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Bidirectional Power Factor Correction Converter Control of an EV On-board Charger for V2G Application

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Abstract

Vehicle-to-Grid (V2G) is an idea to utilize stored electricity of Electric Vehicles (EV) in the connected grid to either balance power demand or provide emergent power. To this end, the power interface shall have bidirectional capability to charge or discharge the energy of the EV onboard battery. Existing onboard chargers integrated on EVs are mostly designed to implement unidirectional AC/DC conversion and charging regulation. This paper presents a bidirectional boost Power Factor Correction (PFC) converter based on an advanced bridgeless interleaved boost topology. The proposed converter can be an active front end of the bidirectional onboard charger for rectifying the grid AC power or taking the DC battery power back via the general boost PFC and a phase-shift controls, respectively. The simulations are performed to verify the proposed converter can achieve the bidirectional operations.

Keywords: charger, DC-AC, V2G

1 Introduction

As the threat of global warming and the mandatory reduction of greenhouse gases, Electric Vehicle (EV) that can achieve zero emissions plays an important role to the future of the human life. The EV powered by rechargeable battery attracts more attention relative to the EVs with the different power sources since the relative maturity of the technology. The lithium-ion batteries that have the highest energy density among the rechargeable batteries have been widely applied in existing commercialized EVs. However, one fully-charged lithium-ion battery pack on each EV can barely provide a range less than 160 km, e.g. Nissan Leaf. That means it has to be recharged frequently more than an internal combustion engine car refuels. Therefore, the charging safety and infrastructure establishment are crucial to the acceptance of the EVs.

There are two methods to charge the onboard battery, i.e. conductive or inductive charging. The former one has higher ampacity and higher efficiency of power transmission. On the contrary, the latter one could provide safer and flexible power connection. Even though each one has its own dominants on the charging rate, infrastructure setup, and operation convenience, the conductive charging has been mostly applied on the EV market due to the simplicity of connection interface and easiness of unification. For instance, the international standards SAE J1772 and CHAdeMO define the communication protocol and couplers for the AC and DC conductive charging, respectively.

In order to apply the AC charging, there shall be an onboard charger to make AC/DC rectification and charging current regulation. Its design shall consider the quality of power factor, stability of energy delivery, and safety of charging process. To achieve this, several candidate topologies for the onboard charger are proposed [1-4]. Furthermore, the selection guidelines of power stage topologies with the considerations of charger efficiency and Power Factor Correction (PFC) is given [5]. It is noted that the PFC boost converter as an active front power stage followed by an isolated DC/DC converter is popular and applicable integration for the EV battery charging application [1],[4],[5]. In such a system, the boost PFC converter regulates AC input current to be proportional to and in phase with the input voltage waveform. Also the output is controlled to track the voltage reference. There are several topologies can be chosen for the design of the boost PFC converters [8-11]. To achieve the PFC effectiveness, the controller design and strategies are proposed in existing literatures [12-14].

In recent years, the Vehicle-to-Grid (V2G) that describes a concept to intelligently control the electricity flow between EV and its connected grid has been introduced to the design and of EV charging system and the management of smart gird. Such idea can provide the merit of load balance so as to mitigate the demand on peak power and facility expansion. To this end, the charging system for the EVs shall bidirectionally charge or discharge the battery electricity via smart management. Accordingly, some issues related to the effect of reactive power transfer [6] and the smart charging strategies [7] are discussed. Even the existing boost PFC converters perform well for EV battery charging, they cannot be applied to the V2G grid straightforward for the unidirectional limitation. This paper proposes a bidirectional boost PFC converter based on a bridgeless interleaved boost topology. The proposed converter has the same features of the bridgeless interleaved boost PFC converter while handling the charging process and takes the battery DC power back to the gird by using additional phase-shift control on the modified topology. This paper is organized as follows. In Section 2, the bridgeless interleaved boost PFC converter is introduced. It is modified to perform bidirectional operations and the controller is conceived as well. In Section 3, two simulations for the boost PFC and AC/DC conversion are demonstrated to validate the proposed modification. In Section 4, the conclusion is given.

