DESIGN AND DEVELOPMENT OF NON-ISOLATED THREE PORT BIDIRECTIONAL BOOST+CUK DC-DC CONVERTER FOR ELECTRIC VEHICLES

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ABSTRACT: A large number of conventional vehicles in use around the world has caused and continues to cause serious environmental hazards like pollution and resource depletion which in turn has affected humans and other forms. Electric Vehicles (EVs), Hybrid Electric Vehicles (HEVs) and Fuel Cell Electric Vehicles (FCEVs) have been typically proposed to replace conventional vehicles soon as a solution to the problem. This paper proposes a novel non-isolated three-port bidirectional boost-cuk (NI-TPBBC) DC-DC converter for electric vehicle applications. The proposed converter combines the characteristics of Boost and Cuk converters, providing five viable modes of operation along with provision for regenerative energy utilization. The converter is compatible with the use of two input sources. The proposed converter is extensively studied and the simulated results are carried to verify their viability for practical use.

KEYWORDS: Bidirectional DC-DC Converter, Non-isolated converter, Boost and Cuk converter, Multiport Converter, High-voltage gain, electric vehicle application.

I. INTRODUCTION

Renewable energy sources play an important role in the present energy scenario in spite of having low voltage characteristics. Therefore, for practical applications, a high voltage gain and high-efficiency DC-DC converters are necessary to control the characteristics of the low voltage into a utilization voltage level.

Bidirectional DC-DC converters can implement the electrical energies of the storage units (batteries/capacitors) to be converted and transferred in two directions thereby providing flexibility and possible integration of renewable energy by providing more than one port as input energy. The voltage of the storage units is set to be low and the DC link voltage between the sources and application(DC motor) is set to be high. Hence, a bidirectional converter that can operate in both boost and buck modes is crucial to obtain voltage matching.

In this scenario, the requirement of a bidirectional DC-DC converter with high efficiency and conversion ratio is still an area of research interest in the power electronics field.

The proposed converter attempts to meet the required converter model. The converter operates in bidirectional mode with a high voltage conversion ratio and a reduced number of active components complying with reduced loss and higher efficiency setting.

It has five modes of operation which are extensively studied and experimented upon for practical viability. A prototype is built to validate the calculated values. The converter also gives the provision of two input ports making it compatible with renewable energy applications such as electric vehicles.

II. TOPOLOGY OF THE PROPOSED CONVERTER

The proposed converter (Figure 1) consists of two inputs namely a PV source and battery. The configuration is based on the integration of a Boost converter with a Cuk converter. The boost and buck static gain of these types of converters are beneficial features for wide range voltage conversion. Power flow is bidirectional in the new converter.

The converter consists of a branch network to compensate two input modes and the Boost-Cuk circuit. The supply network employs switch *T* to control power flow from the PV source. The supply network consists of three IGBTs, an inductor, and a relay *Rs* to manipulate the power to the Boost network. The supply branch provides the necessary topology for battery discharging and charging through PV supply as well as a path for regenerative power to charge the battery.

The Boost-Cuk circuit consists of three power switches *S1*, *S2*, and *S3*; capacitors *C1*, *C2*, and *C3*; and inductors *L1* and *L2*. The proposed topology is achieved by developing [7]. The bidirectional setting is achieved by modifying the circuit to the required specification. The proposed converter is examined on the assumption that it operates in continuous conduction mode (CCM), and that all the components are ideal.

