Bi-Directional DC /AC and DC / DC Converter Design and Control for Plug-in Hybrid Cars

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Abstract

A single-phase bidirectional AC-DC converter and bidirectional DC-DC converter is proposed to transfer electrical power from the grid to an electrical vehicle (EV) and from an EV to the grid while keeping improved power factor of the grid. In first stage, a 230 V 50 Hz AC supply is converted in to 380V dc using a single-phase bidirectional AC-DC converter and 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 1.2 kW at 120V 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. A proportional-integral (PI) controller is used to control the charging current and voltage. Simulated results validate the effectiveness of proposed algorithm .

Keywords: Reactive Power Compensation, D-STATCOM , Fuzzy Logic Controller,Power quality Improvement .

I. INTRODUCTION

The global shift toward clean and sustainable energy systems has significantly increased the penetration of electric vehicles (EVs) and plug-in hybrid electric vehicles (PHEVs). These vehicles not only reduce greenhouse gas emissions but also serve as flexible, mobile energy storage units that can interact dynamically with the power grid [1], [2]. As the number of EVs rises, there is an increasing need for efficient and intelligent power electronic converters to manage bidirectional power flow between the grid and vehicle batteries. This bidirectional capability supports both Grid-to-Vehicle (G2V) charging and Vehicle-to-Grid (V2G) discharging modes, enabling features such as peak load shaving, frequency regulation, and demand response services [3], [4]. However, designing a reliable bidirectional charging system poses several technical challenges. These include ensuring high power quality, maintaining unity or near-unity power factor at the grid interface, controlling charging and discharging currents accurately, and adapting to varying grid and battery conditions [5]. To address these, power converter topologies with advanced control strategies are employed. A common architecture consists of a two-stage power conversion system. The first stage uses a single-phase bidirectional AC-DC converter, which interfaces directly with the 230 V, 50 Hz grid and regulates the intermediate DC link voltage (typically around 380 V). It also ensures power factor correction and minimal harmonic distortion in the grid current [6], [7]. The second stage employs a bidirectional buck–boost DC-DC converter, which connects to the EV battery. This converter operates in buck mode during G2V charging and in boost mode during V2G discharging, enabling flexible voltage conversion and precise control of battery current and voltage [8], [9]. In the context of PHEVs, which commonly use battery packs around 120 V, such a converter must be capable of efficiently handling power levels in the range of 1–2 kW while ensuring safe charging profiles and preventing overcharge or deep discharge conditions. The control strategy—typically based on proportional-integral (PI) control—must provide fast dynamic response and steady-state accuracy under different load and grid conditions [10].

Recent research has explored a variety of methods to enhance converter performance, including digital control schemes, soft switching techniques, and integration of renewable energy sources [11]-[16]. Nevertheless, many existing systems are limited by complexity, cost, or lack of adaptability[17]-[22]. Therefore, there is a strong need for cost-effective and scalable converter designs that offer high efficiency, low total harmonic distortion (THD), and robust bidirectional operation.

This paper proposes a dual-stage bidirectional converter system designed for PHEV applications. The system uses a single-phase AC-DC converter followed by a buck–boost DC-DC converter to manage a 1.2 kW, 120 V battery. The control algorithm incorporates PI-based regulation to maintain grid compatibility and ensure proper energy flow. Simulation results are presented to validate the performance of the proposed topology under different operating scenarios.

II. SYSTEM OVERVIEW

The bidirectional charger consists of:

1. Single-phase Bidirectional AC-DC Converter (grid interface)
2. Bidirectional Buck-Boost DC-DC Converter (battery interface)

This two-stage architecture allows:

- Grid-to-Vehicle (G2V) charging
- Vehicle-to-Grid (V2G) discharging

A. AC-DC Converter: Single-Phase Bidirectional PWM Rectifier - Grid Interface Modelling

Input AC Voltage:

$$v_s(t) = V_m sin(\omega t)$$

Grid Current:

$$i_s(t) = I_m sin(\omega t + \phi)$$

V_m: Peak grid voltage

$\omega = 2\pi f$: Angular frequency

ϕ: Phase angle between voltage and current (ideally 0 for unity PF)