2 Schematic and Control of Bidirectional PFC Boost Converter

The design of front-end AC/DC PFC converter for EV battery charger firstly began with a conventional boost topology that utilizes a full-bridge rectifier followed by a boost stage to regulate input current to follow the input voltage wave shape. Even though such schematic is very simple and easy implementation, the dissipation of the rectifying diodes increases with the rise of input current due to its line voltage drop. As a result, the bridgeless boost topology that removes the front rectifying stage and has dual boost converters connected to AC positive and negative line, separately, is proposed. On the other hand, an interleaved boost converter that is similar to the conventional boost topology and has two parallel boost converters operating 180° out of phase has been proposed to effectively reduce the current ripple. Lately, a bridgeless interleaved boost converter that combines the concepts of the bridgeless topology and interleaved control has been proposed [11]. This topology has more components in the power stage so that the designed charger will become relatively bigger and more expensive as only drawback.

An applicable bridgeless interleaved boost schematic is shown in Fig. 1. There are dual boost converters that are, respectively, composed of coupled inductors L1//L2 and L3//L4, MOSFETs Q1//Q2 and Q3//Q4, diodes D1// D2 and D3// D4, and a common load capacitor Co for individually implementing the interleaved operations during the positive and negative line cycle. Cx is installed as line capacitor for suppressing the differential mode noise and Lc is a choke coil to suppress the common mode noise. Cy1 and Cy2 are line bypass capacitors for enhancing the suppression of common mode noise. These three types of components form a conventional EMI filter for AC power filtering. Db2 and Db4 are added to bypass each boost loop so as to avoid the line floating to the PFC ground. Db1 and Db3 are configured to bypass the current to pre-charge Co before boosting and are reverse bias during the boost operations. It can also be noted that Db1-Db4 forms a full-bridge structure during the pre-charge step.

Since the topology shown in Fig. 1 can effectively reduce the rectifying loss and the current ripple of coupled inductors, the conversion efficiency can reach more than 98% in Continuous

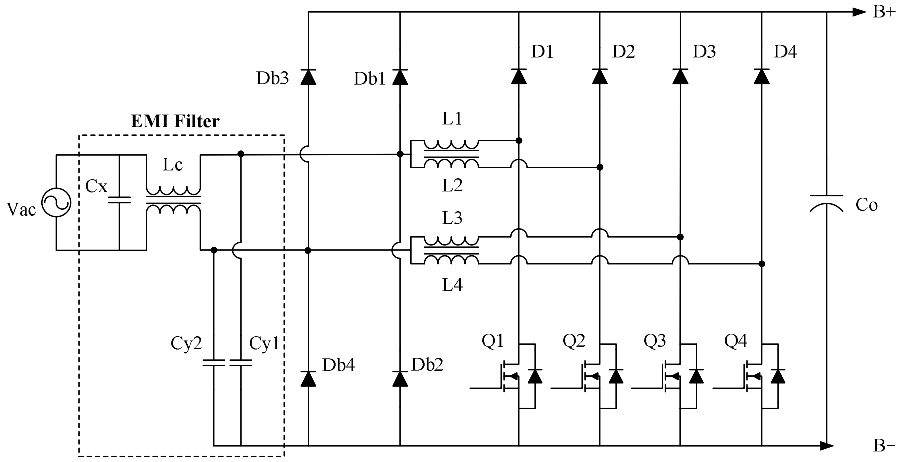


Figure 1: Schematic of a bridgeless interleaved boost converter for PFC application

