

A Bidirectional DC-DC Battery Interface for EV Charger with G2V and V2X Capability

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ABSTRACT: Electric vehicles are gaining importance in the present situations as it is the most reliable transportation system in near future with less environmental pollution, fuel economy and energy efficiency. The concept of microgrid and smart grid has added a rage to distributed generation and increased communication between customers and utility. The idea of bidirectional interaction between grid and Electric vehicle has brought the V2G, V2H etc. technologies. 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.

KEYWORDS: Electric vehicle charger, Bidirectional DC-DC converter, 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 green house gas emission. Besides the environmental concerns EVs provide fuel economy and convenience in refueling 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 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 smartgrid 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. Besides the active power support the EVs can be used for reactive power support, active filtering, voltage regulation etc. functions. Hence this interaction mode is generally termed as V2X technology.

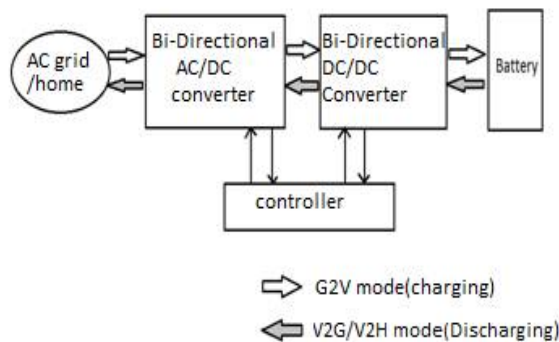


Fig. 1 Typical Bidirectional EV charger block diagram

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
Level3(fast) (200-600V AC/DC)	Commercial Filling stations	50kW-100kW	0.4-1 hours

Table I : EV Charger systems power levels

II. CONVERTER TOPOLOGY AND OPERATING MODES

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 requires 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 converter consists of 5 switches and 5 diodes and the inductor L and capacitor C.

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.

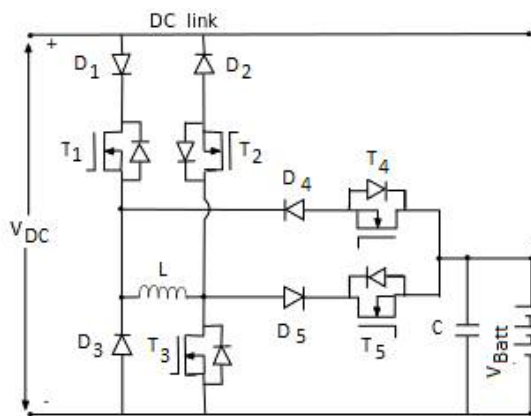


Fig 2. Integrated Bi-directional DC-DC converter circuit diagram

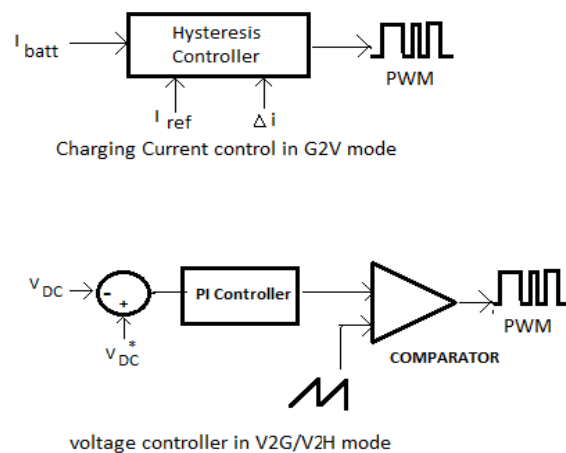


Fig 3. Control schemes during G2V and V2X modes

The operating modes of DC-DC converter is as follows (Fig 4):

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 T5 is fully on in this mode. PWM is applied to switch T1. When T1 is ON, current flows through D1-T1-L-D5-T5 to battery and inductor is charged. When T1 is off, inductor discharges and current freewheels through L-D5-T5-battery-D3. By controlling the turn on time of T1 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.

$$V_L = V_{dc} - V_{batt} \quad \text{when T1 is ON} \quad (1)$$

$$V_L = -V_{batt} \quad \text{when T1 is OFF} \quad (2)$$

Mode 2: V2X discharging-boost mode: During V2G 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 T2 and T4 are always ON and PWM is applied to switch T3. When T3 is ON current flows from battery through T4-D4-L-T3 and back to battery. So Inductor L stores energy. When T3 is OFF, current flows from battery through T4-D4-L-T2-D2 to DC link. During this stage the energy stored in inductor is released.

$$V_L = V_{batt} \quad \text{when T3 is ON} \quad (3)$$

$$V_L = V_{batt} - V_{DC} \quad \text{when T3 is OFF} \quad (4)$$

In G2V charging mode the converter is controlled to provide constant charging current. Whereas 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.

