveforms were mentioned. Section V deals with hardware implementation with the designed converter parameters.

2. Proposed Model Description

A bidirectional converter is a device that allows power to flow bi-directionally. Power semiconductor switches such as IGBT have a significant advantage in power electronic devices due to their lower on-state voltage drop and ability to handle higher voltages than other power semiconductor switches. Despite its advantages over other switches, the IGBT has certain drawbacks. Low switching speed, limits its use in applications that require high switching speeds but the low on-state voltage drop makes it a suitable device for this application. Here, two IGBTs have been employed for two different objectives. There are two modes of operation: vehicle-to-grid and grid-to-vehicle [9]. The bidirectional converter has the advantage of con- trolling overload current by limiting it to a maximum value of 2A. The converter works either in buck or boost mode based on the SOC level in the battery. The battery is used as a load for both simulation and hardware. In addition, a resistive load has also been implemented as a load for attaining variation in load current with different set resistance values by adjusting the rheostat.

Operation of a Bidirectional Converter

1. Grid-to-Vehicle: The grid-to-vehicle power flow depicts the standard path of electrical energy from the grid to the battery of an electric vehicle. The process comprises AC/DC conversion, which uses a controlled rectifier to convert the AC voltage to the necessary DC voltage. In addition to that, an input filter can be used to remove EMI from the input source using an LCL filter. Concerning the variation in output, the converter can function as an inverter or a controlled rectifier. This is achieved by controlling the value of Alpha in the controller. After the controlled rectifier, the process moves to the DC/DC converter, which charges the battery in buck mode [10].
2. Vehicle-to-grid: The vehicle-to-grid system operates as per grid requirements or demand. As the world's electric vehicle adoption increases, the grid may become imbalanced due to increased load during peak hours. To avoid this and give the best solution for this problem, this strategy used to operate during vehicle isolation could prove to be more useful and more effective. The DC/AC conversion begins at the DC bus of the inverter. This is a controlled converter that is utilized in the input

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stage of a DC/DC converter. By altering the alpha value, the desired output for grid voltage and current can be achieved by performing the switches in the correct sequence. The adoption of an LCL filter, which filters out the reactive power and high-frequency components, results in only active power being transmitted back to the grid [10].

3. Design Methodology

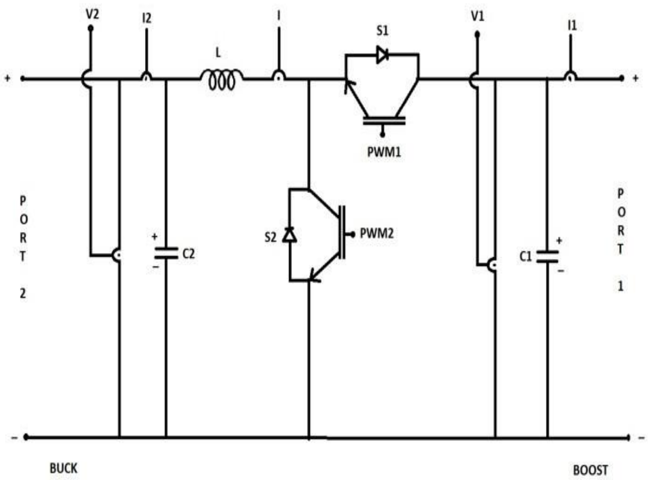

Figure 1 **Bidirectional Converter Topology**

a. Bidirectional Buck-Boost Converter

It is often used in applications that require bidirectional energy transfer, such as battery energy storage systems, regenerative braking systems, and electric vehicle charging. The bidirectional buck-boost converter was designed for a prototype model [11] with low voltage and current ratings and a maximum power output of 50 watts is shown in Figure 1

Buck Mode of Operation: When the switch S1 shown in Figure 2 operates, the circuit acts as a buck converter, stepping down the voltage based on the given Vdc voltage, concerning the desired Vbatt voltage [12]. During the Toff state, the stored energy in the inductor is discharged through Diode D2 which is connected anti-parallel with S2, and capacitor C2 which is connected in parallel to the switch S2 [13].

