IJSRD - International Journal for Scientific Research & Development| Vol. 7, Issue 03, 2019 | ISSN (online): 2321-0613

Design and Control of Bidirectional DC - DC Converter for Electric Vehicle Application

S.G. Archana Priyadharsini[1] Dr.K. Yasoda[2]
[1,2]Department of Electrical & Electronics Engineering
[1,2]Government College of Technology, Coimbatore, India

Abstract— This paper presents the development of a bidirectional battery charger for Electric Vehicles (EVs) targeting Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), a bidirectional DC – DC converter for charging batteries used for electrical vehicle application. The converter circuit acts as a buck converter during charging and boost converter during discharging of the battery. The control technique is designed to perform the charging process under constant current mode and the constant voltage mode based upon the state of charge (SoC) of the battery. When the SoC of the battery is less than 80% the battery charges under constant current mode otherwise the battery is charged under constant voltage mode. The model has been designed and simulated using MATLAB - Simulink.

Key words: Electric Vehicle (EV), SoC(State of Charge), CC Mode, CV Mode, Bidirectional Battery Charger, Grid-To-Vehicle (G2V),Vehicle-To-Grid (V2G)

I. INTRODUCTION

This project presents the configuration for the bidirectional energy transfer between the vehicle and grid enabling the vehicle to grid technology. Electric vehicles can be used as a substitute for meeting the grid's energy demand by extracting power during off peak time and delivering power back to the grid at peak demand time. During Vehicle-to-Grid mode, the stored energy in the battery can be given back to the grid and during Grid-to-Vehicle mode; the grid supply is used to charge the battery.

A DC to DC converter is used for storage and retrieval of electrical power transfer across the electric vehicle and the grid targeting Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) technologies. A bidirectional DC to DC buck-or-boost converter is used to implement the charging and discharging of the electric vehicle's battery.

EVs were actually a mode of transportation. But nowadays it can be considered as a then the cost issue can be solved. The electric technology vehicle draws power from grid, during the low energy demand by loads from the grid. During the peak energy demand by loads from the grid, the electric vehicle's battery acts as a source to meet the energy demand by feeding the energy back to the grid. This brings in some economic advantage to the user

The EVs battery charging process (Grid-to-Vehicle, G2V) must be regulated to preserve the power quality in the power grids .Nevertheless, with the proliferation of EVs a considerable amount of energy will be stored in their batteries, arising the opportunity of the energy flow in opposite sense(Vehicle-to-Grd, V2G).

Since Many converter topologies were available the DC to DC converter connected by a capacitor that shares a DC link voltage is selected here its modes of operation, control strategy and all the design procedure are explained in the simulation study done in the area of charging and discharging of battery and the results obtained are analysed.

II. SYSTEM OVERVIEW

The objective of the project is to develop a bidirectional dc – dc converter used for electric vehicle (EV) application. During the Grid-to-Vehicle (G2V) operation mode the batteries are charged from the power grid. During the Vehicle-to-Grid (V2G) operation mode the energy stored in the batteries can be delivered back to the power grid contributing to the power system stability. A bidirectional DC to DC buck-or-boost converter is used to implement the charging and discharging of the electric vehicle's battery. And a control strategy is proposed based on state of charge (SoC) of the battery.

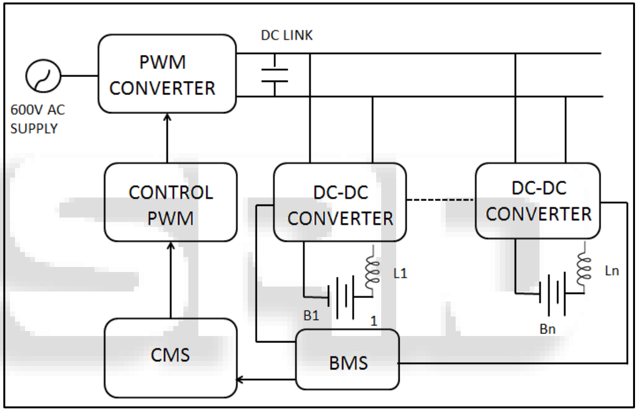


Fig. 1: Proposed System of Bi-Directional Converter

The above system shows the full block diagram of the proposed system which contains a PWM converter at the grid side and a bidirectional DC – DC converter at the vehicle side

