

Grid-Tied Single-Phase Bi-Directional PEV Charging/Discharging Control

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ABSTRACT

This paper studies the bi-directional power flow control between Plug-in Electric Vehicles (PEVs) and an electrical grid. A grid-tied charging system that enables both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) charging/discharging is modeled using SimPowerSystems in Matlab/Simulink environment. A bi-directional AC-DC converter and a bi-directional DC-DC buck-boost converter are integrated to charge and discharge PEV batteries. For AC-DC converter control, Predictive Current Control (PCC) strategy is employed to enable grid current to reach a reference current after one modulation period. In addition, Phase Lock Loop (PLL) and a band-stop filter are designed to lock the grid voltage phase and reduce harmonics. Bi-directional power flow is realized by controlling the mode of the DC-DC converter. Simulation tests are conducted to evaluate the performance of this bi-directional charging system. The simulation results show that the integrated PCC, PLL, and band-stop filter can achieve fast dynamic response, low Total Harmonics Distortion (THD) of grid voltage and current, and unity power factor.

Keywords: Plug-in Electric Vehicles, bi-directional power flow, PWM AC-DC converter, PWM DC-DC buck-boost converter, Vehicle to Grid, Predictive Current Control, Phase Lock Loop, band-stop filter, Total Harmonic Distortion, unity power factor

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INTRODUCTION

PEVs are being increasingly adopted in transportation systems as environmentally friendly vehicles. U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) have jointly developed a fuel economy & greenhouse gas standard to regulate the greenhouse gas emission and fuel economy [1]. According to Vehicle Technology Office of the Department of Energy (DOE), transitioning to a light-duty fleet Hybrid Electric Vehicles (HEVs) and PEVs could reduce U.S. foreign oil dependence by 30-60% and greenhouse gas emissions by 30-45% [2]. As the fast development of PEVs and their deep penetration into distribution system, the interaction between PEVs and grid becomes a new challenge. The need to charge large amount of PEVs bring a heavy burden on existing electricity grid. In addition, there are some scenarios where vehicles are required to operate in reverse power flow mode, Vehicle-to-Grid (V2G) mode in which PEVs behave as an electrical energy resource to offer power support and balancing. From this perspective, the bi-directional power flow technology plays a crucial role between PEVs and grid. To realize the bi-directional energy flow between the grid and PEVs, a number of research work has been conducted and reported, which is summarized in three aspects.

The first aspect is the study of rectifier/inverter control strategies. For single phase AC-DC converters, the control strategies can be classified as indirect current control and direct current control. Indirect current control is a phasor control method that indirectly control the grid-side line current based on its relation with grid-side

voltage. This method can achieve good transient performance, however, the current response is slow [3, 4]. Direct current control method directly controls the sensed grid-side current that gets faster current response. Direct current control is the major control method researchers used, such as the ramp comparison, hysteresis control, predictive current control, and Delta modulation controls [5, 6]. Ramp comparison is a conventional control method, by which a tri-angular waves is used to compare with the line current error to generate PWM signals. However, the crossing effect that results from phase and amplitude errors of line current [5] or improperly selected carrier frequency [7] is unneglectable. Hysteresis control utilizes hysteresis comparator to restrict the error between sensed current and reference current and generate PWM signals accordingly. Hysteresis controllers have the advantages of fast dynamic response, fine robustness, simple structure, and easy to achieve, but also have undesirable current harmonics ripple due to variable switching frequency that highly depends on load parameters [8, 10]. Predictive current control forces the grid-side current to track a reference current in one switching period, and the DC-link voltage is used to estimate the reference current for the sensed line current. This method has a fixed frequency and the best potential to achieve good current regulation with less distortion and harmonics [8, 9, 10]. However, the robustness is poor and the transient overshoot is higher than hysteresis control method, hence, a good knowledge of the system is required [6, 10, 11, 12]. In this paper, one goal is to achieve low current harmonics, as a tradeoff, those disadvantages are minimized, and the predictive current control method is selected.

The second aspect is the control strategies for bi-directional DC-DC converters. Prior research work for the application in electric vehicles includes the bi-directional power flow between batteries and motors [13, 14] and energy transfer between the battery and high-voltage bus [15]. Most existing literature studies the control methods based on resistive load. In addition, the control strategies mainly focus on generating a constant DC-link voltage to feed passive loads instead of providing a reasonable charging method, like, constant current (CC) or constant voltage (CV). Therefore, these control methods may not applicable for G2V or V2G applications.

