

A Non-Isolated Multiport Converter for E-Vehicle Applications

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Abstract

The necessity to reduce the risks in the environmental pollution has paved way for the options that help in minimizing it. Electric vehicle is one such option and the most evolving means in this field. The EV system in order to achieve a high peak requires multiple sources to be integration. So, a bidirectional buck boost DC to DC converter with four port is realized in this research for integration of many sources instead of using dedicated converter. This non isolated multi-port converter with compact size, minimum number of components and simple controlstructure enhances converter reliability and makes it more economical. This converter has the ability to accommodate energy sources with varying current and voltage characteristics. This converter has two input ports the DC supply & the Batteryas well as two output ports motor and auxiliary loads. This multi-port converter exhibits bidirectional power flow capability during the regenerative braking of an E-Vehicle. The converter employs three switches to control the flow of power. The article aims in studying the performance of the controller structure used in regulating the flow in power of energy sources and analyses its dynamic as well as the steady state characteristics. The design is validated using MATLAB Simulink tool to ensure its performance.

Keywords: Integration of various sources, Bidirectional power flow, Non-isolated multi-port converter, Regenerative Braking

1. Introduction

In recent years attraction towards the Electric Vehicle (EV) are increased due to the technology developments in storage units, drives etc. With the comparison of vehicles using fossil fuels and the EV, the EV has lesser number of systems. The advantages of EV are environment friendly, less noise, low maintenance, etc. To ensure the reliable power supply in EV more than one energy source is required. EV's powered by Solar PV (or) DC Supply are commercially launched in many countries for public use. In this condition battery is used as a storage unit to support the EV system powered by the DC supply.

EV requires DC converters to integrate the Fuel Cell (FC) or photovoltaic cell (PV) and the drive system. An efficient motor drive system is propelled with the converter working on DC power without much power losses.

It is essential for the converter (power electronic) to have bidirectional capabilities for EV's on interfacing motor drive system and the battery with the energy sources.

A multi-port converter is used to integration of sources [1],[2],[4][13]. A novel non isolated multiport converter integrating a PWM converter and phase shift converter with four switches [12]. A coupled inductor three port non-isolated converter is proposed. [16] A three port converter with analogous connection of buck and boost converter is presented. [17]

1.1 Objective

Multi-port converter is essential for following reasons

- Integration of different energy sources with unidirectional/bidirectional Power flow capability
- It has less number of power devices. So, it reduces the cost and size of the system.
- It has individual power control between the sources and it provides reliable supply to the load.

2. Conventional System

On employing multiple energy sources a dedicated converter is used for incorporation of energy sources. Figure 1 shows the block diagram of conventional system. Energy Generation Source (EGS) as DC Source and Energy Storage Source (ESS) as Battery is employed. For transferring power from DC Source to Drive Train (Motor) and transferring power from Battery to Auxiliary loads then Dedicated DC to DC Converter is used. In addition to distinct Bidirectional DC/DC Converter is utilized for regenerative braking of motor. If number of sources are increased, then number of power converter used is also increased, it leads to a higher number of components like switches, diodes, inductors, capacitors, etc. Another drawbacks of conventional system are high cost and more conversion steps. [1]

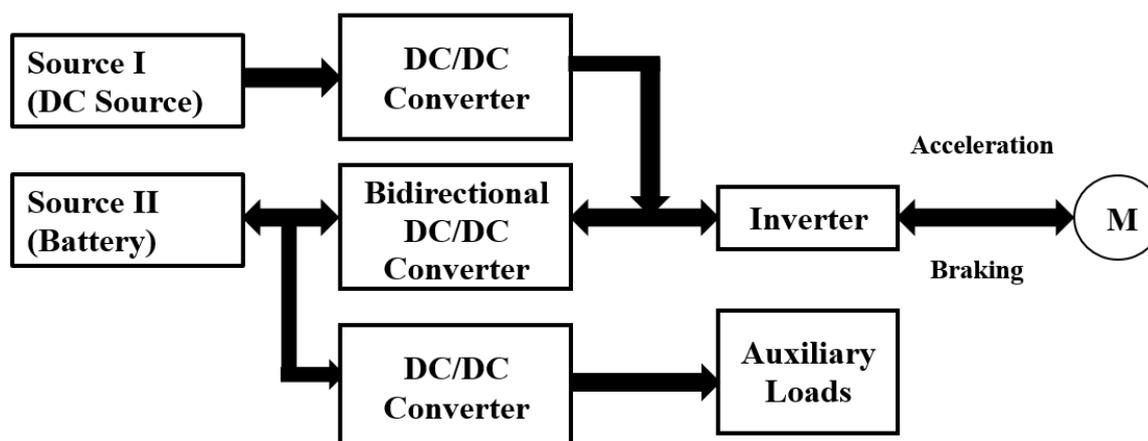


Figure 1. conventional system

3. Proposed System

The integration of various sources by multiport converter is shown in Figure 2. This multi-port reduces the system size because single module is used instead of using separate converter. This converter operate in different operating states. A port is either used as input or output depending on each operating state.