B. DC Link Voltage Dynamics

Assume a DC-link capacitor C and grid-side inductor L:

$$v_s(t) = V_m sin(\omega t)$$

$$L\frac{di_s(t)}{dt} = v_s(t) - v_{inv}(t)$$

$$C\frac{dV_{dc}(t)}{dt} = i_{inv}(t) - i_{load}(t)$$

$v_{inv}(t)$: Inverter voltage (controlled via PWM)

V_{dc}: Intermediate DC voltage (~380 V)

III. CONTROL OF PROPOSED SYSTEM WITH CONVERNTIONAL CONTROL

Use synchronous reference frame (d-q transformation): Control real and reactive power independently , PI controllers regulate:

I_d → real power (charging/discharging)

I_q → reactive power (set to 0 for unity PF)

$$\frac{di_d}{dt} = \frac{1}{L}(v_d - Ri_d + \omega L i_q - v_{conv,d})$$

$$\frac{di_q}{dt} = \frac{1}{L}(v_q - Ri_q - \omega L i_d - v_{conv,q})$$

A. Battery Interface Modelling:

In the present research ,the DC link voltage and battery voltage considerations are as mentioned below.

V_{dc}: DC link voltage (~380 V)

V_b: Battery voltage (~120 V for PHEV)

L: Inductor

D: Duty cycle

i_L: Inductor current

Modes of Operation:

i. G2V (Buck mode):

$$V_b = D \cdot V_{dc}$$

ii. V2G (Boost mode):

$$V_{dc} = \frac{V_b}{1 - D}$$

State Equations

$$L\frac{di_L}{dt} = V_{dc} \cdot D - V_b$$

C_b: Battery capacitance

R_{load}: Equivalent battery resistance/load

$$C_b\frac{dV_b}{dt} = i_L - \frac{V_b}{R_{load}}$$

Control Strategy

Use PI controller to regulate output voltage or battery current:

Error Signals:

$$e_I(t) = I^*_{batt}(t) - I_{batt}(t)$$

$$D(t) = K_p e_I(t) + K_i \int e_I(t)dt$$

Where:

- K_p, K_i: Proportional and Integral gains

- D(t): Modulated duty cycle

RESULTS & DISCUSSION

Design Considerations :

The following are the design specifications for the proposed system.

Efficiency > 90%

Low THD < 5%

Power range: 1–2 kW

Battery voltage range: 100–150 V (PHEVs)

DC-link voltage: ~380 V

Switching frequency: 20–50 kHz

The Simulink diagram of proposed system is shown in Figure 1. The current delivered to and from the grid is shown to be sinusoidal and in phase with the grid voltage as shown in Figure 2. This eliminates current harmonics and maintains a unity power factor. When delivering power to the grid, the injected current is in the reverse direction of the grid voltage, which can be seen from 180^0 phase difference. In this case, zero crossing of the grid voltage and injected current are still matching each other.

The voltage across DC bus is shown in Figure 3. Although some brief voltage transients occur during abrupt load changes, the converter maintains 380 V across the DC bus while supplying or absorbing the required current. The rise in the battery voltage while charging and fall in the battery voltage while discharging are shown in these Figure 4 corresponding to the maximum and minimum battery voltage in the charging and discharging modes, the voltage profile is demonstrated at 1.35 to 1.45s. There is change in the mode of operation i.e. from buck mode to boost mode. In Figure 4 at 1.9 to 2.2 s, discharging to charging mode of operation is shown i.e. boost mode to buck mode and at the same point of time the direction of current is in 180^0 phase opposition. This shows the reversal of current and flow of power in reverse direction. In Figure 6, 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.