$$V_{batt} = V_{in} \times D \qquad (1)$$

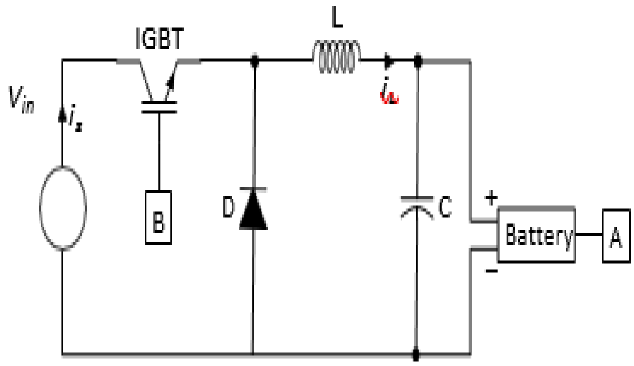

Figure 2 **Bidirectional Converter in Buck Mode**

Boost mode of operation: When the switch S2 shown in Figure 3 operates, the circuit acts as a boost converter, stepping up the voltage based on the given V batt voltage concerning the desired Vdc voltage. During the Toff state, the stored energy in the inductor L and capacitor C2 is discharged through Diode D1 which is anti-parallel with S1.This results in boosting the output voltage due to two energy storage elements present in the input side of the boost circuit [13].

$$V_{in} = V_{batt}/1\text{-}D \qquad (2)$$

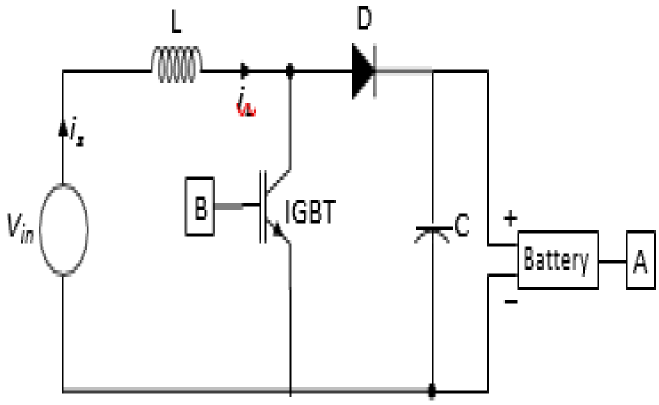

Figure 3 **Bidirectional Converter in Boost Mode**

As shown in Table 1 the values of the Inductor, Capacitor, and Duty cycle have been designed, based on the design parameters of the circuit configuration for the buck and boost mode of operation.

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Table 1 Converter Design Parameters

Parameters	Values
Power(P)	50W
Input voltage (Vin)	24V
Battery voltage(Vbatt)	12V
Switching Frequency(Fs)	10kHz
Maximum output current(Iomax) in Buck mode(A)	P/Vbatt
Maximum output current(Iomax) in Boost mode(A)	P/Vdc
Ripple current(A)	0.01*Iomax
Ripple voltage(V)	100mV
Inductor (L)	1mH
Capacitor (C)	1000 μF
Rheostat(Ω)	0-360Ω
Battery	12V,7Ah
Duty cycle (D)	50%

The optimization algorithm-based PI controller has been implemented in the MATLAB SIMULINK environment, Where the algorithm runs the 'N' number of iterations and checks each iterated value with the pi controller to get an optimized and efficient way to operate the converter. [14] Control Algorithm for Bidirectional Converter are shown in Figure 4.
The algorithm has been developed based on the following steps,

1. The Input Voltage is measured and the voltage is compared with a preset value.
2. If the condition 9<V<=12 is satisfied, then the process will follow the boost mode, if not then it will follow the buck mode, only when the condition 18<V<=24 is true.
3. The converter then performs the conversion, and the output voltage is fed back into the error correction system.
4. After this the error calculation will be done, based on the difference between the reference and the output signal, and the error value will be processed with the kp and ki constants.
5. After this, the PWM pulses will be generated and the respective switches will be turned on, based on the mode of selection

