An Integrated Bi-Directional Power Electronic Converter with Multi-level AC-DC/DC-AC Converter and Non-inverted Buck-Boost Converter for PHEVs with Minimal Grid Level Disruptions

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***Abstract*-In order to increase energy independency and decrease harmful vehicle emissions, plug-in hybrid electric vehicles (PHEVs) have been suggested as viable replacements for conventional internal combustion (IC) vehicles. In the event that PHEVs do command a large market share, their interactions with the grid could either become a large asset or a large burden for the grid, depending on the interface used and how it is implemented. This paper will present a bi-directional converter that not only enables beneficial vehicle-to-grid (V2G) interactions, but also ensures that all power delivered to and from the grid has good power factor and near zero current harmonics. To accomplish this task, a multi-level bi-directional AC-DC converter is combined with an integrated bi-directional DC-DC converter. The proposed converter has four different modes of operation that allows it to supply power to or from the battery to either the grid or the high voltage bus of the PHEV. These capabilities make this topology an ideal candidate for HEV to V2G equipped PHEV conversions.**

I. INTRODUCTION

PHEVs and HEV to PHEV conversions have started to emerge in the automotive industry due to the possibility for large gains in efficiency and reductions in emissions [1]-[3]. These PHEVs achieve such high efficiencies in part by displacing some of their energy demand onto the grid [4], [5]. It has also become apparent that if PHEVs achieve a large market share and their charging is left uncoordinated, the grid could suffer [6]. These effects could be multiplied if the vehicle chargers draw current harmonics and have a poor power factor [7]. It is important to realize that PHEVs have the capability of representing a large energy resource for the grid. Tapping this resource could eliminate grid issues that are simply a result of the demand fluctuations that occur every day in addition to the constant need for voltage and frequency regulation [8]. PHEVs equipped with a V2G enabled interface that allows coordinated charging could significantly reduce these issues with electrical demand [9], [10]. A V2G equipped PHEV market penetration of only 10% could replace up to 25% of the electrical generation capacity in most regions of the United States [11].

This study introduces an integrated bi-directional power electronic converter that enables V2G interactions and minimizes any negative effects on the grid. In order to achieve this, a bi-directional multi-level AC-DC/DC-AC converter is integrated with a non-inverted buck-boost converter that has an integrated high-voltage bus. The multi-level AC-DC converter was chosen for its ability to supply current to or from the grid with near zero current harmonics and unity power factor. The low device stresses and small filter make it more feasible than other topologies for this high power application [12]. The non-inverted buck-boost converter with an integrated high-voltage bus was chosen [13] because it only requires one high-current inductor and incorporates the HEV high voltage bus into the design. In combination, these two circuits form a converter that is capable of four different modes of operation, which are plug-in charging of the battery, vehicle-to-grid discharge of the battery, high voltage bus charging the battery for regenerative braking, and battery discharge to high voltage bus for supplying power to the HEV.

II. SYSTEM DESCRIPTION

As shown in Fig. 1, the proposed integrated bi-directional power electronic converter is made up of a multi-level AC-DC converter on the left and an integrated DC-DC converter on the right. The bi-directional multi-level AC-DC converter consists of L_1, R_1, D_1 and D_2, C_1 and C_2, and T_1-T_6 with their respective internal diodes. The bi-directional non-inverted buck-boost DC-DC converter contains L_2, D_3-D_6, C_3, B_1, S_1, S_2, and T_7-T_{10} with their respective internal diodes. The four modes of operation can be divided into plug-in and high voltage bus categories. During high voltage bus modes, T_1-T_6 remain off since the AC-DC converter is not needed. For the two plug-in modes, T_1-T_6 are switched through 6 different patterns according to the control strategy. It should be noted that the L_1 inductance is the converter's inductance and has no relation with the grid's internal inductance. The R_1 represents the internal resistance of the inductor and it is very low.