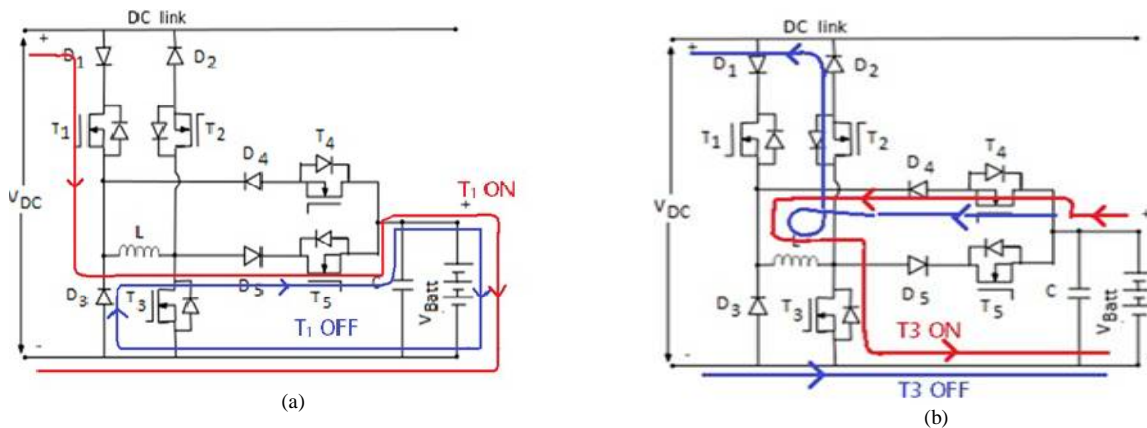


Fig. 4 : DC-DC Converter operation modes a) G2V mode b) V2X mode

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, SimPowerSystems, Signal Processing Toolbox, and Control System Toolbox products (fig.5). 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.

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

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 470 μ F.Using the designed values the converter is simulated in various modes. The simulink model of the converter is shown in fig 5.

Fig. 6 shows the input and output voltage and current waveforms of the converter in model 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 to battery. 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 6-e shows the Battery parameter waveform-SOC. 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.

