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# Integrated Bidirectional DC-DC converter for EV charger with G2V, V2G and V2H capabilities

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**Abstract**: The importance of Electric vehicles are increasing as they will form major sustainable transportation system in near future with less environmental pollution, fuel economy and energy efficiency. Bi-directional chargers adds the benefit of EVs by enabling energy transfer from vehicle to grid (V2G) or vehicle to home (V2H) in addition to charging from grid to vehicle(G2V). Typically, Bidirectional chargers consists of a AC-DC stage followed by DC-DC stage. This paper presents a non-isolated integrated bi-directional DC-DC converter for interfacing the vehicle battery to the DC link in both charging modes and discharging modes. The DC-DC converter is formed by integrating buck and boost converters and thus it is able to operate in buck as well as boost modes in both direction (charging and discharging). During charging (G2V) the dc link voltage is stepped down by the DC-DC converter to battery voltage and provides required charging current by current control. This is buck operation during charging. During V2G or V2H operation the function of the DC-DC converter is to boost the battery voltage to provide the dc link voltage. As it can also operate in boost mode in charging direction, the converter can charge the battery from a low voltage DC source such as photovoltaic panels by providing it directly to dc stage of the charger.

**Keywords**: Bidirectional dc-dc converter, Electric vehicle charger, Vehicle to Grid (V2G), Vehicle to Home (V2H).

## I. INTRODUCTION

Electric Vehicles are best candidates for future's transportation needs. Their importance is increasing in the present world as they rise up as a solution to the issues like depleting fossil fuels and greenhouse gas emission. Besides the environmental concerns EVs provide fuel economy and convenience in refuelling as it can be done from home itself [1]. But as the number of EVs on road increase, they will increase the burden on the electricity grid. But on the other hand EVs can be considered as 'mobile power banks' since they store considerable amount of energy in them and that can be used to benefit the grid. An efficient charger system is a key component for electric vehicle. Broadly the EV chargers can be classified into conductive and inductive based on power transfer method. Also they are classified into unidirectional chargers and bi-directional chargers based on power transfer direction. Based on the power level capacity the chargers are grouped into three levels- level 1, level 2 and level 3 as shown in table 1. Usually single-phase solutions are used for Levels 1 and 2. Level 3 and DC charging is used for commercial and public applications like public recharge stations. Stations for public use are likely to use Level 2 or 3 chargers installed in parking lots, shopping centres, hotels, rest stops, theatres, restaurants, etc. and use three phase supply from grid. But public charging points have to address wide battery range [2]. Typically an EV charger consists of two converters- a power factor corrected AC-DC converter which is followed by DC-DC converter for interfacing the battery. But generally such converters are unidirectional in nature so they operate only in G2V charging mode. In order to

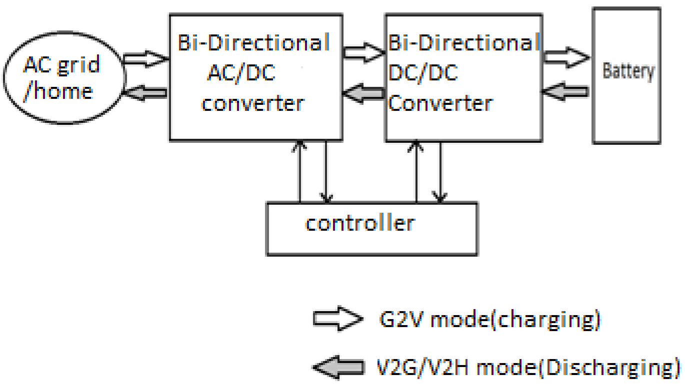


Fig. 1 Typical Bi-directional charger for electric vehicle-Block diagram

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Enable V2G and V2H technologies the converter must be bi-directional with sufficient power rating. In V2G technology the energy stored in vehicle battery is delivered to grid where as in V2H mode the converter supplies the home loads. In these modes the vehicle is operated as a generating unit. But V2G mode requires extensive control and co-ordination between the customer and utility. In future it is expected to be used in coordination with renewable energy microgrids and smart grid technology. In addition to active power support V2G technology provide a wide scope of applications like reactive power support and active filtering [3]-[6].