The last but most important aspect is the integration of bi-directional charging system and PEVs' batteries with the grid. As aforementioned, a lot of work have been done at component level of the charging system. Further study is needed at system level to ensure the performance of an integrated system. In existing literature, charger research mainly focuses on three-phase converter control and the power flow is mostly unidirectional [16,17,18]. In [18], AC Voltage Sensorless control is studied for the control of a bridgeless power factor correction AC-DC converter. A DC-DC buck converter is utilized to charge the battery. This charging system has high power factor but can't realize bidirectional power flow [18, 19]. In Berker's paper [20], a simplified control strategy is designed to eliminate controller parameters setting. The controlled output has fast enough transients, but the ripples in both current and voltage are higher compared with conventional PI controller due to sampling-time-dependent switching frequency. Some other work uses power control method to realize bi-directional power flow capability [21, 22], but lacks of battery voltage and current analysis. Another research work [23] applies load frequency control strategy to achieve bi-directional power flow, however, the odd order current distortion is not considered. For the voltage and current control, conventional inner-current loop and outer-voltage loop controlled PWM converters are adopted in [16, 22, 24, 25, 26]. Encouragingly, in [27], a set of experimental results are completed with predictive current control method, this provides a good reference for the model-based study in this paper.

In this paper, a bi-directional charger is designed for the following objectives: enabling bi-directional power flow; meeting the harmonic limits requirement of THD defined in IEEE Std 519-1992 [28], and having unity power factor. The rest of the paper is organized as follows. In section 2, the configuration of the charging system is demonstrated. In section 3, a 240 VAC single split phase power source is simulated. In section 4, the battery selection and major battery parameters are discussed, meanwhile SAE standardized charging levels are briefly introduced as well. In section 5, the bi-directional AC-DC converter model and control strategy are introduced, respectively. In section 6, the working principle and control strategy of bi-directional DC-DC converter are illustrated. In section 7, simulation results are presented and analyzed. Finally, the conclusions are made in section 8.

THE CONFIGURATION OF GRID CONNECTED BIDIRECTIONAL PEV CHARGING SYSTEM

Figure 1 shows an overview of the presented bi-directional PEV charging system. The charging system consists of three parts, power grid, charger module, and battery pack. A phase-split transformer is used to generate 240V AC source. In G2V mode, the AC-DC converter behaves as a rectifier to convert sinusoidal voltage to a desired constant DC voltage and the DC-DC converter works in buck mode to charge the battery. In V2G mode, AC-DC converter performs as an inverter and DC-DC converter works in boost mode to feed the energy stored in battery to the grid. PCC strategy is employed to generate PWM signals for AC-DC converter. PLL technique is applied to adjust the grid voltage phase error due to the discrete sampling and control delay. A band-stop filter is used to get rid of odd order harmful harmonics pollution in reference AC current. Constant current - constant voltage (CC-CV) control strategy is used to achieve desired direction of power flow. The design and control of individual components are presented in the following sections.