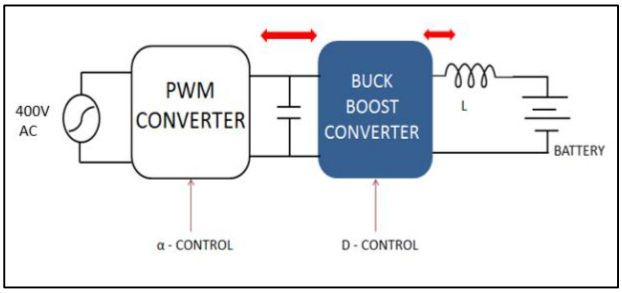


Fig. 2: Grid to Vehicle System

To achieve a flow of power between the power grid and the electric vehicle in both the directions. The system consists mainly of two power converter blocks: one which is a bidirectional AC to DC converter and the other being a bidirectional DC to DC converter that share a common DC link. The full-bridge AC to DC bidirectional converter acts as a rectifier during the G2V operating mode and the same acts as inverter during the V2G mode. DC to DC bidirectional converter acts as step down converter while charging the battery and in the step-up mode during the discharge of the battery. This converter acts as buck in G2V mode and as boost in V2G mode.

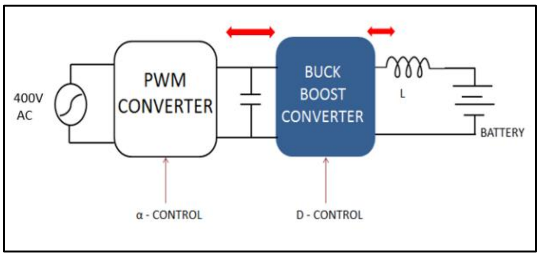


Fig. 3: Bidirectional Dc – Dc Converter System

The converter can be made to work in buck topology or in a boost topology by changing the switching on of the MOSFETs and the duty ratio. The DC link voltage is always higher than the traction batteries voltage and for this reason during the G2V operation mode the reversible DC-DC converter operates as buck converter.

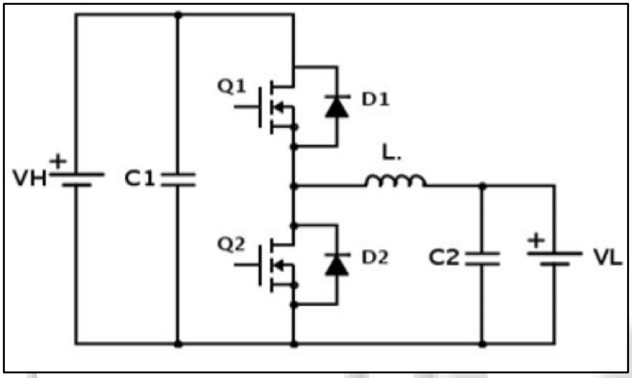


Fig. 4: Bidirectional DC to DC Converter topology

The terms DC–DC converters and choppers are one and same. The Choppers can be operated in either a continuous or discontinuous current conduction mode. They can be built with and without electrical isolation.

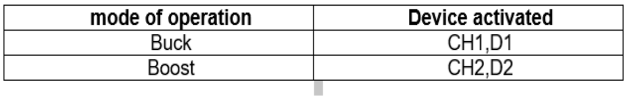
A chopper is a static device that converts fixed dc input voltage to a variable dc output voltage directly. A chopper is considered as DC equivalent of an AC transformer since it behaves in an identical manner. The choppers are more efficient as they involve in one stage conversion.

A chopper is a high-speed on/off semiconductor switch. It connects source to load and disconnects the load from source at high-speed. In other words, the principle of chopper is application of fixed dc voltage intermittently to the load. This is achieved by continuously triggering ON and triggering OFF the power switch (SCR) at rapid speed.

