A Single Phase Bidirectional Converter for V2G Operation of Electric Vehicles

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Abstract - *A bidirectional converter is the primary requirement for an EV charger with advanced charging modes like V2G. The commonly used building modules of such a Bidirectional charger comprises an AC/DC converter at the front end and DC/DC converter at the back end both bidirectional and a DC link capacitor in between. The topology of the AC/DC and DC/DC bidirectional converter used varies according to the purpose of converter design. In this article, we try to study a simple topology related to H bridge AC/DC converter and a Bidirectional non isolated buck-boost converter interface. The related control strategy is also presented. Here in this paper an easy to implement model consisting of an H bridge AC/DC converter and a non-isolated buck boost bidirectional converter is analyzed. The AC/DC converter works as a sine PWM Inverter during V2G mode; and as a synchronous rectifier during G2V/Charging mode. The passive elements are designed for efficient converter operation during both V2G and G2V modes. A MATLAB/SIMULINK model has been constructed and analyzed for efficient power flow conditions and battery parameters.*

Key Words: **Bidirectional AC/DC converter, Bidirectional DC/DC converter, Electric Vehicle, V2G, G2V.**

1. INTRODUCTION

Electric Vehicles are deemed as the future of mobility. With a push to increase electric mobility in India and thus to reduce our long time dependence on fossil fuel imports the Govt. of India has set up different programs promoting EV related researches .A large part of such researches are focused on making EV technology more reliable, easy to use and economically efficient. The V2G technology gains much importance in this context and is studied earnestly.

Plug in Electric vehicles can be seen as loads as well as energy sources connected to the grid. The load presented by PEV varies according to their charging behaviour, charging parameters and patterns [1]. There are two different modes of operation namely V2G and G2V. During Grid to Vehicle operation (G2V) the vehicles act like normal loads while V2G is where energy is fed back to grid. Another mode of V2G is called V2H where the stored energy in vehicle batteries is used similar to home UPS systems [1].

Based on the power levels, EV chargers can be usually classified as on-board / off-board types. Conventionally, for power levels up to (3-6 kW) on-board chargers with single phase supply are preferred. A simple unidirectional charger is enough to charge a vehicle battery meeting specifications for voltage and current waveforms. In contrast, an advanced charger can perform different operations advantageous to the EV owner. The advanced chargers designed for V2G can provide services like: 1) voltage support, 2) reactive power compensation, 3) harmonic filtering, 4) power factor regulation, 5) load balancing, and 6) peak shaving. Also in the event of a grid failure the charger should support energy feedback operation with the EV battery working like a UPS battery system enabling vehicle-to-home (V2H) or vehicle-to-any load (V2X) mode [2].

With the advent of newer information and communication technologies power grids are being transformed into smart grids and EVs can be used as a platform for efficient integration of alternate energy sources into the grid [3] .The bidirectional chargers can allow the EV battery to act like a distributed energy storage facility that can collect and feed the energy back into grid as requirement surfaces. The primary aim with the development of such a charging interface is it should be able to draw and give back sinusoidal current ensuring reduced harmonic current during both G2V and V2G modes [2]. The profit maximization from such a V2G scheme depends on the coordinated charging implementation in place of dumb charging ensuring that EV charging is done during times of less demand and cost and energy feedback during peak demand and hi higher energy cost. Algorithms for the optimization of such a scenario are another research topic of interest [10].

The Simplicity of architecture and ease of implementation are two important factors considering for such a bidirectional converter design. Accordingly in this paper a bidirectional converter with an H bridge AC/DC converter as the front end and a non-isolated buck boost converter as the bidirectional DC/DC converter is selected. The working of such a converter under both V2G/G2V is studied with the help of simulations.

