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Multiport Bidirectional DC-DC Converter for Electric Vehicle

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***Abstract*: Nowadays, dc-dc converter is used as power electronic interface in various application such as electric vehicle. In this project, a multiport dc-dc converter will be designed to interface from renewable energy sources such as solar, energy storage system as battery and ultracapacitor. The main characteristics of this proposed converter is its ability to handle diversified energy sources with different voltage and current characteristics. Then dc-ac converter is used to interface between dc link and traction motor as induction motor. The four-port bidirectional buck boost converter will be designed to create an interface between source and load in a single stage conversion. This proposed single stage converter can be operated in buck, boost and buck-boost mode. This is a 3:1 dc-dc converter which has three source namely solar, battery and supercapacitor and output load will be traction motor. The amount of power flow between the input and the output can be controlled by adjusting the duty cycle of the dc-dc converter.**

***Keywords*: Bidirectional, converter, energy storage system, Single stage conversion, traction motor, ultracapacitor.**

1. Introduction

The Automotive Vehicles which use electric energy to power their traction system partially or completely fall under the category of Electric Vehicle. Based on the type of traction system electric vehicles are further divided into many types. These vehicular applications (i.e., in EV) require power electronic converters to transfer electrical power from various types of sources to the traction system. In this paper, a modular four port bidirectional buck boost converter is designed for integrating various energy sources such as battery, supercapacitor and a PV source. Then the output of this bidirectional converter is fed into the three-phase inverter to convert the dc power into ac and then to get a smooth sinusoidal curve, a LC filter is applied so the load which is a traction motor can run at stable speeds without any distortion. The independent converter with energy source either connected in parallel or series. If the conductor connected in series, then it has to conduct the same current and if the converter is in parallel then it has to be in same voltage level. These two conditions are practically not desirable. But the MISO (Multi input single output) is appreciable because it is more cost effective with high efficiency. The proposed converter can be operated in various mode like single input dual output (SIDO), dual input single output (DISO) and also as single input tri output (SITO).

Thus, it is proficient in transferring power from diversified source to load either individually or simultaneously. The compact structure with reduced component improves the reliability of the converter.

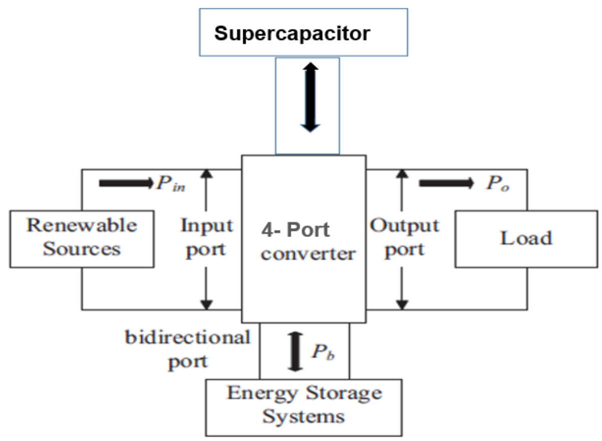


Fig. 1. Proposed Bidirectional 4-Port Converter Diagram

2. Simulation Design

A. Simulation of 4-Port Bidirectional Buck Boost converter

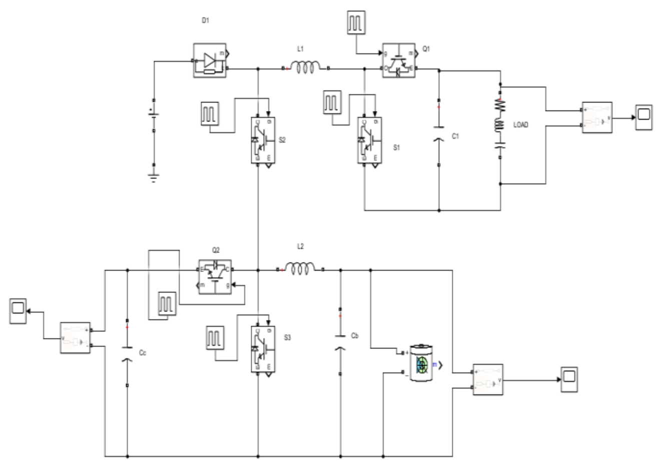
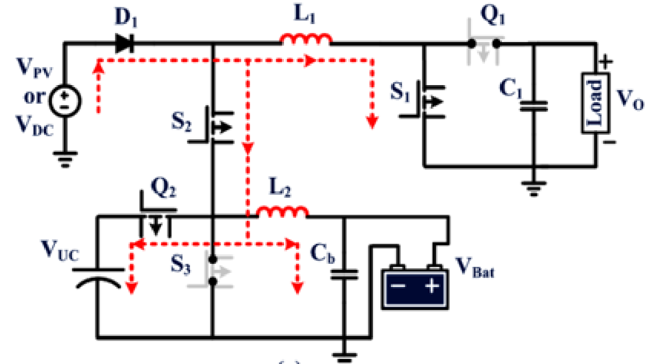