This paper presents an integrated bidirectional DC-DC converter which is a candidate for bidirectional DC-DC stage of the EV charger. The converter has buck as well as boost capability in both charging and discharging directions. The DC link voltage is taken as higher than battery voltage. So during charging operation the converter does buck operation with constant current. During V2G/V2H mode the battery voltage is boosted to DC link voltage with required power. Since the converter has ability to perform boost operation also in charging direction, the battery can be charged from low voltage DC supplies such as solar power with sufficient power capacity.

TABLE I: CHARGER POWER LEVELS

| **Power Level Types** | **Typical Usage sites** | **Power Level** | **Charging Time** |
|---|---|---|---|
| Level 1 230V AC | Home office | 1.4-1.9kW (12A-20A) | 4-36 hours |
| Level 2 415VAC | Private or public outlet | 4-19.2kW (17-80A) | 1-6 hours |
| Level 3(fast) (200-600V AC/DC) | Commercial Filling stations | 50kW-100kW | 0.4-1 hours |

## II. CONVERTER TOPOLOGY AND OPERATING MODES

*A.* Converter topology

The DC-DC converter in electric vehicle charger interfaces the DC link and the battery. Either isolated converters or non-isolated converters are used for this purpose. But isolated converters increase the weight, complexity and cost of the system. Non isolated converters must be provided with proper protection means since there is no isolation. The converter must be able to operate in buck and boost modes as per the system operation. In a bidirectional charger system, the converter must also have bidirectional capability. Buck boost converters are simple and reliable but they don't have bidirectional operation. A conventional two quadrant converter can operate in buck mode in one direction and boost in the other but vice versa is not possible [7]. Dual active bridge converters require transformer and hence has the disadvantages mentioned above. Also some topologies require a number of inductors and PWM switching which increases the complexity and cost. A detailed review of bidirectional converter topologies is given in [8]. The DC-DC converter presented here can operate in 4 modes and with minimum inductors and capacitors. Besides, it has simplicity that at a time only one switch operates in PWM scheme whereas the others are in either completely off state or on state [9]. Fig 2 shows the circuit diagram of the converter. The

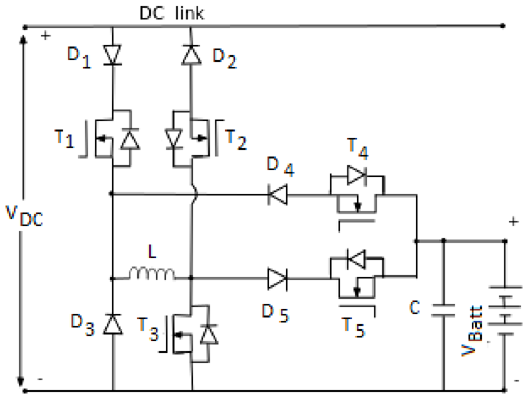


Fig. 2 Integrated Bi-directional buck-boost converter circuit diagram converter consists of 5 switches and 5 diodes and the inductor L and capacitors C.

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*B.* Operation modes of the converter

Since the converter is able to do buck and boost operation in both directions there can be 4 modes of operation. In the charger system the battery voltage is assumed to be of lower voltage than the DC link voltage (rectified AC voltage) and since power factor correction is used this DC link voltage will be usually higher than the peak of ac grid voltage. Hence during G2V charging mode the converter performs buck-charging mode. Similarly, during V2G or V2H modes the converter boosts the battery voltage to DC link voltage and power flow is from battery to DC link. This mode is boost-discharging mode. The operating modes of DC-DC converter is as follows:

Mode1: G2V charging –buck mode: In this mode power flows from DC link to battery. The converter operates as buck converter and with controlled current to charge the battery. Switch $T_5$ is fully on in this mode.PWM is applied to switch $T_1$. When $T_1$ is ON, current flows through $D_1$-$T_1$-L-$D_5$-$T_5$ to battery and inductor is charged. When $T_1$ is off, inductor discharges and current freewheels through L-$D_5$-$T_5$-battery-$D_3$.By controlling the turn on time of $T_1$ the output voltage is controlled. Output voltage can be controlled in such a way that desired current is provided to battery while charging. The state of charge (SOC) of battery increases in this mode.