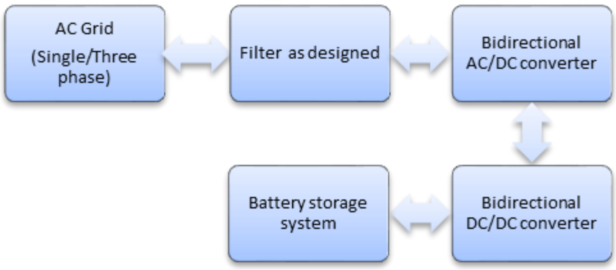

Fig.1 General Architecture of Bidirectional charging interface

2. THE SINGLE PHASE BIDIRECTIONAL CONVERTER

The objective of this paper is the study of a single phase Bidirectional converter developed with the aim of feeding energy back to the grid i.e. V2G operation of EV. The bidirectional converter is implemented using the subunits as mentioned in Fig.1.The choice of each sub modules depends on the purpose for which the converter is designed. V2G implementation with different types of circuits is reported in the literature. A full-bridge IGBT based Bidirectional AC/DC converter coupled to a non-isolated buck-boost BDC through a dc-bus capacitor is studied in [5]. Here the working of the charger for G2V, V2G, V2H modes and their control algorithms using PI Controllers are explained. In [3] also the circuit structure and the controller structure remains the same but the PI controller action is implemented in association with the Energy management system or the smart meter signals. Here the system design has been evolved ensuring a continuous communication with the grid and battery parameters and thus the flexibility and reliability of the V2G feedback is considerably improved. In [7] Rajalakshmi et.al has proposed a hysteresis current controller for the PWM control and grid synchronization of the AC/DC converter. In [2] the reactive compensation capability of such a bidirectional circuit is researched in detail.

Here in this paper the Bidirectional converter circuit consisting of a Full bridge converter with simple current control coupled to a non-isolated buck-boost Bidirectional DC/DC converter through a dc-bus capacitor is studied. The system is designed to charge a 120V, 10AH battery particularly in usage for Light motor vehicles commonly used in India. The V2G mode is designed with the intention of feeding power back into the 230V, 50Hz grid at the rate of 10A.The design and implementation of the passive parameters and its control circuitry is explained. The converter that is developed could charge the batteries of electric vehicles or discharge the battery to Grid depending on the condition of power supply availability and the state of charge present in battery.

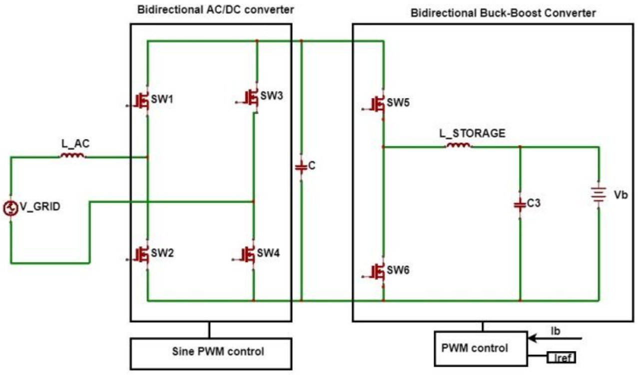

Fig.2 Bidirectional Converter circuit

2.1 G2V or Grid to Vehicle mode

In grid to vehicle or G2V mode the charging of battery occurs. A charging Interface should be able to ensure clean sinusoidal current in phase with the grid void of harmful harmonic currents and near UPF operation. The H bridge converter acts as a synchronous rectifier, the output of which is fed to the DC link Capacitor. The DC link maintains the balancing between the AC-DC converter and DC-DC converter. The bidirectional DC/DC converter acts like a buck converter with current control and steps down the DC link voltage to nominal Battery voltage required for charging of batteries.