Conduction Mode (CCM). Therefore, it is particularly suitable for EV charger application since the constant current mode runs for almost full range of battery capacity. The output DC power can charge the onboard battery straightforward or be connected to an isolated DC/DC converter for better insulation and charging controllability. However, the boost topology makes it impossible to be applied to the V2G based gird. Thus the bridgeless interleaved boost converter is modified as illustrated in Fig. 2 to handle bidirectional operation. It can be seen that the four diodes Db1-Db4 are replaced, correspondingly, by the MOSFETs Q5-Q8 to become a full-bridge switching topology. In the pre-charge or boost operations, Q5-Q8 are all inactive and their anti-diodes play the same roles as Db-Db4 do. It is shown in Fig. 3(a) and (b) that the anti-diodes of Q8 and Q6 conduct current during positive and negative line cycles, respectively. The red-solid and green-dashed lines represent the two parallel loops are individually operated according to the interleaved control. It shall be noted that the MOSFETs Q1 and Q2 (or Q3 and Q4) could be turned ON or OFF simultaneously. During the DC/AC conversion, the line voltage is generated by conducting Q5-Q8 as the full-bridge primary side of a conventional DC/DC converter does. As shown in Fig. 3 (c) and (d), the battery DC voltage is across on the AC line by conducting MOSFETs Q5 and Q8, or Q6 and Q7, alternatively. As a result, the output voltage with sinusoidal waveform at specific frequency can be generated with proper Pulse Width Modulation (PWM) control of the MOSFETs. It is justified the proposed topology is capable of performing the bidirectional operations.

To achieve the bidirectional operations for the

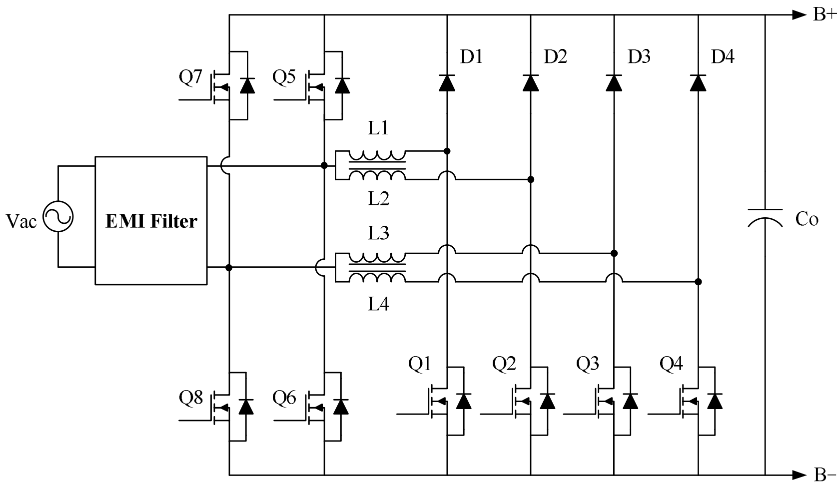
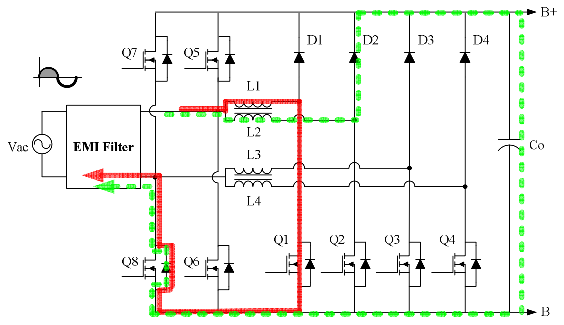