$$V_L=V_{dc}-V_{batt} \quad \text{when } T_1 \text{ is ON} \qquad (1)$$
$$V_L= -V_{batt} \quad \text{when } T_1 \text{ is OFF} \qquad (2)$$

Mode 2:V2G discharging-boost mode: DuringV2G mode of operation the power flow is from battery to dc link. The DC link voltage($V_{DC}$) is higher than battery voltage. So the converter boosts the battery voltage and feed the DC link. During this mode switches $T_2$ and $T_4$ are always ON and PWM is applied to switch $T_3$.When $T_3$ is ON current flows from battery through $T_4$-$D_4$-L-$T_3$ and back to battery. So Inductor L stores energy. When $T_3$ is OFF, the current flows from battery through $T_4$-$D_4$-L-$T_2$-$D_2$ to DC link. During this stage the energy stored in inductor is released.

$$V_L=V_{batt} \quad \text{when } T_3 \text{ is ON} \qquad (3)$$
$$V_L=V_{batt} - V_{DC} \quad \text{when } T_3 \text{ is OFF} \qquad (4)$$

Mode 3: Low voltage DC charging-boost mode: Since the converter is able to do boost operation also in charging direction the feasibility of charging from a DC voltage lower than battery voltage is examined. In order to obtain this operation the DC supply is given directly to the DC link. This voltage is boosted by the converter to feed the battery with desired charging current. In this mode the switches $T_1$and $T_5$ are always ON and PWM is applied to switch $T_3$.When $T_3$ is ON, current flows through $D_1$-$T_1$-L-$T_3$ to supply and inductor stores energy. When $T_3$ is OFF the Current flows through $D_1$-$T_1$-L-$D_5$-$T_5$ to battery. During this stage inductor releases its stored energy.

$$V_L=V_{DC} \quad \text{when } T_3 \text{ is ON} \qquad (5)$$
$$V_L=V_{DC} – V_{batt} \quad \text{when } T_3 \text{ is OFF} \qquad (6)$$

*C.* Control of the converter

Here in G2V charging mode the converter is controlled to provide constant charging current. Where as in V2G discharging mode the converter delivers the required voltage to DC link. Various control schemes has been proposed in literatures for EV chargers. Mostly control action is done by using direct duty Ratio variation by using PI controller. PI controllers are simplest and conventionally used controllers in closed loop applications. The error obtained by comparing the actual value and reference value is amplified and fed to PI controller. The output is compared with a repeating sequence such as triangular wave and the output of comparator is used to control the gate pulse. The width of pulse depends on the error. Here in the buck mode a hysteresis controller can be used to control the current through the inductor thus controlling the charging current.

In V2G or V2H mode the converter provides a constant low ripple DC link voltage .This control action is also done by using a PI controller. The DC link voltage is compared with reference voltage and rest of the control action is same as mentioned before.

TABLE III: MODES OF OPERATION OF CONVERTER

| Direction | Mode | T1 | T2 | T3 | T4 | T5 |
|---|---|---|---|---|---|---|
| $V_{dc}$ to Battery | buck | PWM | Off | Off | Off | On |
| $V_{dc}$ to Battery | boost | On | Off | PWM | Off | On |
| Battery to $V_{dc}$ | buck | Off | On | Off | PWM | Off |
| Battery to $V_{dc}$ | boost | Off | On | PWM | On | Off |

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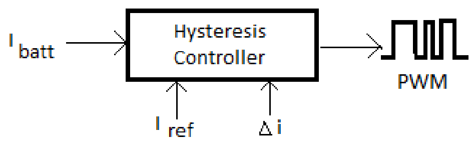
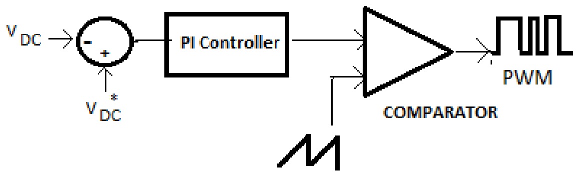