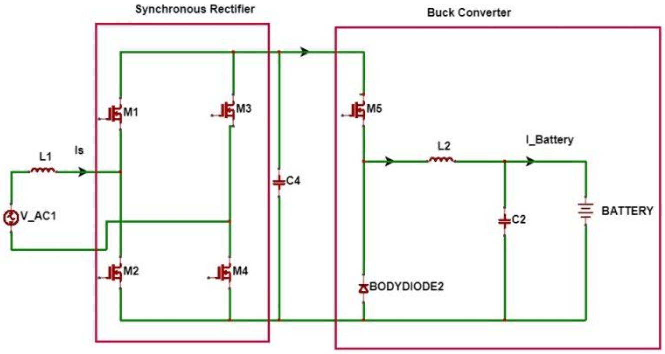

Fig.3 Bidirectional converter circuit during G2V mode

2.2 V2G or Vehicle to grid mode

In this mode the energy stored in the EV battery is fed back to the grid .The DC/DC converter works as a boost converter and pumps up the voltage value to the DC link value from the nominal battery voltage. Here the AC/DC Converter acts as an Inverter and converts the DC into sinusoidal AC with as less harmonic components as possible. Grid synchronization is ensured with the help of the controller that generates unit sine current according the reference given and the energy is fed back into the grid. The current through grid connected Inductor L_AC is measured and compared with the reference and the PWM switching pulses are produced. The reference signal is a unit sine wave imposed by the current reference in phase to the grid. This ensures sine PWM modulation and sinusoidal waveforms during the feedback. If we are able to control the phase of the current being fed back into the grid reactive compensation could also be tried.

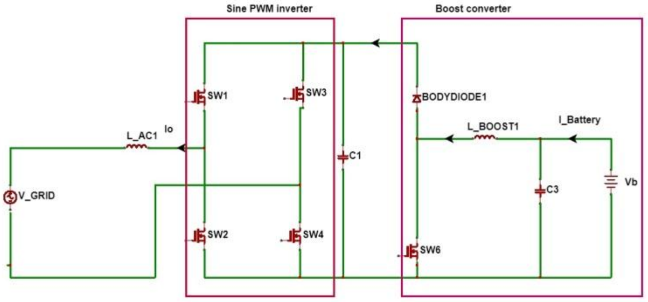

Fig.4 Bidirectional converter circuit during V2G mode

2.3 Control Strategy

Here the Bidirectional Buck boost converter is controlled by two separate PI loops governed by the current reference according to the modes. The current in the buck boost inductor is continuously compared to a reference during each of the modes and the PI controller generates switching signals for each of the switches as the mode in which converter works. During the V2G mode SW6 is switched on while the body diode of the SW5 conducts ensuring the working in boost mode .While in G2V mode then the current flows into the battery thus charging it. Here SW5 is switched on while the body diode of SW6 conducts thus ensuring buck mode operation. The output of these PI controllers are compared with high frequency carrier waveforms of 25KHZ frequency and PWM switching pulses are produced.

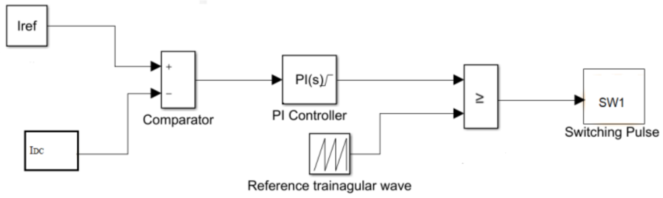

Fig.5 The control block diagram for DC/DC converter

For the AC/DC converter a dual loop control method is used. Here first the DC link Voltage is compared with the reference voltage and the error is given to a PI controller which generates the control signal over which a unit sine wave in the grid frequency is imposed over so as to maintain the in phase requirement when the power is fed back into the grid. The output current control is taken as reference for an inner current control loop which compares this value and the sensed input inductor current value. The output of this loop is compared with a fixed-frequency triangular carrier wave and switching pulses for the MOSFETs of single-phase bidirectional AC-DC converter are generated.

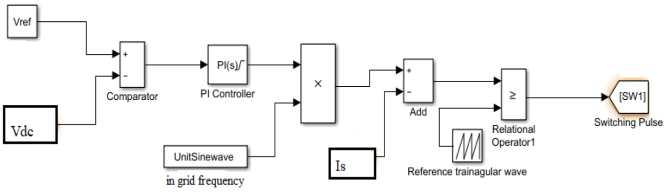

Fig.6 Control block diagram for AC/DC converter

3. DESIGN OF THE SINGLE PHASE BIDIRECTIONAL CONVERTER

The Bidirectional AC/DC converter is designed for a power of 2.4 KW. Such converters are needed to work in PFC mode during synchronous rectification and as Sine PWM inverters during the energy feedback mode. One of the major factors to be taken into consideration during the energy flow modes is the interaction between Grid and the Vehicle. So modeling the grid accordingly is an important task. The Grid voltage is considered sinusoidal and is expressed as:

$$v_s(t) = \sqrt{2}V_s \mathrm{Sin}(\omega t) \qquad (1)$$

Where $v_s(t)$ being the instantaneous grid voltage and V_S being the RMS value. The relation for fundamental component of converter voltage can be given as:

$$v_c(t) = \sqrt{2}V_c \sin(\omega t - \theta) \qquad (2)$$

Where θ being the angle between $v_s(t)$ and $v_c(t)$ [6].
Also the grid instantaneous current can be taken as:

$$i_s(t) = \sqrt{2}I_s \sin(\omega t - \emptyset) \qquad (3)$$

with $\emptyset$ being the angle between $i_s(t)$ and $v_c(t)$ [6].
The direction of power flow is determined by the phase difference between $v_s(t)$ and $v_c(t)$. The active power is provided by the grid as long as $v_s(t)$ leads $v_c(t)$, and it is taken in to the grid when $v_s(t)$ lags $v_c(t)$. Since both $v_s(t)$ and $v_c(t)$ are assumed sinusoidal, $i_s(t)$ is also sinusoidal and its phase angle, $\emptyset$ determines the direction of the reactive power flow [6].

Taking the modulation index m as equal to 0.9 and V_{DC}, the DC link voltage being equal to 400V and the power taken as 2.4KW, the inverter output voltage V_C = 254V. Then the grid inductance can be calculated using the equation:

$$V_s^2 + (I_s^2 * X_L^2) = V_C^2 \qquad (2)$$

where the V_C indicates the converter voltage as calculated above and V_S indicates the RMS source voltage and Is indicates the RMS source current and is found to be equal to 6.73MH.The value of the DC link Capacitor can be found by the equation:

$$C_{DC} = \frac{I_{DC}}{(2*\omega*V_{DCripple})} \qquad (3)$$

where I_{DC} can be obtained by $\frac{P_{DC}}{V_{DC}}$; $V_{DC\,ripple}$ is about 5% of V_{DC}, and the ω indicates angular frequency. Therefore we get the DC link capacitance value around 1mF.Now to calculate the filter or the output inductance of the bidirectional DC/DC converter: For buck converter Source voltage is the DC link Voltage and Output voltage is battery voltage

$$V_B = V_{DC} * D \qquad (4)$$

where VB is the Battery voltage and VDC is the dc link voltage and D being the duty ratio of buck converter. Similarly the output voltage of boost converter is given as

$$V_B = V_{DC} * (1-D) \qquad (5)$$

So overall the inductance can be calculated by the equation:

$$L = \frac{(V_B\ )*(1-D)}{\Delta I_L * f_{sw}} \qquad (6)$$

And the value is obtained as 7.34 μH.

Design of PI controllers for the Buck boost DC/DC converter is done based on current reference control. The PI controller closely tracks the reference current and gives a control signal to minimize the current error which is calculated from the reference converter current and a sensed converter current at any instant of time.
The PI control can be described by combining the Equations for the proportional mode and integral mode as:

$$P = K_P e_p + K_p K_i \int e_p + p_{i(0)} \qquad (7)$$

Where $p_{i(0)}$= Integral term value at t = 0 (initial value).

In a PI controller the proportional gain always changes the net integration mode gain; on the other hand the integration gain can be independently adjusted. The controller output is provided through a combination of proportional and integral action that finally leaves the error at zero. The controller specifications of a converter are designed as to obtain Minimum steady state error and lowest settling time.

4. SIMULATION ANALYSIS

The model of the bidirectional converter was simulated in MATLAB/SIMULINK with the parameters as given below.