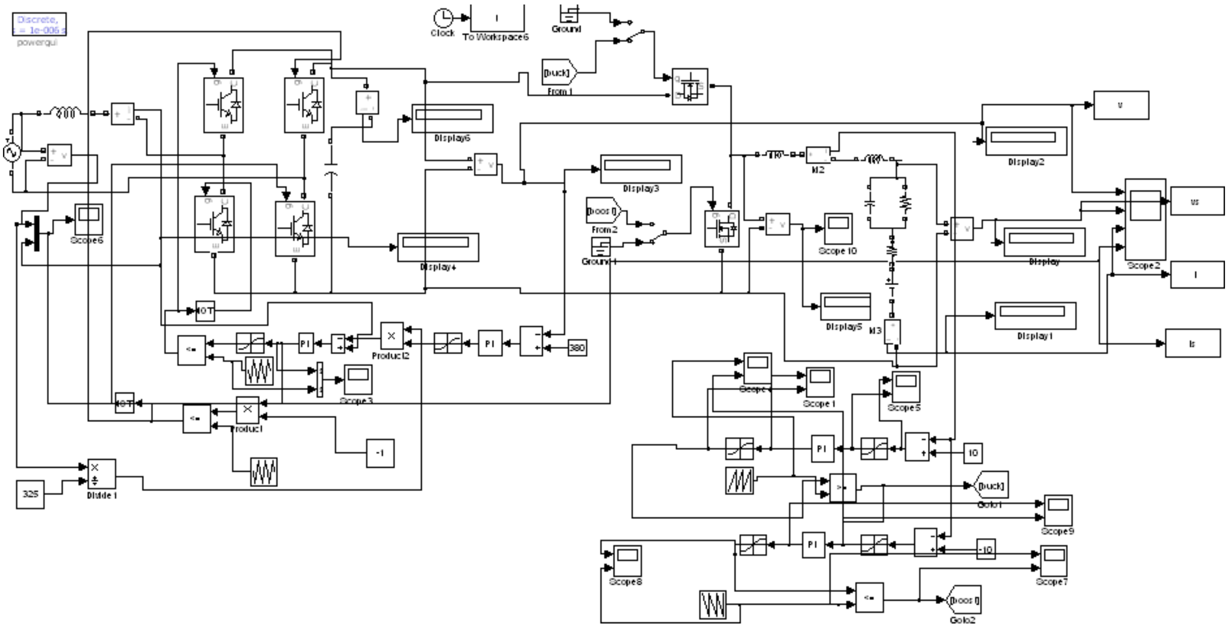

Figure 1: MATLAB/SIMULINK model for energy transfer from vehicle to grid and grid to vehicle.

Figure 5 shows the current harmonics spectra of charging as well as discharging grid current. The THD (Total Harmonic Distortion) of the grid current in both modes is found below a limit of 5% a