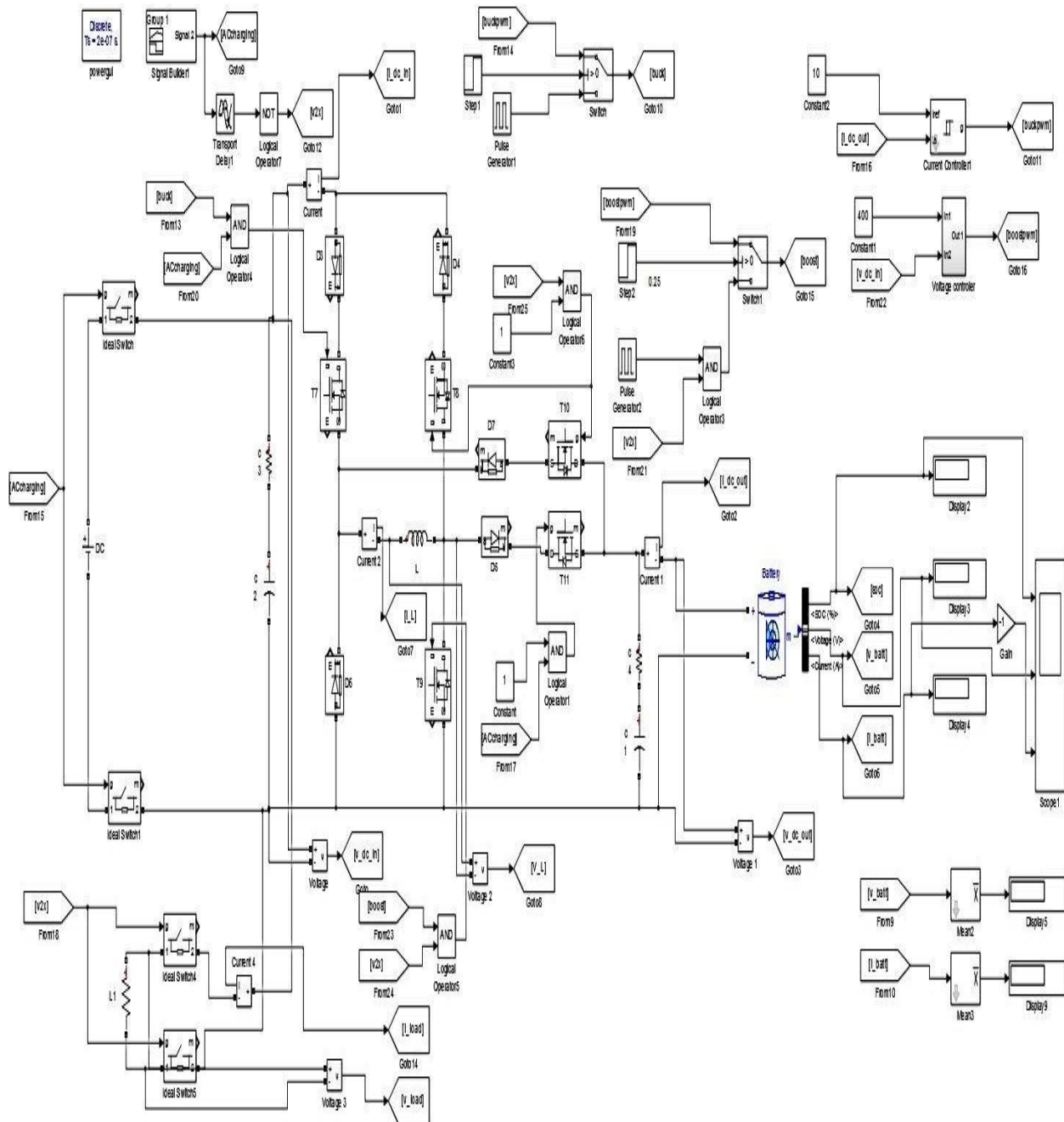


Fig. 5: MATLAB model of integrated bidirectional DC-DC converter

So by setting a reference current in the controller the charging current provided in G2V mode can be controlled. Fig 8. shows the waveforms of the converter operation in V2G or V2H mode or generally V2X mode. During this mode the converter boosts the battery voltage to required 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 9 is the converter waveforms with a closed loop control with reference 400V. Fig 9 shows that the controller is maintaining the converter output voltage at 400V.

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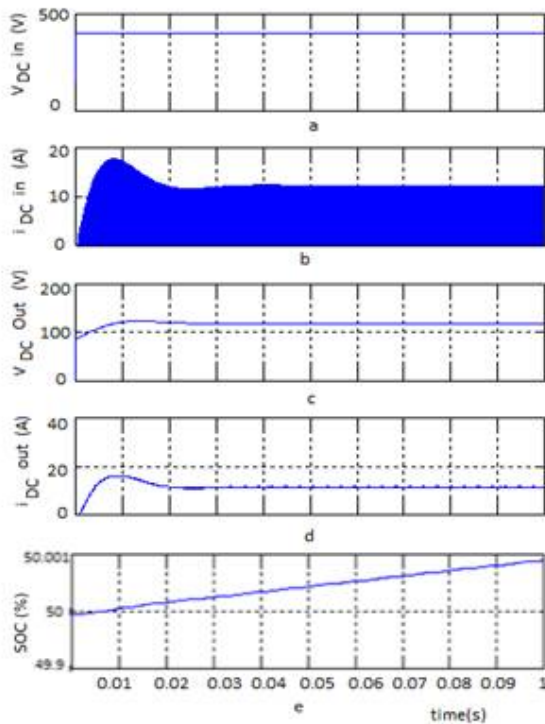


Fig. 6: G2V mode a) input (DC link) voltage b) input current c) output voltage d) output (charging) current e) SOC

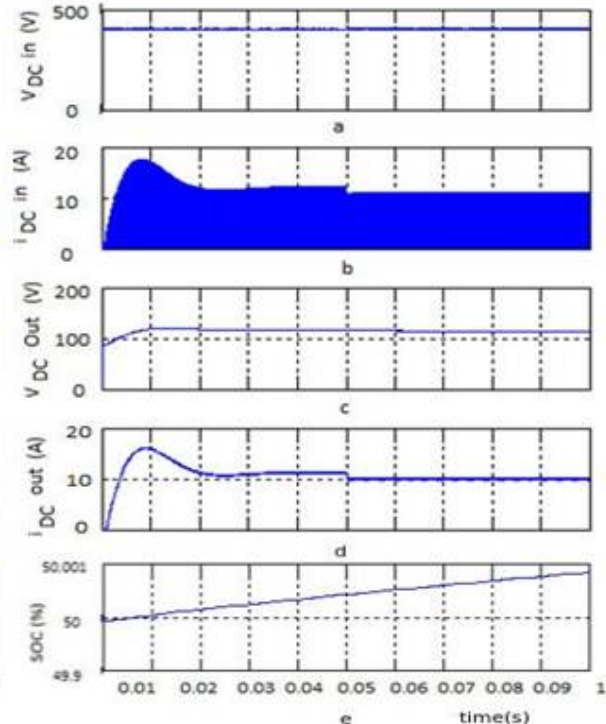


Fig. 7: G2V mode with current controller (10A) activated at 0.05 Second a) input (DC link) voltage b) input current c) output voltage d) output (charging) current e) SOC