Table -1: Simulation Parameters

Simulation Parameters	*Values*
VAC, IAC	230V,10A
Prated, VDC	2.4KW,400V
L_AC	6.73mH
CDC	1mF
L_storage	7.34μH
Vb	120V

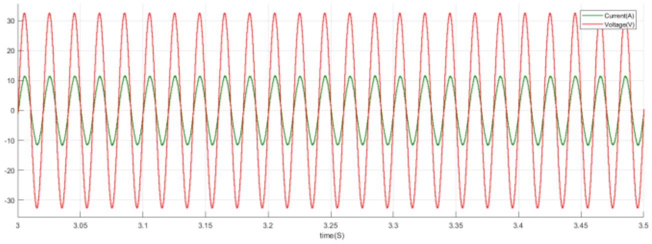

Fig.7 Voltage and Current waveforms during G2V i.e. charging mode

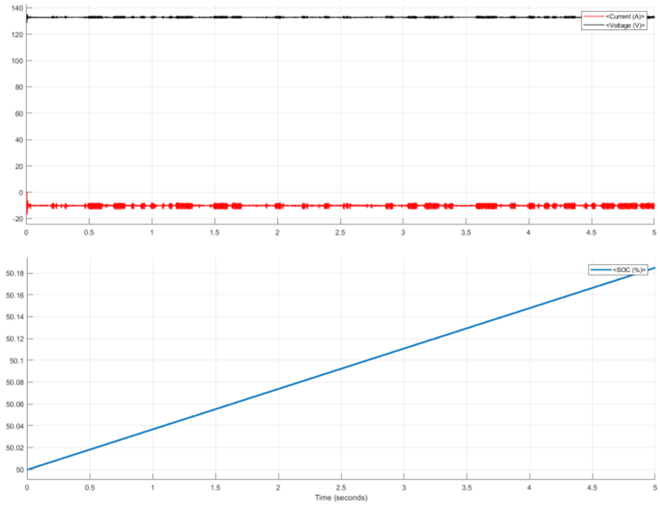

Fig.8 Battery side parameters during charging operation (G2V mode)

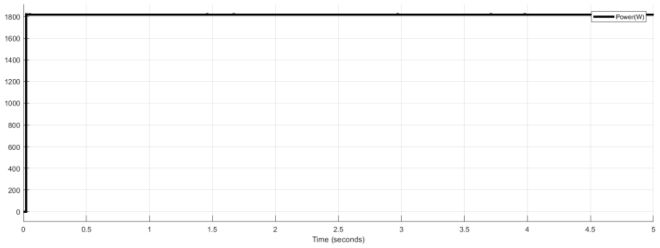

Fig.9 Power taken by converter during G2V mode

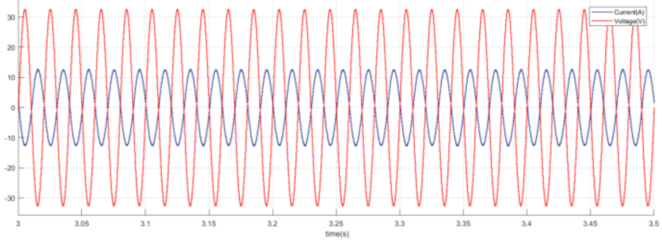

Fig .10 Voltage and Current being fed back in V2G mode.

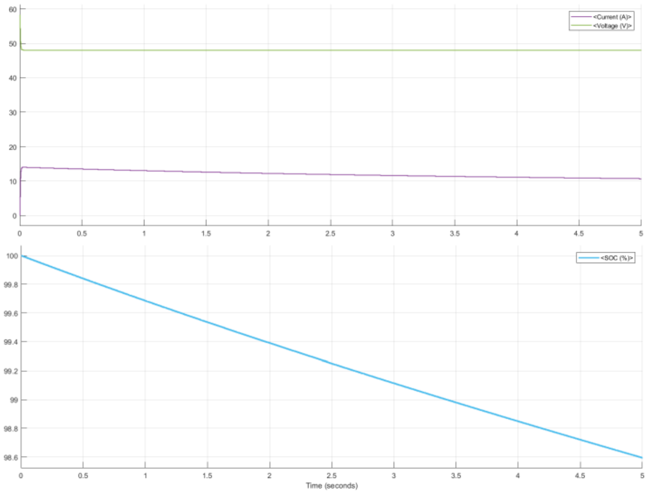

Fig. 11 Voltage, Current and SOC of the battery during V2G mode.