Charging Current control in G2V mode




voltage controller in V2G/V2H mode

Fig. 3. Controller for Integrated Bi-directional buck-boost converter

## III. SIMULATION RESULTS

A simulation for the bidirectional DC-DC converter provides major waveforms and results for analysis. Simulations are performed using MATLAB with Simulink, Sim Power Systems, Signal Processing Toolbox, and Control System Toolbox products. For simulation purpose the DC link voltage is taken 400V and battery chosen is 110V, 32Ah lead acid battery. During G2V mode the converter provides 10A charging current. During V2G or V2H modes the converter boosts the battery voltage to 400V.The value of inductor L is chosen using the equation of current ripple.

$$\Delta I = \frac{1}{2}\frac{V_2 - V_1}{L}\frac{V_1}{V_2}\frac{1}{f_s}$$

Where ΔI is current ripple (0.5A),
$V_2$=DC link voltage (400V),
$V_1$=battery voltage (125V, charged voltage),

and $f_s$=switching frequency(20kHz).By putting these values in the equation and providing a multiplication factor of 1.5 to avoid discontinuous current the value of L is chosen as L=6mH.The output capacitor C is taken as 470μF.Using the designed values the converter is simulated in various modes. The Simulink model of the converter is shown in fig 4.

Fig. 6 shows the input and output voltage and current waveforms of the converter in open loop. In actual case the DC link voltage will be the output stage of the front end PFC rectifier. Here for the purpose of simulating DC-DC converter the DC link voltage is given by a DC source. The input DC link voltage is 400V and battery state of charge is set to be 50%. Converter output is connected. The waveform shows converter provides 11.2A charging current. The input current to the converter is 3. 54A.The output voltage ripple is obtained as 0.1% and output current (charging current) ripple is observed as 2.6%.

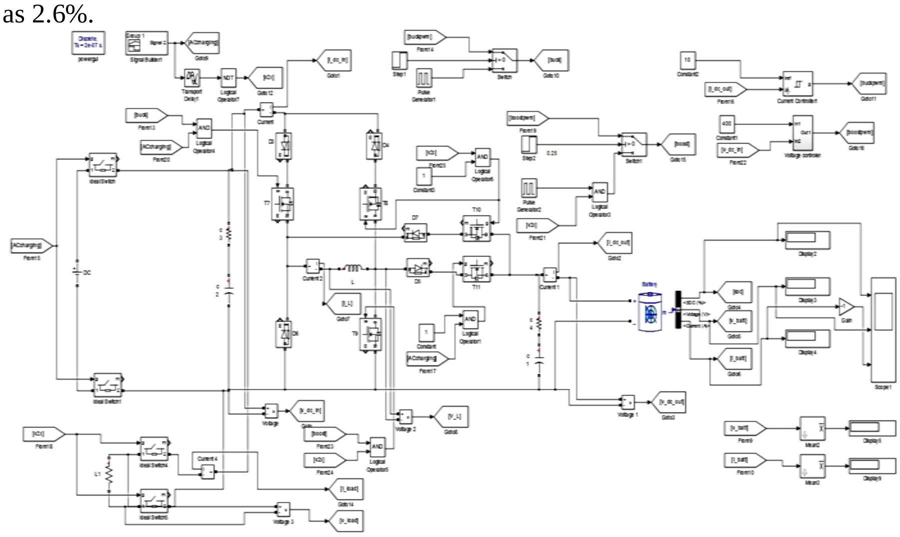


Fig. 4. MATLAB model of integrated bidirectional DC-DC converter

Fig 5 shows the Battery parameter waveforms. The state of charge (SOC) is increasing. This indicates the charging process of the battery. In fig 7 the current controller is activated at 0. 05s.The reference charging current to the battery is set as 10A.The waveforms shows that as the charging current has changed to 10A from previous 11.2A the SOC curve's slope has decreased. So by setting a reference current in the controller the charging current provided in G2V mode can be controlled.