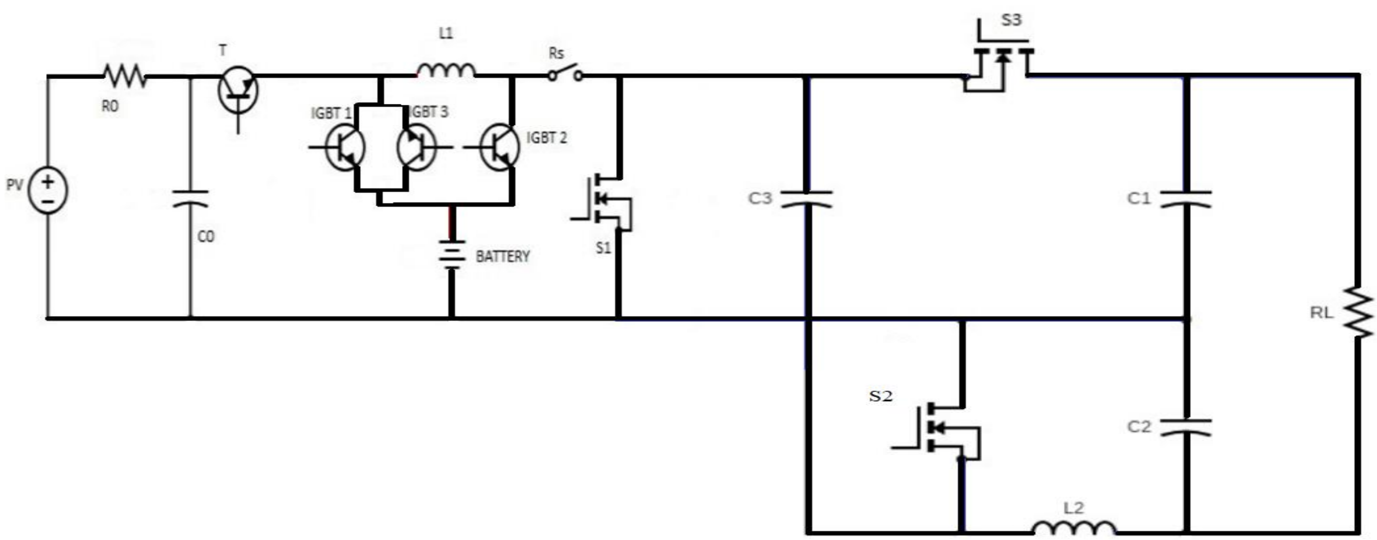


Figure 1 Topology of the Proposed Converter

III. OPERATIONAL MODES

1. PV Supply to Load (SISO – 1)

In this mode, the PV supplies to the load. The battery circuit is detached from the network by opening switches *IGBT 1*, *IGBT2* and *IGBT3*. The switch *T* is turned ON along with the relay *Rs*. Two sub-modes arise due to the switching operation of switch *S1*. During ON State (Figure 2a), the Switch *S1* is ON. At this period, the current from PV source flows through Switches *T* and *S1* thereby completing the current path. The Inductor *L1* charges at this period. Capacitor *C3* discharges through switch *S1*. Capacitor current branches into two components.
The switches *S2* and *S3* are reverse biased.
This is because the voltage across capacitor *C1* is greater than that of across capacitor *C3*. Capacitor *C1* discharges and supplies to the load. Capacitor *C2* charges at this period. The inductor *L2* charges and the current path is completed.

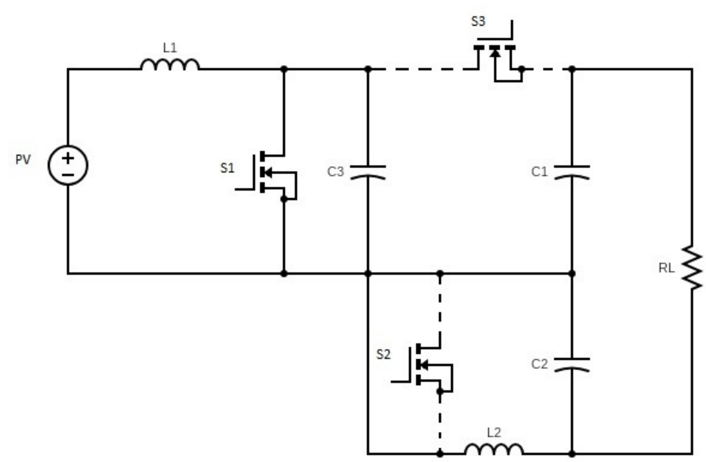


Figure 2a ON State (Switch *S1- ON , S2,S3 – OFF) – Mode 1*

During the OFF state of switch S_1*(Figures 2b - 2c)*, there arise two scenarios. When the voltage across capacitor *C1* is greater than the voltage across capacitor *C3*(*Vc1>Vc3*), the inductor *L1*current discharges through the relay *Rs*. Capacitor *C3* charges. Switch *S2* is forward biased. Inductor *L2* discharges through diode *S2* and charges the capacitor *C2*. The capacitor *C1* discharges feeding the load.

When the voltage across capacitor *C3* is greater than the voltage across capacitor *C1* (Vc3>Vc1), the inductor *L1* continues to discharge. Due to the charging of capacitor *C3*, the voltage builds up and increases to more than that across capacitor *C1*. Hence, switch *S3* is forward biased. The capacitors *C1* and *C3* are charged. Capacitor *C2* discharges. Inductor *L2* discharges through diode *S2*.

Table 1 Switching Chart for Mode 1

MODE (Switch *S1)*	Rs	S_1	S_2	S_3
ON	1	1	0	0
OFF (Vc1>Vc3)	1	0	1	0
OFF (Vc3>Vc1)	1	0	1	1

Table 1 shows the switching sequence employed in each state.

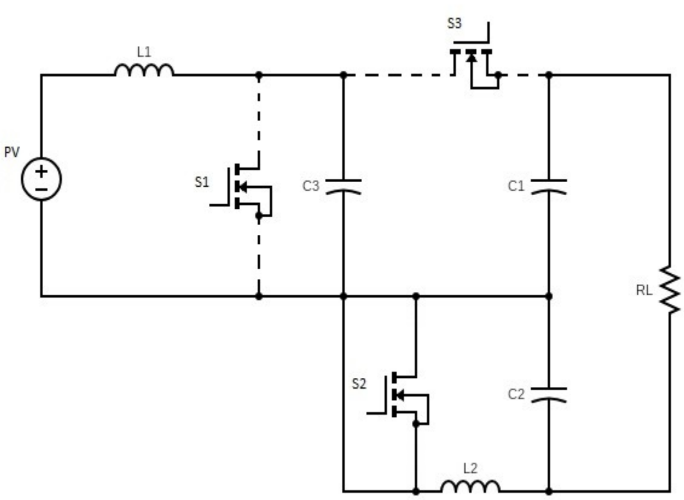


Figure 2b OFF State *(Vc1>Vc3) (*Switch *S1, S3 – OFF, S2 – ON) – Mode 2*

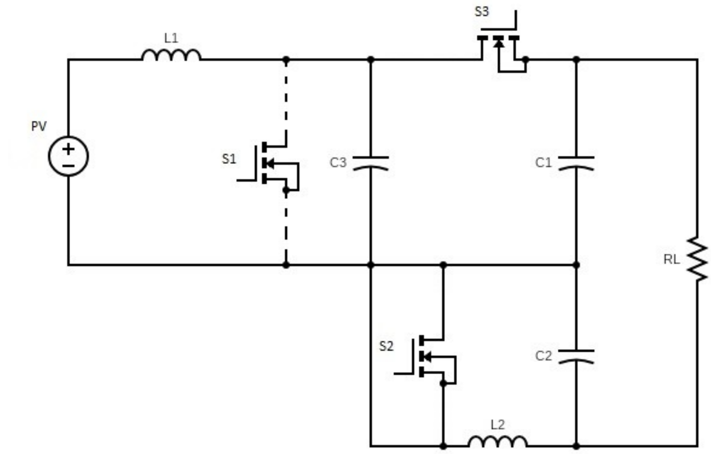


Figure 2c OFF State *(Vc1>Vc3) (*Switch *S2, S3 – ON, S1 – OFF)- Mode 2*

2. Battery to Load (SISO – 2)

In this mode, the battery supplies to the load. It is similar to Mode 1. The PV circuit is detached from the network by opening switch *T*. The switch $IGBT_3$ is turned ON along with the relay *Rs*.

