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Multi Functional Bi-directional Converter for Plug-in Hybrid Electric Vehicle

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ABSTRACT. Integrated bidirectional converter for plug-in hybrid electric vehicles (PHEVs) is a new method of charging of battery pack and energy conversion from battery to high voltage bus of PHEV. Integrated converter has less cost, volume, weight, and less number of current transducers and high current inductors. The converter has three operating modes, they are plug-in ac/dc charging of the battery, boost operation from the low voltage add-on battery to the high voltage bus of the HEV, and buck operation from the high voltage bus to the add-on battery for regenerative charging. The converter discussed in this paper can implement three tasks by sharing switches and inductors all in one system. In the first case, the converter discussed in this project act as a ac to dc battery charging. In the second case, the converter act as dc-dc boost converter. In the third case, the converter discussed in this project act as a dc to dc buck converter.

I.INTRODUCTION

Conversion of conventional hybrid electric vehicles (HEVs) into plug-in HEVs reduces fuel consumption has been considered by both academia and the automotive industry. The conversion is achieved by either adding a high- energy battery pack or exchanging the prevailing battery pack of HEV to increase the all-electrical ranges. In either case, the high-energy battery pack ought to be charged from external ac outlet, as well as regenerative braking, and must supply the stored electrical energy to the electric traction system. AC outlet charging inevitably needs a battery charger with Power Factor correction (PFC) which has various configurations based on an ac/dc converter. Plug- in Hybrid Electrical Vehicles (PHEVs) can play an important role in future transportation systems because of their potential in terms of energy security, ablated environmental impact, improved fuel economy, and better performance.

An integrated converter in [2] utilizes a number of semiconductor devices to achieve each mode; therefore, it may not be an efficiency optimized and cost-effective solution. In addition, the presence of a large number of devices, this converter requires a complex control strategy to turn on the switches. An integrated converter in [3] has only boost charging capability; thus, the selection of wide range of battery voltages is compromised. In [4], an integrated converter does not have buck/boost operation in any mode; thus the selection of the dc-link and battery voltage range is sacrificed. A three-level quasi two-stage converter in [5] with two inductors has buck/boost operation only in charging mode as a result, aforementioned advantages of buck/boost operation in each mode is sacrificed. In [6, 7], a SEPIC- based converter has been proposed for the battery charging using three inductors and at least one extra inductor is also required for propulsion and regenerative braking modes. Thus, the increase of magnetic components has a negative effect on weight, cost and volume of the charger. The authors in [8, 9] have proposed a CUK converter based on-board battery charger, which operates only in charging mode, does not include vehicle running and regenerative braking modes. A single-stage converter in [10] operates only battery charging mode using four switches, eight diodes and two inductors. However, to achieve other modes of the vehicle, some more components will be employed. Therefore, this converter will utilize a large number of active and passive components, which will have an adverse effect on cost and compactness of the charger. The authors [6] have proposed front-end power factor correction (PFC) converter for EV battery charger, which is a bridgeless type converter that uses four inductors and at least one additional inductor requires to achieve other modes of the vehicle. A single stage based inductive charger has been proposed in [7] that provides a wide range of voltages for battery charging, but this converter uses a large number of passive components and semiconductor devices; therefore, the floor area of the charger will increase and less suitable for on-board application of PEVs.

The topology described in [8] has high efficiency for low voltage application, less cost due to limited amount of passive as well as semiconductor devices, narrow voltage conversion range and high switching stress. So it is not suitable for commercial HEV but best applicable for small capacity EV. Voltage gain of the topology described in [9] is double in boost mode and half in buck mode of operation than the topology presented in [8]. Voltages across the switches are half of HV side voltages. This topology requires high numbers of switches and capacitors. It is best suited to mild electric vehicle due to its inherited nature of responding to sudden load change. The Topology described in [10] has high gain and efficiency due to soft switching action. Due to high frequency operation, the size of transformer used in this converter is small. This circuit requires high input capacitance value hence amount of ripple current is large. The topology [11] has same device rating as that of the Topology described in [9], with less number of switch count and lower ripple current at input side. Main drawback is split DC capacitor which has to carry full load current. Due to less ripple current it is best suited for pure electric vehicles because of smooth operation of electric motor.

