Grid to vehicle and vehicle to grid energy transfer using single-phase half bridge boost AC-DC converter and bidirectional DC - DC converter

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Abstract

A system configuration based on a single-phase unity power factor (PF) half-bridge boost converter and bidirectional DC-DC converter based energy transfer from electrical vehicle to grid(V2G) and grid to vehicle (G2V) is proposed with detailed analysis. The efficiency of this conversion system is high because there is only one series semiconductor on-state voltage drop at any instant. The analytical results are verified through simulation using switched and averaged circuit models of the system at 230V AC input and DC output. The simulation result demonstrates an improved power factor at AC mains. In the second stage, a bidirectional buck–boost DC-DC converter is used to charge and discharge the battery of the PHEV (Plug-in Hybrid Electric Vehicle). In discharging mode, it delivers energy back to the grid at 230V, 50 Hz. A battery with the charging power of 3.6 kW at 240V is used in PHEV. The buck-boost DC-DC converter is used in buck mode to charge and in a boost mode to discharge the battery.

Keywords: Plug-in Hybrid Electric Vehicle (PHEV), Half Bridge Boost AC-DC converter, DC-DC converter, Vehicle to grid (V2G), Bidirectional DC-DC converter, Power quality

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1. Introduction

There are many bidirectional AC-DC PFC converters which can be used in the energy transfer from vehicle to grid (V2G) and grid to vehicle (G2V). V2G is a version of battery-to-grid power applied to vehicles. There are three different versions of the vehicle-to-grid concept (Singh et al., 2003).

• A hybrid or fuel cell vehicle, which generates power from storable fuel, uses its generator to produce power for a utility at peak electricity usage periods. Here the vehicles serve as a distributed generation system, producing power from conventional fossil fuels or hydrogen fuel cell.

• A battery-powered or plug-in hybrid vehicle uses its excess rechargeable battery capacity to provide power to the electric grid in response to peak load demands. These vehicles can then be recharged during off-peak hours at cheaper rates while helping to absorb excess night time generation. Here the vehicles serve as a distributed battery storage system to buffer power (Kempton et al., 2005; Han Sekyung et al., 2010).

• A solar vehicle uses its excess charging capacity to provide power to the electric grid when the battery is fully charged. Here the vehicle effectively becomes a small renewable energy power station (http://en.wikipedia). The concept allows V2G vehicles to provide power to balance loads by charging at night when load demand is low and sending power back to the grid when demand is high. An electric vehicle pack has a large amount of energy stored in its battery. The energy from electrical vehicle can be transferred to the grid when there is peak demand of loads or when it is kept in parking and...
simultaneously can be charged in lean period of loads. The efficient control of charging and discharging of the battery is essential to maintain good battery life, safety, and reliability.

In this paper, a configuration with single-phase half bridge bidirectional power converter is proposed for the bidirectional power transfer of a PHEV battery (http://en.wikipedia; Pandey et al., 2004). The system can charge storage battery up to 15A current at 240V. It can also transfer energy back to the 230V, 50 Hz single-phase power at 22A rate. The proposed system is composed of two parts: a single-phase bidirectional half bridge boost AC-DC converter and a DC-DC converter. Single-phase bidirectional half bridge boost AC-DC converter is to convert AC to DC voltage (Jain et al., 2000). The buck-boost DC-DC converter is used in buck mode for charging battery and a boost mode when discharging the storage battery. The charging and discharging of the battery demonstrate the feasibility of the system.