During ON State (figure 3a), the Switch S_1 is ON. At this period, the current from the battery flows through Switches *T* and S_1 thereby completing the Current path. The Inductor L_1 charges at this peiod. Capacitor C_3 discharges through switch S_1. It branches into two components. The switches S_2 and S_3 are reverse biased. This is because the voltage across *C1* is greater than that of across C_3. Capacitor C_1 discharges and supplies to the load. Capacitor C_2 charges at this period. The inductor L_2 charges and the current path is completed.

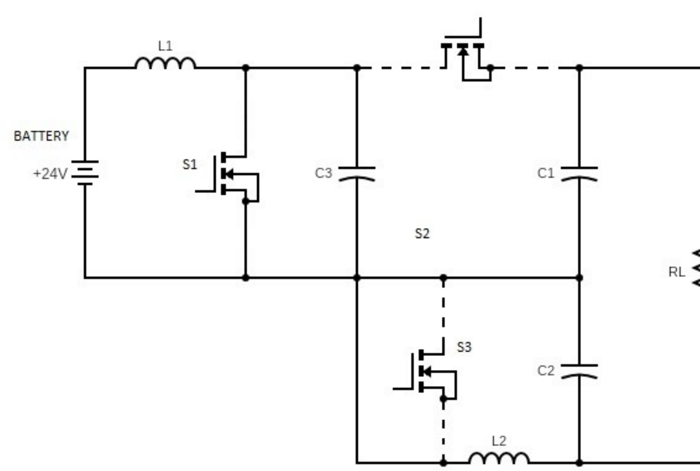


Figure 3a ON State (Switch *S1- ON , S2,S3 – OFF) – Mode 2*

During the OFF state (figure 3b – 3c), there arise two scenarios. When the voltage across capacitor *C1* is greater than the voltage across capacitor *C3*(*Vc1>Vc3*), the inductor L_1 discharges through the relay. Switch S_1 is OFF. Capacitor C_3 charges. Switch S_2 is forward biased. Inductor L_2 discharges through switch S_2 and charges the capacitor C_2. The capacitor C_1 discharges feeding the load.

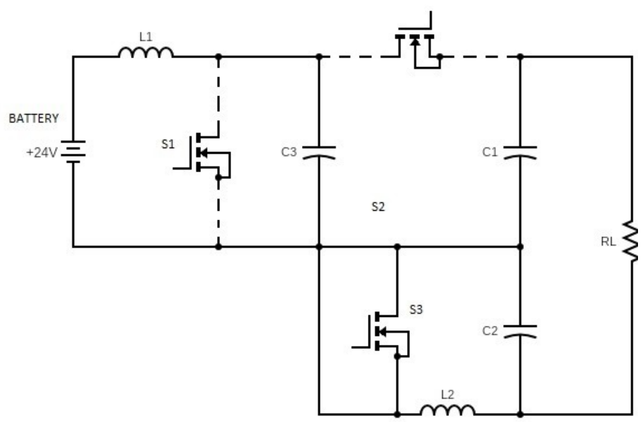


Figure 3b OFF State *(Vc1>Vc3) (*Switch *S1, S3 – OFF, S2 – ON) – Mode 2*

When the voltage across capacitor *C3* is greater than the voltage across capacitor *C1*(*Vc3>Vc1*), the inductor L_1 continues to discharge. Due to the charging of capacitor C_3, the voltage builds up and increases to more than that across capacitor C_1. Hence, diode S_3 is forward biased. The capacitors C_1 and C_3 are charged. Capacitor C_2 discharges. Inductor L_2 discharges through diode S_2.

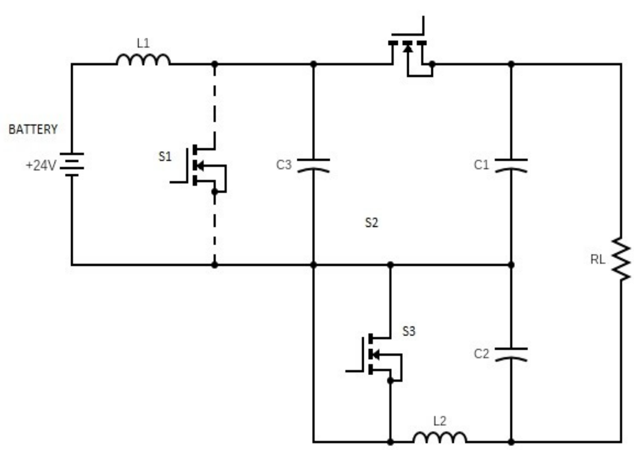


Figure 3c OFF State *(Vc1>Vc3) (*Switch *S2, S3 – ON, S1 – OFF)- Mode 2*

Table 2 Switching Chart for Mode 2

MODE	T	IGBT$_1$	IGBT$_2$	IGBT$_3$	Rs	S_1	S_2	S_3
ON	0	0	0	1	1	1	0	0
OFF(Vc1>Vc3)	0	0	0	1	1	0	1	0
OFF(Vc3>Vc1)	0	0	0	1	1	0	1	1