Fig 9. shows the waveforms of the converter operation in V2G or V2H mode. During this mode the converter boosts the battery voltage to require DC link voltage, ie; 400V.The battery current is negative because it is operating in discharge mode. In open loop operation the voltage is observed as 404v. The converter provides 3.03A output current. The ripple is observed as 0.06%. The battery discharge current is 11A with a ripple of 1.75%. Fig 11 is the converter waveforms with a closed loop control with reference 400V.Fig 11 show the controller is maintaining the converter output voltage at 400V.

In addition to the conventional charging schemes, charging of the battery from a lower DC voltage that is 48V is also simulated. Here the low Voltage DC is directly given to DC link. The converter waveforms are shown in fig.12. The converter provides an average charging current of 9.68A. The input current drawn is 27.04A. So the converter can charge the battery from a lower voltage DC source with sufficient power capacity.

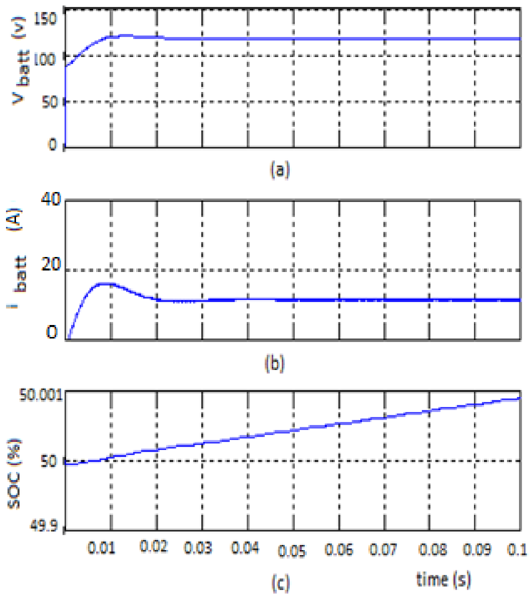



Fig. 5. Battery waveforms during G2V mode (a) battery voltage (b) battery current (c) state of charge (SOC)

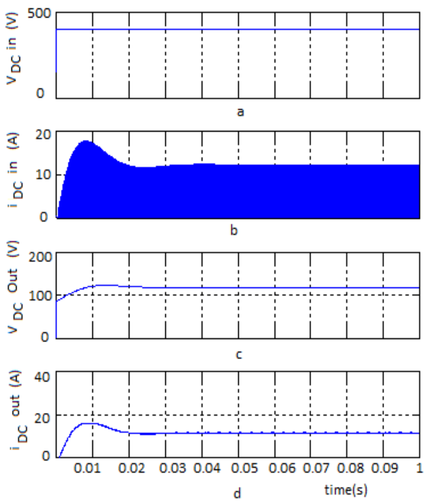



Fig. 6. Input and output waveforms of the converter during G2V mode a) input (DC link) voltage b) input current c) output voltage d) output current

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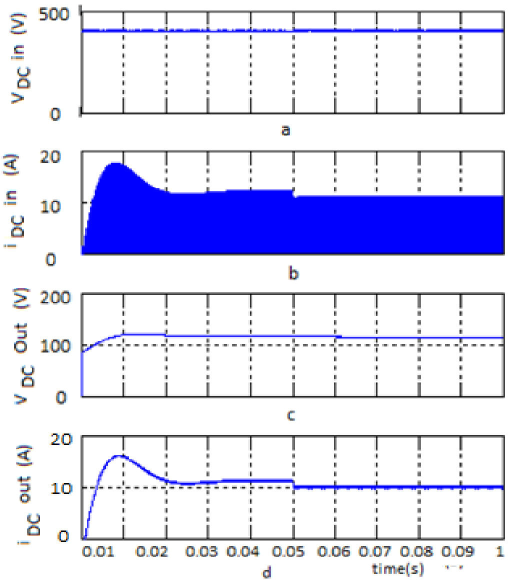


Fig.7.Converter waveforms with current controller activated at t=0.05s
a) input (DC link) voltage b) input current c) output voltage d)output current