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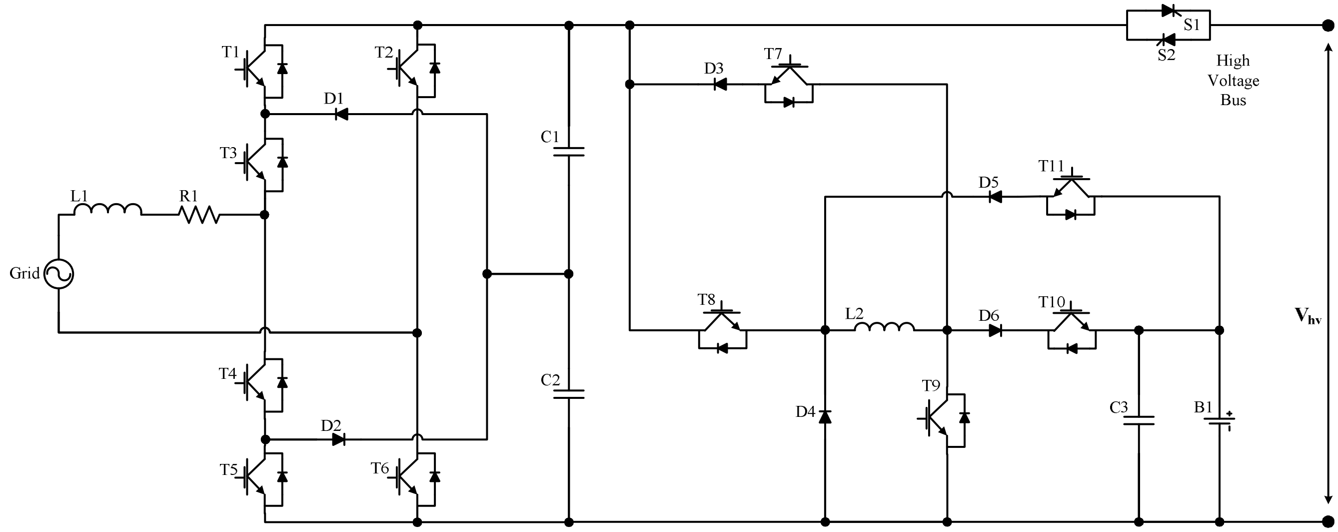

Fig. 1. Integrated Bi-directional Power Electronic Converter.

In AC-DC mode 1 (Fig. 2), T_1, T_3, and T_6 are switched on to apply $V_{DC\text{-}DC}$ across L_1, R_1 and the grid. This way, both C_1 and C_2 are charged or discharged at the same time and the current delivered to or from the grid decreases because of the negative voltage across L_1.

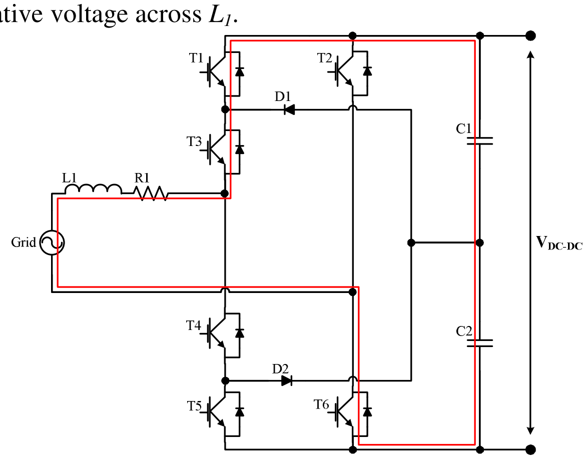

Fig. 2. AC-DC mode 1.

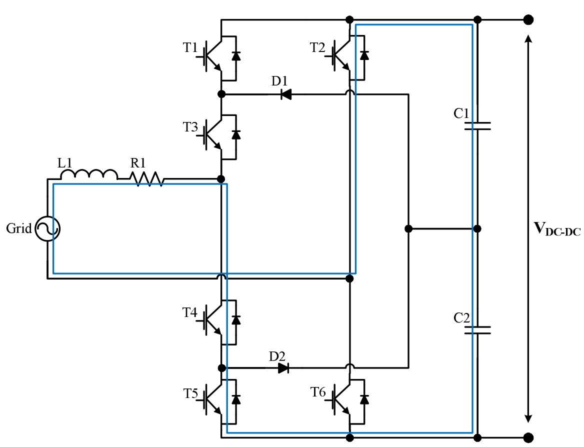

Fig. 3. AC-DC mode 2.

AC-DC mode 2 (Fig. 3) applies -$V_{DC\text{-}DC}$ across L_1, R_1 and the grid to once again charge or discharge C_1 and C_2 at the same time. The grid current increases throughout this mode since the voltage across L_1 is positive. In other words, this mode operates like mode 1, but for negative grid voltages instead of positive.