3. PV Supply and Battery to Load (DISO)

During peak load requirement i.e when the electric vehicle is in operation and requires power more than the average operating power requirement, there arises a need for both the primary and the secondary source to supply the traction system. Also, the supply from PV and BATTERY are alternated based on the availability of PV energy and the energy required by the load.
During the first cycle of operation (0 – t1), PV supply is used to cater to the load. In the next cycle of operation (t1 - t2), PV supply is removed by opening switch T, and battery supply is included by closing IGBT3. The load sharing is controlled using the duty cycle of the control switch T and IGBT3. The two sub-modes are:
1)PV to LOAD 2)BATTERY to LOAD
During each of the above modes, the switching operation corresponding to each of the individual modes is performed in their respective period of operation, thus the operational characteristics mentioned in *(1)* and *(2)* hold good in this mode.

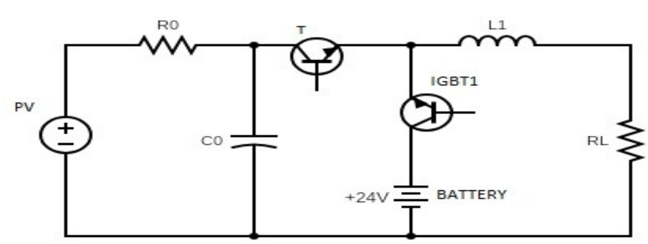


Figure 4 Mode 3 Operation

Table 3 Switching Chart for Mode 3

CONDITION	MODE	T	IGBT$_1$	IGBT$_2$	IGBT$_3$	Rs	S_1	S_2	S_3
PV Supply	ON	1	0	0	0	1	1	0	0
	OFF(Vc1>Vc3)	1	0	0	0	1	0	1	0
	OFF(Vc3>Vc1)	1	0	0	0	1	0	1	1
Battery	ON	0	0	0	1	1	1	0	0
	OFF(Vc1>Vc3)	0	0	0	1	1	0	1	0
	OFF(Vc3>Vc1)	0	0	0	1	1	0	1	1

4. *Regenerative Braking (SISO – 3)*

The regenerative braking action is executed by using the pressure inserted onto the brake levers during the regular braking action to convert the motoring action of the traction system into an intermittent generating action, wherein the voltage produced by the generating action of the traction system, is fed to the battery by the buck operation of the converter.

Whenever the braking action takes place, the traction motor temporarily shifts to generating action, thus producing a current flow into the circuit. This is where the Bi-directionality of the converter comes into use. The Switch T and switch Bs are in Off state. Thus current flows through the inductor L1 thereby charging it. IGBT2 and IGBT3 are in OFF state, thus the current produced from the braking action is fed to the battery through the IGBT1.

Table 4 Switching Chart for Mode 4

$IGBT_1$	S_1	S_2	S_3
1	1	0	0
1	0	1	1

Figure 5.21 shows the capacitor voltages, Inductor currents, and switching currents when the switches are operated in the above sequence.

5. *PV to Battery*

Apart from the above four modes of operation, there is a possibility to modify the converter design to accommodate one more operating mode.

To implement the operation of PV to Battery power flow, the need to add additional switches to the proposed design arises. Hence switch "Bs" is added for this mode of operation.The stationary phase of the EV is when the battery gets charged to cater to the demand in the recurring operational modes.

During this time, the PV source has to feed the energy storage systems through the converter as a buck operation is to be executed for the same.In the initial cycle of operation, the Switch *T* is closed. Hence the power arriving from the PV source charges the Inductor and feeds the battery through the IGBT2 thereby completing the current flow. During this mode, the switch *Bs* is in the OFF state.

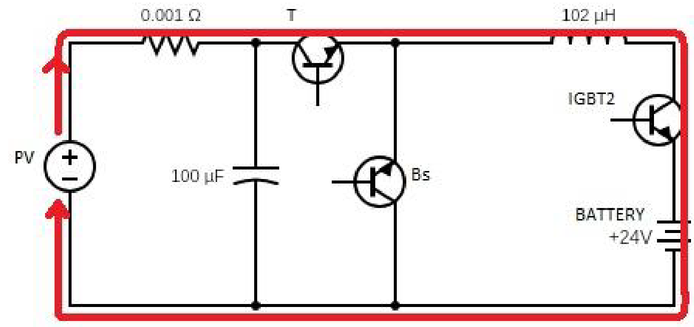


Figure 4a PV to Battery State – 1

During the second cycle of operation, the switch *T* is now opened and the Switch *Bs* is closed, thereby moving into ON state. The inductor which was charged in the previous cycle, now discharges through the *IGBT2*, thereby charging the energy storage system.