The duration for which the SCR remains in ON and OFF states are called ON time and OFF time respectively. By varying the ON time and OFF time of the SCR, the average voltage across the load can be varied.

A. *Modes of Operation*

There are two basic modes of operation the converter in this paper: Buck mode during battery charging process and Boost mode during discharging of battery.



mode of operation	Device activated
Buck	CH1,D1
Boost	CH2,D2

Table 1: Modes of Operation

1) Buck Mode During Battery Charging

In this mode of operation, the vehicle battery is charged from grid. Grid’s AC voltage is rectified to DC by an AC to DC converter operating in the rectifier mode. The output of this converter is fed to the DC link. The DC to DC converter operates in buck mode by stepping down the DC link voltage to the required battery charging voltage.

2) Boost Mode During Battery Discharging

In this operating mode, energy stored in the battery is feed back to the grid. The DC voltage from the battery is stepped up using the DC-DC converter operating in boost mode and is then converted to AC using the

AC-DC Converter operating in the inverter mode and is fed to grid. To feed the power back to grid, output of inverter should be synchronized with that of the grid.

III. DESIGN SPECIFICATIONS

A. *Selection of Power Switches*

The switching device in any converter is selected based on the ideal i–v static characteristic requirement. The static i–v characteristic requirement is obtained from the operative converter circuits during the periods when the particular switch is ON and OFF. During the period when the switch is ON, the current flow requirement is obtained. During the period when the switch is OFF, the voltage withstanding capability requirement is obtained.

B. *Inductor Design*

1) Inductor Design For Buck Coverter Topology

For buck converter, the input is obtained from DC link voltage and output voltage is the battery voltage. Under steady state analysis, input output voltage relationship is given by

$$Vo = D\ Vi$$

Where Vi is the voltage of DC link, Vo is the voltage of the battery and D is the duty ratio and it is given by,

$D = T_{on} / T_s$

D lies in the closed interval of (0 and 1). So, $Vo < Vi$.

Input output current relationship is given by,

$$I\ in = (Vo / Vi)\ Io$$

$I\ in = D\ Io$

The inductor value is calculated based on the amount of current ripple $\Delta\ i_L$, that is decided to be allowed for a given application. The common choice of $\Delta\ i_L$ based on application is assumed to be

$$\Delta\ i_L = 10\ \%\ of\ Io$$

Then the value of L is given by

$L = (Vo\ (1- D\ )) / \Delta\ i_L\ fs$

To regulate Vo with variations in Vi, the value of V should be changed.

If Vimax → maximum input voltage swing

Dmin → minimum duty cycle to optain specified Vo

Dmax → maximum duty cycle to optain specified Vo

Vimin → minimum input voltage swing

For regulated Vo, the value of L is calculated at the duty ratio Dmin which is given by,

$$L = (Vo\ (1- Dmin\ )) / \Delta\ i_L\ fs$$

2) Inductor Design For Boost Coverter Topology

For boost converter, the input voltage is obtained from battery voltage and the output is the DC link voltage. Under steady state analysis, input output voltage relationship is given by

$$Vo = Vi / (1- D)$$

Where Vi is the voltage of DC link, Vo is the voltage of the battery and D is the duty ratio and it is given by,

$$D = Ton / Ts$$

D lies in the closed interval of (0 and 1). So, Vo > Vi.

Input output current relationship is given by,

$$I\ in = (Vo / Vi)\ Io$$
$$I\ in = Io / (1\text{-}D)$$

The inductor value is calculated based on the amount of current ripple $\Delta\ i_L$, that is decided to be allowed for a given application. The common choice of $\Delta\ i_L$ based on application is assumed to be

$$\Delta\ i_L = 10\ \%\ \text{of}\ Io$$

Then the value of L is given by

$$L = (Vi\ D) / \Delta\ i_L\ fs$$

To regulate Vo with variations in Vi, the value of V should be changed.

