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Vehicle to Grid Bidirectional Energy Transfer: Grid Synchronization using Hysteresis Current Control

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***Abstract*—This paper 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-Vehiclemode,the grid supply is used to charge the battery.A 1-Φ bidirectional AC to DC converter and DC to DC converter is used for the electrical power transfer across the electric vehicle and the grid targeting Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) technologies. Grid's AC supply is rectified to a DC supplywith the help of a bidirectional AC to DC power converter. A bidirectional DC to DC buck-or-boost converter is used to implement the charging and dischargingof the electric vehicle's battery. Grid synchronization is done using the Hysteresis Current Control method. The topology is verified through MATLAB Simulink simulation.**

Keywords*—Electric Vehicle(EV), Grid-to-Vehicle (G2V), Vehicle-to-Grid (V2G), Bidirectional AC to DC converter, Bidirectional DC to DC converter, Hysteresis Current Control.

I. Introduction

EVs were actually a mode of transportation. But nowadays it can be considered as a backup power source. PHEVs (Plugged in Hybrid Electric Vehicles) are the newest trend. The conventional Internal Combustion engine vehicles are going to be replaced by PHEVs in the near future, the Vehicle-to-Grid technology will gain its importance. Electric vehicles sale is down in the market due to the cost issue. If Vehicle-to-Grid technology is facilitated then the cost issue can be solved. The electric 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.

In [1], the authors discusses about a practical strategy for implementing V2H in an urban housing complex thereby resulting in multiple benefits such as improved transformer sizing, reduced distribution losses, and reduced transformer losses and financial incentives through V2G transactions.

Vehicle to Home is another trend. The energy stored in the battery is used to power homes. One electric vehicle can give an output of 10 kWh which is the average energy drawn by 10 houses [2] [3]. [4] gives the impact of V2G in the Indian scenario.

Many converter topologies and their performance indices are discussed in [5]. [6] gives the topology for AC to DC converter for plugged in hybrid EV. [7] gives the topologies for the AC to DC converter and the DC to DC converter connected by a capacitor that shares a DC link voltage.

There are many ways to synchronize an inverter to the grid. The inverter's output frequency, phase, voltage etc. has to be synchronized with the grid. Many grid synchronization methods are available like Zero-crossing detection, Delayed signal cancellation, Adaptive notch filter, Artificial intelligence as explained in [8][9]. [10] discuses on the method of hysteresis current control for the grid synchronization of a grid connected inverter.

After introduction, Section 2 describes the system overview explaining the modes of operation. Section 3 presents the control strategy where all the converters and the grid synchronization method is explained in detail. Section 4 gives all the design specification. Section 5 talks about the simulation study done in the area of Vehicle to Grid and the results obtained are analyzed. Finally, Section 5 deals with the main conclusions obtained.

II. System Overview

The system designed is a circuit consisting of converter to operate both in V2G and G2Voperating modes. The overall developed system is shown as a block diagram in Fig.1.

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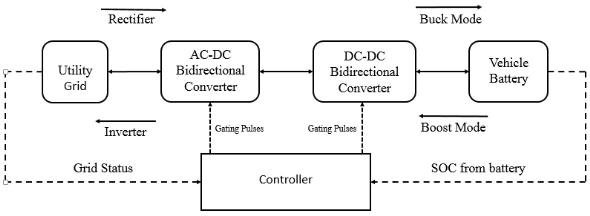

Fig.1. Proposed system of Vehicle-to-Grid.

The primary objective of this paper is to achieve a flow of power between the power grid and the electric vehicle the 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 converterwhile charging the battery and in the step up mode during the discharge of the battery.

A. Modes of Operation

There are two basic modes of operation: Grid-to-Vehicle(G2V) mode and Vehicle-to-Grid (V2G) mode.

i. Grid-to-Vehicle Mode of Operation

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 operatesin buck mode by stepping down the DC link voltage to the required battery charging voltage.