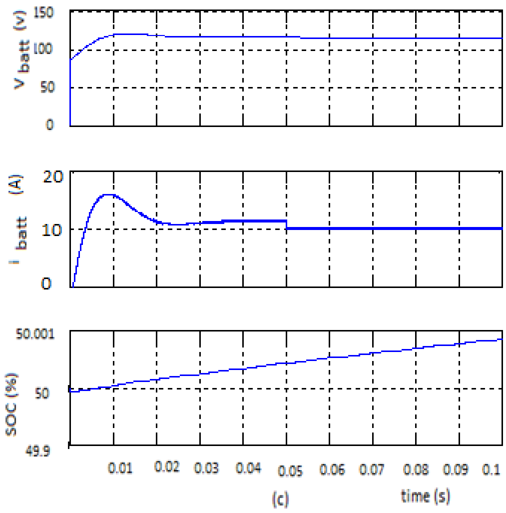


Fig. 8. Battery waveforms during G2V mode with current controller at 0.05s (a) battery voltage (b) battery current (c) state of charge (SOC)

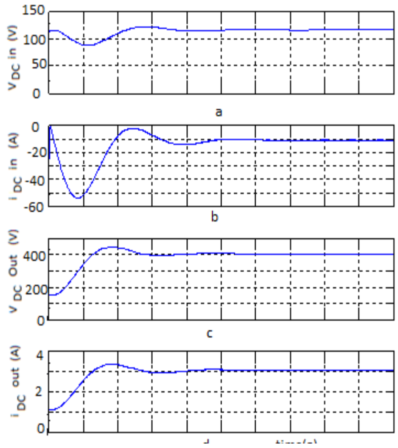


Fig.9.Converter waveforms during V2G/V2H mode in open loop
a) input (battery) voltage b) input (battery discharge) current c) output voltage (DC link voltage) d) output current

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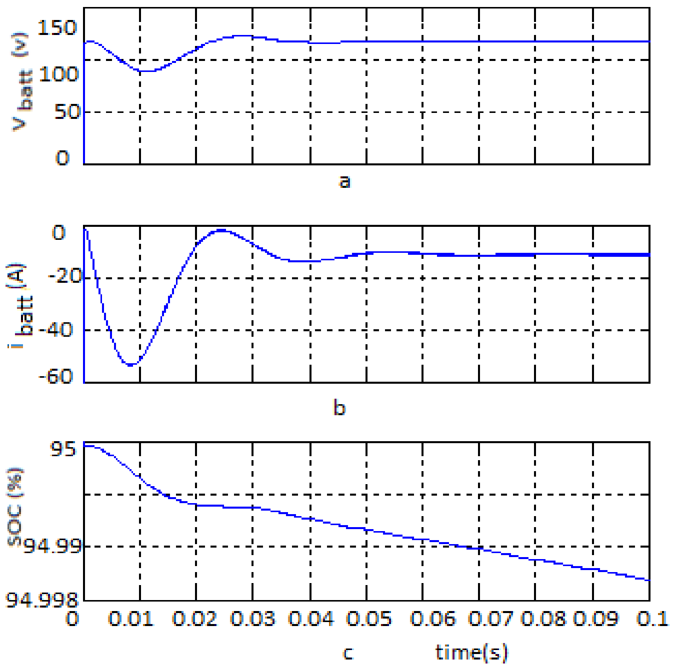


Fig. 10. Battery waveforms during G2V mode in openloop (a) battery voltage (b) battery current (c)state of charge (SOC)

