DESIGN AND IMPLEMENTATION OF V2G REACTIVE POWER SUPPORT FUNCTIONALITY OF PEV BIDIRECTIONAL CHARGER

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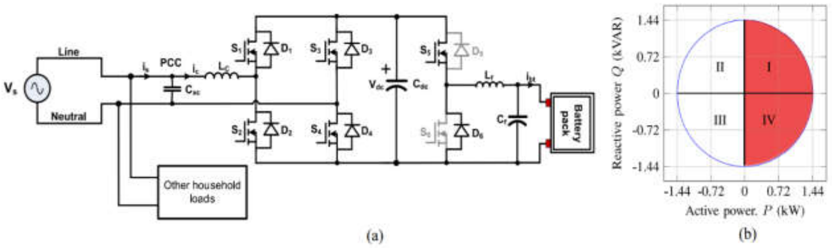
ABSTRACT

In addition to charging the vehicle's battery, the single-phase on-board bidirectional plug-in electric vehicle (PEV) charger described in this paper's design and implementation may assist the utility grid's reactive power needs. A full-bridge ac-dc boost converter and a half-bridge bidirectional dc-dc converter make up the topology's two stages. The charger has five different operating modes and operates in two quadrants of the active-reactive power (PQ) power plane (i.e., charging-only, charging-capacitive, charging-inductive, capacitive-only, and inductive-only). In addition, a unified controller for following utility PQ directives in a smart grid context is presented in this study. The grid sends active and reactive power directives to the cascaded two-stage system controller, which generates line current and battery charging current references and offers a steady dynamic response. The vehicle's battery is not affected during reactive power operation in any of the operation modes. Testing the unified system controller with a 1.44 kVA experimental charger design demonstrates the successful implementation of reactive power support functionality of PEVs for future smart grid applications.

KEY WORDS- Battery charger, plug-in electric vehicle (PEV), reactive power, vehicle-to-grid (V2G)

I . INTRODUCTION

PLUG- In the upcoming years, sales of plug-in electric vehicles (PEV) are anticipated to rise as a more affordable alternative to traditional internal combustion engine (ICE) automobiles. PEVs operate more effectively, which results in greater fuel cost reductions [1]. However, due to the significant increase in peak load caused by the huge number of PEV connections to the electricity network, reliability issues with the grid, particularly at the low voltage distribution network, are raised [2], [3]. The PEVs' coordinated and intelligent charging will lessen the grid's negative effects. The power grid would further benefit from PEVs if they were used as distributed energy storage units using the accessible on-board charger [4], [5]. The ac grid voltage is converted into dc via on-board chargers, which are typically have unidirectional power transfer capability. Using a more advanced topology and controller compared to conventional methods available in the market, the onboard charger can also supply power quality functions such as reactive power compensation (inductive or capacitive), voltage regulation, harmonic filtering, and power factor correction [6]–[10]. Today, in the utility grid, reactive power consumed at the residential load is compensated using capacitor banks, static VAR compensators, static synchronous compensators, etc. However, compensation of the reactive power very close to the residential load is more efficient and reduces the installation and maintenance costs associated with the aforementioned devices. Therefore, on-board chargers could be suited to support advanced functions with limited modifications to the conventional topologies. Furthermore, reactive power support does not affect the battery state of charge (SoC) or battery lifetime. The ac–dc converter losses during reactive power compensation are supplied by the utility grid and, therefore, battery SoC is preserved. However, it is important to note that reactive power operation affects components such as dc-link capacitors since more charge-discharge cycles take place [6]. Considering its benefits, smart charging with vehicle-to grid (V2G) has been found advantageous and attractive in the long term operation of the electricity grid [5], [11]. In the future, utilities would want to communicate PEV charging power with the customer and control it with an incentive in return [5], [11]–[13]. With increasing interest in V2G applications for the utility grid, studies have investigated standalone and grid support operation modes of battery supplied bidirectional converters [6]–[10], [14]–[19]. In general, a two stage topology with cascaded ac–dc converter and dc–dc converter is proposed in the literature for bidirectional battery charger operation due to two main reasons: 1) to implement galvanic isolation; and 2) to decrease second harmonic (2-f) ripple component in the dc battery charging current to protect lithium-ion (Li-ion) battery lifetime. 2-f ripple is the natural by product of single phase ac– dc rectification of the power [20]. In [8], [9], [16], and [18], two separate controllers are commonly used for ac–dc and dc–dc converter stages. Therefore, controller uses separate references for ac–dc and dc–dc stages.



(a) (b)

Fig. 1. Bidirectional PEV charger and its operation region in active-reactive power (PQ) plane. (a) Charger and grid connection. (b) Operation area of the charger (shaded).