During AC-DC Mode 3 (Fig. 4), V_{C2} is applied across R_1, L_1 and the grid by switching T_3, T_4, and T_6 on. Since C_1 and C_2 are identical, this amounts to about half $V_{DC\text{-}DC}$. The current delivered to or from the grid increases or decreases depending on the relationship between V_{Grid} and V_{C2}.

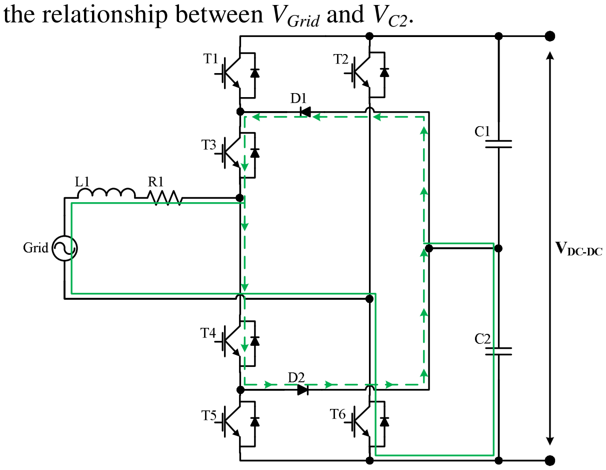

Fig. 4. AC-DC mode 3.

AC-DC Mode 4 (Fig. 5) shows how T_2, T_3, and T_4 are switched on to apply -V_{C2} across R_1, L_1 and the grid. Because C_1 and C_2 share the same capacitance, this should be roughly equal to half -$V_{DC\text{-}DC}$. The current delivered to the grid increases or decreases depending on the relationship between V_{Grid} and V_{C1}.

In AC-DC Modes 5 and 6 (Figs. 6 and 7), T_1, T_2, and T_3 or T_4, T_5, and T_6 can be turned on to result in the application of 0 volts across R_1, L_1 and the grid. This allows the current to or from the grid to increase or decrease depending on the sign of the grid voltage.

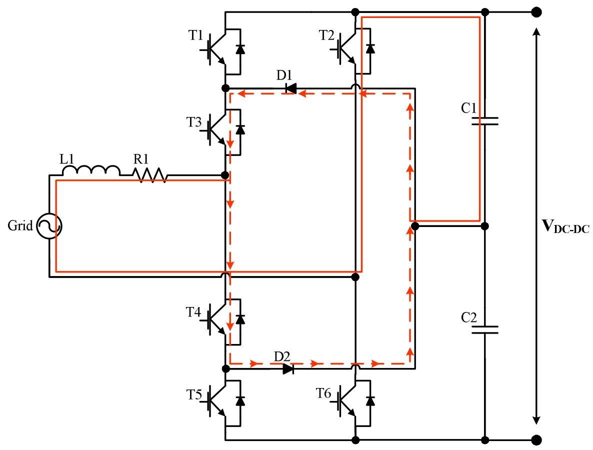

Fig. 5. AC-DC mode 4.

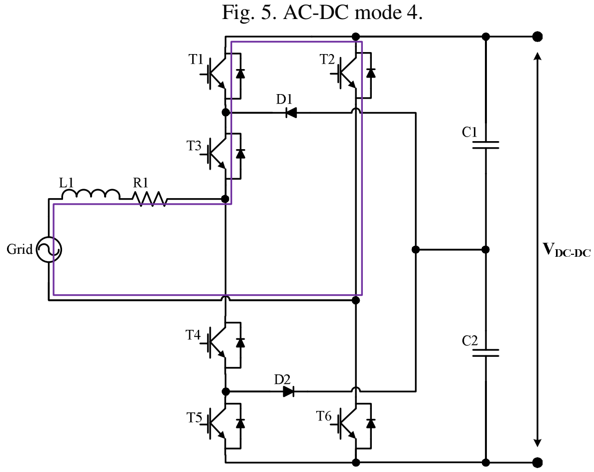

Fig. 6. AC-DC mode 5.

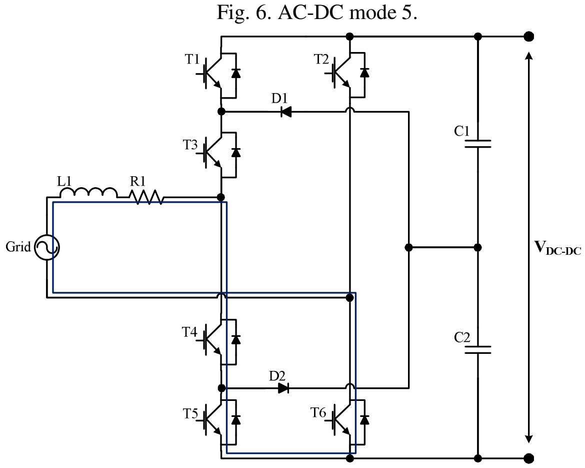

Fig. 7. AC-DC mode 6.