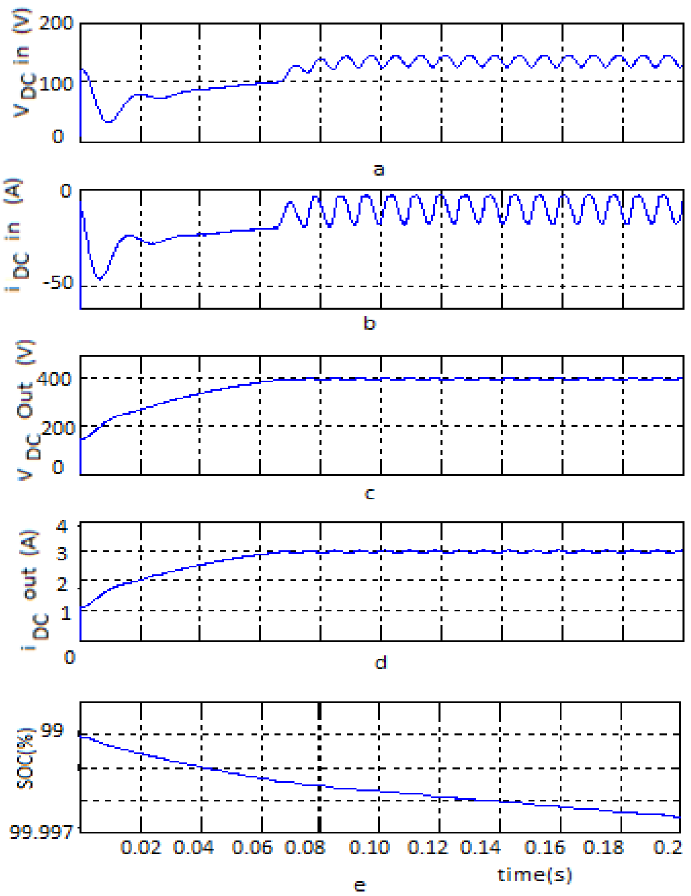


Fig.11.Converter waveforms during V2G mode in closed loop control
a) input (battery)voltage b) input (battery discharge) current c) output voltage(DC link voltage) d)output current and e)battery SOC

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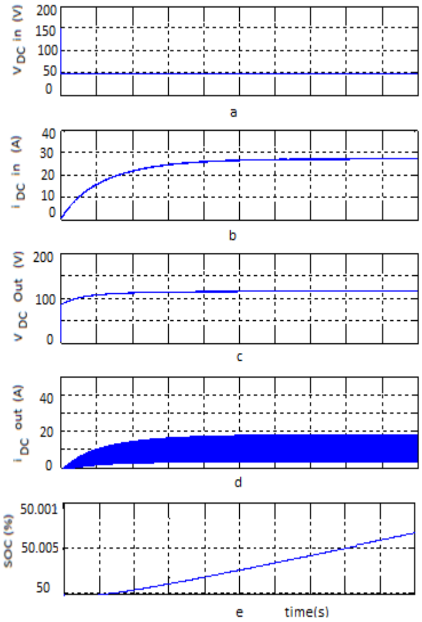


Fig.12.Converter waveforms during boost charging mode from 48V DC
a) input DC voltage b) input current c) output voltage(battery voltage) d)output (charging) current and e)battery SOC

## IV. CONCLUSION

Electric vehicles can be used to benefit the grid by enabling bidirectional power flow. With bidirectional chargers the energy stored in the vehicle can be fed back to grid with the modesV2G or can be used to deliver home loads with V2H technology. The charger consists of Bidirectional AC-DC converter and Bidirectional DC-DC converter .This paper presented an integrated bidirectional DC-DC converter for the Charger. The converter is able to operate in both buck and boost modes in both the directions. The converter is simulated with MATLAB simulink and the results are verified with a battery model of 110V 32Ah and DC link voltage of 400V. The simulation results show the converter performed satisfactorily in the designed modes. During G2V-charging mode the converters stepped down the DC link voltage 400V to battery voltage and charge the battery with low voltage and current ripple. With a current controller the converter charges the battery at the reference current set ie; 10A. During V2G or V2H mode (discharging) the converter boosted the battery voltage to DC link voltage. A closed loop voltage controller is used to maintain the DC link voltage. The converter delivered 1.2kW power to the DC link with only 0.06% ripple in output current. Since the converter is able to operate in boost mode in charging, a DC charging mode in which battery is charged from a DC voltage of 48V is verified. The converter was able to boost it to deliver 115V to battery and provided a dc charging current of 9.68A.The converter is a non isolated type DC-DC converter .Though there are 5 diodes and 5 switches ,In any mode only one switch will be PWM controlled. This reduced the complexity of control. Hence the converter is a good candidate for DC-DC stage of a Bidirectional EV charger with G2V, V2G and V2H modes.

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