Fig. 2. Circuit design of 4-Port Bidirectional Buck boost converter

The functional diagram of the electric vehicle system in fig 2

*Corresponding author: sallugail1999@gmail.com consist of PV panel, battery backup, ultracapacitor and a dc-dc multiport converter interfaced with the power-inverter drive system. In this proposed four port converter, PV is the main renewable energy source, battery and ultracapacitor act as a



(a)

energy storage system which can store energy via charging and also during regenerative braking and can provide extra energy during acceleration. This multiport converter consists of two inductors L_1, L_2 , two capacitors C_1, C_b, five switches $S_1, S_2, S_3, Q_1 Q_2$ and one diode. $S_1, S_2, S_3, Q_1 Q_2$ are operated with proper selection of duty cycles (*d1, d2, d3, d11, d22*). In this proposed topology, input sources with different magnitude power the load individually or simultaneously. When PV fails to power the load, then battery and ultracapacitor can supply the load and thus reliability improves. The operation of this proposed converter is categorized in four different cases:

CASE 1: - (SITO) when PV is supplying power to the load (battery, capacitor is charging.

Mode (a) (0<t<to): - In this mode the switches S_1, S_2 , D_1 are ON and S_3 is turned OFF then $Q_1$is OFF andQ_2 is ON. L1 and L2 are charging and Cb and Ccap is discharging mode.

Mode (b) (to<t<t1): -In this mode the switches S_1, S_2 are OFF and , D_1 is also OFF and S_3 is turned ON, then Q_1 and Q_2 is ON. L1 and L2 are discharging and Cb and Ccap is charging mode.

CASE 2: - (SIDO) when battery is supplying power to the load, capacitor is charging.

Mode (c) :-(0<t<to) In this mode the switches S_1, S_2, S_3 are ON, , D_1 are OFF then Q_1 and Q_2 is ON. . L1 and L2 are charging and Cb is discharging and Ccap is charging.

Mode (d): - (to<t<t1) In this mode the S_1 is OFF, S_2 is ON and S_3 is OFF, then Q_1 and Q_2 is ON. L1 and L2 are discharging and Cb is discharging and Ccap is charging.

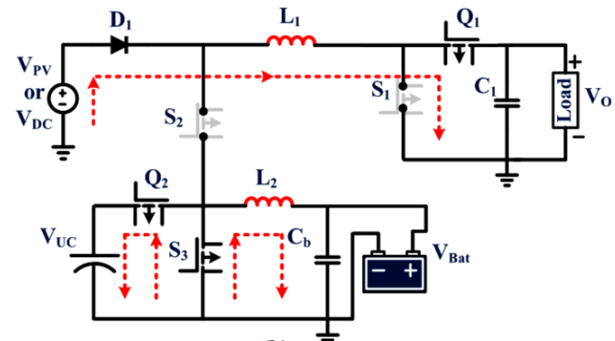
CASE 3: - (SIDO) when ultracapacitor is supplying power to the load, battery is charging.

Mode (e): - (0<t<to) In this mode S_1, S_2 are ON and S_3 are OFF, , D_1 are OFF then Q_1 and Q_2 is OFF. L1 and L2 are charging and Cb is charging and Ccap is discharging.