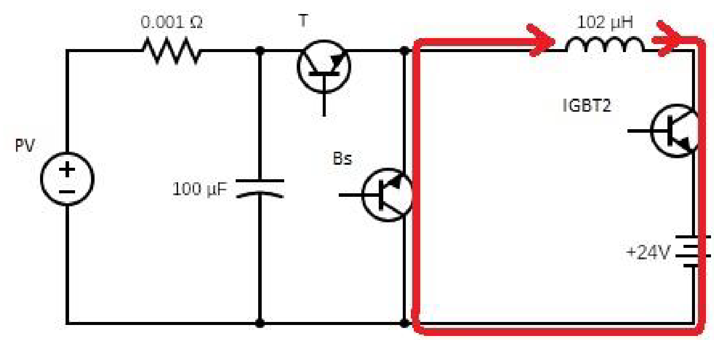


Figure 4b PV to Battery State – 2

Table 5 Switching Chart for Mode 5

Mode (Switch T)	Bs	IGBT 2
1	0	1
0	1	1

IV. VOLTAGE GAIN EQUATION

By applying the volt-second balance equation to *L1* and *L2* according to Fig.7, the voltage gain V_g of the proposed NI-TPBBC converter in CCM can be obtained as:

$$\frac{1}{T}\int_0^T v_L(t)dt = 0$$

By substituting the inductor (L1, L2) equations:

$$\frac{1}{T}\int_0^d V_{in}dt + \frac{1}{T}\int_d^1 \frac{V_{in}-V_o}{2}dt = 0 \quad (1)$$

$$V_{in}d + \frac{1}{2}(V_{in}-V_0)(1-d) = 0 \quad (2)$$

$$V_{in}d + V_{in} - V_0 + V_0 d = 0 \quad (3)$$

$$Vg = \frac{V_0}{V_{in}} = \frac{1+d}{1-d} \quad (4)$$

V. SOFTWARE AND HARDWARE ANALYSIS

The proposed and theorized converter model is simulated using Matlab software and the obtained results are matched with a 250 W laboratory prototype.

Table 6 Parameters

Component	Abbrevation	Rating
PV Supply	Vpv	40 V
Battery Pack	Vb	24 V
Inductors	L1-L2	100uH
Capacitors	C1-C2 C3	50uF 3.3uF
Switching Frequency	f_s	15kHz
Power Rating		250W

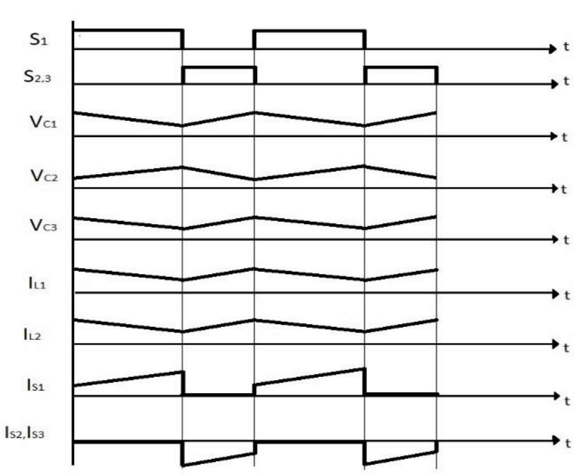


Figure 7 Principle Waveforms of proposed NI-TPBBC Converter; S1,S2,S3 – Pulse period,Vc1, Vc2,Vc3 – Capacitor Voltages, IL1 – Inductor L_1 current, IL2 – Inductor L_2 current, Is1 – Switching current of S_1, Is2 – Switching current of S_2, Is3 – Switching current S_3

By applying the Kirchhoff voltage law on the proposed NI-TPBBC converter, the voltage stress can be obtained as:

$$V_{s1,s2,s3} = \frac{V_{in}}{1-d}$$

Similarly, by applying the Kirchhoff current law, the current stress can be expressed as follows:

$$I_{s1} = \frac{2}{1-d}I_{in}$$

$$I_{s2,s3} = \frac{1}{1-d}I_{in}$$

Where "d" is the duty cycle of switching.

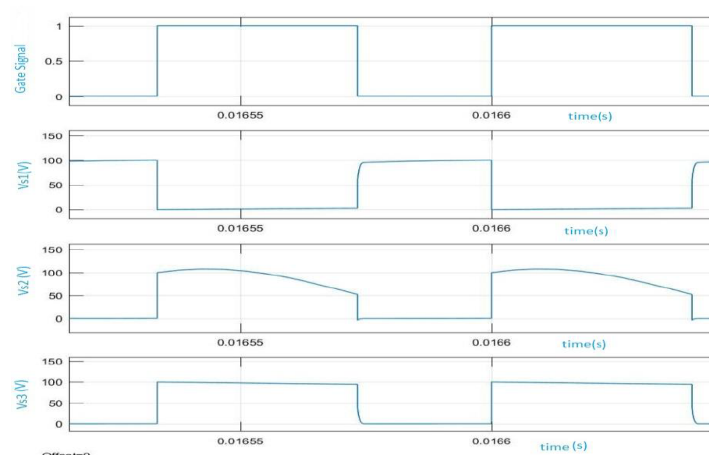


Figure 5 Voltage Stress on Switches

Figure 5 shows the voltage stress on switches S1, S2, and S3. It is observed that when S1 is in OFF condition, a maximum of around 97 V appears across it.