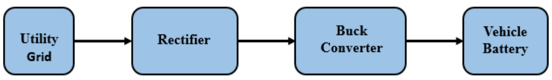

Fig.2. Block diagram of G2V mode of operation.

ii. Vehicle-to-Grid Mode of Operation

In this operating mode, energy stored in the battery is fed 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. Here the proposed grid synchronization technique is using a hysteresis current control.

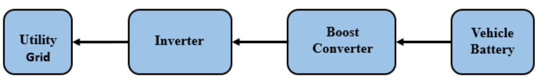

Fig.3. Block diagram of V2G mode of operation.

III. CONTROL STRATEGY

The control strategy for the proposed Vehicle to Grid system is explained in the following flow chart shown in Fig.4.

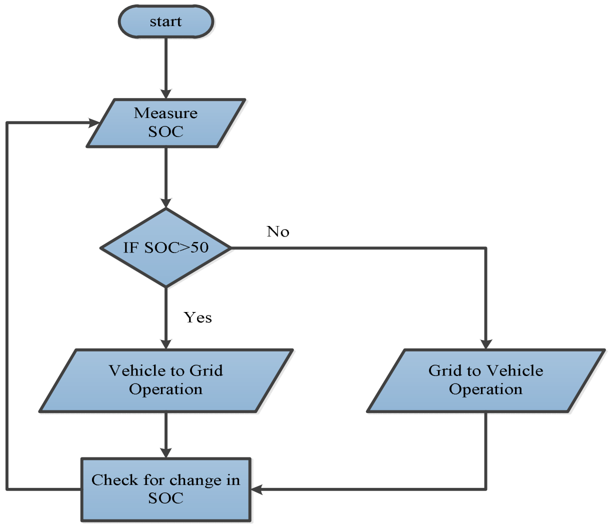

Fig.4. Flow chart of control strategy.

The system consists of two power converters whichbasically shares a common DC link capacitance. For interfacing the battery with grid, a 1-Φfull-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 step up converter in the V2G mode. It is mandatory that the inverter output before feeding to the grid is to be synchronized with the grid. Hysteresis current control method is used for the grid synchronization.

A. Bidirectional AC to DC Converter

This converter acts as both rectifier and inverter in the two modes. In the rectifier mode of operation this converter acts as a diode bridge rectifier by changing the gate pulses for triggering. In the inverter mode of operation the MOSFETs are triggered. The hysteresis mode of current control method has been implemented for synchronizing the inverter output with that of the grid.

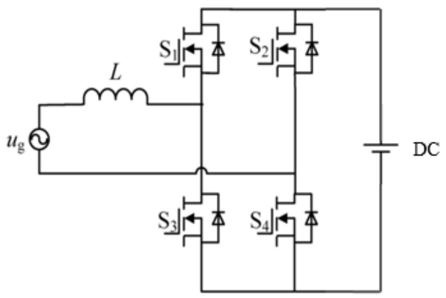

Fig.5. Bidirectional AC to DC converter topology.

B. Bidirectional DC to DC Converter

This converter acts as buck in G2V mode and as boost in V2G mode. 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.

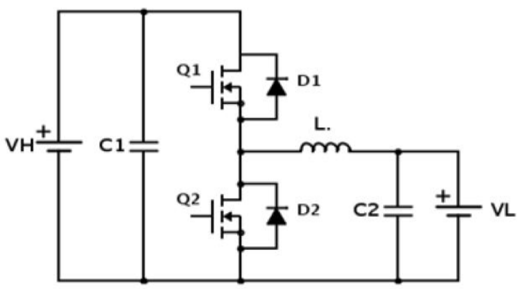

Fig.6. Bidirectional DC to DC converter topology.

C. Grid Synchronization: Hysteresis Current Control

Hysteresis current control method is implemented in the AC to DC bidirectional converter in inverting mode. The inverter circuit consists of four switches, out of which S1 and S2 are switched in fundamental frequencies and S3 and S4 are high frequency switches. A hysteresis band is selected and the inverter output current is controlled to be in between the band. And thus the output currentof the inverter is made in phase to the connected grid voltage.