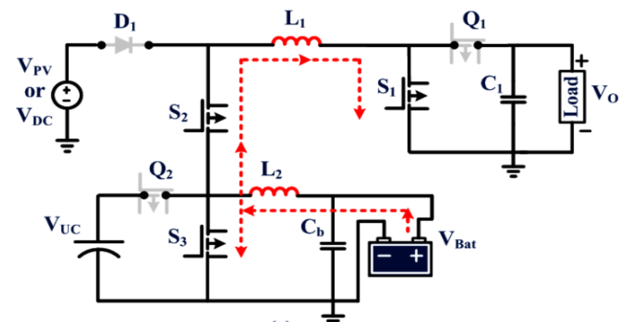
Mode (f): - (to<t<t1) In this mode S_1 is OFF, S_2 are ON and S_3 are OFF, , D_1 are OFF then Q_1 is OFF and Q_2 is ON. L1 and L2 are charging and Cb is charging and Ccap is discharging.

CASE 4: - (SIDO) when load is supplying power to the battery and capacitor.

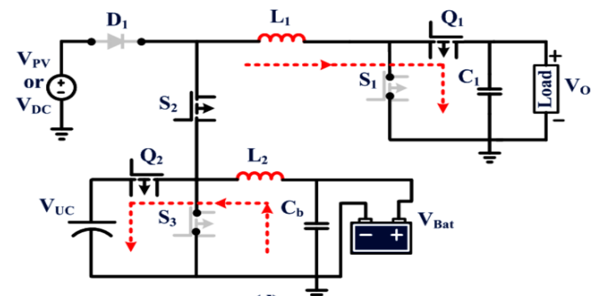
Mode (g) (0<t<to) - In this mode the switches S_1, S_2 is ON , D_1 are OFF, then Q_1 and Q_2 is ON. L1 and L2 are charging and Cb and Ccap is charging mode.



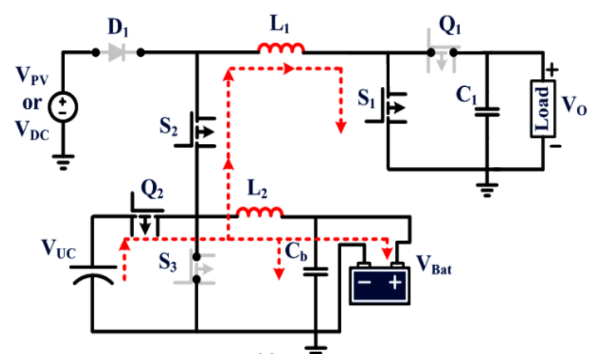
(b)



(c)



(d)



(e)

Mode (h) (to<t<t1): - In this mode the switches S_1 is OFF, S_2 is OFF and S_3 is turned ON, thenQ_1 is ON and Q_2 is OFF. L1 and L2 are discharging and Cb, Ccap is charging.

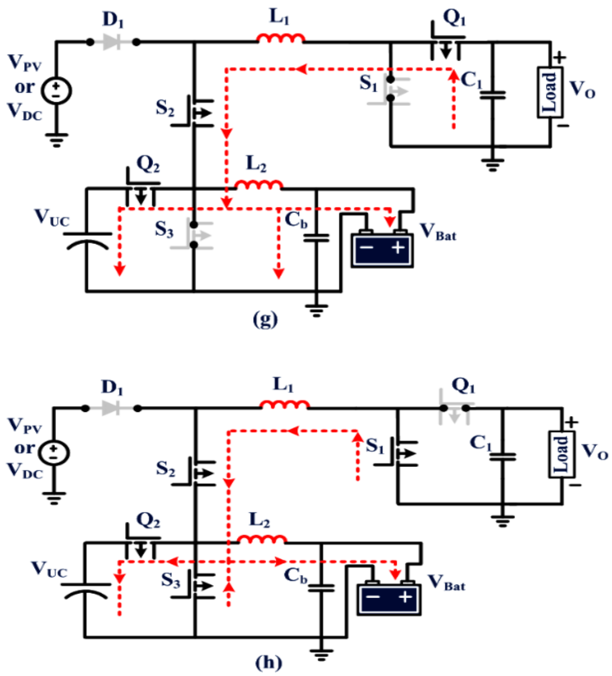
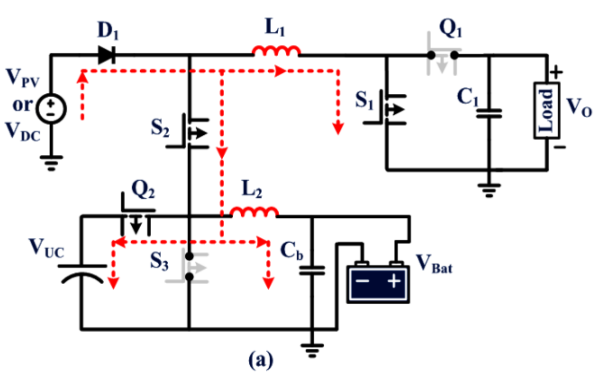


Fig 3. Operation of FPB[3]C, (1) Case 1 [Mode (a) and Mode (b)], (2) Case 2 [Mode (c) and Mode (d)], (3) Case 3 [Mode (e) and Mode (f)], (4) Case 4 [Mode (g) and Mode (h)].