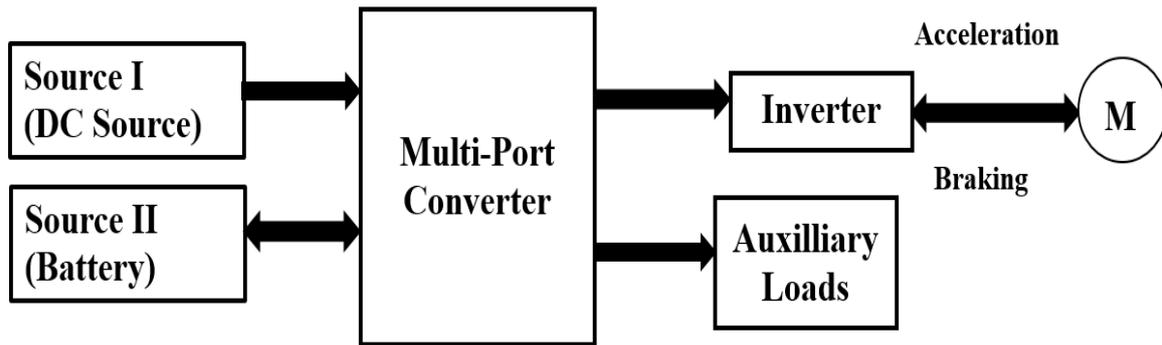


Figure 2. Block diagram of proposed system

Different types of sources used in EV applications such as DC source (or) PV and battery pack, Operating states of the converter are changed corresponding to the change in the power converter's input or output. The converter has six operating states such as:

State I: In this state energy transfers from source to load (V_o) and auxiliary loads (V_{o1}) and the converter act as a One Input and Two Output state.

State II: In this state energy transfers from source to battery, load (V_o) and auxiliary loads (V_{o1}) and the converter act as a One Input and Three Output State.

State III: In this state energy transfers from battery to load (V_o) and auxiliary loads (V_{o1}) and the converter act as a One Input and Two Output State.

State IV: In this state energy transfers from source and battery to traction motor (V_o) and auxiliary loads (V_{o1}) and the converter act as a Two Input and Two Output State.

State V: During regenerative braking, energy transfers from load (V_o) to battery pack and auxiliary loads (V_{o1}) and the converter act as a One Input and Two Output State.

State VI: During regenerative braking, energy transfers from load (V_o) to battery pack and the converter act as a One Input and One Output State.

3.1 Circuit Diagram of Proposed system

The modified structure of the transformer less multi-port buck boost converter is depicted in Figure 3. The converter can deliver energy in both directions as Source to load and vice versa. In this converter Q_1 , Q_2 and Q_3 are three switches as MOSFETs, the main

elements that control the both energy flow and output voltage. In this system, boost converter is in input side and Boost (or) Buck – Boost Converter in output side of the modified structure of multi-port converter. This topology integrates different energy sources such as DC supply and rechargeable lithium ion battery. This topology uses electric traction motor (BLDC motor) as one output and auxiliary loads such as, Light, Heater, Air Conditioner, etc. used in the Electric Vehicle as second output. The converter acts in various states depending on the inputs.