If Vimax → maximum input voltage swing
Dmin → minimum duty cycle to optain specified Vo
Vimin → minimum input voltage swing
Dmax → maximum duty cycle to optain specified Vo

For regulated Vo , the value of L is calculated at the duty ratio Dmin which is given by,

$$L = (Vimax\ Dmin) / \Delta\ i_L\ fs$$

IV. CAPACITOR DESIGN

A. Capacitor Design for Buck Converter Topology

The capacitor value is calculated by applying the amp-second role. If there is to be no charge build up or charge reduction in the capacitor, then the area under capacitor current curve in one period should be zero. Area under the positive portion of the current curve implies charging of the capacitor and that under the negative portion implies discharging of the capacitor. For charge balance both these areas should be equal. The change is the capacitor charge ΔQ is given by the area under either the positive portion or the negative portion of the capacitor current curve.

$$\text{Thus } \Delta Q = C\ \Delta\ Vo = (1/2)\ X\ Base\ X\ Height$$
$$= (1/2)\ X\ (Ts/2)\ X\ (\Delta\ i_L / 2)$$
$$= \Delta\ i_L / 8\ f_s$$
$$C = \Delta\ i_L / (8\ \Delta\ Vo\ f_s)$$

Here Δ Vo is known from the output ripple specification. i_L & fs are design choices.

B. Capacitor Design For Boost Converter Topology

The capacitor value is calculated by applying the amp-second role. If there is to be no charge build up or charge reduction in the capacitor, then the area under capacitor current curve in one period should be zero. Area under the positive portion of the current curve implies charging of the capacitor and that under the negative portion implies discharging of the capacitor.

For charge balance both these areas should be equal. The change is the capacitor charge ΔQ is given by the area under either the positive portion or the negative portion of the capacitor current curve. For the boost converter geometrically, it is easy to find the area under the negative portion of the capacitor curve.

$$\text{Thus } \Delta Q = C\ \Delta\ Vo$$
$$= Io\ DT_s$$
$$= (Io\ D) / f_s$$
$$C = Io\ D / (\Delta\ Vo\ f_s)$$

Here Δ Vo is known from the output ripple specification. iL & fs are design choices.

V. LI-ION BATTERY

A. Charging Of Lithium Ion Battery

There are different charging methods of a battery are

1) Constant current charging (CC charging)
2) Constant voltage charging (CV charging)
3) Constant current-Constant voltage charging (CC-CV Charging)

The manufacturers of Li-ion Battery recommend strict standards for charging the Li-ion batteries. The Li-ion batteries must be charged by Constant Current-Constant Voltage Charging method. So, designing a Li-ion battery charger needs an intelligent circuitry which can switch the battery charging in between CC and CV charging modes.

There are three states in Li-ion battery charging as shown in the graph below –

1) Trickle charge state
2) Constant current state (CC state)
3) Constant voltage state (CV state)

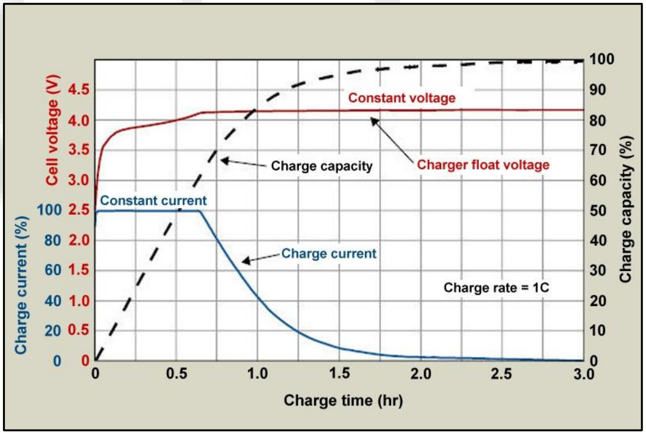


Fig. 5: Charging Profile of Li Ion Battery

VI. CONTROL STRATEGY

In order to perform the batteries charging process, most of the battery manufacturers recommend two charging stages: constant current followed by constant voltage. The first stage consists in charging the batteries with constant current until the voltage reaches the recommended maximum voltage, and in the second stage the voltage is maintained constant until the current consumed by the batteries falls to a residual value.