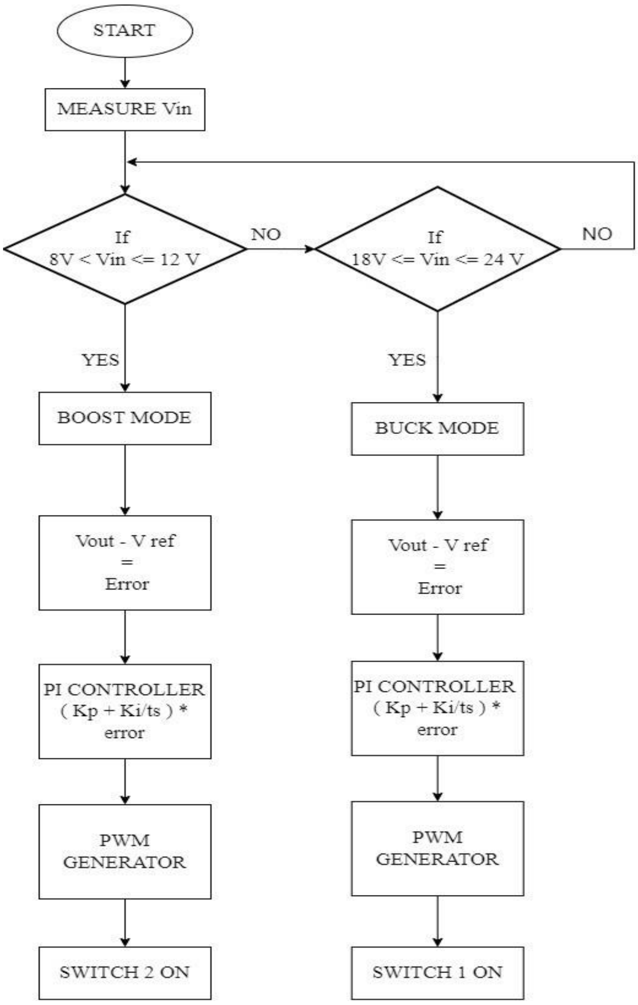

Figure 4 Control Algorithm for Bidirectional Converter

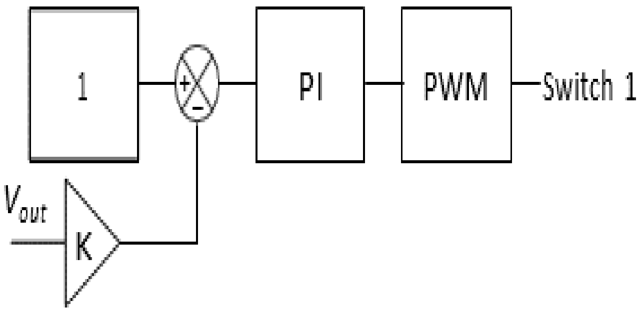

Figure 5 Control for Buck Mode

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The control circuit is designed in MATLAB SIMULINK for the Buck mode, is shown in Figure 5. The output of the battery voltage Vbatt or Vout is taken as a reference voltage, which is then given as the gain input, to compare it with the constant value, and the error value. The error value is then multiplied with Kp and Ki constants, which are tuned based on Ziegler Nichol's method of tuning. Where the output should be less than or equal to 12V.

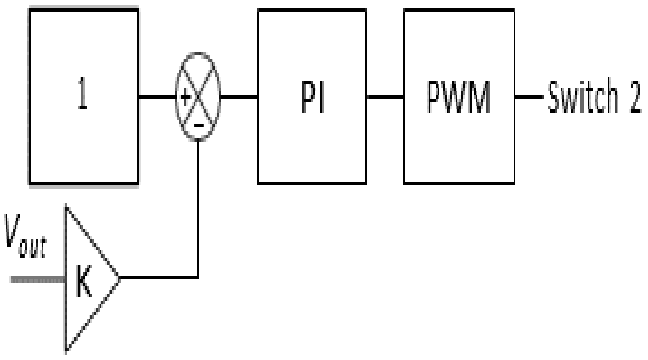

Figure 6 **Control for Boost Mode**

The control circuit is designed in MATLAB SIMULINK for the Boost mode, is shown in Figure 6. The output of the battery voltage Vbatt or Vout is taken as a reference voltage, which is then given as the gain input to compare it with the constant value.