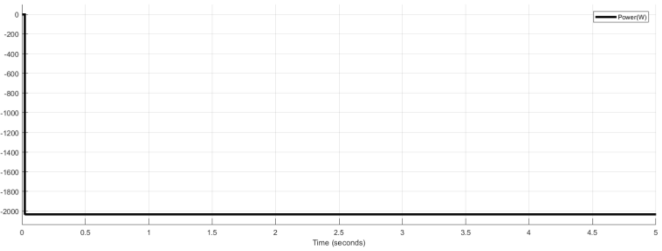

Fig.12 Power being fed back during V2G mode

The simulation results show the current and voltage being fed back during the V2G mode. In fig.5 it is shown that while power is being delivered to the grid, the injected current is in the reverse direction of the grid voltage, which can be seen from phase opposition condition of the voltage and current waveforms. Even then, zero crossing of the grid voltage and injected current are still matching each other. Fig.6 shows the active power being fed back from the battery into the grid. Since the power is fed back it shows a negative value.Fig.7 shows the battery parameters during the discharge phase. Fig.8 shows the battery parameters during charging. .As we can see the battery voltage and current are being maintained constant during both charging and discharging modes.

The dual loop controller for the AC side and the PI controller for the DC side works vigorously and controls the battery side and grid side parameters to be constant during both V2G and G2V modes. The control strategy works very effective allowing very little transient disturbance as can be seen from the waveforms below.

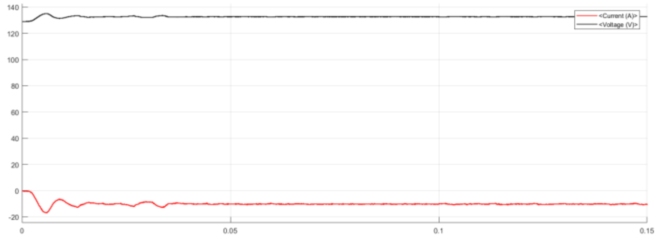

Fig.13 DC/DC converter Current and voltage waveform at the initial instants of G2V mode

Also the controllers limit the current and voltage effectively within the allowable range and the variation is very little. The settling time is considerably less and the waveforms settle down with a smooth variation.

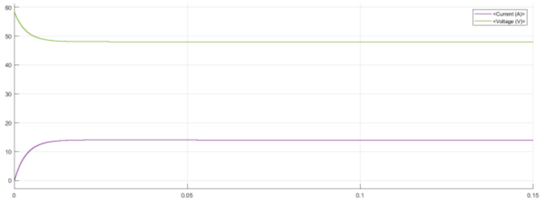

Fig.14 Current, Voltage waveforms of DC/DC converter during initial instants of V2G mode.

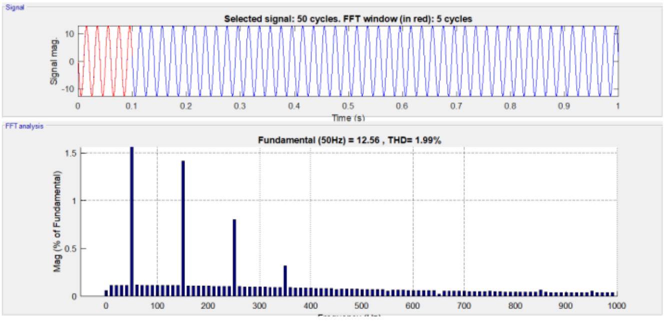

Fig.9 FFT analysis of the current during V2G mode

The THD (Total Harmonic Distortion) of the grid current is found below 5% and therefore complies with IEEE standards.

5. CONCLUSION

A Bidirectional Converter for V2G application is designed and simulated. The Bidirectional converter includes two sub modules namely an H bridge bidirectional AC/DC converter and a Buck boost non isolated DC/DC converter being coupled by a DC link capacitor. Both AC/DC and DC/DC converters are implemented with independent current controls. The DC/DC converter is being controlled by two different PI loops which work on reference current values. The Converter was simulated using MATLAB/SIMULINK software and the results were analyzed.

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