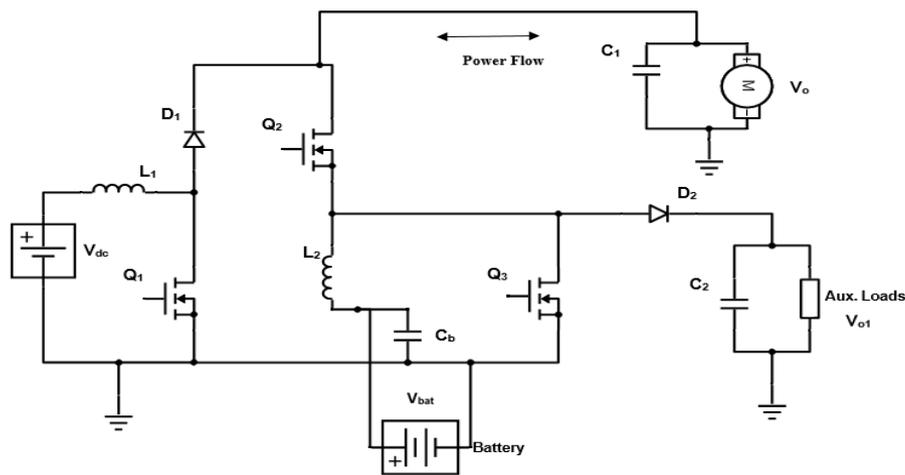


Figure 3. Circuit diagram of proposed system

3.2 Operating States of the Converter

Multi-port converter operation is as follows. Timing diagram of Multi Port converter is shown in Figure 4.

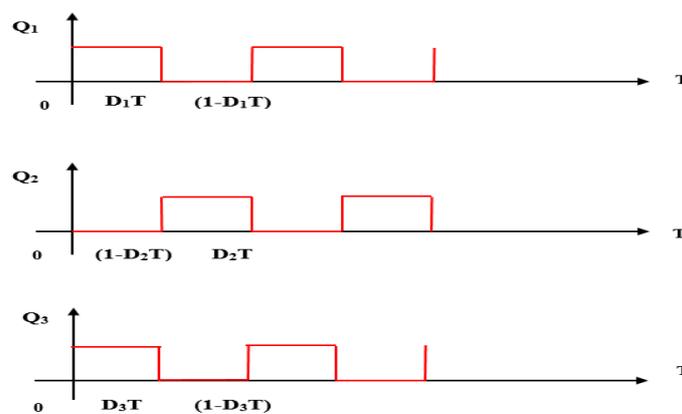


Figure 4. Timing diagram

3.3 State I

In this state, multi port DC to DC Converter function as single input dual output converter. Because converter transfers the power from source (V_{dc}) to two loads such as traction motor (V_o) and auxiliary loads (V_{o1}). During the operating state switches Q_3 and Q_1 are closed and Q_2 is open in interval 0 to D_1T . When $V_{dc} > V_{bat}$, the voltage V_{dc} charges the inductor L_1 . When D_1T to T , Q_3 and Q_1 are open and switch Q_2 is closed. The inductor discharges via diode D_1 . The switch Q_1 is operated in duty cycle (D_1) and the output voltages are operated in same duty cycle (D_1). Steady state output voltage in this state is given by,

$$V_o = \frac{1}{1-D_1} V_{dc}$$

$$V_{o1} = \frac{1}{1-D_1} V_{dc}$$

3.4 State II

In this state, multi port DC to DC Converter function as three output and one input converter. This state operation is similar to state I. In state II, the primary DC source (V_{dc}) serves as the input and the battery (V_{bat}), traction motor (V_o) and auxiliary loads (V_{o1}) are serves as outputs. Q_2 works with $D_2 < 0.5$ the battery gets its charge from input DC supply. Q_1 and Q_3 work with $D_1 > 0.5$ to distribute gained output transversely to the loads. The duty cycle D_1 and D_2 are operated in complimentary manner. For this state voltage equation are as follows,

$$V_o = \frac{1}{1-D_1} V_{dc}$$

$$V_{o1} = D_2 V_{dc}$$

$$V_{bat} = D_2 V_{dc}$$

3.5 State III

In this state, multi port converter function as one input and two output converter. When $V_{dc} < V_{bat}$ battery serves as the input source to the converter (V_{bat}) and traction motor serves as the output and the auxiliary load of converter (V_o), (V_{o1}) respectively. In interval 0 to D_3T , the energy from the battery charges the inductor L_2 . The inductor L_2 current is discharged,

during the interval D_3T to T . By turning on and turning off of switch Q_3 , the boosted voltage appears across traction motor and the auxiliary loads. The switch Q_1 is not taken in account because the switch Q_1 is opened throughout the state. The switch Q_3 is operated in duty cycle (D_3). Both output voltages are operated in duty cycle (D_3). For this state voltage equation are as follows,