From the above operating principle of four port converter, switching sequence are shown below for different cases of motion of electric vehicle.

Table 1
Converter Switching Sequence Table

Motion Type	S1	Q1	S2	Q2	S3	D1
Vpv>Vbat,Vc	ON	OFF	ON	ON	OFF	ON
Uniform	OFF	ON	OFF	ON	ON	ON
Vbat>Vc,Vpv	ON	OFF	ON	OFF	ON	OFF
Uniform	OFF	ON	ON	ON	OFF	OFF
Vc>Vbat,Vpv	ON	OFF	ON	ON	OFF	OFF
Uniform	OFF	ON	ON	OFF	ON	OFF
Vo>Vbat&Vc	ON	ON	ON	ON	OFF	OFF
Braking	OFF	OFF	ON	ON	ON	OFF
Vpv=Vbat>Vc	OFF	ON	ON	OFF	OFF	OFF
acceleration	OFF	ON	ON	ON	OFF	OFF



3. Mathematical modelling and Steady State Analysis for the 4 - Port 3:1 bidirectional dc-dc converter

In the proposed topology of four port bidirectional buck boost converter, the analyzation is done for four cases in which input source of equal and unequal magnitude will deliver power to the load. The amount of power flow will depend on duty cycle of the proposed converter. The steady state analysis will give the magnitude of output voltage for particular input source and it will also provide the state of the converter like whether it is buck, boost or buck-boost. The steady state analysis is done to compare the output voltage between the simulation results and theoretical result. The state of the proposed converter for each case will show the motion of the electric vehicle. We have already consider four cases and these are: -

CASE 1: - when only PV is available (battery and super capacitor charging) – Uniform motion.
CASE 2: - when only battery is discharging and supercapacitor charging- Uniform motion.
CASE 3: - When only supercapacitor charging, battery discharging- Uniform motion.
The following parameter of the equivalent circuit of four port converter are: -

$V_{PV.}$= pv cell voltage	V_{S2}= Voltage across switch S2
V_{bat}= battery voltage	V_{S3}= voltage across switch S3
V_{uc}= ultracapacitor voltage	V_{Q1}= voltage across switch Q1
$V_{o\,.}$= output voltage	V_{Q2}= voltage across switch Q2
$V_{D1.}$= diode voltage	d1= duty cycle of switch S1
V_{L1}= inductor L1 voltage	d2=duty cycle of switch S2
V_{L2}= inductor L2 voltage	d3= duty cycle of switch S3
$V_{c1.}$= capacitor C1 voltage	d4= duty cycle of switch S4
$V_{cb\,.}$= battery capacitor voltage	d11= duty cycle of Q1
V_{S1} = Voltage across switch S1	d22= duty cycle of Q2

1) Analysis for Case 1 – PV is supplying Power to the Load

We have categorized in two modes to get the correct result of analysis so below analysis is done for mode a and mode b from fig.3a and 3b.

Mode a: - $S_{1.}S_{2.}$ **ON,** S_3 **OFF**

From fig 2.6a, by applying KVL equation in loop 1

$$V_{PV.} - V_{D1.} - V_{L1} - V_{S1} = 0 \qquad (i)$$

Now as we have considered the ideal case the voltage drops due D1 and S1 are taken as negligible, So the above equation can be written as

$$V_{PV.}=V_{L1} \qquad \text{(ii)}$$

From loop 2

$$V_{o\,.} = V_{c1\,.} \qquad \text{(iii)}$$

From loop 3

$$V_{PV.} - V_{D1.} - V_{S2} - V_{L2} - V_{bat} = 0 \qquad \text{(iv)}$$

Again similarly, $V_{D1.} = V_{S2} = 0$ (ideal cases), so the above equation can be written as

$$V_{L2} = V_{bat} - V_{pv} \qquad \text{(v)}$$

Mode b: - $S_{1.}S_{2.}$**- OFF,** S_3 **ON**

From the fig 2.6b, by applying KVL equation in loop 1

$$V_{PV.} - V_{D1.} - V_{L1} - V_{Q1} - V_{c1} = 0 \qquad \text{(i)}$$

Similarly, again, $V_{D1.} = V_{Q1} = 0$(ideal case)