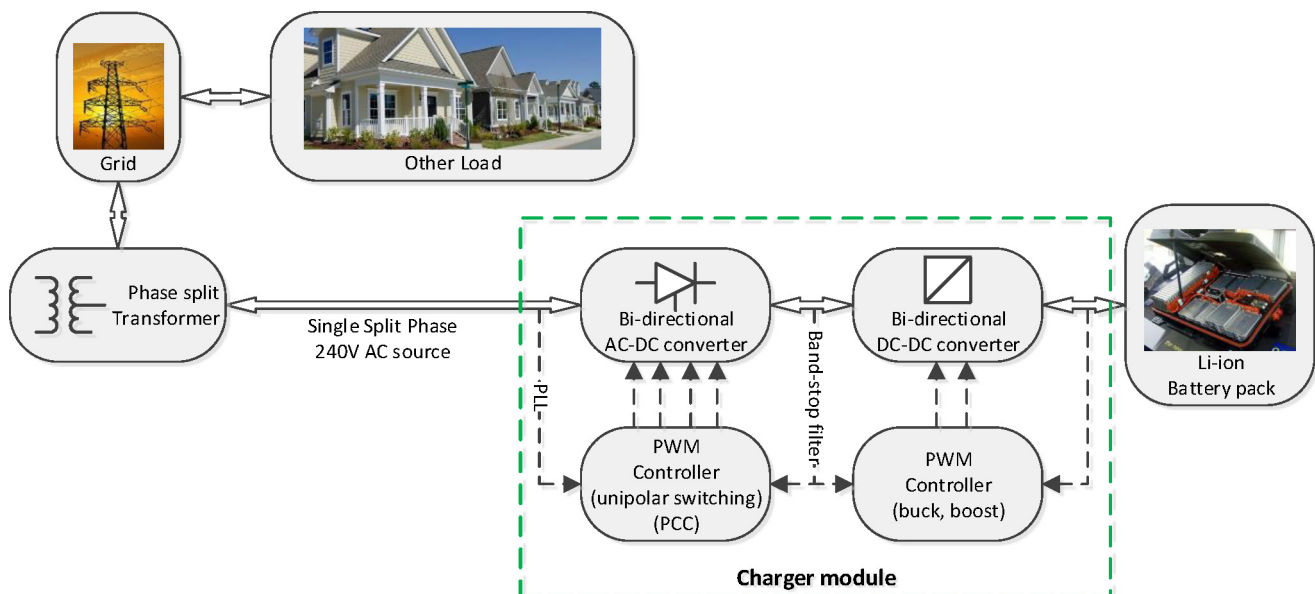


Figure 1. Overview of the presented Bi-directional PEV charging/discharging system



240 VAC SINGLE SPLIT PHASE POWER SOURCE

Figure 2 shows the Simulink model of single split phase, three wires distribution system. In North American distribution system, residential area receives power from 120V/240V split phase source that is fed from a phase split transformer. According to the standard of the distribution system, the primary side of the transformer can be 2.4kV, 7.2kV, 12.47kV, 13.2kV, or 13.8kV. In this paper, a three phase voltage source with 13.2kV of phase-to-phase voltage is selected as the grid source.

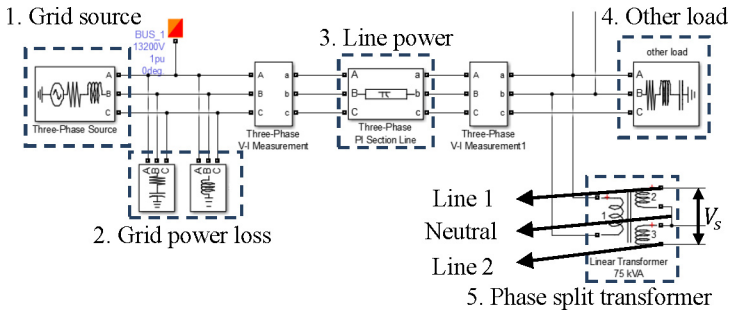


Figure 2. Simulink model of 240 VAC Single Split phase source

In **Figure 2**, block 1 is the 13.2kV grid source. Block 2 simulates the power loss between grid source and the first node. Block 3 is a Three-Phase PI Section Line that implements a balanced three-phase transmission line model where the resistance, inductance, and capacitance are uniformly distributed along the line in a PI section. Block 4 represents other loads connected to the grid. In real world, the power loss in transmission and distribution networks highly depends on the physical characteristics of the system, and a loss around 7% is typical [29]. The primary side of the split phase transformer is connected to any two of the three phases that has a phase-to-phase voltage of 13.2kV. The secondary side of the transformer has a grounded center tap that supplies two 120 VAC voltage V_{LIN} and V_{L2N} from Line 1 and Line 2. The voltage V_{12} between Line1 and Line 2 is 240 VAC.

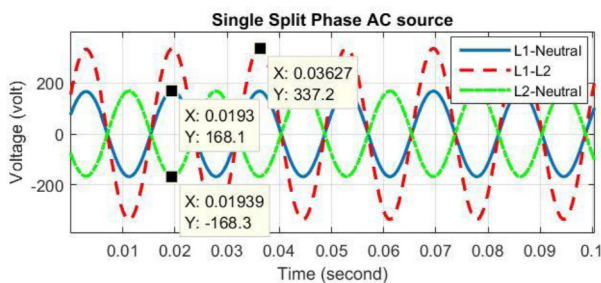


Figure 3. Single Split phase voltage waveforms

In Figure 3, it is observed that V_{L1N} and V_{L2N} have 180 degrees phase difference, and V_{12} has the same phase as V_{L1N} . According to equations (1) and (2), the peak value of each waveform shown in Figure 3 proves the validity of split phase model design.