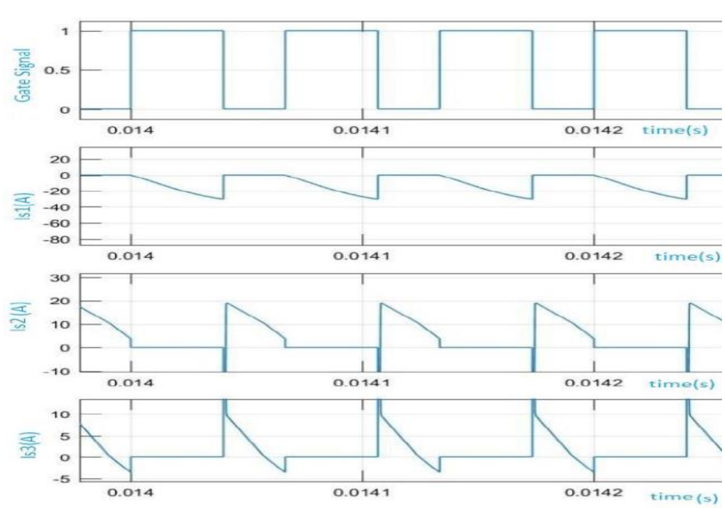
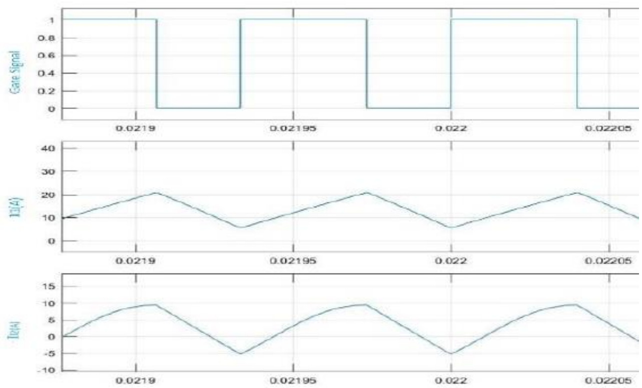


Figure 6 Current Stress on Switches

Figure 6 shows the current stress across switches S1, S2, and S3. It is observed that when S1 is in ON condition, a maximum of 30 A appears in it.

With the above-mentioned parameters, experimental results for the proposed NI-TPBBC Converter are obtained as in Figure 6.



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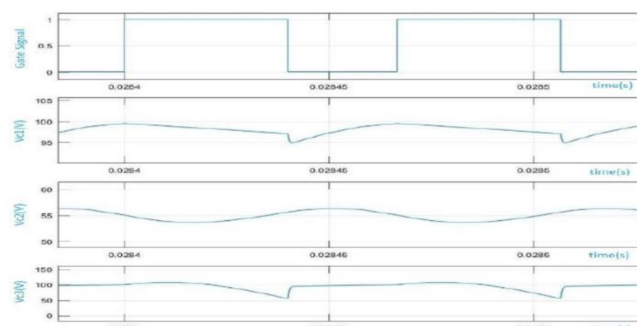

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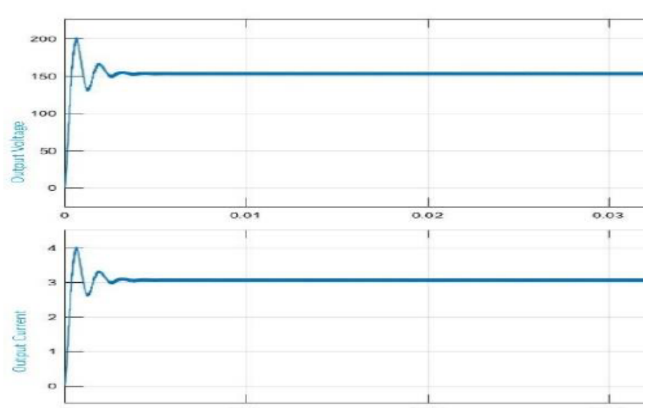

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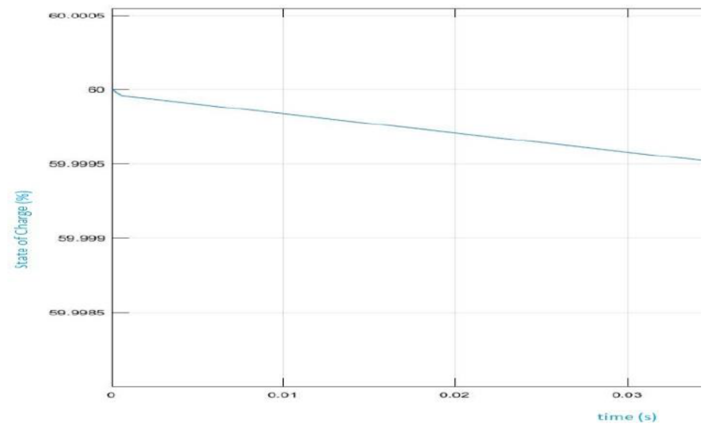

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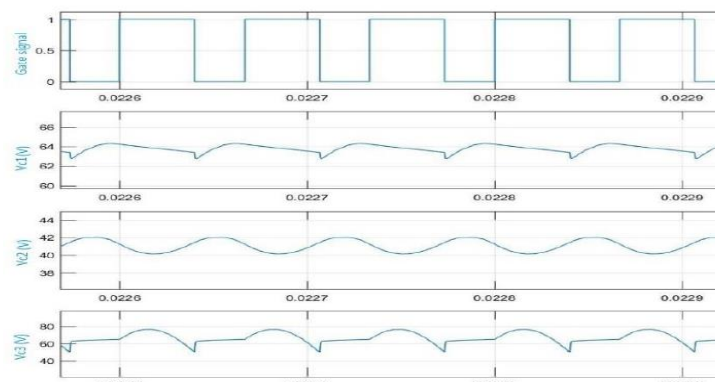