The hysteresis band width is selected as:

$$h = 0.4 \times I_{grid} (1) Band = I_{grid} + h (2)$$

When the positive half cycle of the grid voltage occurs, S1 is switched on, S4 is switchedon and off to make the inverter output current to be in between the band. And when the negative half cycle of the grid voltage occurs, switch S2 is switched on and the bottom switch S3 is turned on and off to make the inverter current to be in between the band.

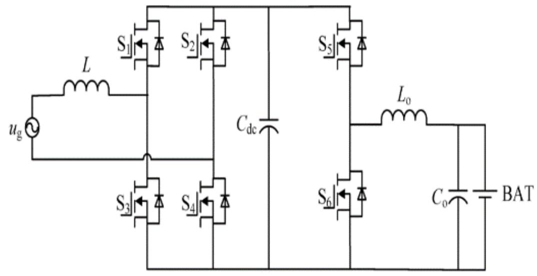

Fig.7. Circuit diagram for the Vehicle-to-Grid.

TABLE I. SWITCHING SEQUENCE FOR INVERTER SWITCHES PROVIDING HYSTERESIS CURRENT CONTROL

Cycle	S1	D1	S2	D2	S3	D3	S4	D4
Positive half cycle	ON	OFF	OFF	OFF	OFF	OFF	ON	OFF
	ON	OFF	OFF	ON	OFF	OFF	OFF	OFF
Negative half cycle	OFF	OFF	ON	OFF	ON	OFF	OFF	OFF
	OFF	ON	OFF	OFF	ON	OFF	OFF	OFF

D. Mode Selection Algorithm: based on SOC of battery

The mode selection between the V2G and G2V is decided based on the SOC of the battery.

If SOC> 50%: V2G mode where battery is discharged to feed the grid.

If SOC<= 50%: G2V mode where battery is charged from the grid.

IV. DESIGN SPECIFICATIONS

The design specifications includes the design for a1-Φ bidirectional AC to DC converter and a DC to DC converter.

A. Design for Bidirectional Buck Boost Converter

For buck converter, the input is obtained from DC link voltage and output voltage is the battery voltage.

$$V_o = DV_s (3)$$

Where $V_s$is the voltage of DC link, V_o is the voltage of the battery and D is the duty ratio.

V_s=400V, V_o=48V and D=0.12. Let the switching frequencyf_{sw}=20 kHz.

The inductance value and the capacitance value is given by

$$L = \frac{V_s - V_o}{\Delta i_L f_{sw}} (4)$$

$$C = \frac{1-D}{8L\frac{\Delta V_o}{V_o}{f_{sw}}^2} \quad (5)$$

By substituting the values in the (4) and (5) equations the inductance value is obtained as 15 mH and the capacitance is $1\mu F$.

For the boost converter, the input is fed from a battery which acts as the input voltage. The boost converter's output voltage V_O is given by equation (6).

$$V_O = \frac{V_S}{1-D} \quad (6)$$

Where V_S being the battery voltage, V_O is the DC link voltage and D is the duty ratio.

V_S=48V, V_O=400V and D=0.88. Let the switching frequency f_{sw}=20 kHz.

The inductance value and the capacitance value is given by

$$L = \frac{V_S\, D}{\Delta i_L\, f_{sw}} \quad (7)$$

$$C = \frac{D}{R\frac{\Delta V_O}{V_O} f_{sw}} \quad (8)$$

By substituting the values in the (7) and (8) equations the inductance value is obtained as 0.6 mH and the capacitance is $20\mu F$.

So the inductance is selected to be 15 mH and the capacitance to be $20\mu F$.

B. Design of Bidirectional AC to DC Converter

Inductance value for the AC to DC bidirectional converter can be calculated as

$$L_{min} = \frac{1}{\%ripple} \times \frac{{V_{ac_{min}}}^2}{P_O}\left(1 - \frac{\sqrt{2}V_{ac_{min}}}{V_O}\right) \times \frac{1}{f_{sw}} \quad (9)$$

The inductance using the equation (9) is obtained as 3.2mH.

C. Filter design

An LC filter is used for removing the harmonics defined by

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (10)$$

For a $f = 100Hz$ assuming C=$100\mu F$ the inductance L is calculated to be 25.3 mH.