2. System Configuration

The system configuration is shown in Fig.1. A single phase bidirectional half bridge boost AC-DC converter and a bidirectional buck boost DC-DC converter are included in the system (Pandey et al., 2004; Jain et al., 2000). The structure of system shown in Fig.1 consists of an inductor connected between single phase AC and single phase bidirectional half bridge boost AC-DC converter which is necessary to boost DC output in order to charge the battery (Heydt et al., 2010). The single-phase bidirectional half bridge boost converter is designed for 4 kW and storage battery of 3.6 kWh is charged at 240V and 15A rate using bidirectional DC-DC converter. The DC-DC converter is shown in Fig.2. In charging mode, the DC bus voltage must be higher than the battery voltage, in charging mode the circuit becomes buck converter circuit (Mohan et al., 1995). Through controlling the PWM duty ratio in buck mode, the charging current is controlled. In discharge mode this circuit becomes a boost converter circuit.

3. Design of the System

The design of the various components of proposed configuration for energy transfer from grid to vehicle and vehicle to grid consists of a single phase half bridge boost AC-DC converter, a bidirectional DC-DC boost converter, and a battery energy storage system. The detailed design of each part is given in the following sections.

3.1 Design of Single-Phase Half Bridge Boost AC-DC Converter

In the half-bridge boost AC-DC converter topology shown in Fig. 1, the voltage drop of semiconductor devices at any instant of time is only one device. In addition to the above advantage, the half-bridge boost converter can regenerate the output power, while the single-switch boost rectifier cannot feed energy back to the source (Wall et al 1997). The half-bridge boost rectifier may be used in application requiring high DC bus voltage such as UPS systems, a line conditioner and a single-phase to three-phase power conversion. Let us consider that the input source voltage $V_s$ is given as,

$$V_s = V_{sm} \sin \omega t$$

where $V_{sm}$ is the maximum value of the source voltage the value of $V_{sm}$ is 325V for $V_s = 230V$ rms and $\omega = 2\pi f$. The input current is given as (Ramesh et al., 1998),
\[ i_s = \frac{V_s}{R_e} = I_{sm} \sin wt \]  \hspace{1cm} (2)

where \( R_e \) = emulated resistance. The value of \( V_s \) is 230V. The normalized input voltage \( M_s \) is given as,

\[ M_s = \frac{V_{sm}}{V_{dc}} = M_g \sin wt \]  \hspace{1cm} (3)

where the value of \( V_s \) is 325V and the value of \( V_{dc} \) is 800V. The calculated value of \( M_s \) from eq. (3) is 0.40625. The value of emulated resistance \( (R_e) \) is given as,

\[ R_e = \frac{V_{sm}^2}{2P_0} \]  \hspace{1cm} (4)

where \( V_{sm} \) is 325V and \( P_0 \) is output power. The value of \( P_0 \) is 4kW. The calculated value of \( R_e \) is 13.20\( \Omega \).

\[ \theta_1 = \sin^{-1} \left( \frac{1}{M_s} \frac{\Delta I_{smax}}{I_{smax}} \right) \]  \hspace{1cm} (6)

The calculated value of the \( \theta_1 \) from eq. (6) is 18.70\(^\circ\). The output capacitor of half bridge boost AC-DC converter is given as (Rajesh et al., 2007),

\[ C_1 = C_2 = \frac{P_0}{\omega V_{dc}^2} \frac{1}{2} \left( \frac{\Delta v_{0(max)}}{V_{dc}} \right) \left( \frac{2}{M_s} \cos \theta_1 + 2 \sin \theta_1 \right) \]  \hspace{1cm} (7)

where \( \omega = 2\pi f \) and \( \Delta v_{0(max)} \) is \% ripple voltage and the value of ripple voltage is taken as 10\%. The calculated value of the output capacitor from eq. (7) is 3.06mF. The input power factor of the configuration is given as (Rajesh et al., 2007),

\[ \cos \theta = \cos \left( \tan^{-1} \left( \frac{X_L}{R_e} \right) \right) \]  \hspace{1cm} (8)

The calculated value of the power factor from eq. (8) is 0.9818 (Ramesh et al., 1998; Rajesh et al., 2007). Detailed model parameters are given in Appendix.