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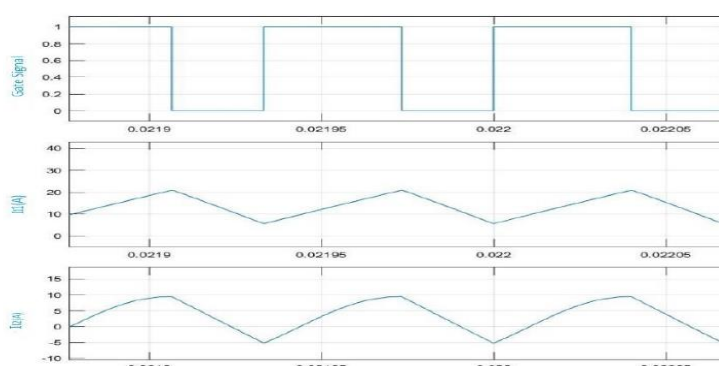
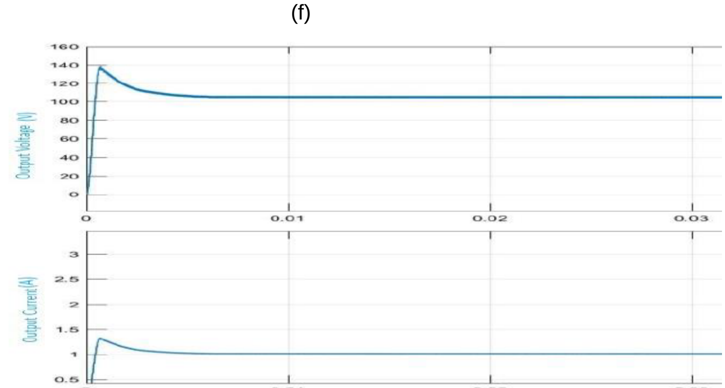


(f)



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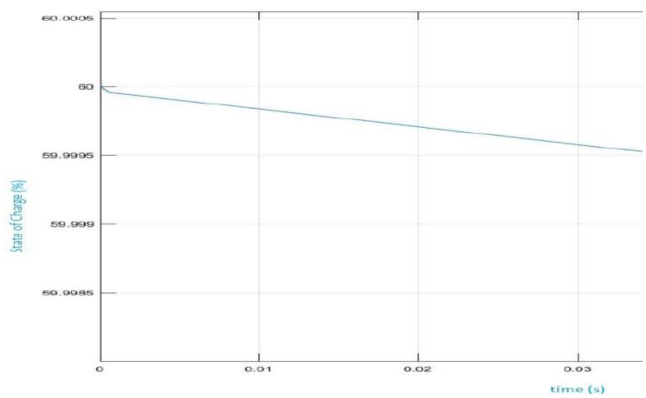

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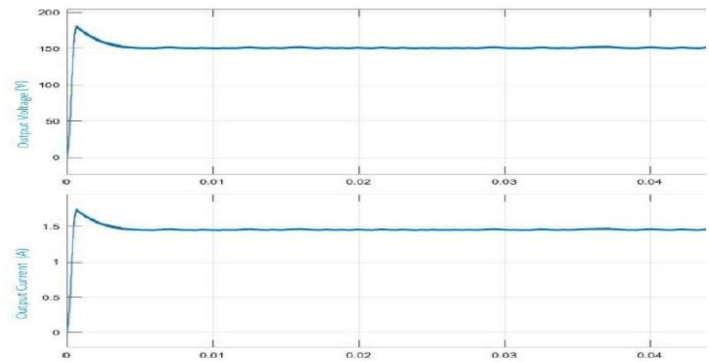

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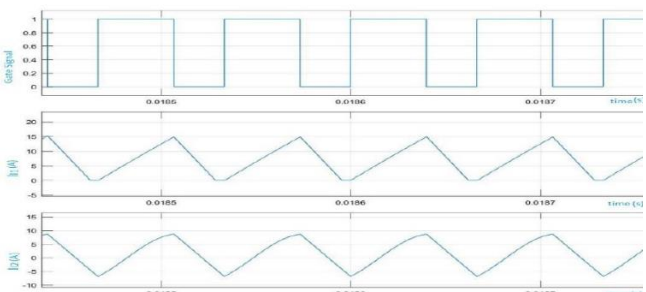

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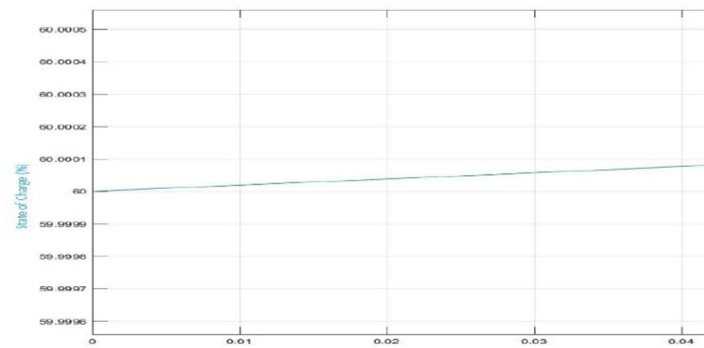

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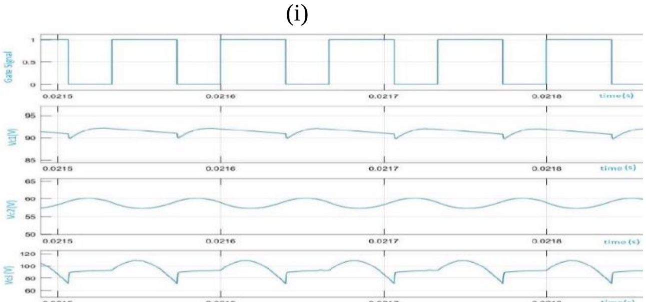