II. OPERATING MODES OF THE DISCUSSED INTEGRATED CONVERTER

The main elements for the conversion comprise an ac/dc charger, a high energy battery added to the HEV, a bidirectional dc/dc converter, and a D-space. These main elements are in cascade, except the D-space. The plug- in charger is composed of two parts: 1) ac/dc rectifier and 2) dc/dc converter. The bidirectional dc/dc converter is placed between the add-on battery and the high-voltage bus of the HEV. The D-space controller has the duty to control and monitoring, of the ac/dc charger and bidirectional dc/dc converter, battery state of charge, and communication with external systems. Discussed converter deals with three voltage sources, i.e., ac outlet voltage Vac, battery voltage Vbatt, and the high-voltage bus of HEV Vhv. Basically, the three modes of operations do not occur at the same time, in that plug-in charging is not allowed while the vehicle runs. Discharging and regenerative charging of the battery is exclusive in operation. The discussed converter works in three modes of operation. These three modes are described below.

Mode 1: Non inverting Buck-Boost Operation or Plug-in charging of the low voltage battery uses switches Q1, Q2, Q3, diodes D1, D3, and inductor L1. This mode can provide a plug-in charger function with PFC without regard to whether battery voltage Vbatt is higher than the peak value of the ac outlet Vacpk. Switches Q1 and Q2 are in PWM switching mode, and Q3 remains in the ON state during the operation. The desired output voltage and current are regulated by the appropriate combinations of the buck and boost mode. The input/output voltage measured across the resistors Rs1, Rs2, Rs3, Rs4 and inductor current is measured through the current transformer CT1. The other switches and diodes Q4, Q5, Q6, D4, D5, and D6 stay in the OFF state to disconnect the high-voltage bus of the HEV from both the ac input and the low voltage battery

Mode 2: Mode2 is the boost operation from the low voltage battery to the High-Voltage Bus of the HEV. In this mode, Vbatt and Vhv sequentially become input and output voltages. Inductor L1, Switches Q2, Q4, Q5, and diodes D4, and D5 form a boost converter, in that a Vhv higher than Vbatt is assumed. Switch Q2 is in PWM switching mode, and Q4 and Q5 are in the ON state, so that the current path can appear between the battery and the high-voltage bus. The other switches and diodes Q1, Q3, Q6, D1, D3, and D6 maintain the OFF state to separate the ac outlet. The input/output voltage and inductor current are measured through resistors Rs3, Rs4, Rs5, Rs6, and current transformer CT1. Power from the battery to the high-voltage bus can be estimated using the measured battery voltage and current so that transferable power at a certain state of charge should be regulated appropriately.Mod3: Mode 3 is the regenerative charging of the low voltage battery using buck operation from the high-voltage bus to the battery. In this mode, inductor L1, switches Q3, Q6, diodes D1, D3, and D6 are used for the buck converter.Here Vhv higher than Vbatt is assumed. Switch Q6 works for PWM switching, Q3 stays in the ON state, and D1 provides a freewheeling path. Other switches and diodes Q1, Q2, Q4, Q5, D4, and D5 are in the OFF state . To measure input/output voltage and current resistors Rs3, Rs4, Rs5, Rs6, and current transformer CT1 are used respectively.