### 3.2 Design of Bidirectional Buck Boost DC-DC Converter

The bidirectional buck-boost DC-DC converter is shown in Fig.2. The solid state switch \( S_3 \) is used for buck mode of operation while the switch \( S_4 \) is used for the boost conversion mode. The buck mode is used for charging and boost mode is used for discharging the battery. The relationship between switching frequency \( f_{sw} \), inductance \( L_i \), in buck–boost mode is given as (Saber et al., 2010),

\[ f_{sw} = \frac{1}{2 \pi L_i \left( \frac{1}{V_{dc}} + \frac{1}{V_b} \right)} \]  \hspace{1cm} (9)

where \( P \) is conversion power, \( V_{dc} (V_{dc}+V_{dc}) \) is input voltage and \( V_b \) is output voltage and \( f_{sw} \) is the switching frequency and its value is 50 kHz. The value of \( P \) is 4 kW, \( V_{dc} \) input voltage 800V and \( V_b \) is output voltage is 240 V. From eq. (9), the value of \( L_i \) is 3.23 mH (Kisacikoglu et al., 2010). Detailed design parameters are given in Appendix.
3.3 Design of Storage Battery

The charging and discharging of battery play an important role in PHEV. A lead-acid model battery is implemented in MATLAB/simulink using a model given in (Massimo et al., 2000). Fig. 3 shows a Thevenin’s equivalent of the storage battery as an energy unit. Its storage energy is represented in kWh which is stored in an equivalent capacitor \( C_b \) expressed as,

\[
C_b = \frac{(kWh \times 3600 \times 1000)}{0.5(V_{ocmax}^2 - V_{ocmin}^2)}
\]

where \( V_{ocmax} \) is the voltage at the terminal of the battery when it is fully charged and \( V_{ocmin} \) is the voltage at the terminal of the battery when it is fully discharged. In this equivalent model of the battery (Massimo et al., 2000), \( R_s \) is the equivalent series resistance of the battery, the value of \( R_s \) is taken 0.01 \( \Omega \). The parallel circuit of \( R_b \) and \( C_b \) represents the self discharging of the battery. The value of \( R_b \) for this battery is taken as 10k \( \Omega \). Here the battery is designed, having capacity of 3.6 kW for 15 Hrs, and with the variation in the voltage of order of 212 V to 272V. The calculated value of \( C_b \) for this battery is from eq. (10) is calculated as 3616.92 F (Massimo et al., 2000).

4. Control Algorithm

The control algorithm for different blocks of proposed system is given in this section. The control algorithm plays an important role in the operation of such system and it is explained as follows.

4.1 Control of Half Bridge Boost AC-DC Converter

A half-bridge converter system is shown in Fig.1. In each switching cycle \( T_s \), the converter switches \( S_1 \) and \( S_2 \) are turned on and turned off by complementary gating pulses. \( S_1 \) is turned on for duration of \( DT_s \) and \( S_1 \) for \( (1-D) \) \( T_s \), where \( D \) is the duty ratio. With \( S_2 \) on and \( S_1 \) off, the voltage applied across inductor \( L \) is \( (V_s + V_{o2}) \). Again, with \( S_1 \) on and \( S_2 \) off, the same is \( (V_s - V_{o1}) \). The switching frequency \( (f_{sw} = 1/T_s) \) is considered to be high. The duty ratio \( D \) is given by the volt-second balance across the inductor is given as

\[
V_s = V_{o1} - D(V_{o1} + V_{o2})
\]

(11)

Since a half-bridge converter has a split DC bus, both the output voltages \( V_{o1} \) and \( V_{o2} \) must be controlled. These two voltages must also be equal in the steady state condition. Here a PI (Proportional integral) voltage controller is used each for controlling \( V_{o1} \) and \( V_{o2} \) as shown in Fig. 1. The outputs of the two controllers \( P_1 \) and \( P_2 \) are \( V_{m1} \) and \( V_{m2} \), respectively. The two outputs \( V_{m1} \) and \( V_{m2} \) are used to control the emulated resistance, \( R_e \), of the whole converter. The output of PI controller 1 is given as,

\[
V_{m1} = V_{ref} - (V_{o1} + V_{o2})K_1
\]

(12)

where \( V_{ref} \) is considered as 800V.