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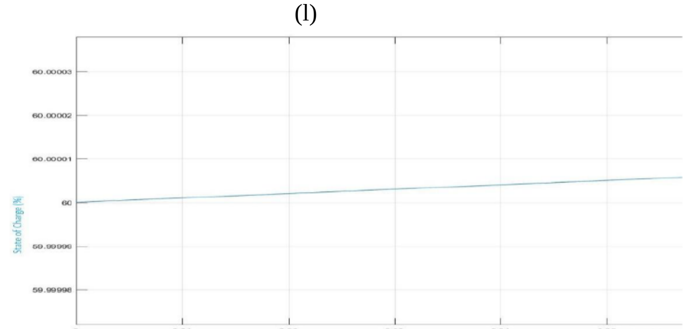

(m)

Figure 7 (a)Inductor Currents – PV to Load, (b)Capacitor Voltages – PV to Load, (c) Load Voltage and Load Current-PV to Load (d)Battery Condition – Battery to Load, (e) Capacitor Voltages – Battery to Load, (f)Inductor Currents – Battery to Load, (g) Load Voltage and Load Current-Battery to Load (h) Battery Condition – PV and Battery to Load, (i) Inductor Currents – PV and Battery to Load, (j)Capacitor Voltages – PV and Battery to Load, (k) Load Voltage and Load Current-PV and Battery to Load, (l) Battery Condition-Regenerative Braking, (m) Battery Condition-PV to Battery.

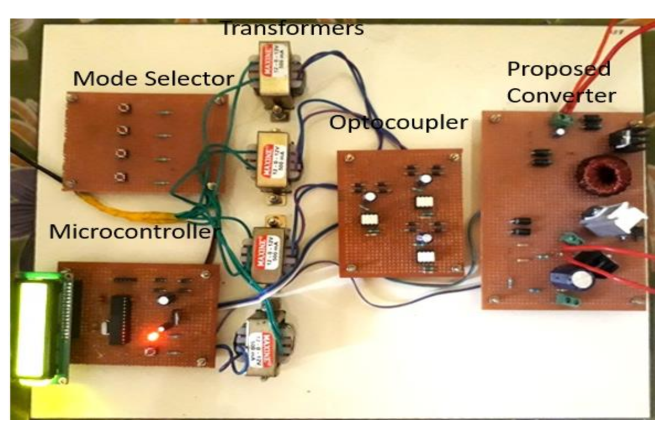

Figure 8 Hardware Prototype

In order to validate and verify the simulation results, a 200 W laboratory prototype of the proposed NI-TPBBC converter is built. The PV supply is mimicked using a Regulated Power Supply (RPS). The battery pack is made of 24 V/10 Ah rating with discharge capacity more than 3C for fast discharging. The switches, inductors, and capacitors are connected according to the proposed design to obtain the Boost-Cuk topology. 50μF, 100μF capacitors, and 1mH inductors were used as C and L respectively. The switching frequency is set at 15kHz. The output was expected to be around 250 W. Figure 8 shows the hardware prototype of the proposed NI-TPBBC Converter.

Table 7 shows the comparison of the proposed NI-TPBBC converter with other converter topologies in terms of components, voltage gain, and features.

Table 7

CONVERTER IN REFERENCE	NUMBER OF ACTIVE SWITCHES	NUMBER OF DIODES	NUMBER OF INDUCTORS	NUMBER OF CAPACITORS	SWITCHING FREQUENCY	BIDIRECTIONAL/ UNIDIRECTIONAL	VOLTAGE EQUATION	VOLTAGE GAIN	REPORTED POWER RATING
[11]	4	2	2	3	100 kHz	Unidirectional	$V_o = d_1 V_{PV}$ $V_{ba} = (1-d_3)V_o$	Low	400 W
[12]	8	0	2	1	20 kHz	Bidirectional	$V_o = \frac{V_b}{(1-D)}$	Medium	30 kW
[13]	3	1	1	3	50 kHz	Unidirectional	$\frac{1}{1-D}$	Medium	80 W
[14]	4	2	2	0	50 kHz	Unidirectional	$\frac{1}{1-D}$	Medium	2 kW
[15]	3	5	2	2	50 kHz	Bidirectional	$\frac{1+n}{1-D}$	High	300 W
[16]	4	2	2	1	20 kHz	Bidirectional	$D_i / 1-D$	Low	1 kW
Proposed NI-TPBBC Converter	3	3	2	3	15 kHz	Bidirectional	$\frac{V_0}{V_{in}} = \frac{1+d}{1-d}$	High	250 W

The converter design in [13] consists of a similar number of components but it does not possess the feature of bidirectionality and has lesser voltage gain.
The topologies proposed in [11], [12], [14] all have a comparatively high number of switches leading to greater switching losses and are less compact.
The voltage gain of the proposed NI-TPBBC converter is higher when compared to other converter topologies. The reduced voltage stress and current stress in the proposed NI-TPBBC converter ensures lesser switching losses and facilitates the use of low rated components thereby decreasing the cost and providing a compact design. The multi-input feature in the proposed converter enables the integration of additional energy sources such as renewable energy. The bi-directionality is an added advantages making the design more energy-efficient and compatible with upcoming applications such as electric vehicles.

VI. CONCLUSION

A non-isolated dual-input Boost-Cuk converter topology has been proposed in this paper. The main advantages of the proposed converter are minimal design, simple control strategy, concurrent or independent power transfer capability of input ports, reduced number of components (switches, inductors, capacitors) and bidirectional power flow capability. Power regulation capability between the PV supply, battery and output is an advantageous property. The Converter as a design parameter has been extensively investigated and calculated for different input and load scenarios for all the modes of operation. The efficiency of the proposed topology has been verified by detailed analysis and experimental results. Hardware and simulation results validate the satisfactory working of proposed topology. The proposed converter can be capable of implementation in HEV/EV.

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