However, a uniform controller that would only communicate active power command (Pcmd) and reactive power command (Qcmd) [or power factor (pf)] between EV and utility grid is more feasible for a smart-grid connection due to physical interoperability [21]. It is more feasible and standardized to communicate two signals (Pcmd and Qcmd) to the utility grid and derive other references from those signals. In [10], [17], and [22], a uniform controller is used that responds Pcmd and Qcmd signals from the grid as proposed in this paper. Moreover, Pcmd is used as the reference for dc battery charging power, and ac–dc converter regulates the dc-link voltage and tracks Qcmd. As a result, Pcmd is not the reference for the actual active power (P) measured at the point of common coupling (PCC). This introduces a power mismatch (between Pcmd and P) because of neglecting the losses in active and passive devices of ac–dc converter. However, active power at the PCC must follow Pcmd from the utility grid, and the controller should derive the required battery reference current (ibt) that is needed to respond Pcmd. In addition, bidirectional operation in the above mentioned studies do not explicitly shows the controller performance on how fast charger responds to Qcmd or Pcmd variations. A cascaded system controller demonstration should be performed to help system integration analysis of PEV V2G applications. Therefore, a unified system controller is preferred in which the utility grid only sends two signals (Pcmd and Qcmd) and expects the charger to follow those commands. This paper proposes a control strategy for a bidirectional on-board charger to utilize it for battery charging and reactive power operation support. The system controller unifies the ac– dc and dc–dc converter control, and fulfils Pcmd and Qcmd transmitted between the PEV and the utility grid. The proposed control strategy is first developed in power sim (PSIM), and then a 1.44 kVA bench-top on-board charger is designed and tested to show the controller performance. The dynamic performance and steady-state operation tests of the on-board charging system are realized in simulation and in the experimental prototype. The results show that the proposed control method operates successfully providing good dynamic response under grid demand variations, and meets steady-state operation conditions proposed system controller development. Section IV focuses on simulation verification of the proposed system controller.

II. SYSTEM DESCRIPTION OF THE BIDIRECTIONAL PEV CHARGER

The topology used in this paper to investigate the PEV grid interaction is shown in Fig. 1(a). The PEV on-board chargers typically include two stages: 1) the ac–dc rectification (i.e., full-bridge ac–dc rectifier) and 2) dc–dc conversion (i.e., dc–dc buck converter). Practical applications usually require galvanic isolation. However, this paper employs a nonisolated topology.

The focus of this paper is to implement charging and reactive power control at the same time with meeting the design requirements (which are presented in the system description). Therefore, most of the effort has been on the controller design and implementation, and on the analysis of the experimental results. Bipolar modulation is used for the front-end ac–dc converter, meaning that the rectifier input voltage is either +Vdc or −Vdc. When S1 and S4 are on, switches S2 and S3 are turned off, and vice versa.

The peak voltage that the metal oxide-semiconductor field-effect transistors (MOSFETs) and diodes block is equal to Vdc, and the peak current they need to conduct is equal to √2Ic where Ic is the charger rms current. The battery voltage level used in PEVs usually ranges between 200 and 390 V [1]. Therefore, two different dc link voltage levels [Vdc in Fig. 1(a)] are tested in this paper: 1) 250 and 2) 400 V. The buck operation is achieved using switch S5 and D6. When S5 is turned on, the current flows through S5 and Lf , and charges Cf and the battery. When S5 is turned off, diode D6 conducts the free-wheeling inductor current through inductor Lf and battery while Cf is discharged into the battery.

The switches S6 and D5 are not used in this paper since the battery is not discharged. However, the system hardware is implemented for V2G active power applications. The system parameters of Fig. 1(a) are listed in Table I. The grid current (is) must have a total harmonic distortion (THD) less than 5% and the individual harmonic components must also be well regulated [23], [24]. This is achieved by using an inductor-capacitor filter at the front end and by appropriately designing the ac inductor current feedback controller. The charger's output voltage and current are regulated using a low pass filter at the output and by tuning the output current (ibt) controller parameters. Some of the employed practices for Li-ion and/or lead-acid batteries are charging rms current ripple of 5%–10% of the rated charging current and RMS ripple voltage of 1.5% of the rated battery voltage [25]

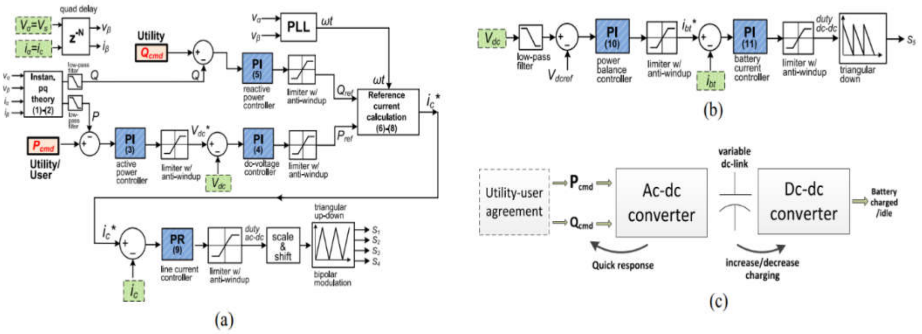


Fig. 2. Proposed system controller and operation. Controller for (a) ac–dc converter and (b) dc–dc converter. (c) Controller operation sequence.