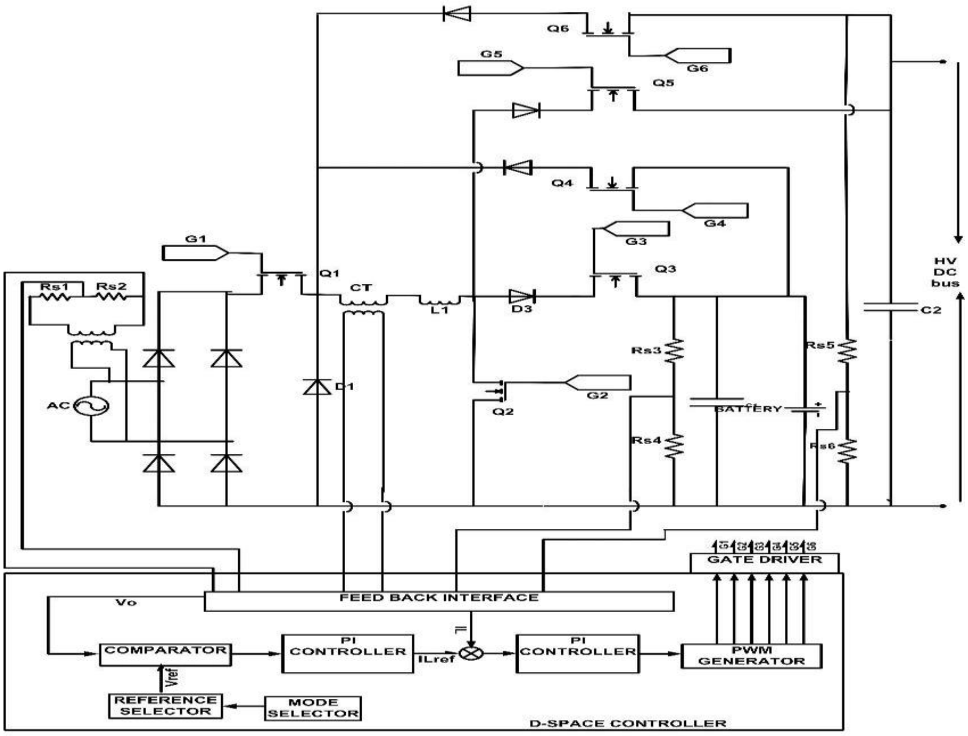

Figure 1. Discussed System

III. CONTROLLER

For mode 1 switch Q1 and switch Q2 are PWM controlled switches. Mode 1 has two control loops. One is voltage controlled loop and another one current controlled loop. Each loop has one PI controller. Output voltage is sensed and compared with reference battery voltage. It will produce an error signal. This error signal will give to the input of voltage PI controller. Output of PI controller is reference input current. This reference inductor current is compared with the sensed inductor current. It will produce an error signal. These error signal is given to the input of current PI controller. Output of current PI controller is given to the PWM generator. Which will produce the necessary gating signal for the switches Q1, Q2 and Q6. In mode 2, voltage controlled loop is used. Voltage controlled loop has one PI controller . Here the voltage across capacitor C2 is the feedback voltage. Vc2 is compared with reference signal and it will produce error signal. These error signal is given to the input of PI controller and it will produce an error signal, which is given to the PWM generator . In mode 3 also voltage controlled loop is used. Voltage Controlled loop have one PI controller. Here the voltage across capacitor C1 is the feedback voltage. Vc1 is compared with reference signal and it will produce error signal. These error signal is given to the input of PI controller and it will produce an error signal, which is given to the PWM generator. Figure 2 shows the control block diagram for three modes.

Mode 1

Voltage across capacitor C1 is measured and given to the voltage sensor. Voltage sensor output is given to the D-space controller. These voltage is compared with reference voltage and error signal is given to the PI controller. PI controller outputs inductor current reference. Inductor current reference is compared with feed backed inductor current. Error output will give to the current PI controller and it will produce the control signal. These control signal is given the input of PWM generator. For selecting buck or boost mode Vc1 is compared with magnitude of rectified voltage. If Vc1 is less than rectified voltage boost operation will take place. If Vc1 is greater than the rectified voltage buck operation will takes place. Proportional constant and Integral constant of voltage PI controller are 0.036 and 43.4 respectively.

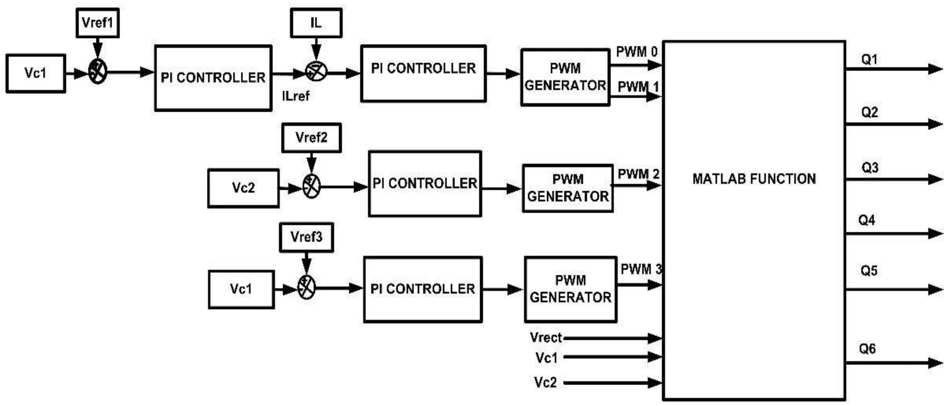

Figure 2. Control block diagram.