Whose error value is then multiplied with K p and Ki constants, which is tuned based on Ziegler Nichol's method of tuning. Where the output should be greater than or equal to 24V. The control modes are executed based on the input voltage V in, the control will be decided whether a buck or boost mode based on the value of V in.

4. Simulation Results

The circuit is developed and simulated in the MATLAB SIMULINK platform. The design values and the battery ratings used in the simulations are mentioned in the previous sections. The simulation circuit and the results obtained are mentioned in this section.

Converter in Buck mode:

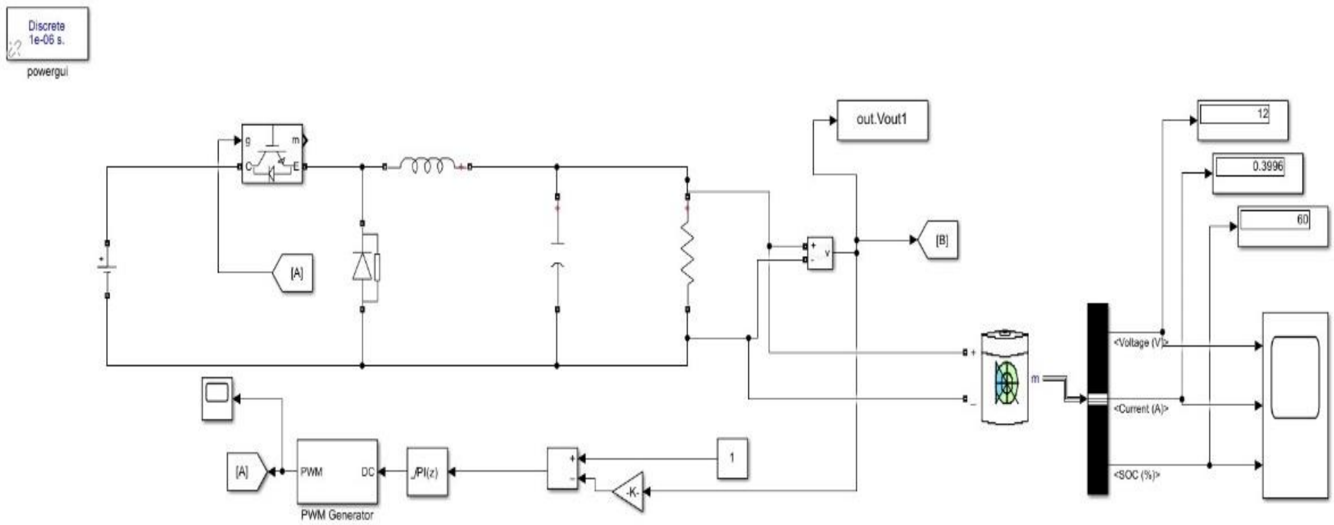

Figure 7 **Simulation in Buck Mode**

In a bidirectional DC/DC converter during Buck mode, a 24V DC supply is given as the input to port 1 as stated in the bidirectional converter topology. Then the output voltage is stepped down to 12V as Obtained in Figure 7. Hence, this mode is known as grid-to-vehicle mode. Output Voltage, Output Current and SOC in Buck Mode are shown in Figure 8.