$$V_o = \frac{1}{1-D_3} V_{bat}$$

$$V_{o1} = \frac{1}{1-D_3} V_{bat}$$

3.6 State IV

In this state, multi port converter function as dual input dual output DC-DC converter. When $V_{dc} = V_{bat}$, input sources are both primary source (V_{dc}) and battery packs (V_{bat}) and the corresponding output in this state is traction motor (V_o) and the auxiliary loads (V_{o1}). The Q_1 , Q_3 is ON for period of 0 to D_1T . The inductor current I_{L1} and I_{L2} are increased linearly because of charging the inductor. The switch Q_2 operates on and off in complimentary manner. When Q_1 and Q_3 are off, I_{L1} and I_{L2} are decreased. So the gained energy is transferred from both sources to the loads through the diodes D_1 and D_2 . For this state voltage equation are as follows,

$$V_o = \frac{1}{1-D_1} V_{dc} \text{ (or) } V_o = \frac{1}{1-D_3} V_{bat}$$

$$V_{o1} = \frac{1}{1-D_1} V_{dc} \text{ (or) } V_{o1} = \frac{1}{1-D_3} V_{bat}$$

3.7 State V

In this state, multi port converter function as single input dual output DC-DC converter. When $V_{load} > V_{dc}$ then the energy is transferred from the traction motor (V_o) to the battery pack (V_{bat}) so battery is charging and battery transfers power to auxiliary loads (V_{o1}). When regenerative braking occurs then energy stored in motor is fed to the battery pack and it charges the battery pack. During the charging of the battery pack, the switch Q_1 is off throughout the entire state, the Q_3 is ON and the Q_2 is in ON-OFF complimentary condition. For this state voltage equation are as follows,

$$V_{bat} = D_2 V_o$$

$$V_{o1} = D_3 V_o$$

3.8 State VI

In this state, multi port converter functions as one input and one output DC-DC converter. When $V_{load} > V_{dc}$ then the energy is dissipated from the traction motor (V_o) to the battery pack (V_{bat}) only. When regenerative braking occurs then stored energy in the motor feeds to the battery pack and it charges the battery pack. During the charging of the battery pack, the switch Q1 and Q3 is off throughout the entire state and the switch Q2 is permanently on. For this state voltage equations are as follows,

$$V_{bat} = D_2 V_o$$

4. Simulation Results

Figure 5 shows the simulation diagram of a four port bidirectional buck boost converter circuit when implemented in MATLAB Simulink. MOSFET is a power switch. By the signal of pulse width modulation (PWM) power switch is controlled and its frequency is 10 KHz.

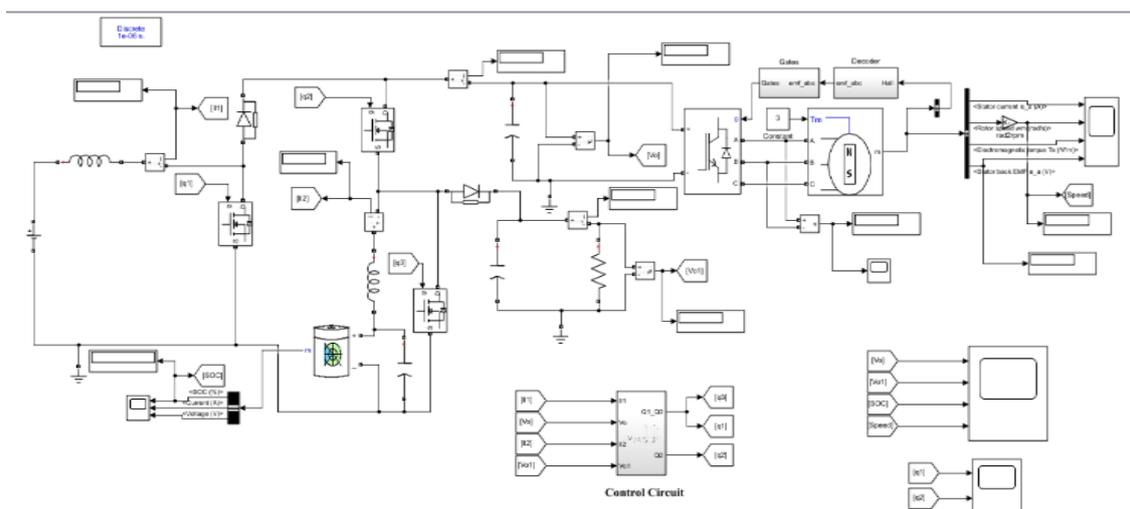


Figure 5. Simulation diagram of proposed converter

The ratings of converter are provided in table 1 to simulate the circuit.