The charging mode selection between the constant current (CC) and the constant voltage (CV) is decided based on the SOC of the battery. If SOC < 80%: Constant Current (CC) mode is selected for charging battery. If SOC >= 80%: Constant Voltage (CV) mode is selected for charging battery. The system consists of two power converters which basically shares a common DC link capacitance. For interfacing the battery with grid, a full-bridge bidirectional AC to DC converter is used along with a bidirectional DC to DC Buck or Boost converter is used with a DC link capacitance. Bidirectional AC-DC converter acts as a rectifier in the G2V mode of operation and as an inverter in the V2G mode of operation. The bidirectional DC to DC converter acts as a buck converter in the G2V mode and the same converter acts as boost converter in the V2G mode. It is mandatory that the inverter output before feeding to the grid is to be synchronized with the grid.

A. Mode Selection Algorithm:

Based upon SOC of battery the mode of charging between the CC mode and CV mode is decided based on the SOC of the battery.
If SOC >= 80%: CV mode is used to charge the battery.
If SOC< 80%:   CC mode is used to charge the battery.

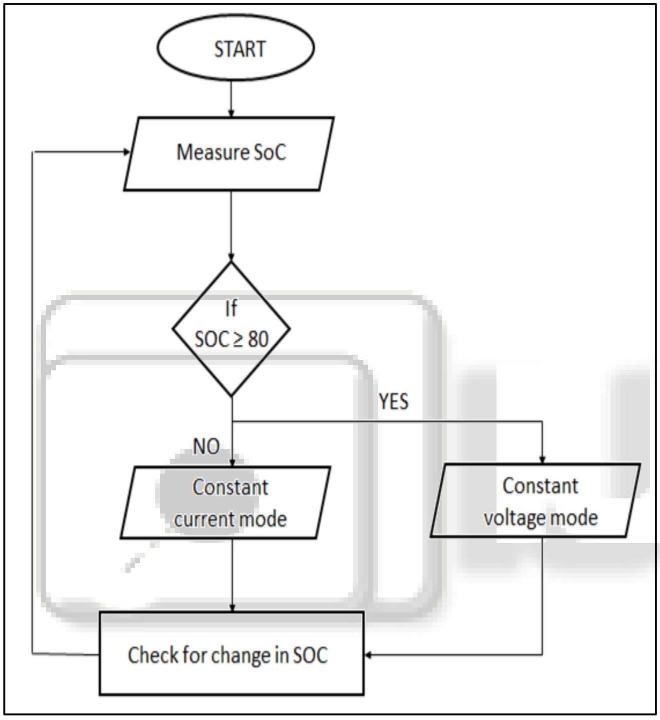


Fig. 6:.Flow Chart of Control Strategy

VII. SIMULATION STUDY

Simulation of bidirectional dc – dc converter with constant current and constant voltage charging

A control technique is established for constant current and constant voltage charging based upon the SoC of the battery.
If SoC < 80%, constant current charging takes place
If SoC > 80%, constant voltage charging takes place
The simulated model is given by,

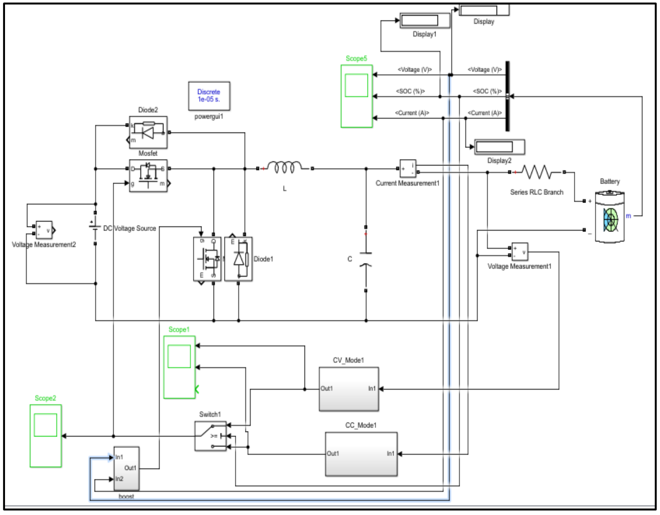


Fig. 7: Bidirectional Dc – Dc Converter With CC And CV Charging

In the output voltage it is clear that output is maintained constant at Vo=365V with the battery being charged