Mode2

Voltage across capacitor C2 is measured and given to the voltage sensor. Voltage sensor output is given to the D- space controller. This voltage is compared with reference voltage and error signal is given to the PI controller and it will produce the control signal. These control signal is given the input of PWM generator. Proportional constant and Integral constant of a PI controller are 1.1 and 10.1 respectively.

Mode 3

Voltage across capacitor C1 is measured and given to the voltage sensor. Voltage sensor output is given to the D- space controller. These voltage is compared with reference voltage and error signal is given to the PI controller and it will produce the control signal. These control signal is given the input of PWM generator. Proportional constant and Integral constant of a PI controller are 0.04 and 42.5 respectively.

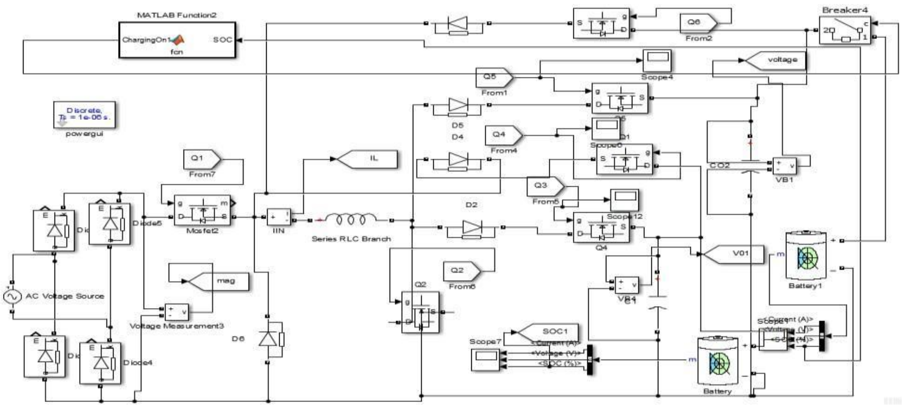

Figure 3. Simulink model of the discussed system

Converter has been simulated in Matlab Simulink model for a duration of 2 second. For mode1 Vac and Vbatt (Low voltage battery voltage) are the input and output voltages, respectively. For mode 2 Vbatt and Vhv (high voltage bus) are the input and output voltages, respectively. Mode 3 is the buck operation from the high-voltage bus to the add-on battery. Now, Vhv becomes the input voltage and Vbatt is that the output voltage of the convertor. To simulate the regenerative voltage when the vehicle is decelerated, Vhv has been assumed to be 360V. Buck operation starts when Vhv becomes higher than Vbatt, and buck operation ends when Vhv decreases to Vbatt. Figure3 shows the complete simulation model of the bidirectional converter. Fig 4(a) shows the inductor current for the three modes of operation. Figure 4(b) shows the low voltage battery

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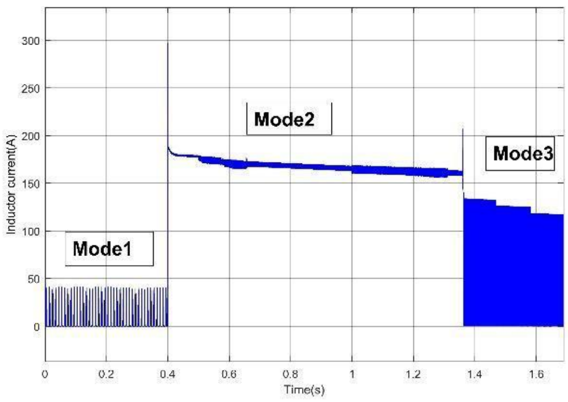
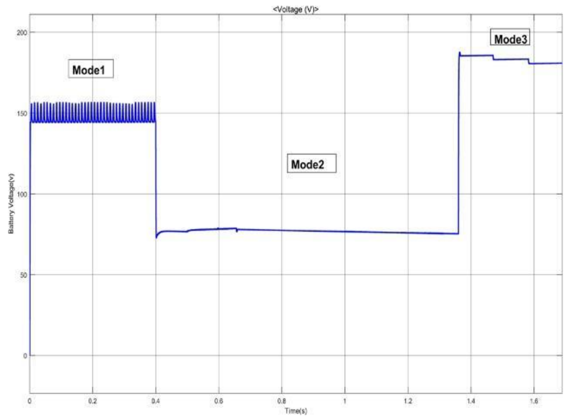
voltage for the three modes of operation. Up to 0.4 second integrated converter works in mode 1. So that the battery gets charged and battery voltage is 150V. From 0.4 second to 1.38 second integrated converter works in mode 2, that is boost mode of operation. So that in this duration battery voltage reduces suddenly. From 1.38 second to 2 second converter works in regenerative breaking mode. Figure 5(a) shows the SOC for the three modes of operation. Up to 0.4 second integrated converter works in mode 1. So SOC increases up to 0.4 second. When it switches to mode 2 sudden decrease of SOC occur because battery is discharging. For mode 3 from 1.38 seconds SOC increases because of boost mode of operation. Figure 5(b) shows the low voltage battery current for the three modes of operation. Up to 0.4 second integrated converter works in mode 1. So that the battery gets charged and battery current is negative. From 0.4 second to 1.38 second integrated converter works in mode 2, that is boost mode of operation. In this mode battery is discharging. So that in this duration battery current will be positive. From 1.38 second to 2 second converter works in regenerative breaking mode.