If it is assumed that the voltage of B_1 is lower than V_{Grid}, then whether operating in plug-in or high voltage bus modes, it can be concluded that the DC-DC portion of the circuit follows only two different behaviors. It either charges the battery by bucking from C_1 and C_2 to B_1 or discharges the battery by boosting from B_1 to C_1 and C_2. Because C_1 and C_2 are connected in parallel with the high-voltage bus whenever the vehicle is unplugged and connected in parallel to the AC-DC converter whenever it is plugged-in, the two DC-DC modes can function as four modes in total when either plugged in or unplugged.

To charge B_1, the DC-DC converter acts in buck mode (Fig. 8) [13]. The topology in Ref. [13] is modified with the addition of the S_1, S_2, D_3, and T_7 and the reduction of two switches. These modifications enabled the battery discharge to grid mode and took advantage of the triac as a static switch. To buck the high voltage from C_1 and C_2 down to the voltage of B_1, T_{10} remains on while T_8 is switched on and off by a PWM controller. All other switches remain off. This works for plug-in charging of the battery or high voltage bus charging the battery through regenerative braking when S_1 and S_2 are activated and the car is unplugged.

To deliver power from B_1 to the grid when plugged in or high voltage bus when unplugged, the DC-DC converter acts in boost mode (Fig. 8). To boost the voltage of B_1 up to the amplitude voltage of the AC source or V_{hv}, T_{11} remains on while T_7 and T_9 are switched on and off complementary by PWM controllers.

III. CONTROL STRATEGY

The employed control methodology ensures that the current delivered to/from the grid is near sinusoidal and always in phase. It also allows the battery to get charged or discharged to/from the capacitors C_1 and C_2. Considering the fact that vehicle will never be driven while plugged-in, the two plug-in modes can be separated from the two high voltage modes. This enables the single DC/DC converter to perform the functions of two modes. The only point that differentiates the plug-in and high voltage modes (as far as the DC/DC converter is concerned) is the voltage that is maintained on C_1 and C_2.

During both plug-in modes, the same switching strategy is used for T_1-T_6. The goal is to apply the voltages V_{DC-DC}, $(V_{DC-DC})/2$, 0, $-(V_{DC-DC})/2$, and V_{DC-DC} with varying pulse width across L_1, R_1 and the grid. This is accomplished using the control system shown in Fig. 9.

The *Boolean x* is determined by generating a reference current I^*, comparing it to the actual current I_S, and then checking to see if this difference is less than or equal to *0*. The reference current I^* is generated by finding the difference between the desired voltage across both C_1 and C_2, $(V_{pk-pk})/2$, and the measured value across C_1 and C_2, V_{DC-DC}, and multiplying this amplitude by the normalized grid voltage, and finally adding a term that accounts for the difference between the voltages of C_1 and C_2. The *Boolean y* checks to see if the absolute value of the grid voltage, V_S, is greater than or equal to a fourth of the peak-to-peak grid voltage, V_{pk-pk}. Finally, *Boolean z* determines the sign of the grid voltage, V_S. The variables *x*, *y*, and *z* are then interpreted according to Table I to indicate the mode of operation of the converter [12]. Table II shows the gate switching patterns for each mode and the corresponding voltage applied across L_1, R_1, and the grid.