Figure 2: Proposed bidirectional boost PFC converter schematic

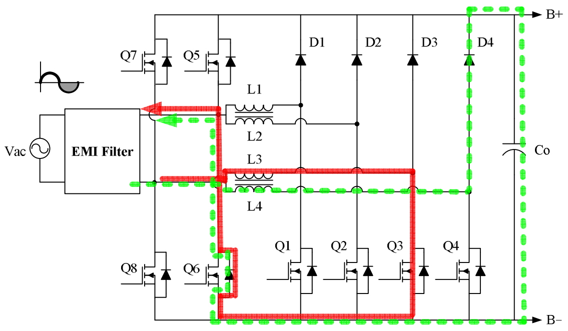
proposed converter, a hybrid controller for the interleaved PFC and DC/AC conversion modes is conceived. A conventional scheme shown in Fig. 4(a) is given for the interleaved PFC control. Vdc, Vac, and Iac are the output DC voltage, input AC voltage, and input AC current, respectively. The phase-lock loop tracks the AC voltage to generate the corresponding unity sinusoidal wave in phase. A PI controller is employed to calculate the required load current via the importing error signal that is the difference between Vdc and its command value. The desired input AC current Iac_ref is obtained from multiplying the unity waveform by the required load current. The current error between Iac_ref and Iac is then calculated via a designed compensator to yield the duty cycle. The interleaved PWM signals G1 (G3) and G2 (G4) can be generated by comparing to two count-up-and-down counters having a phase shift of 180°. On the other hand, the phase-shift PWM control is applied on the replaced MOSFETs for the DC/AC conversion as shown in Fig. 4(b). In the control scheme, the desired output AC wave can be generated either to synchronize with grid voltage Vac_ref via phase-lock loop module or by an oscillator circuit as a single AC power source. A PI controller is employed to eliminate the error between Vac_ref and the output voltage Vac. In our control scheme, the resulting duty cycle signal is compared to a saw-tooth wave to generate phase shift for switching the active MOSFETs G5 and G6 of the right legs ON. Comparatively, the MOSFETs G7 and G8 on the left-leg are passively controlled by a constant 50% duty cycle. Unlike a conventional full-bridge control, the control for two diagonal MOSFET sets shall be deactivated alternatively according to the sign of the line voltage by seeing Fig. 4(b).

3 Simulation Results

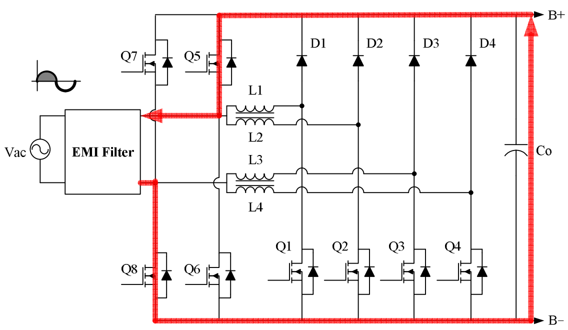
Two simulation examples built in PSIM are performed to verify the bidirectional operations of the proposed converter. The parameters of the components in Fig. 2 or Fig. 1 required for the simulations are given as Cx = 10 uF, Lc = 30 uH, Cy1 = Cy2 = 10 pF, L1 = L2 = L3 = L4 = 200 uH, and Co = 2 mF. For the boost PFC operation, the AC input is set as 200 Vp-p @ 60 Hz and the DC output is 15 A @ 400 V demanded. The control results are shown in Fig. 5(a) - (b), the AC input current is in phase with the voltage and



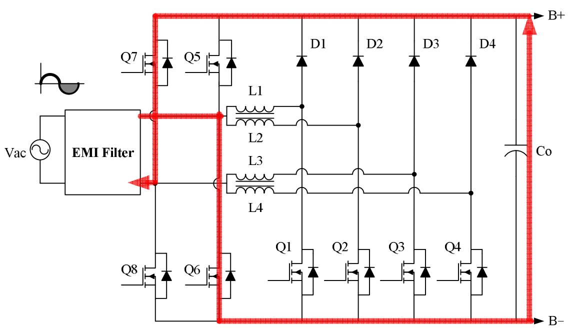
(a) PFC operation during positive line cycle