Table 1: System Parameters Used In This Paper

Parameter	symbol	Values
Charge Apparent Power	S	1.44 Kva
Grid Voltage	Vs	120 V
Grid Frequency	F	60 Hz
Coupling Inductance	Lc	1.0 Mh
Ac-Dc Converter	Fsw1	24 Khz
Dc-Link Voltage	Vdc	250v/400v
Dc-Link Capacitance	Cdc	330uf
Dc-Dc Converter	Fsw2	42 Khz
Battery Side Capacitor	Cf	200 Uf
Battery Side Incuctor	Lf	400 Uf

III.SIMULATION OF THE PROPOSED CONTROLLER

A simulation scenario is developed to show the operation of the charger and its response performance to the grid commands. Since, the required time to simulate the utility level operation of the charger is too long, a condensed version of the scenario is developed. It is assumed that the PEVs are plugged into the grid during peak hours (4:00–8:00 P.M.) when the load is at its highest level and the battery requires full charging.

Therefore, the simulation starts with charging only operation. Then, it is expected that the voltage at the substation decreases as the reactive power and active power consumption at the residential units increases. The utility makes an action to support the distribution voltage by utilizing some of the PEVs for reactive power supply. Later, if the utility needs to decrease the substation voltage, the PEV can also consume reactive power. Table III lists the steps of this scenario in the given order. Table III is implemented with a 7-s simulation. Fig. 4 shows the developed simulation diagram in PSIM. The proposed charger controller code is developed in C language and embedded into the system simulation structure.

The PSIM Li-ion battery model is used in the simulation [30]. Necessary parameters are extracted from the data sheet of Li-ion batteries available in the laboratory [31]. The system parameters used in the simulation and shown in Table I am the same as the experimental hardware set-up that will be explained in the next section.

The utility commands for active and reactive power are embedded into the C code and activated through a time counter mechanism to realize Table III. Simulation results provided very similar behaviour with the real set-up during start-up and dynamic performance tests. Therefore, it provided a fast controller code development process and reduced implementation failures. The simulation results are completed for two different cases.

Since, the selection of the dc-link voltage depends on the battery pack voltage, controller performances are confirmed for Vdc = 250 and 400 V. Fig. 5 shows the results for 400 V

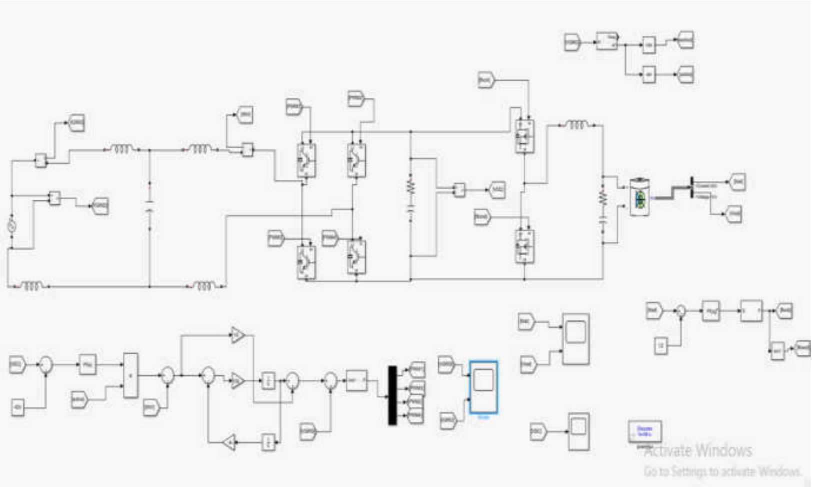


Fig 3: Simulation diagram of the charger developed in PSIM.