$$V_{L1N_{peak}} = V_{L2N_{peak}} = 120V \times \sqrt{2} = 169.7V$$

(1)

$$V_{12_{\text{peak}}} = 240\text{V} \times \sqrt{2} = 339.4\text{V}$$

(2)

PEV BATTERY CHARACTERISTICS

Battery Selection

The main types of battery used in PEVs are NiMH and Li-ion batteries. Due to higher energy capacity and longer lifetime, Li-ion batteries are preferred in PEV applications even though the price is higher. In this paper, the main parameters of the battery cell and battery module use the parameters of Nissan Leaf battery [30]. The specifications of the simulated battery are listed in [Table 1](#).

Table 1. Battery Specifications

Pack Specification	
Nominal voltage	180 V
Number of modules in a pack	24
Module Specification	
Number of cells in a module	4 (prismatic cells)
Construction	2 in-series pairs in parallel
Cell Specification	
Rated capacity	33.1 Ah (0.3C)
Nominal (Average) voltage	3.8 V

The battery model in SimPowerSystems is a generic dynamic model as shown in Figure 4 [31, 32]. The battery current is positive at discharging and negative at charging. The relation between v_{batt} and E_{batt} is shown in equation (3).

$$v_{batt} = E_{batt} - i_{batt} \times R_{int} \quad (3)$$

where, E_{batt} is a nonlinear voltage source (V); v_{batt} is the terminal voltage; R_{int} is the internal resistance; and i_{batt} is Battery current (A).

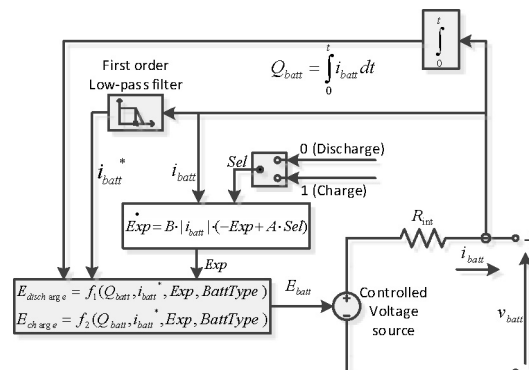


Figure 4. Battery model in SimPowerSystems

The battery type is Lithium-ion. The charge and discharge voltage source is calculated by equation (4) [32].

$$\begin{cases} E_{batt} = E_{discharge} = f_1(Q_{batt}, i_{batt}^*, Exp, BattType) \\ = E_0 - K \cdot \frac{Q}{Q - Q_{batt}} \cdot i_{batt}^* - K \cdot \frac{Q}{Q - Q_{batt}} \cdot Q_{batt} + A \cdot \exp(-B \cdot Q_{batt}) \\ (i_{batt}^* > 0) \\ E_{batt} = E_{charge} = f_2(Q_{batt}, i_{batt}^*, Exp, BattType) \\ = E_0 - K \cdot \frac{Q}{Q_{batt} + 0.1 \cdot Q} \cdot i_{batt}^* - K \cdot \frac{Q}{Q - Q_{batt}} \cdot Q_{batt} + A \cdot \exp(-B \cdot Q_{batt}) \\ (i_{batt}^* < 0) \end{cases} \quad (4)$$

where, E_0 is the battery constant voltage (V); Exp represents exponential zone voltage (V); Sel represents the battery mode, 0 means charging, 1 means discharging; K is the polarization constant (Ah^{-1}); i_{batt}^* is the low frequency current component (A); Q is the maximum battery capacity (Ah); A is the initial voltage of exponential zone (V); and B is the exponential capacity ($(Ah)^{-1}$).

Two battery parameters, the nominal voltage and rated capacity, are obtained from table 1, and the other parameters use the default setting of battery block based on battery type and nominal values. The nominal current discharge characteristics of battery are shown in Figure 5. The higher current results in faster discharge.