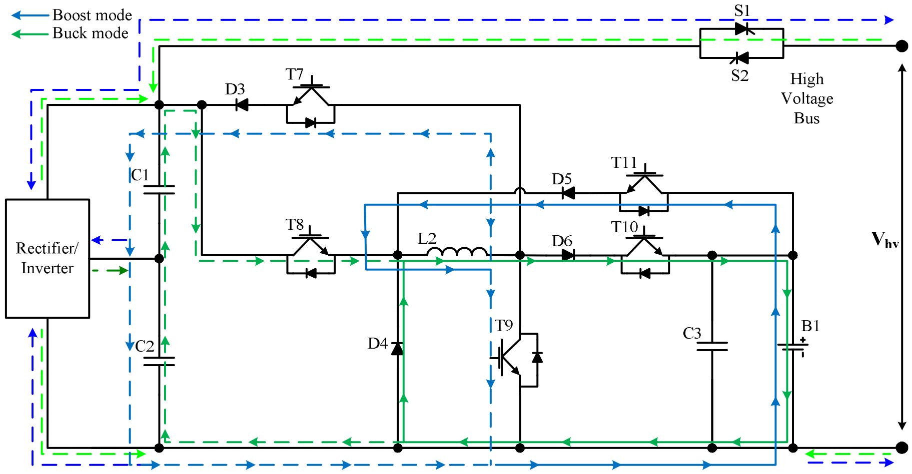

Fig. 8. DC-DC buck and boost modes.

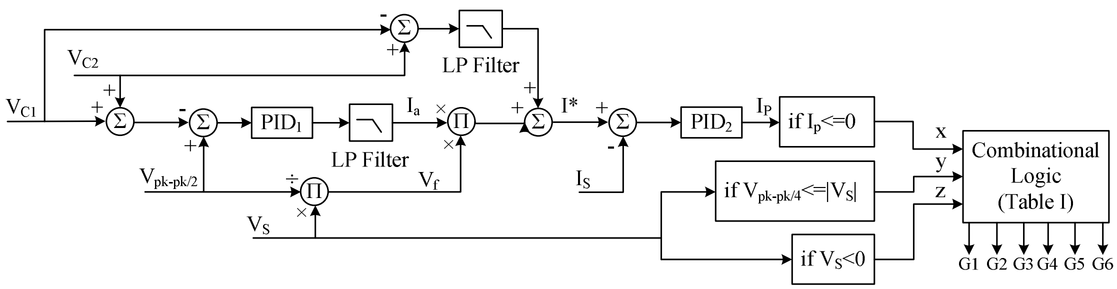

Fig. 9. Control system of the AC/DC converter operation.

TABLE I

COMBINATIONAL LOGIC FOR AC/DC CONVERTER CONTROL SYSTEM

x	y	z	Mode	Voltage
0	0	0	6	*0*
0	0	1	3	$(V_{DC\text{-}DC})/2$
0	1	0	3	$(V_{DC\text{-}DC})/2$
0	1	1	1	$V_{DC\text{-}DC}$
1	0	0	4	$-(V_{DC\text{-}DC})/2$
1	0	1	5	*0*
1	1	0	2	$-V_{DC\text{-}DC}$
1	1	1	4	$-(V_{DC\text{-}DC})/2$

TABLE II

SWITCHING PATTERNS FOR DIFFERENT MODES OF OPERATION

Mode	G1	G2	G3	G4	G5	G6	Voltage
1	1	0	1	0	0	1	$V_{DC\text{-}DC}$
2	0	1	0	1	1	0	$-V_{DC\text{-}DC}$
3	0	0	1	1	0	1	$(V_{DC\text{-}DC})/2$
4	0	1	1	1	0	0	$-(V_{DC\text{-}DC})/2$
5	1	1	1	0	0	0	*0*
6	0	0	0	1	1	1	*0*

Since the V_{C1} and V_{C2} are two of the controller inputs, their voltage balance is provided along all modes of operation. The switching pattern provided in Table II results in varying low switching frequency rather than a constant high switching frequency. This feature eliminates the need for an EMI filter since L_1 is not involved in high frequency switching.

The DC/DC portion of the converter uses a battery power controller for plug-in modes and a cascaded voltage and current controller for high-voltage bus modes. The battery power controller, shown in Fig. 10, allows the desired power to/from the battery to be applied. In this way, the proper battery discharging or charging power can be controlled by the application of the desired reference power. This reference power can be determined based on the state of charge of the battery, user requirements, and the state of the grid. The cascaded voltage and current controller shown in Fig. 11 allows the high voltage bus to be kept at the proper voltage while also accommodating the power demanded or supplied by the high voltage bus during vehicle driving. This enables regenerative recharging of the battery from the high voltage bus and discharging of the battery to the high voltage bus, all while maintaining the proper voltage level for the vehicle.

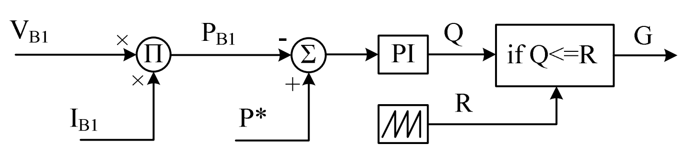

Fig. 10. DC/DC converter's charging/discharging power controller.