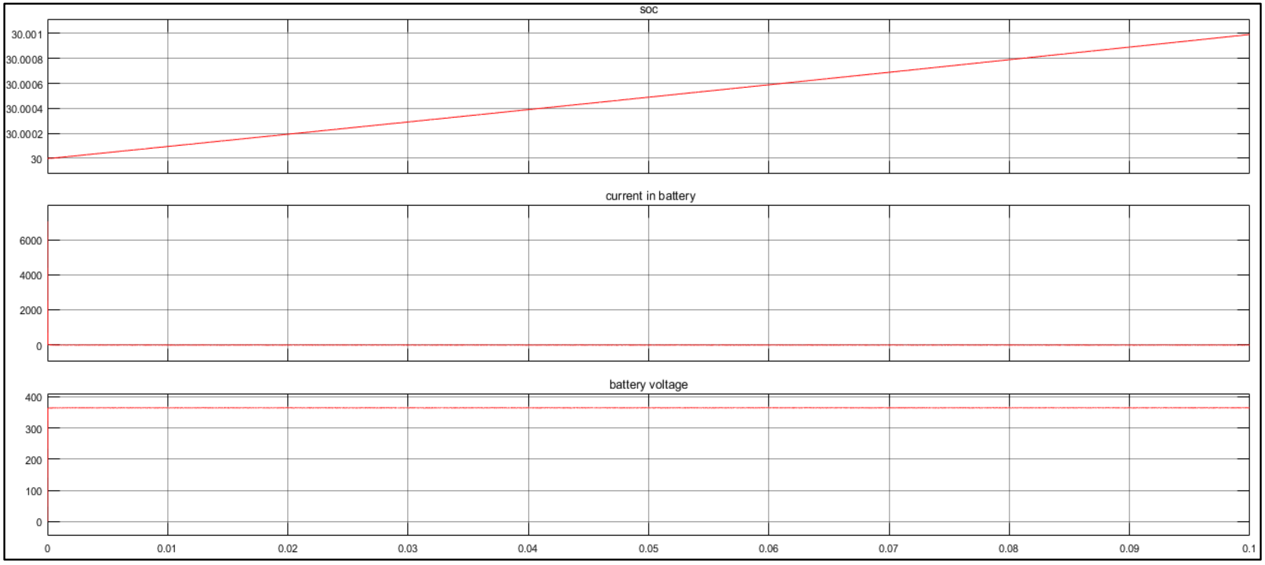


Fig. 8: SoC, Battery Charging Current and Charging Voltage In Buck Mode

he output waveform of bidirectional converter with CC – CV charging based on SoC

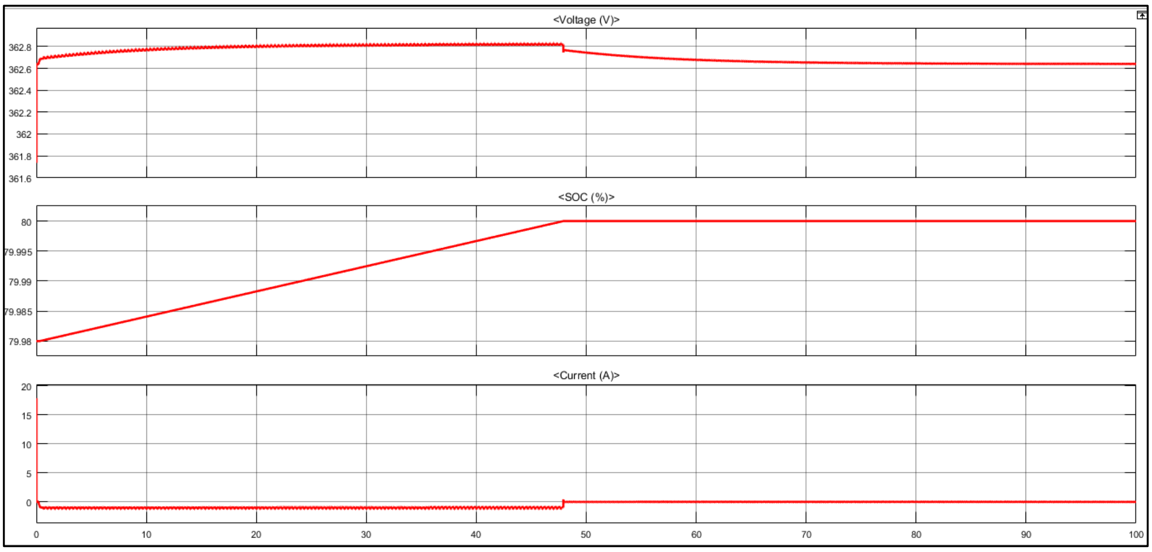


Fig 9.SoC, Battery charging current and charging voltage in CC and CV mode

The output waveform of bidirectional converter in boost mode with decreasing voltage and increasing current.

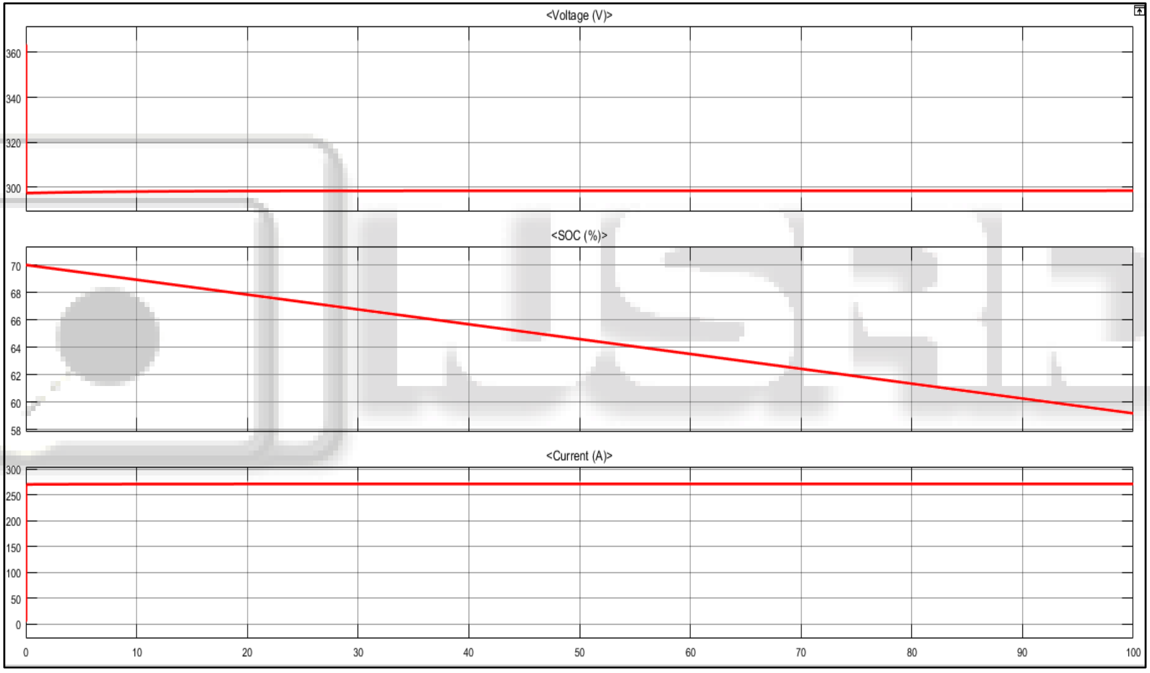


Fig 10. SoC, Battery charging current and charging voltage in boost mode

VIII. CONCLUSION

The prime aim of designing and controlling the bidirectional dc – dc converter for charging electric vehicle battery in both the constant current control mode as well as constant voltage control mode has been established. The bidirectional property which the DC-DC converter had to achieve has also been established. The bidirectional property of the integrated system has been established and is verified through simulations. Using an LC filter the harmonics has been reduced and the bidirectional power transfer between the grid to vehicle and vehicle to grid is completed.

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