(b) PFC operation during negative line cycle



(c) Inverting to generate positive half of sinusoidal wave

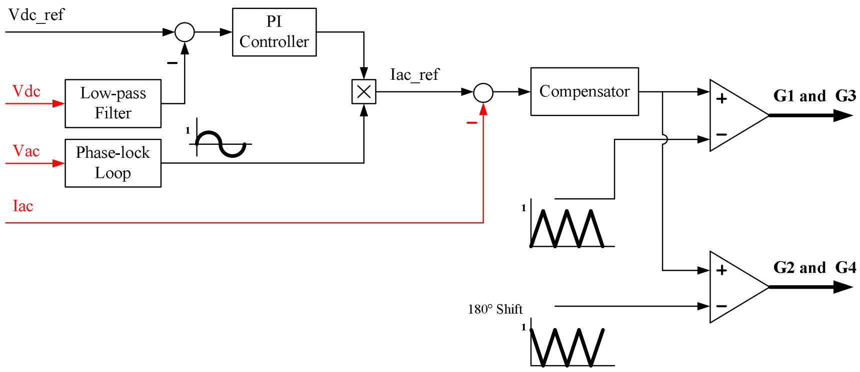


(d) Inverting to generate negative half of sinusoidal wave

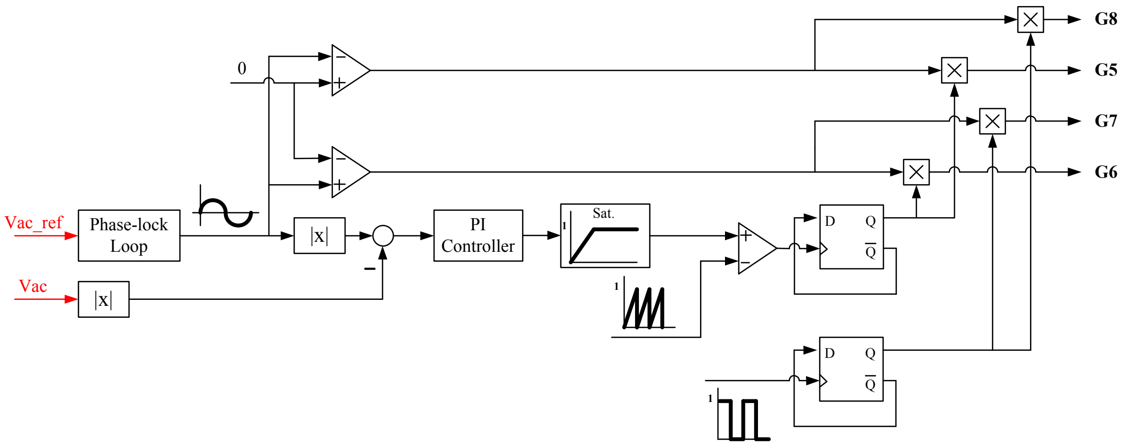
Figure 3: Principle of bidirectional operations

has little shape distortion as well as small ripple, demonstrating the unity of the power factor can be achieved.

The current ripples of the coupled inductors working during positive line cycle are shown in



(a) Boost PFC control



(b) DC/AC control

Figure 4: A Hybrid control scheme for the proposed bidirectional converter

Fig. 5(b). It can be seen that the large current ripple induced by each inductor can be remarkably cancelled under the interleaved control. This simulation verifies the proposed converter can maintain the PFC working as the conventional one, shown in Fig. 1, does. For the AC/DC operation, the input DC voltage and AC out load is configured as t 400 V and 10 Ω, respectively. The control result of the output voltage waveform is illustrated in Fig. 6. It can be seen that a pure sinusoidal wave with 220 Vrms @ 60 Hz is generated. These two examples validate the proposed topology together with the hybrid controller can handle bidirectional operations for either boost PFC or DC/AC conversion.

4 Conclusions

Fewer existing boost PFC topologies exploited in EV battery chargers consider the bidirectional power conversions. This work moderately modifies a boost interleaved boost PFC topology to extend it to V2G application. The modification replaces the pre-charge and boost return diodes with four MOSFETs with parallel anti-diodes to become a full-bridge for switch control, which is entailed the additional control and gate drive circuitry. The charger can be rearranged as compact as unidirectional one. In addition, A hybrid scheme with generalized interleaved and phase-shift controls, respectively, for the boost PFC and DC/AC conversion is conceived. It is shown in the simulations that the proposed converter together with the designed controller can achieve the bidirectional power conversions for future V2G applications.