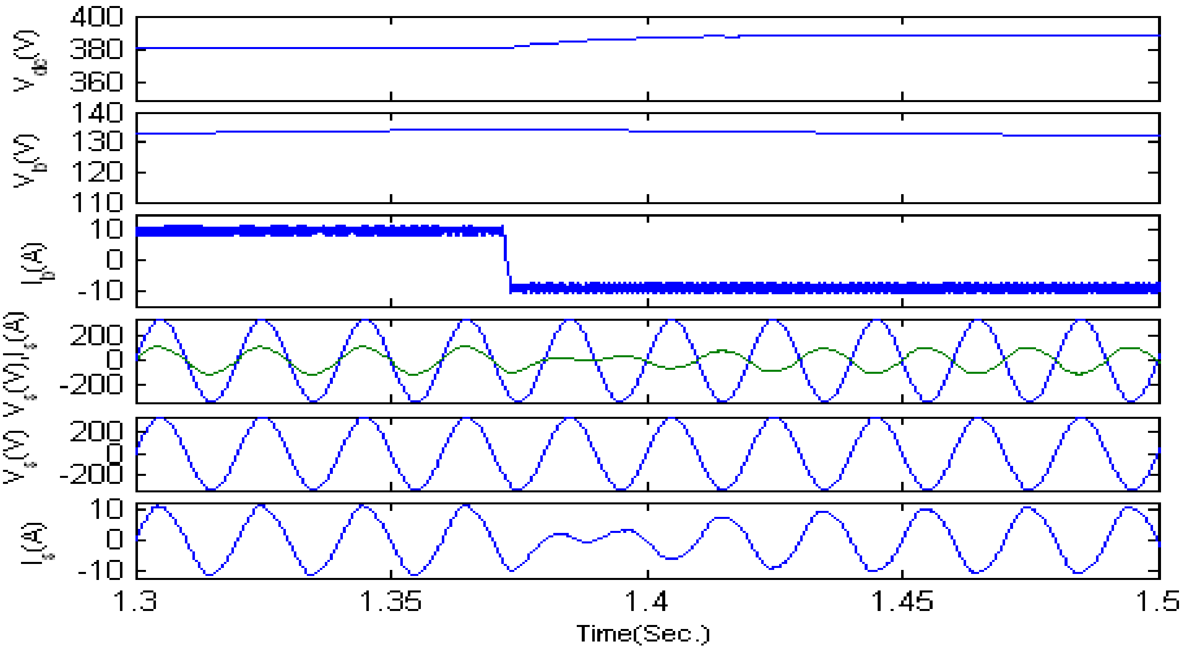

Figure 2: Discharging and Charging of PHEV battery demonstrating unity Power factor operation