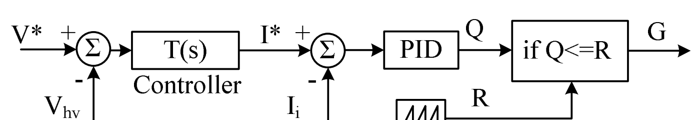

Fig. 11. DC/DC converter's cascaded controller for driving mode.

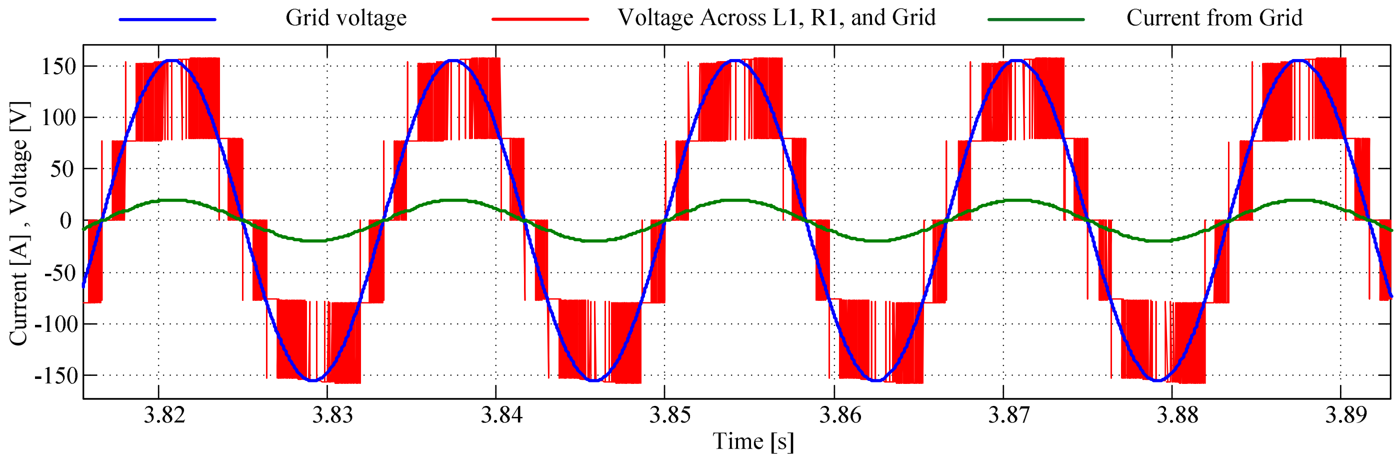

Fig. 12. Voltages and current for plug-in charging mode at 1500W steady-State.

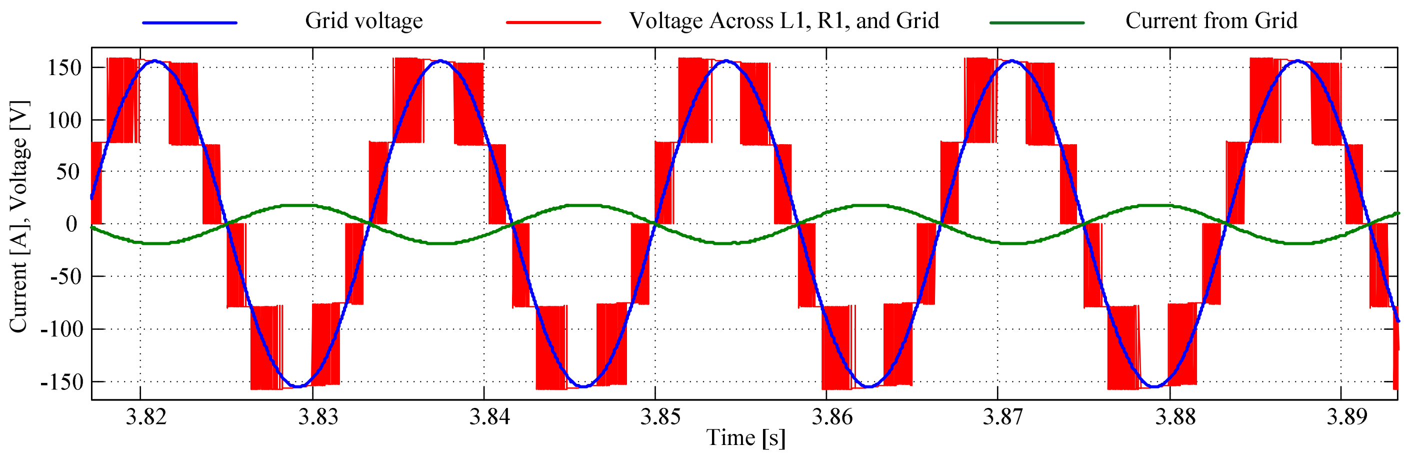

Fig. 13. Voltages and currents for V2G discharge of battery at 1500W steady-State.