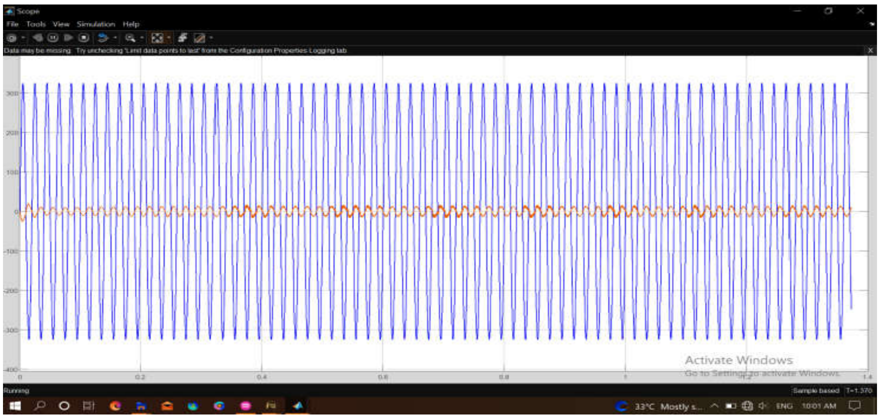


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Fig 4: Verification of the system controller using PSIM for 325 V dc-link voltages

dc-link voltage. P and Q in the figure are the calculated active and reactive power outputs of the charger at the PCC. The controller followed the active and reactive power commands successfully.

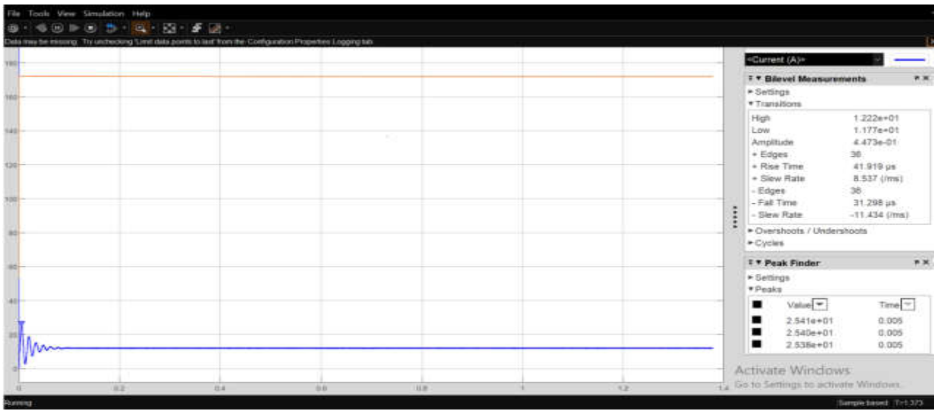
Note that, the charger current RMS value (Ic = 1440/120 = 12 A) stays the same during the simulation since the apparent power is kept constant. The transitions from one mode to another are shown in further detail in Fig. 6. Settling time is less than five grid cycles for Fig. 6(a) and (b).

IV. RESULTS

SIMULINK is a MATLAB tool can be used for modelling, simulating, and analyzing Dynamic systems. It supports linear and nonlinear systems, modelled in continuous time, sampled time, or a hybrid of the two. Systems can also be multi rate, i.e., have different parts that are sampled or updated at different rates.

SIMULINK enables you to pose a question about a system, model it, and see what happens. With SIMULINK, one can easily build models from scratch, or take an existing model and add to it. Thousands of engineers around the world use SIMULINK to model and solve real problems in a variety of industries. When a new control strategy of a converter or a drive system is formulated. It is often convenient to study the system performance by simulation before building the breadboard or prototype.

The simulation not only validates the systems operation, but also permits optimization of the systems performance by iteration of its parameters. Besides control and circuit parameters, the plant parameter variation effect can be studied. Valuable time is thus saved in the development and design of the product. The simulation program also helps to generate real time controller software codes for downloading to a microprocessor or digital signal processor.



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High	1.222e+01
Low	1.177e+01
Amplitude	4.473e-01
+ Edges	38
+ Rise Time	41.919 µs
+ Slew Rate	8.537 (/ms)
- Edges	38
- Fall Time	31.298 µs
- Slew Rate	-11.434 (/ms)

	Value	Time
■	2.541e+01	0.005
■	2.540e+01	0.005
■	2.538e+01	0.005

Fig 5: The output graph for the battery voltage and current

The dc battery current ibt(t) is also illustrated at the bottom of each figure. Note that ibt(t) is close to zero when there is no charging power request, i.e., modes #1-#2. The designed controller operates in different operating modes without any stability problem. This shows that charger is suitable to take different roles for the sake of a more reliable utility grid.

CONCLUSION

This study employs a single-phase on-board bidirectional charger to demonstrate controller development and experimental verification of charging and V2G reactive power operation. The proposed unified system controller regulates the line current and battery current while staying under THD limitations after receiving charging active power and reactive power inputs from the utility grid. It offers a good steady-state performance in addition to a quick dynamic response.

Using a single-phase, Level 1 120 V grid connection, the controller is tested. However, the proposed controller can also be used in Level 2 single-phase charging at higher power levels. Reactive power operation has no impact on the battery's lifespan or the SoC that is accessible. The controller fulfilled step-changes of inductive and capacitive reactive power commands in less than five grid cycles proving quick response to the utility commands. The simulation and experimental results show that the proposed PEV charger control method has a fast dynamic response, good steady-state performance, and operates successfully under grid demand variations.

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