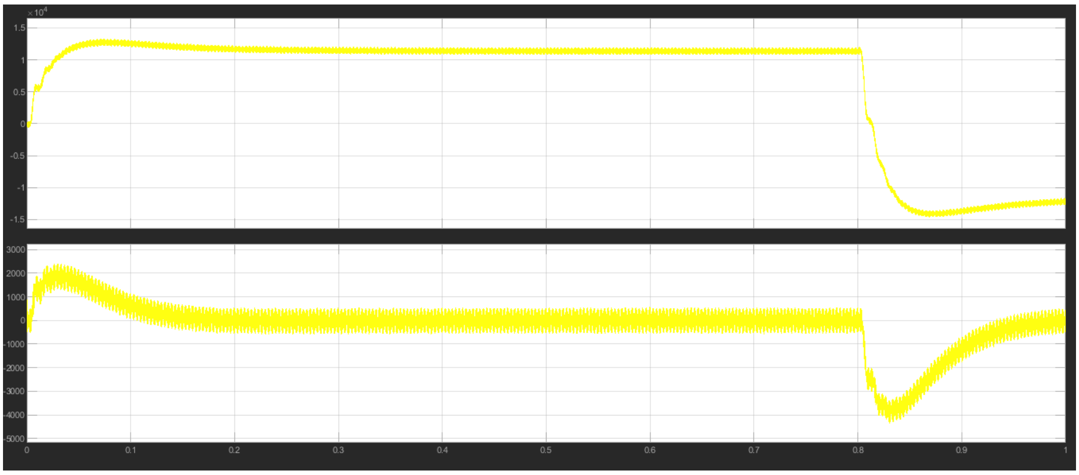

Figure 3: Active and reactive power delivered by grid

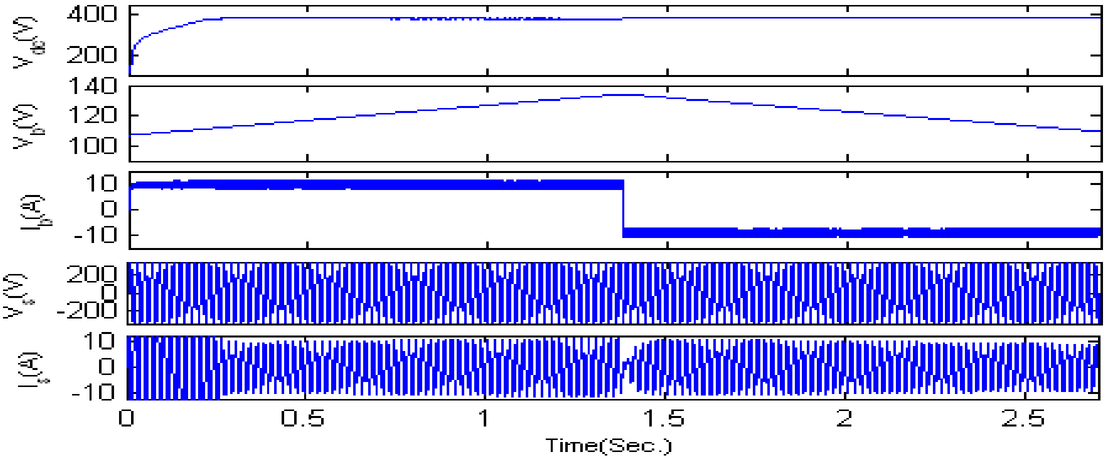

Figure 4:Charging and discharging of PHEV battery

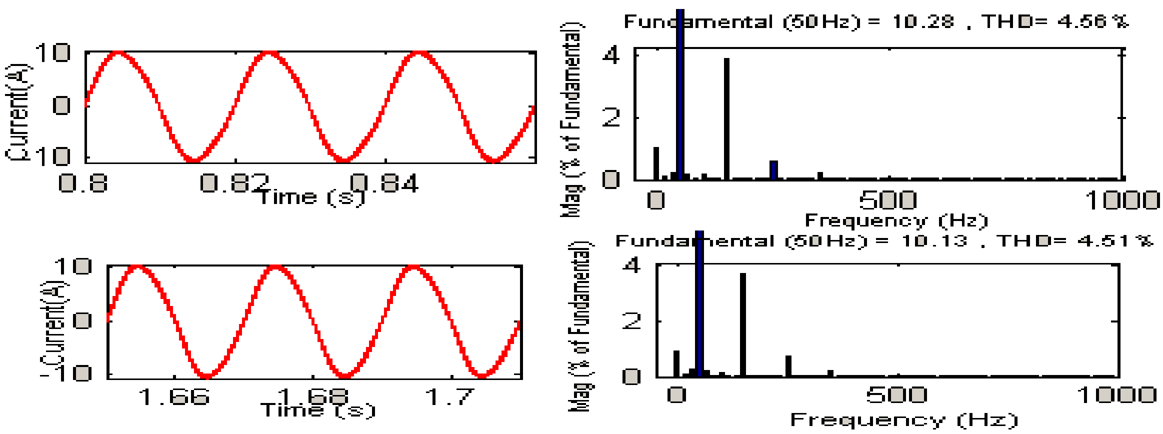

Figure 5:Waveform and harmonics spectrum of the Charging grid current

At 0.8sec the battery changed from discharging to charging mode, thus drawing power from grid which is negative.