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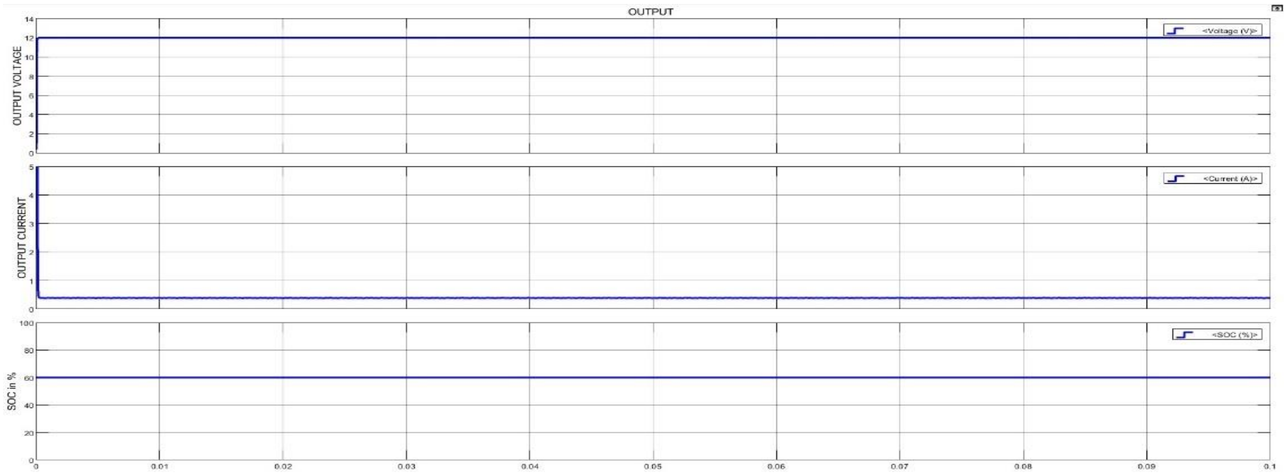

Figure 8 Output Voltage, Output Current, and SOC in Buck Mode

Converter in Boost mode:

- In a bidirectional DC/DC converter during Boost mode, a 12V DC supply is given as the input to port 2 as stated in the bidirectional converter topology.
- Then the output voltage is stepped up to 24V as obtained in Figure 9. Hence this mode is known as a vehicle-to-grid mode. Figure 10 shows the output results in boost mode.