Table 1. Converter ratings

Components	Ratings
Capacitor (C_1 and C_2)	1000 μ F
Inductor (L_1)	1 mH
Inductor (L_2)	120 μ H
Battery (li – ion)	48 V, 7 AH with Initial SOC is 50%

4.1 Control Circuit

The switch MOSFETs (Q_1 , Q_2 , and Q_3) duty cycle is generated by the Proportional Integral (PI) controller. By the comparison of the reference voltages and load voltages (V_o and V_{o1}) the error signal is generated. This error signal is used as references for currents (I_{l1} and I_{l2}). By MATLAB auto tuning method K_p and K_i values are found. The reference signals of Q_1 , Q_2 duty cycle are found from current error. To generate the switching duty cycle for Q_1 and Q_2 , triangle carrier signal with 10 KHz is compared with reference signal. With same duty cycles the Q_1 and Q_3 are simultaneously operated, whereas the switch Q_2 is operated in complimentary manner. So Q_2 duty cycle is generated by using the NOT Gate. Figure 6 shows the converter control circuit. Figure 7 depicts the converter’s switching pulses

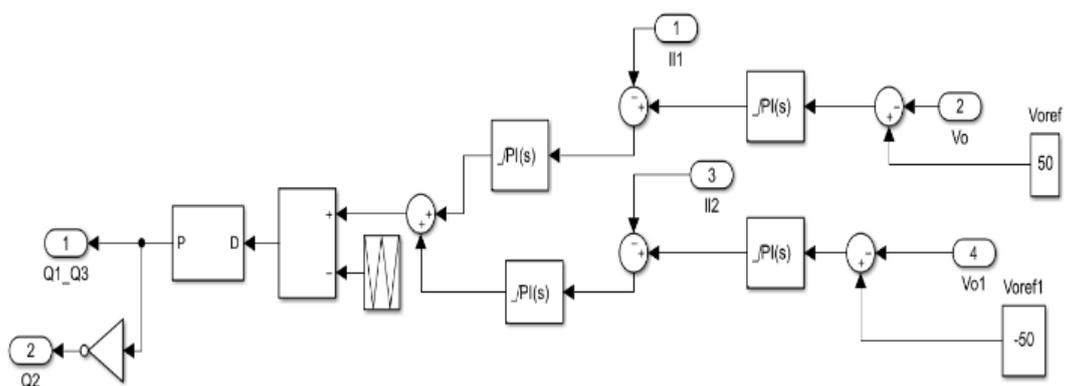


Figure 6. Control circuit of the converter

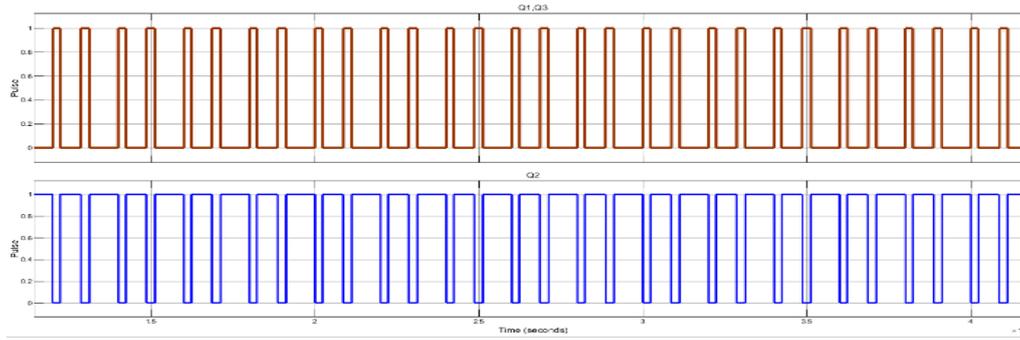


Figure 7. Switching pulse of the converter

4.2 Output for Different States of the Converter

In state I $V_{dc} > V_{bat}$ where ($V_{dc} = 120V$, $V_{bat} = 48 V$) power transfer from source to load (V_o) and auxiliary loads (V_{o1}) and the converter is in single input and dual output State.

State II is similar to state I, so the power transfers from source to both loads and it also charges a battery so the converter is in one input and three output state.

A boosted output is $V_o = 201.7V$, $V_{o1} = 135.5 V$, speed across BLDC motor is 1211 RPM and the increased SOC is 50.001%. The output wave form of State I & II is shown in the figure 8.