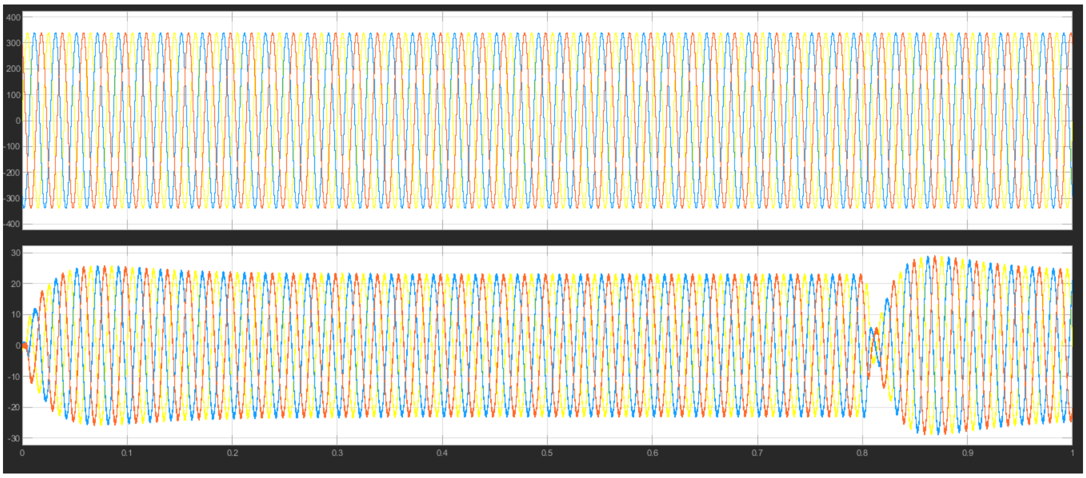

Figure 6:Three phased Grid voltage and current waveforms

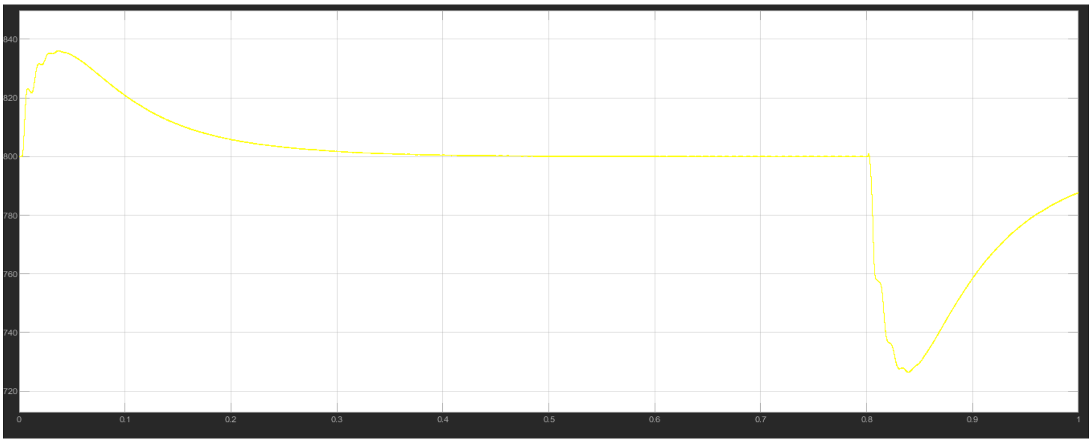

Figure 7: DC link voltage of three phase grid tied inverter

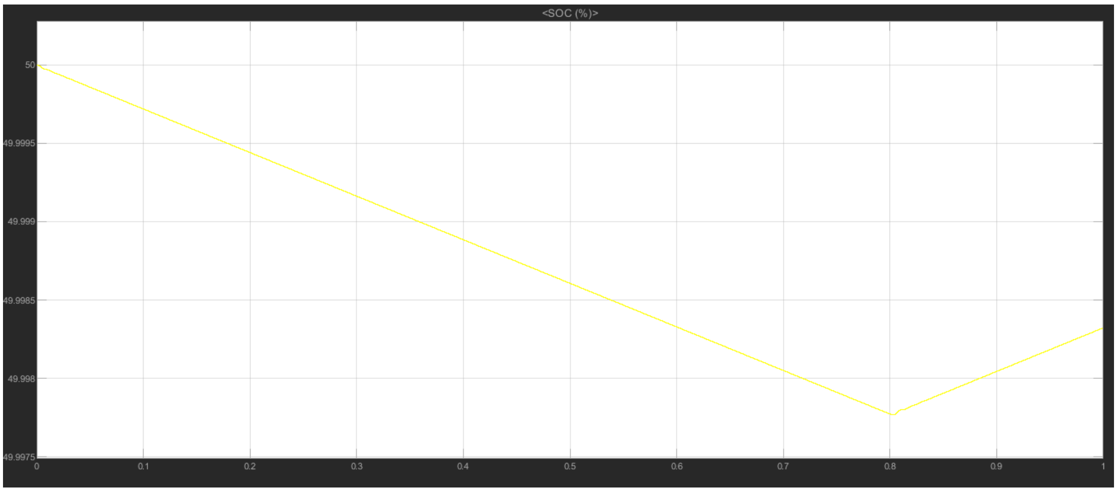

Figure 8: Battery SOC variations while charging and discharging

Reactive power is forced to zero by making Iq=0 by PI controller. Active power positive means that the power is transferring from vehicle to grid and negative when power is transferred from grid to vehicle.

IV. CONCLUSION

The proposed bidirectional converter demonstrates the ability to deliver and absorb AC current from the grid while consistently maintaining unity power factor and exhibiting low current harmonic distortion. These features not only improve overall power quality and minimize the risk of voltage distortion at the grid interface but also contribute to extending the lifespan of both the converter and the battery system. Moreover, the converter's support for Vehicle-to-Grid (V2G) operation enables grid-interactive functionalities such as peak load management and frequency regulation, thereby enhancing the efficiency, reliability, and resilience of modern power systems.

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