(a)



(b)

Figure 4. (a) Inductor Current During Three Modes (b) LV Battery Voltage during Three Modes(a) (b)

Figure 5. (a) SOC of LV during three modes (b) LV Battery Current during three Modes.

IV.CONCLUSION

Discussed converter function as ac to dc battery charger and bidirectional converter for power transfer between battery and high voltage bus. Less number of high current inductors and current transformers used. So it reduces sharp fault current. Proposed converter deals 3 three levels of voltage. Through the simulation and experimental prototype, the functionality for the three operating modes, i.e., the combination of buck and boost for plug-in charging of the add- on battery, boost for discharging the add-on battery, and buck for regenerative charging of the add on battery, have been verified. To verify the practicality of the proposed converter for PHEV applications, an on board testing prototype and vehicle power management system need to be implemented in a real vehicle, and fault tolerance of the system should be tested in real-world applications.

Table 1. Simulation parameters

Parameters	Specifications
Rated power	1.4kw
L1	600µH
C1	470 µF
C2	1200 µF
IGBT	KGF25N120KD
Power Diode	A E15ED2 4
Battery	134-350V

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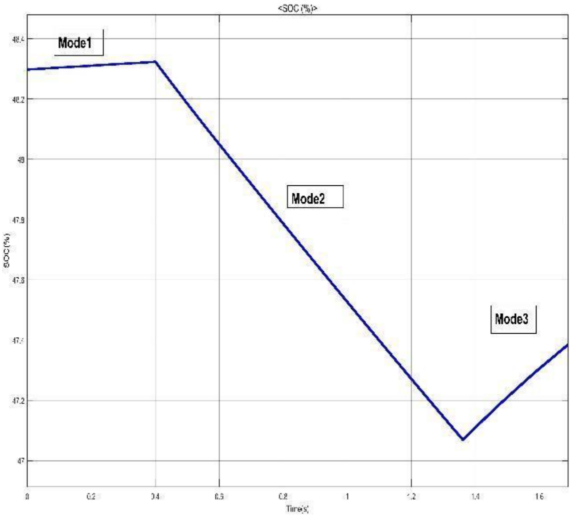

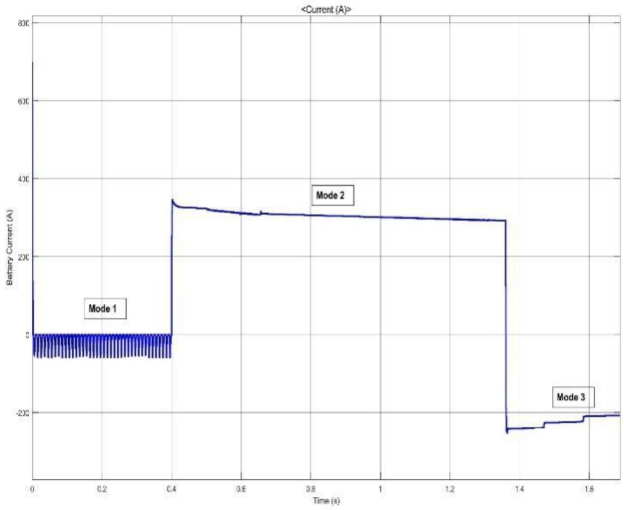

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