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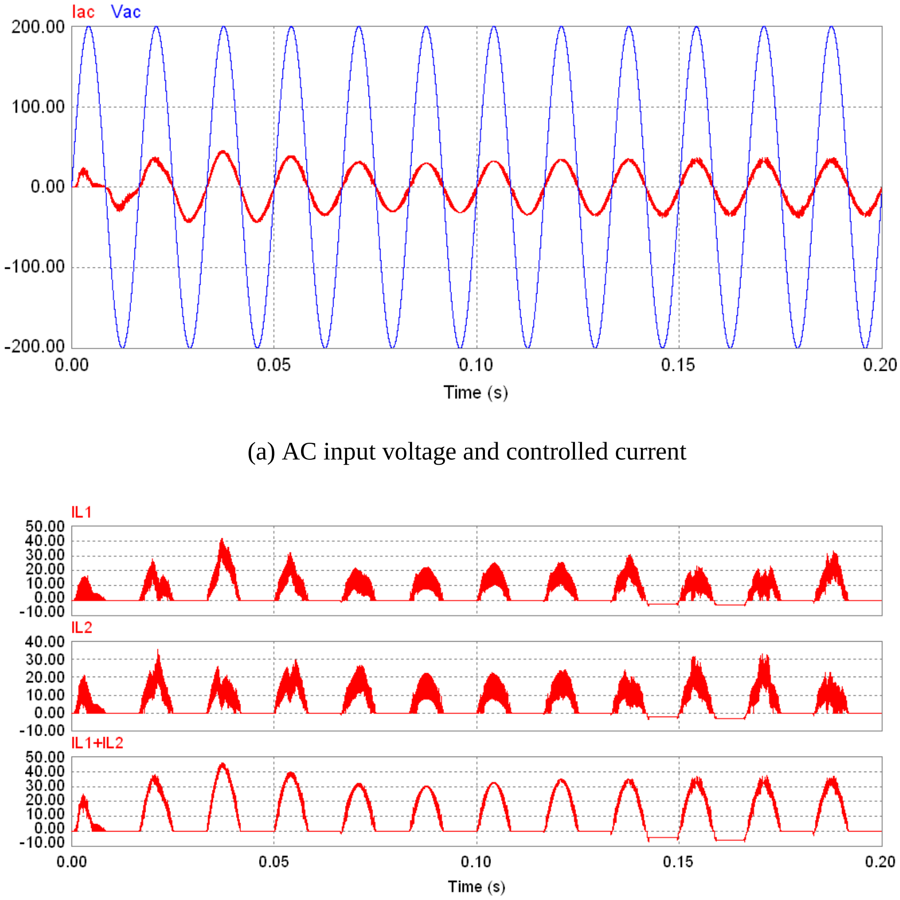

(a) AC input voltage and controlled current

(b) Currents induced by the coupled inductors L1//L2

Figure 5: Control effectiveness of the proposed converter

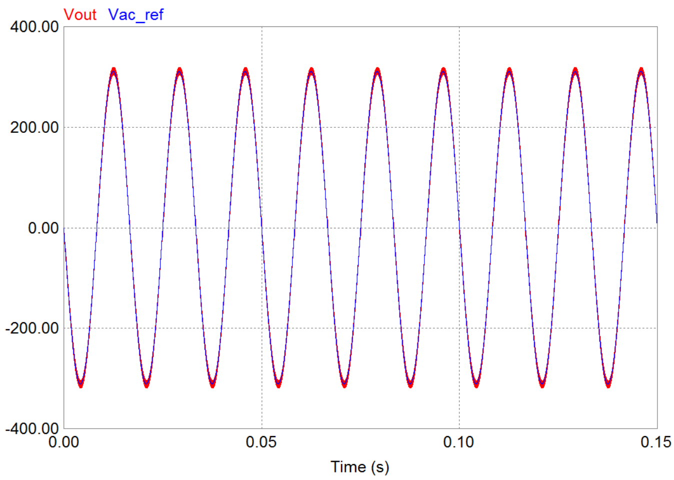

Figure 6: A 60 Hz sinusoidal voltage generated by the designed phase-shift controller