$V_{PV.} - V_{L1} - V_{c1} = 0$ (ii)

From loop 2

$V_{o\,.} = V_{c1\,.}$ (iii)

From loop 3

$V_{bat} = V_{L2}$ (iv)

Now by applying voltage second balance equation,

Boost output can be obtained by switch S1 is closed and open,

$V_{L1}\text{Ton} + V_{L1}Toff = 0$

$V_{L1}\ d1\ Ts + V_{L1}(1 - \text{d1})\text{Ts} = 0$

$V_{PV.}d1\ Ts + (V_{pv} - V_{o\,.})\ (1 - \text{d1})\text{Ts} = 0$

$$\boldsymbol{V_{o\,.}} = \frac{\boldsymbol{V_{PV.}}}{(\boldsymbol{1 - d1})}$$

Again, by applying Voltage second balance equation,

Buck output can be obtained by S2 is closed and open $V_{L2}\text{Ton} + V_{L2}Toff = 0 V_{L2}d2Ts + V_{L2}(1 - \text{d2})\text{Ts} = 0$

$(V_{bat} - V_{pv})\ d2\ Ts + V_{bat}(1 - \text{d2})\text{Ts} = 0$

$$\boldsymbol{V_{bat} = d2\ V_{pv}}$$

2) Analysis For Case 2 – Battery is supplying Power to Load

In case 2, battery is supplying power to the load and PV is not available and supercapacitor is in charging mode. To analyze this case mode c and mode d are consider from fig 3c and 3d.

Mode c: - S1, S2on, Q1off, Q2off, S3on

From fig6c, by applying KVL in loop 1

$V_{bat.} - V_{L2.} - V_{S2} - V_{L1} - V_{S1-}V_{C1.} = 0$ (i)

Again, as for ideal cases voltage drop across S1 and S2 is negligible, so the equation become

$V_{bat.} - V_{L2.} - V_{L1} - V_{C1.} = 0$ (ii)

From loop 2

$V_{o\,.} = V_{c1\,.}$ (iii)

From loop 3,

$V_{bat.} - V_{L2.} - V_{S3} = 0$ (iv)

Again, for ideal case voltage across S3 is negligible, so the equation become

$V_{bat.} = V_{L2.}$ (v)

Mode d: -) S1off, S2off, Q1on, Q2on S3on

From fig2.6d, by applying KVL,

$V_{bat.} + V_{L2.} - V_{S2} + V_{L1} - V_{Q1-}V_{C1.} = 0$ (i)

Similarly, for ideal case voltage drop across S2 and Q1 is negligible, so the equation become,

$V_{bat.} + V_{L2.} - V_{L1} - V_{C1.} = 0$ (ii)

From loop 2

$V_{o\,.} = V_{c1\,.}$ (iii)

From loop 3,

$V_{bat.} - V_{L2} - V_{Q2-.}V_{UC.} = 0$ (iv)

Similarly for ideal case voltage across Q2 is negligible, so the equation become

$V_{L2} = V_{bat.} - V_{UC.}$ (v)

By using voltage second balance equation, the boosted output can be written by considering both the modes as switch S1 is closed and open,

$V_{L1}\text{Ton} + V_{L1}Toff = 0$

$V_{L1}\ d1\ Ts + V_{L1}(1 - \text{d1})\text{Ts} = 0$

$-V_{o.}d1\ Ts + (V_o - V_{bat\,.})\ (1 - \text{d1})\text{Ts} = 0$

$$\boldsymbol{V_{o\,.}} = \frac{\boldsymbol{V_{bat.}}}{(\boldsymbol{1 - d1})}$$

Again, by applying voltage second balance equation,

The boosted output can be written by considering both the modes as switch S3 is closed and open

$V_{L2}\text{Ton} + V_{L2}Toff = 0$

$V_{L2}d3Ts + V_{L2}(1 - \text{d3})\text{Ts} = 0$

$V_{bat}\ d3\ Ts + (V_{bat} - V_{uc})(1 - \text{d2})\text{Ts} = 0$

$$\boldsymbol{V_{uc\,.}} = \frac{\boldsymbol{V_{bat.}}}{(\boldsymbol{1 - d3})}$$

3) Analysis for case 3 – Ultracapacitor is supplying power to Load and Battery is in charging mode.