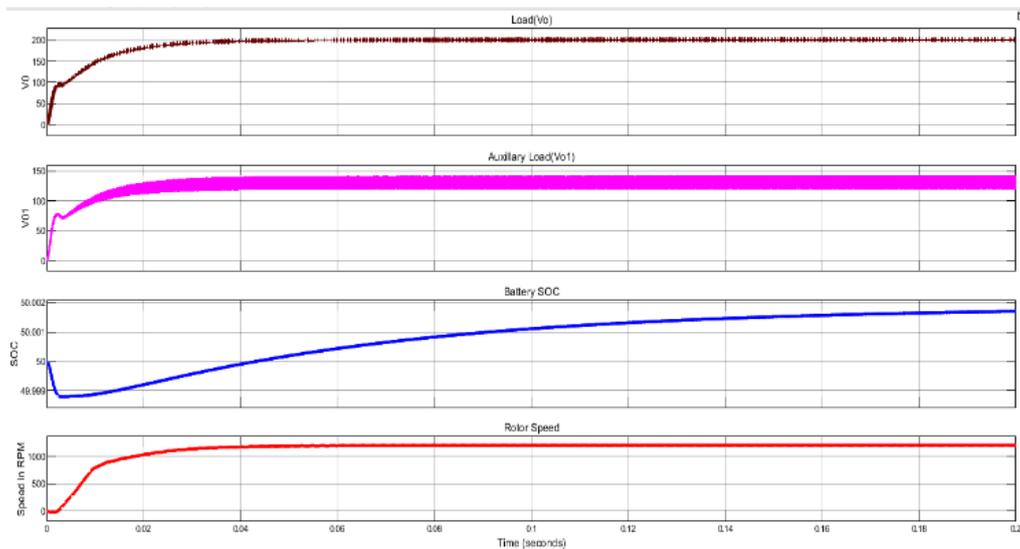


Figure 8. Output wave form of state I & II

When $V_{dc} < V_{bat}$ where ($V_{dc} = 43V$, $V_{bat} = 48 V$) so the energy in battery is delivered to traction motor (V_o) and auxiliary loads (V_{o1}) and the converter act as one input and two

output state. A gained output voltage across $V_o = 54.78$ V, $V_{o1} = 50.94$ V, speed across BLDC motor is 271.2 RPM and SOC is 49.932%. The output wave form of State III is shown in the figure 9.