The values given in the Table2 are used for the simulation study.

TABLE II. DESIGNED PARAMETERS

Parameters	Values
System	1-Φ, 500W
Grid Voltage	230V
Battery Voltage	48V
AC-DC inductance	3.2 mH
DC-DC inductance	15 mH
DC-DC capacitance	20 μF
LC filter inductance	25.3 mH

V. SIMULATION STUDY

This section deals with simulation study of the Vehicle-to-Grid system. The simulation diagram shown below in Fig.8.verifies the bidirectional flow of power in the developed Vehicle-to-Grid system. The battery used is Lead acid battery of 48V and 20Ah capacity.

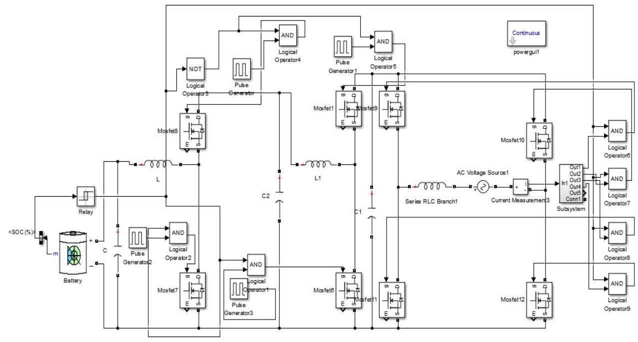

Fig.8. Simulation diagram of Vehicle to Grid system

A. Grid to Vehicle Mode

When the SOC of the battery is less than 50% the battery is charged from the grid. The input voltage and current drawn from the grid is shown in Fig.9.

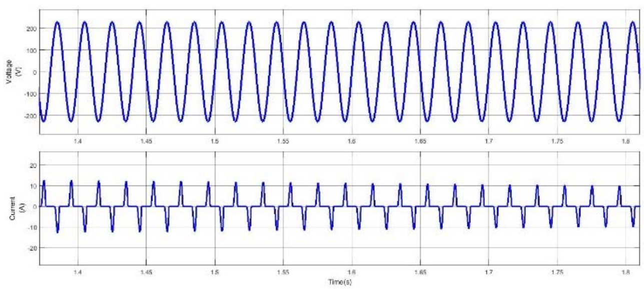

Fig.9. Input voltage and current in the G2V mode.

The peak input voltage of the grid is 325V and the current is 10A. Here the AC-DC converter is under rectifier mode and the DC-DC converter is operating in the bucking mode. The battery charging voltage and current can be seen in Fig.10.

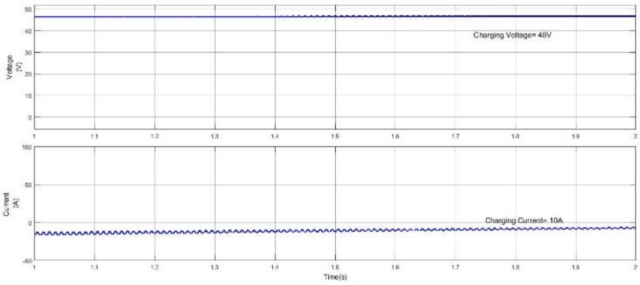

Fig.10. Battery charging voltage and current in the G2V mode.

The output current drawn by the battery is 20A and the voltage across it while charging is 48V.

B. Vehicle to Grid mode

The switching pulses for the inverter is shown in Fig.11. where S1 and S4 are to be switched on for the positive cycleand S2 and S3 are to be turned on for the negative cycle. Hysteresis current control algorithm is such that the top switches (S1 and S2) are switched on for their entire period of operation. And the bottom switches (S3 and S4) are to be switched on and off continuously in their period of operation.