In this case also there are two mode of conduction from fig 3e and 3f .In this case PV is not available and ultra-capacitor is supplying power to the load and battery is also in charging mode.

Mode e: - S1on, S2on, Q1off, Q2on S3off

From the analysis of previous two cases, in this case also we have applied KVL in circuit of fig 2.6e and from different loops of circuit we got the following equation by considering as ideal case,

$V_{L2} = V_{uc.} - V_{bat.}$ (i)

$V_{o\,.} = V_{c1\,.}$ (ii)

$V_{L1} = V_{uc.} - V_{bat.}$ (iii)

Mode f: - S1off, S2on, Q1on, Q2off, S3on

$V_{o\,.} = -V_{L1\,.}$ (i)

$V_{o\,.} = V_{c1\,.}$ (ii)

$V_{bat\,.} = -V_{L2\,.}$ (iii)

By using voltage second balance equation,

The buck output can be written by considering both the modes as switch S1 is closed and open

$V_{L1}\text{Ton} + V_{L1}Toff = 0$

$V_{L1}\ d1\ Ts + V_{L1}(1 - \text{d1})\text{Ts} = 0$

$(V_{uc.} - V_{o\,.})d1\ Ts + (-V_{o\,.})\ (1 - \text{d1})\text{Ts} = 0$

Table 2
Steady state analysis Result of 4-Port converter

CASES OF CONVERTER	MODE	STEADY STATE OUTPUT	CONVERTER STATE
VPV>Vbat,Vc	A & B	$V_{o\,.} = \frac{V_{PV.}}{(1-d1)}$, $V_{bat} = d2\ V_{pv}$, $V_{uc} = d2\ V_{pv}$	Boost &buck
Vbat>Vc,Vo	C & D	$V_{o\,.} = \frac{V_{bat.}}{(1-d1)}$, $V_{uc\,.} = \frac{V_{bat.}}{(1-d3)}$	boost
Vc>Vbat,Vo	E & F	$V_{o\,.} = d1\ V_{uc}$, $V_{bat\,.} = d22\ V_{uc}$	buck

$$\boldsymbol{V_{o\,.} = d1\ V_{uc}}$$

The buck output can be written by considering both the modes as switch Q2 is closed and open. By applying voltage second balance equation.

$V_{L2}\text{Ton} + V_{L2}Toff = 0$

$V_{L2}\ d22\ Ts + V_{L2}(1 - \text{d22})\text{Ts} = 0$

$(V_{uc.} - V_{bat\,.})\ d22\ Ts + (-V_{bat\,.})\ (1 - \text{d22})\text{Ts} = 0$

$\boldsymbol{V_{bat\,.} = d22\ V_{uc}}$

4) Summary of Steady State Analysis

By analyzing different cases of motion of electric vehicle according to the operating principle of proposed 4-port converter, we got the state of converter for each case of motion of electric vehicle like whether the converter is buck, boost or buck boost for motion like uniform, braking and acceleration. In the below table the brief of the result of steady state analysis are shown.

4. Simulation results of the proposed 4-port converter

The proposed four port bidirectional buck boost converter are simulated for different magnitude of input sources and provide the power flow to the load. This proposed converter is used to provide multiple sources to fulfil the load demand according to the motional case of electric vehicle

1) Simulation results for Case 1

In this case PV is supplying power to the load, battery and supercapacitor and battery and supercapacitor is in charging mode and this is the case for uniform motion.

In this case there are single input source i.e., PV and three outputs i.e., load, battery and supercapacitor.