The output of PI controller 2 is given as,

\[
V_{m2} = V_{ref} - (V_{o1} - V_{o2})K_2
\]

(13)

Consider \( V_c \) is the required carrier wave when \( V_{o1} = V_{o2} \), and \( V_{m1} = V_{m2} \). The corresponding switching instants for \( S_1 \) and \( S_2 \) are determined by the intersection of \( I_{ref} \) with \( I_c \). It should be noted that the positive and the negative peaks of \( V_c \) are \( (V_{m1}) \) and \( (-V_{m2}) \) respectively, as per eqs. (11), (12). Now if \( V_{o1} \) tends to become less than the desired reference level, while \( V_{o2} \) is equal to the reference, the voltage controller, controls \( V_{o1} \) and ensures \( (V_{m1} = V_{m2}) \). The modified carrier wave is used to generate the modified gating pulses for \( S_2 \) and \( S_1 \) respectively. This results in transfer of excess energy, stored in \( C_2 \), to \( C_1 \) to balance both \( V_{o1} \) and \( V_{o2} \). Similar explanation may be given for other mode of operation (Medina et al., 2010, Rajesh et al., 2007).
4.2 Control of Bidirectional DC-DC Converter

In order to control the charging and discharging of the battery using a bidirectional buck-boost converter, a technique based on PWM control is used here. A proportional integral (PI) controller is used to control the output DC current. The PI voltage controller closely monitors the reference DC link current and generates a control signal \( V_{cs} \) to reduce the current error \( I_{es}(k) \) which is generated from the reference DC link current \( I^*_b(k) \) and a sensed DC link current \( I_b(k) \) at the instant of time as,

\[
I_{es}(k) = I^*_b(k) - I_b(k)
\]

The output of the PI controller \( V_s(k) \) at the instant is given as,

\[
V_s(k) = V_s(k-1) + K_pv \{ I_{es}(k) - I_{es}(k-1) \} + K_iv I_{es}(k)
\]

where \( K_pv \) and \( K_iv \) are the proportional and integral gains of the voltage controller. This technique is applicable for buck-mode as well as boost mode. The output of the controller \( V_s(k) \) at the instant is compared with fixed frequency (\( f_{sw} \)) saw-tooth carrier waveform to get the control signals for the solid state devices of the bidirectional buck-boost converter (Kisacikoglu et al., 2010). Detailed design parameters are given in Appendix.

5. Matlab based Modeling

The MATLAB/SIMULINK model of the proposed topology for energy transfer from the vehicle to grid and grid to vehicle is shown in Fig.4. It consists of a model of single-phase bidirectional half bridge AC-DC converter. This single-phase half bridge bidirectional AC-DC converter is designed for a power of 4kW. The bidirectional DC-DC buck-boost converter is used for charging and discharging of the battery of PHEV. The detailed design parameters of bidirectional buck-boost converter are given in Appendix. An energy storage system is designed for the capacity of 3.6 kW for 15 Hours within the voltage variation in the voltage of 212 V to 272V. Detailed design parameters of storage battery are given in Appendix. Simulation is carried out in MATLAB version of 7.8 the sim power system toolbox using ode (26tb/stiff/TR-BDF-2) solver in discrete mode at 1e-6 step size.