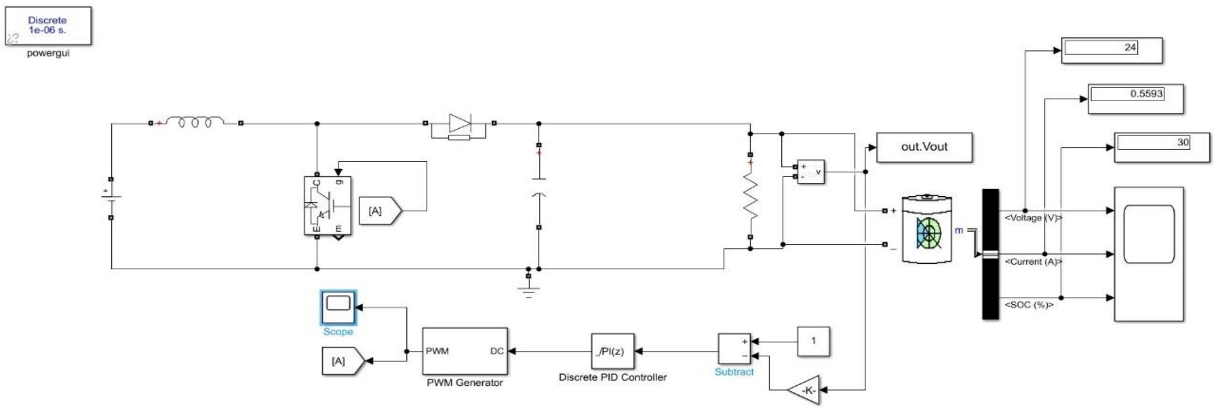

Figure 9 Simulation in Boost Mode

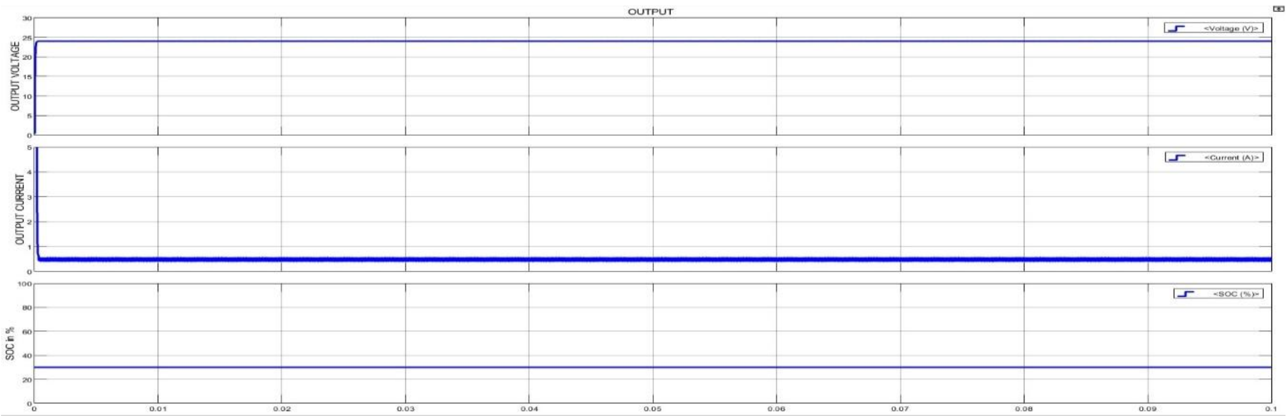

Figure 10 Output Voltage, Output Current and SOC in Boost Mode

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5. Hardware Implementation

Hardware is developed for two different modes. A 230V AC supply is stepped down to +15V/-15V and 5V for the power supply needed for the control circuit of the IGBT. So, three different voltage regulators were used to regulate the 18V DC, which is rectified by the input rectifier. The ICS 7805, 7815, and 7915 are used as voltage regulators. To obtain a measure of the output voltage across the two PORTS in the circuit, we use a comparator to compare the reference voltage and the obtained DC voltage at the output. The input and output voltage waveforms, PWM signals, and current waveform for Buck mode and Boost mode are shown in Figure 11. The hardware developed for the bidirectional DC/DC circuit is illustrated in Figure 12.