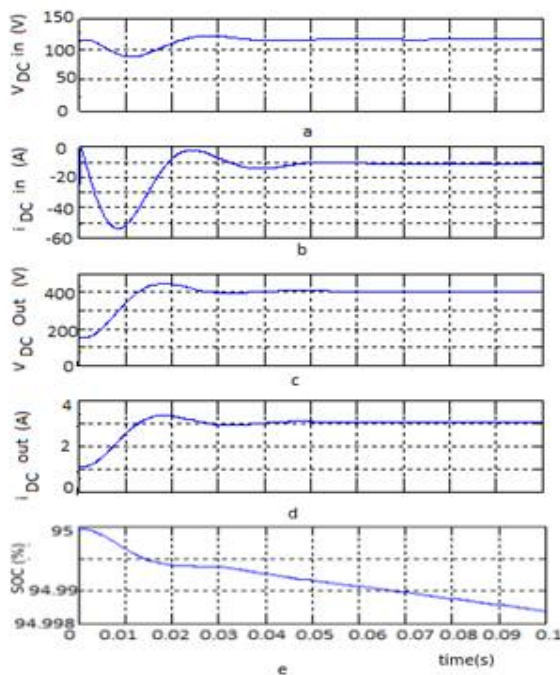


Fig. 8: V2X mode open loop- a) input (battery) voltage b) input (battery discharge) current c) output voltage (DC link voltage) d) output current and e) battery SOC

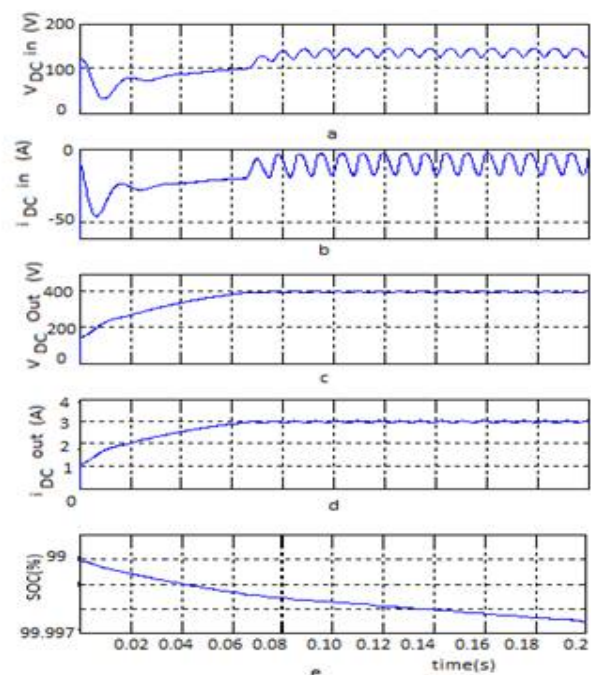


Fig. 9: V2X mode closed loop- a) input (battery) voltage b) input (battery discharge) current c) output voltage (DC link voltage) d) output current and e) battery SOC

Table II: Converter Switching modes

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

Table III: Simulation Results

Parameter	G2V mode	V2X mode
V _{in} (V)	400	116.6
I _{in} (A)	3.54	11.4
V _{out} (V)	116.9	404
I _{out} (A)	10	3.035
V _{batt ripple} (%)	0.1	0.01
I _{batt ripple} (%)	2.3	1.75

IV. CONCLUSION

Electric vehicles and smart grid technology are much related as EVs can be used to benefit the grid by unlocking bidirectional power flow capability with proper communication and control. In the future EVs are expected to dominate over fossil fuel vehicles and will be a burden to the grid if operated merely as a power consuming device. With bidirectional chargers the energy stored in the vehicle can be fed back to grid with the modes V2G or can be used to deliver home loads with V2H technology. Also it provides a wide scope of application such as active filtering, voltage regulation etc. Hence it is commonly termed as V2X 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 battery interface of 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 which is 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. 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 battery interface of a Bidirectional EV charger with G2V and V2X modes.

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