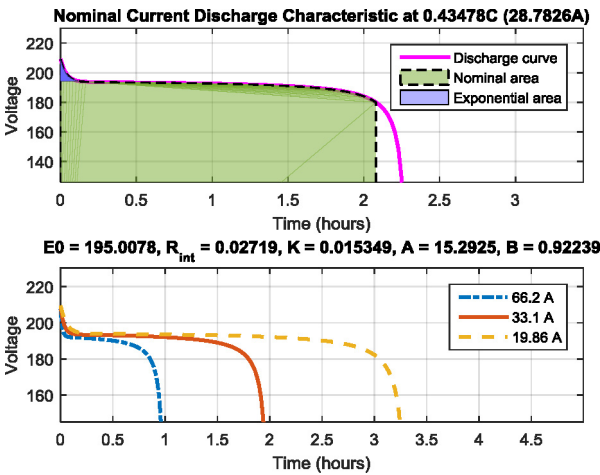


Figure 5. Battery Discharge Characteristic Curve.

PEV Charging Level

In Table 2, the charging levels defined by SAE J1772 standard [33] are summarized. In this paper, the model is built for AC Level 2. The charger power of AC Level 2 can be up to 19.2 kW and the charging current varies from 19.2A to 80A. To test the charger performance at high power, 80 amp charging condition is simulated.

Table 2. Summary of PEV Charging Levels

Charging Level	Power Supply	Charger Power	Miles Range for 1 hour charge	Charge Time (empty to full)
AC Level 1	120VAC Single phase	1.4 kW @12 amp, 1.92kW @16amp (on-board)	~3-5 miles	~17 hours
AC Level 2	208-240VAC Single phase up to 19.2 kW (up to 80 amps)	3.3 kW (on-board)	~8-10 miles	~7 hours
		6.6 kW (on-board)	~17-20 miles	~3.5 hours
DC Level 1	200-450 VDC (up to 80 amps)	19.2kW (residential) & 36kW (public)	~50-60 miles	~28-36 minutes
DC Level 2 Fast charging	200-450 VDC Up to 90kW (approximately 200 amp)	45 kW (off-board)	~50-60 miles (~80% per 0.5 hour charge)	~10-13 minutes

BI-DIRECTIONAL PWM AC-DC CONVERTER

Converter Model Structure

The Bi-directional full-bridge PWM AC-DC converter is the interface between the single phase AC grid and the DC-DC converter. The converter model structure is shown in Figure 6.

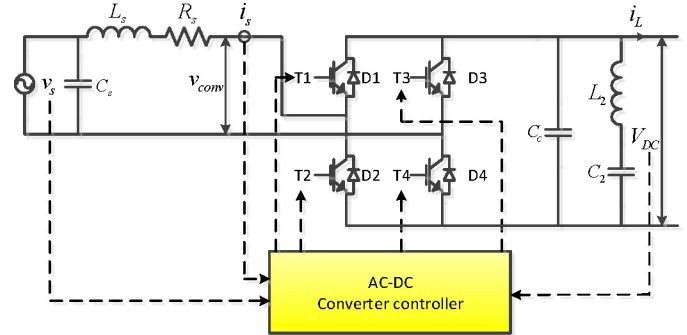


Figure 6. AC-DC converter simulation model

This unipolar PWM converter consists of four IGBT switches with internal antiparallel diodes, two inductors, and three capacitors. The pair of capacitor and inductor on the input side (L_s , C_s) is the AC input filter, and the other pair of capacitor and inductor is the secondary DC output filter (L_2 , C_2). C_c is the DC-link capacitor.

The inductor L_s is designed to filter current ripple and the capacitor C_c is used to maintain a constant DC output. In Figure 6, the fundamental component of PWM switch is given by v_{conv} . The value of R_s is small enough to be ignored. According to the circuit, following equations are obtained.

$$v_s = v_{conv} + v_{L_s} \quad (5)$$

$$v_{L_s} = L_s \frac{di_s}{dt} \quad (6)$$

A phasor diagram corresponding to equation (5) is shown in Figure 7 at the frequency of $\omega = 2\pi f$, and $f = 60\text{Hz}$.

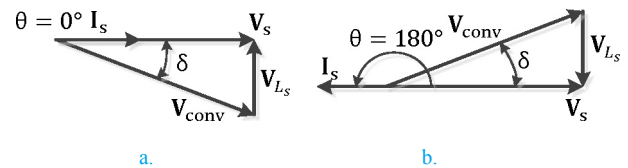


Figure 7. AC-DC converter phasor diagram. a. Rectification; b. Inversion

In Figure 7, the relations between each phasor component are given as equations below:

$$V_s = V_{conv} + V_{L_s} \quad (7)$$