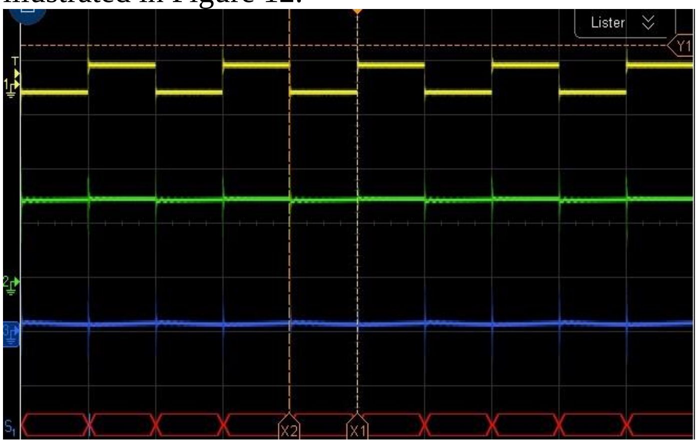

Figure 11 Output Voltage, Current, and PWM Signal in Buck Mode

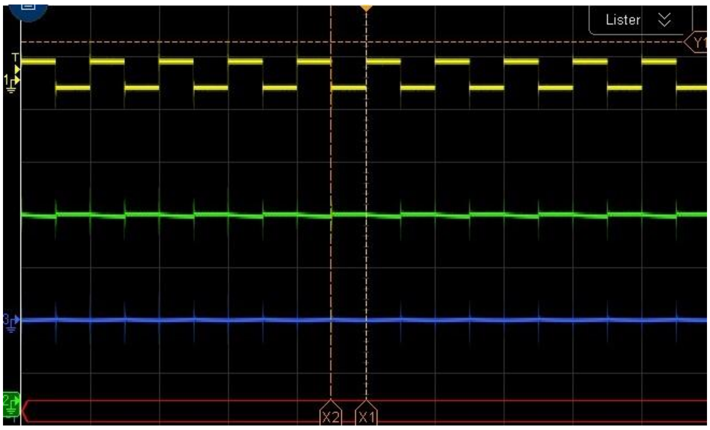

Figure 12 Output Voltage, Current, and PWM Signal in Boost Mode

For various resistive loads, the output voltages and current measurements were taken, and a study on the efficiency of the converter in both modes is shown in Table 2 and Table 3. The study was obtained by experimenting with the converter with various load values within the specified limit of load current. The output waveforms for both buck and boost modes are observed and mentioned.

Table 2 Converter Efficiency Studies in Buck Mode

Vin (V)	Vout (V)	Iin (A)	Iout (A)	R (Ω)	Pin (W)	Pout (W)	η (%)
24	10.2	0.4	0.9	8	9.6	9.18	95.62
24	10.5	0.32	0.51	10	7.68	5.355	69.73
24	10.7	0.5	0.5	20	12	5.35	44.5
24	10.8	0.28	0.5	25	6.72	5.4	80.35
24	11	0.25	0.4	30	6	4.4	73.33
24	11.4	0.2	0.4	34	4.8	4.56	95
24	11.8	0.2	0.35	36	4.8	4.13	86.1
24	12	0.22	0.34	40	5.28	3.84	72.73

Table 3 Converter Efficiency Studies in Boost Mode

Vin (V)	Vout (V)	Iin (A)	Iout (A)	R (Ω)	Pin (W)	Pout (W)	η (%)
12	18.5	0.3	0.1	182	3.6	1.85	51.4
12	19	0.4	0.15	185	4.8	2.85	59.3
12	19.5	0.5	0.15	190	6	2.92	48.6
12	20	0.6	0.2	195	7.2	4	55
12	20.5	0.7	0.25	200	8.4	5.12	61
12	21	0.8	0.3	205	9.6	6.3	65.6
12	21.5	0.9	0.3	210	10.8	6.45	59.7
12	24	0.96	0.4	215	11.52	9.6	83.3

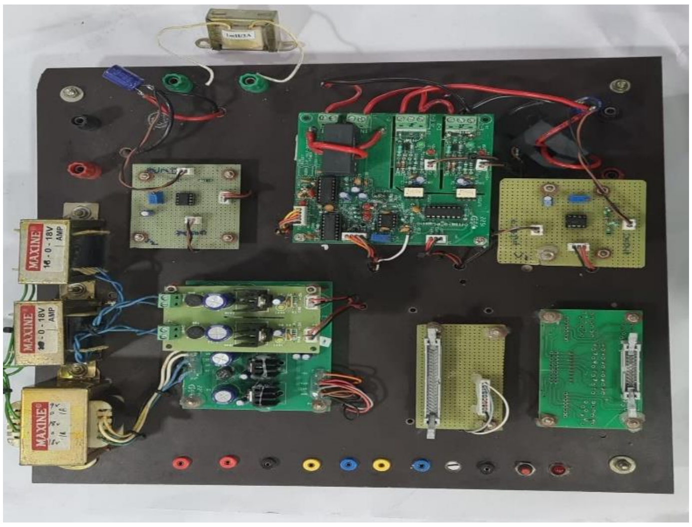

Figure 13 Hardware Model of Bidirectional DC/DC Converter

The hardware model mentioned in Figure 13 is a prototype development for the bidirectional DC/DC converter with the specific values for both voltage and current within the range, which is mentioned in the previous sections. [15]

Conclusion

The performance of the bidirectional DC/DC converter has been studied in both buck mode and boost mode. The efficiency of the converter under various load conditions has been presented, which is assisted by comparing the results of the bidirectional DC/DC converter from MATLAB SIMULINK simulation and the hardware results, which have been added to our work in this paper.

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