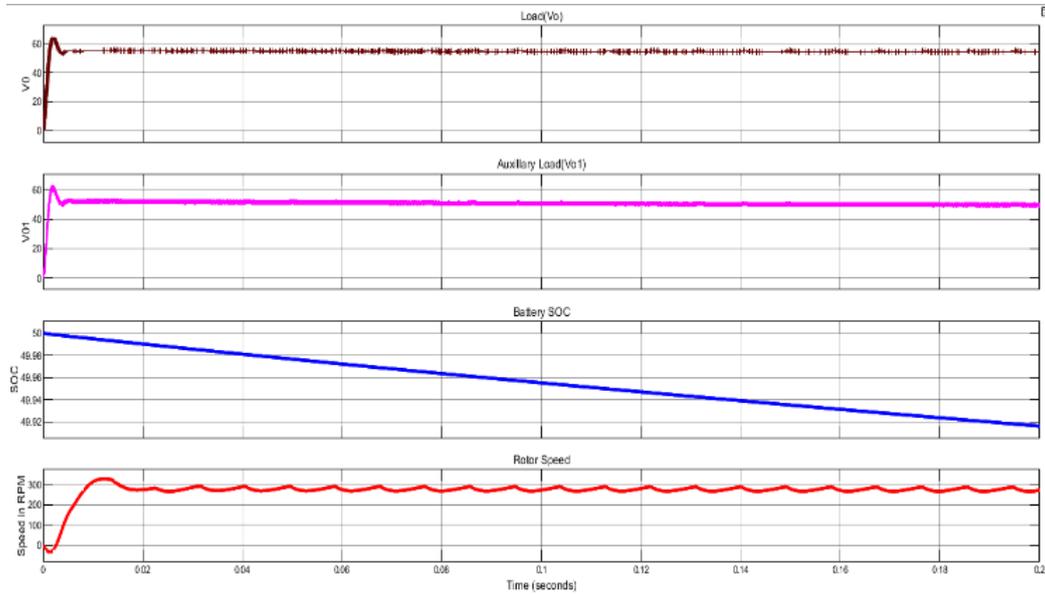


Figure 9. Output waveform of state III

When $V_{dc} = V_{bat}$, where ($V_{dc} = 48$ V, $V_{bat} = 48$ V) in this state primary source (V_{dc}) and battery pack (V_{bat}) transfers energy to the both the loads. This state is used to meet the expected load demand so the converter act as two input and two output state. A simulation output voltage across $V_o = 60.57$ V, $V_{o1} = 54.2$ V, speed across BLDC motor is 304.3 RPM and SOC is 49.93%. The output wave form of State IV is shown in the figure 10.

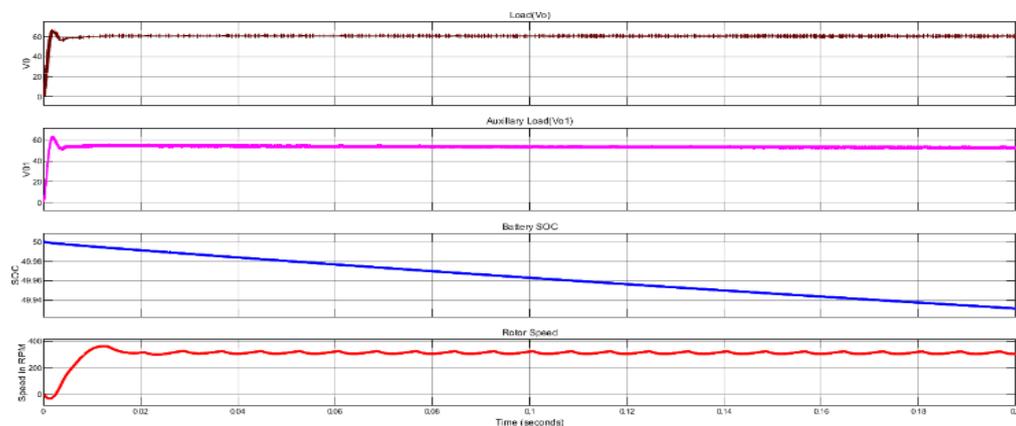


Figure 10. Output waveform of state IV

This state appears when the load power exceeds the input power . This condition occurs during the regenerative braking of motor. In reverse direction motor delivers the power. When $V_{load} > V_{dc}$ where ($V_{dc} = 0V$, $V_{bat} = 10 V$) then energy stored in previous cycle of the motor is recovered and fed back to the battery and battery delivers the power to auxiliary loads (V_{o1}) and the converter act as one input and two output state. A buck output across $V_o = 47.17V$, $V_{o1} = 29.55 V$, speed across BLDC motor is 0 RPM and SOC is 50.002%. The output wave form of State V is shown in the figure 11.

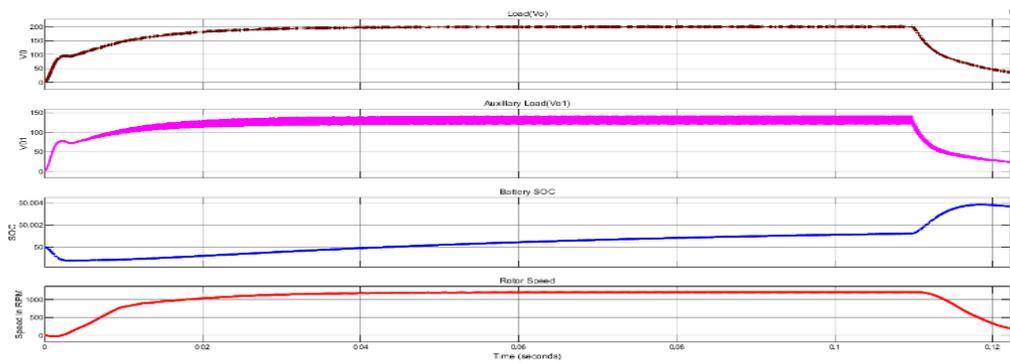


Figure 11. Output waveform of state V

When $V_{load} > V_{dc}$ where ($V_{dc} = 0V$, $V_{bat} = 10 V$) then energy stored in previous cycle of the motor is recovered and fed back to the battery only and the converter act is in input and one output State. A buck output across $V_o = 52.49 V$, $V_{o1} = 301 V$ (Open circuit voltage appears across the auxiliary load), speed across BLDC motor is 0 RPM and in previous state SOC is 50.002% and in this state SOC is increased to 50.06%. The output wave form of State VI is shown in the figure 12.