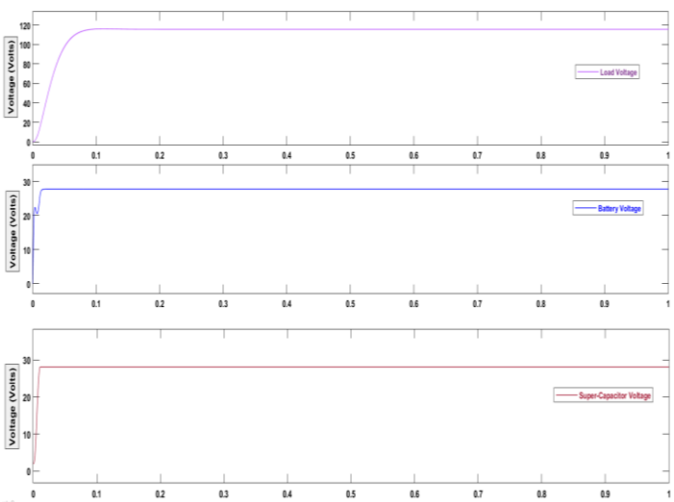


Fig. 4. Graphical output of 4-Port converter for case 1

Here, input voltage i.e., Vpv we have given as 35V, load voltage is boosted to 115V in this waveform and battery and capacitor is in charging mode, so for them the output is buck and output voltage for battery and supercapacitor is 28V.So here only single source is supplying power to the load and boosted output shows that the electric vehicle is in uniform motion.

2) Simulation result for Case 2

In this case PV power is not available, so battery is supplying power to the load as a storage energy. Here supercapacitor is in charging mode. This is also the case of uniform motion and here there is single input i.e., battery and dual output i.e., supercapacitor and load, so it is a case for SIDO,

Table 3
Summary of Simulation Results

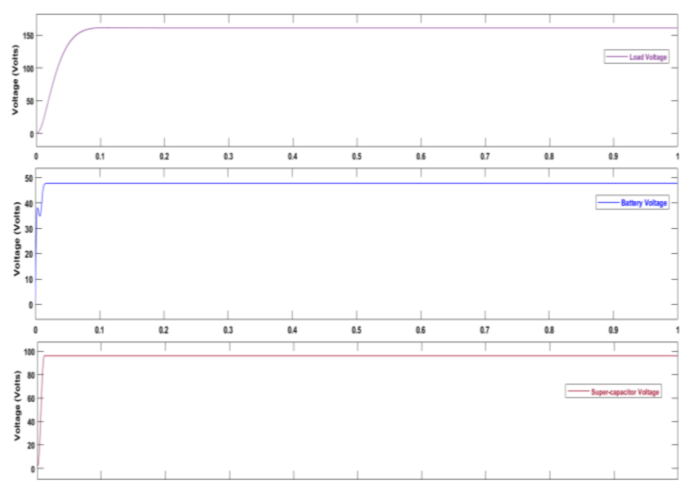
CASES	CONVERTER OUTPUT VOLTAGE
(VPV>Vbat, Vuc, Vo).	Vo= 115V, Vbat=28V
(Vbat>Vuc, Vo)	Vo=155V,Vuc=92V
(Vc>Vbat,Vo)	Vo=40V,Vbat=30V

Fig. 5. Graphical output of 4-Port converter for case 2

For this case in fig 4.5 the input voltage i.e., Vbat we have given as 48V, the load voltage is boosted to 155V in this waveform and here battery is in discharging mode and supercapacitor is in charging mode, so for capacitor it is boosted to 95V. In this case also single input is given and the output is boosted output so this shows that electric vehicle can run in uniform motion.

3) Simulation results for Case 3

In this case PV power is not available, so supercapacitor is supplying power to the load as a storage energy. Here supercapacitor is in discharging mode and battery is in charging mode. This is also the case of uniform motion but with reduced speed and here there is single input i.e. supercapacitor and dual output i.e. battery and load, so it is a case for SIDO (single input dual output).