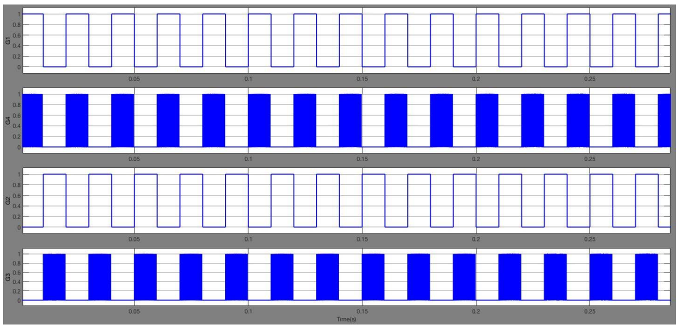

Fig.11. Gating pulses for the inverter switches in the V2G mode.

When the SOC of the battery is greater than or equal to 50% the battery delivers power back to the grid. The output voltage and output current is shown in Fig.12.

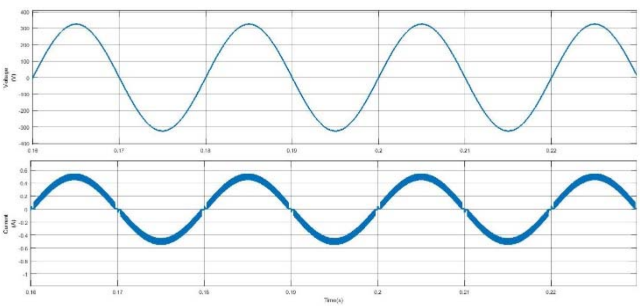

Fig.12. Output voltage and output current in V2G mode.

Output voltage is 325V peak and an output current of 0.8A flows to the grid. The DC to DC converter steps up the battery voltage and the AC-DC converter works in the inverter mode thereby converting the DC voltage to AC and feeds it to the grid. For synchronizing the inverter's output with the power grid the hysteresis current control method is implied.

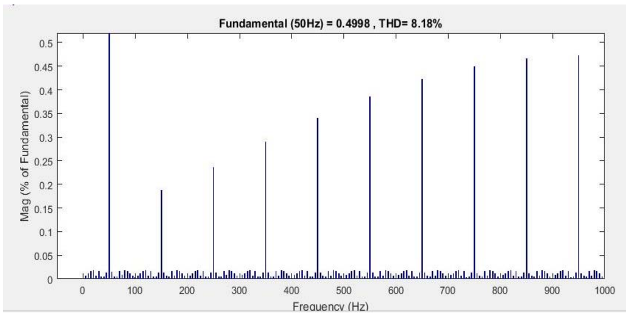

Fig.13. FFT analysis of the inverter output current in the V2G mode.

The output current of inverter is made to undergo a FFT analysis which is shown in Fig.13. Using the powergui toolin the MATLAB Simulink the output current's FFT analysis done. The THD is obtained to be 8.18% with the LC filter.

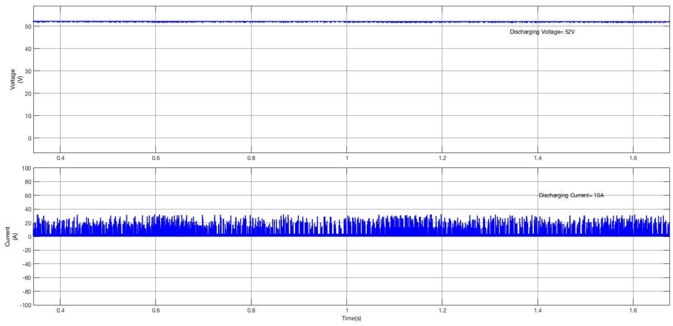

Fig.14. Discharging voltage and current waveforms of battery during V2G mode.

The battery discharging voltage and discharging current are shown in Fig.14.

The details obtained about the battery discharge from the graph is 52V as battery discharging voltage and the discharging current is 0.8A. The battery when full has a voltage of 52V and when the SOC is low the voltage is 48V. So the nominal voltage range is 48-52V. In the V2G mode, the battery SOC is made to 100% and is then simulated. So the battery voltage is 52V.

VI. CONCLUSION

In vehicle to grid technology, main emphasis is on the V2G mode where the grid gets the power from the energy which is stored in a battery. The bidirectional property of the AC to DC power converter 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 vehicle and the grid is completed.

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