6. Result and Discussion

Simulated results are presented for plug-in modes in Figs. 5-8. The current delivered from the grid while charging is shown to be sinusoidal and in phase with the grid voltage. This eliminates current harmonics and maintains a unity power factor. When delivering power to the grid while discharging, the injected current is in the phase opposition of the grid voltage, which can be seen from 180° phase difference and it has maintained unity power factor operation. Although some brief voltage disturbances occur during abrupt load changes, the converter maintains constant DC link voltage, while supplying or absorbing the required current. The rise and fall in the battery voltage while charging and discharging are shown in these figures corresponding to the maximum and minimum open circuit battery voltages. The voltage profile is demonstrated in Figs.5-8. Fig.5 shows the complete profile of charging and discharging of electrical vehicle. From 0 to 3s, the battery of electrical vehicle is in charging mode at 3s the battery is switched in to discharging mode. There are some fluctuations in the DC link voltage at this point which are
minimized with effective control. In Fig.6 the charging mode of battery is switched to discharging mode the switching state of conversion is shown in which the battery current has become negative and the grid current is out of phase with grid voltage. There is change in the mode of operation i.e. from buck mode to boost mode. In Fig.7 at 2s to 2.2 s, charging mode of operation is shown i.e. boost mode. The voltage across capacitors C₁ and C₂ are V₀₁ and V₀₂ which are shown in this Fig.6. The battery is charged at 15A rate.

The value of the source current is 25A. Fig.8 shows the discharging mode of operation from 5s to 5.2s and at the same point of time the direction of current is in 180° phase opposition. This shows the reversal of current and flow of power in reverse direction. The value of the current fed back to grid is 22.5A. In these figures, while showing Vₛ, Iₛ in same figure, Iₛ, grid current is amplified by factor of 10 in order to observe it in comfortably to the given axes. The harmonics spectra for the charging current from grid and discharging current to grid are shown in Fig.9 and Fig.10 respectively. The Total Harmonic distortion (THD) of the charging and discharging current is well within the limit of IEEE-519 standard. The different power quality parameters like current and voltage THD are given in Table-1.
Table 1 shows the parameters like total harmonic distortion (THD) of grid voltage as well as the grid current in charging and discharging mode. The THD of AC mains current are 4.46 and 4.53 respectively which are well within the acceptable limit of IEEE 519. The power factor of the grid current in charging and discharging mode is near to unity and values are 0.9818 and 0.982 respectively.

7. Conclusions

The proposed system has been found suitable for charging and discharging the battery of PHEV. A high efficiency of around 96% is achieved under low-input voltage condition due to a reduced number of semiconductor on-state drops and the use of reduced switches. The proposed converter has delivered the AC current to/from the grid at unity power factor and at very low current harmonics which ultimately prolongs the life of the converter and minimizes the possibility of distorting the grid voltage.
Fig. 9 Harmonic Spectra of the Charging Current

Fig. 10 Harmonic Spectra of the Discharging Current

Table-1: Power Quality Parameter during charging and discharging mode.

| Serial no. | Charging mode | Discharging mode |
|------------|---------------|------------------|
| Current THD % of I | 4.46          | 4.53             |
| Voltage THD % of V | 0.81          | 1.32             |
| Power Factor (P.F) | 0.9818        | 0.982            |

8. Appendixes

Parameters for Single-Phase Half bridge boost AC-DC Converter

\[ K_{i1}=0.25, \, k_{p1}=0.1, \, L_s = 2.3 \text{ mH}, \, K_{i2}=0.009, \, k_{p2}=0.6, \, 4000 \text{ W}, \, 230 \text{ V rms}, \, f_s = 20 \text{ kHz}, \, L = 6.5 \text{ mH}, \, C_1 = C_2 = 3.06 \text{ mH}. \]

Parameters for Bidirectional DC-DC Buck Boost Converter

Buck mode, \( K_{i1}=1, \, k_{p1}=0.001 \) for Boost mode, \( K_{i2}=0.5, \, k_{p2}=0.01, \, f_s = 50 \text{ kHz}, \, L_0 = 3.23 \text{ mH}. \)

Parameters for Storage Battery

\[ R_b=10 \text{ k}\Omega, \, R_s=0.01 \text{ m}\Omega, \, V_{oc}=240 \text{ V}. \]

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