IV. Results and Discussions

The simulation results from the two plug-in modes are shown in Figs. 12 and 13. The current delivered to and from the grid is shown to be sinusoidal and in phase with the grid voltage. This eliminates current harmonics and maintains a unity power factor, which ultimately prolongs the life of the converter and minimizes the possibility of distorting the grid. When delivering power to the grid, the injected current is in the reverse direction of the grid voltage, which can be seen from the 180° phase difference. In this case, zero crossings of the grid voltage and injected current are still matching each other.

Figures 14 and 15 show the simulation results of the loading the high voltage bus. Although some brief voltage transients occur during abrupt load changes, the converter maintains 300 volts across the load bus while supplying or absorbing the required current. Negative loading currents simulate regenerative breaking and positive currents supply power to the HEV high voltage bus.

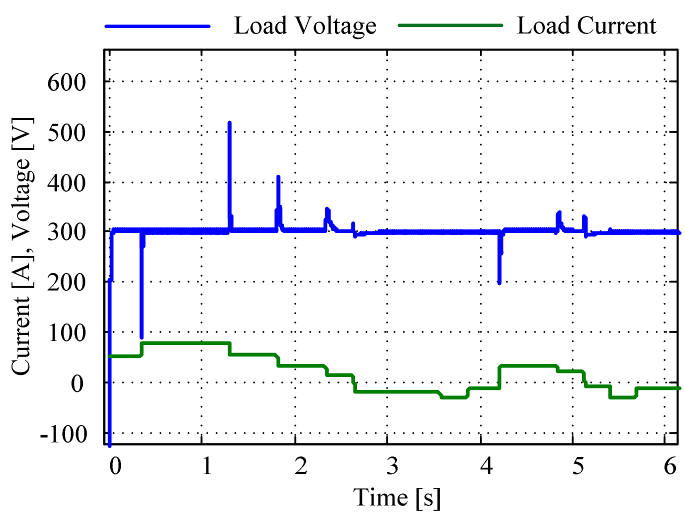

Fig. 14. Voltages and currents of the HEV high voltage bus.

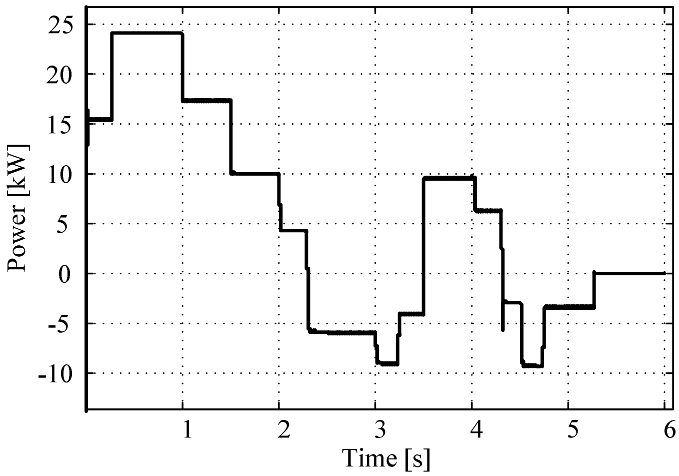

Fig. 15. HEV high voltage bus power

V. CONCLUSIONS AND FUTURE WORK

As PHEVs are emerging as replacements for traditional vehicles, it is important to consider the effects that large numbers of plug-in vehicles might have on the grid. To avoid issues, a grid friendly interface must handle the energy exchange between the vehicle and the grid. The proposed converter delivers current to/and from the grid with unity power factor and very low current harmonics. It also enables V2G interactions which could be utilized to improve the efficiency of the grid in the future. Additionally, the integrated high voltage bus makes this circuit a good choice for HEV to PHEV conversions.

ACKNOWLEDGMENT

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