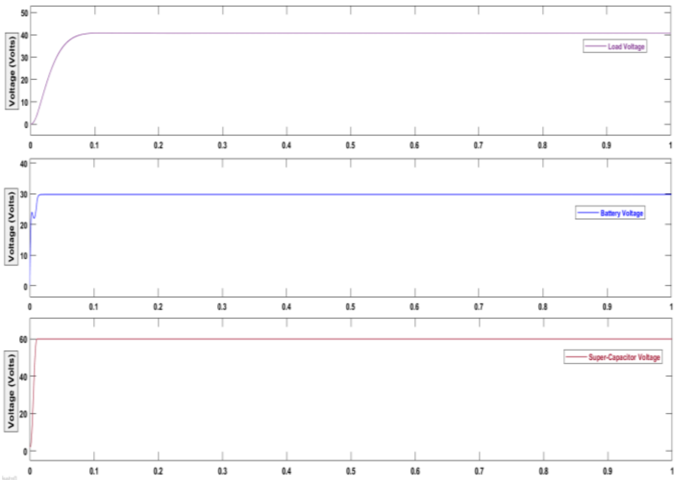


Fig. 6. Graphical output of 4-Port converter for case 3

For this case in fig4.8 the input voltage i.e., Vuc we have given as 60V, the load voltage is buck to 40V in this waveform and here battery is in charging mode and supercapacitor is in discharging mode but battery is stepped down to 30V. In this case also single input is given but the output is step down so this shows that electric vehicle can run in uniform motion but with reduced speed.

5. Theoretical results of Proposed 4-Port converter

To verify this simulation results, theoretical analysis is done for converter, inverter and converter with inverter fed induction motor. For this comparison, the parameter are assumed to be same in simulation and also in theoretical implementation as :

d1 (duty cycle of S1) = 70%	d11 (duty cycle of Q1) =50%
d2 (duty cycle of S2) = 70%	d22 (duty cycle of Q2) =50%
d3 (duty cycle of S3) =50%	Vbat=48
VPV= 35V	Vuc=60V

1) Case 1: - VPV>Vbat, Vc, Vo

In this case VPV is input voltage = 35V.and from steady state analysis we derive the results for Vo, Vbat and Vuc in table 3,$\boldsymbol{V_{o.}} = \frac{\boldsymbol{V_{PV.}}}{(\boldsymbol{1-d1})}$ (Boosted results in output) from this result, from we got the theoretical value of load voltage i.e., Vo= 116.67 V.

Again, for Vbat and Vuc the buck result is $\boldsymbol{V_{bat} = d2\ V_{pv}}$, from this we got the theoretical value of battery voltage and supercapacitor voltage as 25V.As this is the case for SITO, there are three output result, Vo=116.67V(BOOSTED)

Vbat &Vuc= 25V (BUCK)

2) Case 2: - Vbat>Vuc, Vo

In this case Vbat is input voltage = 48V and from steady state analysis we derive the results for Vo and Vuc in table 3, $\boldsymbol{V_{o.}} = \frac{\boldsymbol{V_{bat}}}{(\boldsymbol{1-d1})}$(boosted results in load). From this result, from we got the theoretical value of load voltage i.e., Vo= 160 V.

Again, for Vuc, the boost result is$\boldsymbol{V_{uc.}} = \frac{\boldsymbol{V_{bat.}}}{(\boldsymbol{1-d3})}$, from this we got the theoretical value of supercapacitor voltage as 96V. As this is the case for SIDO, there are two output result,

Vo=160V (BOOSTED)

Vuc= 96V (BOOSTED)

3) Case 3: - Vuc>Vbat, Vo

In this case Vbat is input voltage = 48V and from steady state analysis we derive the results for Vo and Vuc in table 3, $\boldsymbol{V_{o.}} = \frac{\boldsymbol{V_{bat}}}{(\boldsymbol{1-d1})}$(boosted results in load). From this result, from we got the theoretical value of load voltage i.e., Vo= 160 V.

Again, for Vuc, the boost result is$\boldsymbol{V_{uc.}} = \frac{\boldsymbol{V_{bat.}}}{(\boldsymbol{1-d3})}$, from this we got the theoretical value of supercapacitor voltage as 96V. As this is the case for SIDO, there are two output result,

Vo=160V (BOOSTED)

Vuc= 96V (BOOSTED)

6. Conclusion

In this paper, we have proposed and analyzed a Four-Port bidirectional Converter along with the steady state analysis and simulation results. This converter has a smaller number of power electronic components and thus reduced cost along with increased efficiency. The proposed converter is also robust and capable to power the traction system in the event that any of the source fails to power. The proposed converter does not have any transformer and even then is able to perform step-up and step-down voltage operations without using any additional power electronic components. Further in this paper the steady state analysis of proposed converter is done and the comparison of steady state result and simulation results are also done to get the verification. The developed converter gives better results than conventional buck boost converter. The various operating condition of the proposed four port converter are analyzed by simulation in MATLAB Simulink software and it is verified by mathematical analysis of steady state result. As required by the electric vehicle, the converter configuration can be extended suitably to N – number of inputs along with M – number of outputs and can be applicable for dc grid design.

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