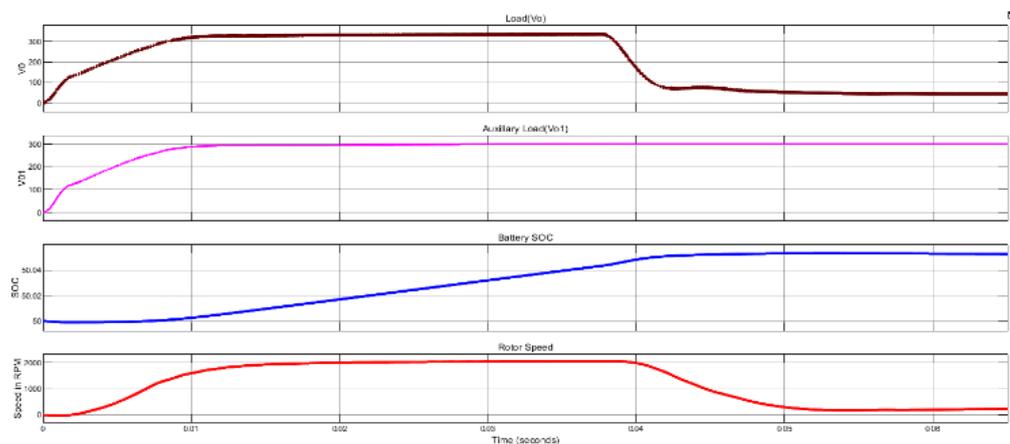


Figure 12. Output waveform of state VI

4.3 Simulation Result in Tabular Column

The table 2 shows the summarized simulation result of the different states of the proposed converter.

Table 2. Simulation result

State	Input	Output status			
		V_o (V)	V_{o1} (V)	Battery SOC in %	Speed in RPM
I & II	$V_{dc} = 120$ V $V_{bat} = 48$ V	201.7	135.5	50.001	1211
III	$V_{dc} = 43$ V $V_{bat} = 48$ V	54.78	50.94	49.932	271.2
IV	$V_{dc} = 48$ V $V_{bat} = 48$ V	60.57	54.2	49.93	304.3
V	$V_{dc} = 0$ V $V_{bat} = 10$ V	47.17	29.55	50.002	0
VI (Without auxiliary load)	$V_{dc} = 0$ V $V_{bat} = 10$ V	52.49	301	50.06	0

4.4 Components Comparison

The table 3 shows the comparison of proposed topology with similar converter topologies. This table shows the advantages of proposed converter in a modified structure with component reduction.

Table 3. Comparison of components

Converters	No. of Switches	No. of Diodes	No. of Passive elements	No. of inputs	No. of outputs
Bidirectional converter [3]	3	3	2	2	1
Three port converter [5]	4	5	3	2	1
Muti Input DC to DC Converter [8]	5	1	4	2	2
Bidirectional DC to DC converter [6]	5	2	3	2	1
Bidirectional converter[7]	5	5	3	1	1
Proposed Converter	3	2	5	2	2

5. Conclusion

The non isolated four port bidirectional converter proposed for applications of EV has the ability to encompass various energy resources such as DC source and Battery of different voltage and current capacity in a one module. The converter with minimum number of components reduces the complexity providing a positive output voltage even without the utilization of transformer. This converter simultaneously operates in various modes such as boost , buck and buck boost with bidirectional power flow.

Based on simulation results, the converter can deliver the boosted voltage from source (either DC Source or Battery) to two outputs (Motor or Auxiliary loads). The converter also has the ability to deliver the power during regenerative braking.

To regulate the output voltage PI controller is designed in this paper.

Different states of converter are validated using MATLAB-SIMULINK.

By the simulation results converter can be used for wide range of electric vehicle applications.

6. Future Scope

To increase the efficiency of the converter, switching loss and conduction loss must be reduced. To reduce this type of losses, converter must be employed with soft switching technique. So further improvement in converter must be dealt with soft switching technique. Thus, the soft switching operation of the converter reduces the hard switching and also improves the overall efficiency of the converter.

For further improvement in control structure, conventional PI controller is modified to the fuzzy logic controller to enhance the performance, robustness and over all stability of the proposed multi-port converter.

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