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A Controllable Bidirectional Battery Charger for Electric Vehicle with Energy Management System

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Abstract: *This paper describes a comprehensive methodology for the design of a controllable electric vehicle charger capable of making the most of the interaction with an autonomous smart energy management system (EMS) in a residential setting. Autonomous EMS aims to achieve the potential benefits associated with energy exchanges between consumers and the grid, using bidirectional and power-controllable electric vehicle chargers. The controllable charger is designed by Alternating current (AC)/Direct current (DC) converter and DC-DC converter. This controllable charger is implemented by using MATLAB Simulink. The results obtained establish the adequate interaction between the proposed charger and a compatible autonomous EMS in a typical residential setting.*

Keywords: *Energy management system (EMS), plugin electric vehicle (PEV), energy storage, bidirectional charger, grid-to vehicle, vehicle-to-grid.*

1. Introduction:

In this world electricity plays a crucial role. The usage of electricity is increasing has predominantly increased in the new age. In the peak times the grid may not be able to manage the system which leads to the system failure. So in order to mitigate the problem, we may use the energy from the other emerging technology in vehicles which is electric vehicle concept. The electric vehicles are operated by using electricity. As the usage of the electric vehicles is increasing, we can use the energy stored in the batteries of electric vehicles at their rest time, in order to mitigate the problems of energy management at peak times. So load on grid will reduce during peak time.

In this paper we are using energy management system (EMS) such as energy box EB works as a background processor which operates with help of information and communication technology (ICT) it manages the energy usage. The implementation of this type of EMS faces some challenges such as design of controllable bidirectional battery chargers between the grid and vehicle battery. The PEV that can be recharged with an electric plug that can be treated as a residential load with ability to return energy to the grid (vehicle to grid V2G). V2G refers to the 2-way flow of electrical energy from the grid, through a charger into an EV and back again. The EB is responsible for controlling G2V or V2G mode of operation through the signals act as reference to the controllers of charger.

PEV Charger topology:

This charger has the maximum power of 2.3 KW which is suitable for the household plug. This power range is based on the EU standards and power grid restrictions.

The topology as shown in fig. 1 is obtained by the IGBT (insulated gate bipolar transistor). IGBT is used due to its fast switching and high efficiency. The AC/DC converter act as an inverter during V2G operation and it act as a rectifier during G2V operation. LC filter also used for filtering and energy storage purpose. The c class chopper acts as a buck converter during G2V mode of operation and as a boost converter during V2G mode of operation.

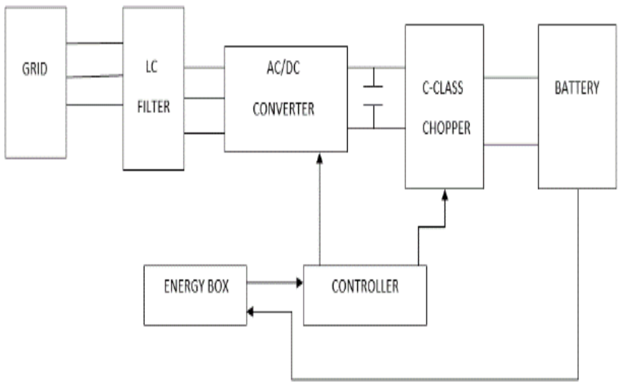

Fig. 1: PEV charger topology

2. Analysis of chopper:

The chopper used in this topology is C class chopper which operates in first two quadrants. The main operation equations can be analysed through the (1) to (4) for buck and (5) to (8) for boost.

$$V_{BAT} = V_{Cbus} - L_{Chopper} \cdot \frac{dI_L}{dt} \quad (1)$$

$$I_L = \frac{1}{L_{Chopper}} \cdot \int_0^{Ton} (V_{Cbus} - V_{Bat}) dt \quad (2)$$

$$V_{BAT} = -L_{Chopper} \cdot \frac{dI_L}{dt} \quad (3)$$

$$I_L = \int_{Ton}^{Toff} -\frac{V_{BAT}}{L_{Chopper}} dt \quad (4)$$

$$V_{BAT} = L_{Chopper} \cdot \frac{dI_L}{dt} \quad (5)$$

$$I_L = \frac{1}{L_{Chopper}} \cdot \int_0^{Ton} V_{BAT} dt \quad (6)$$

$$V_{BAT} + V_{LChopper} = V_{Cbus} \quad (7)$$

$$I_L = \frac{1}{L_{Chopper}} \cdot \int_{Ton}^{Toff} (V_{BAT} - V_{Cbus}) dt \quad (8)$$

The PWM (pulse width modulation) signal control the relationship between the choppers where T_{on} is the drive time and T_{off} is the cut-off time of one period (T). The duty cycle D represents the voltage conversion ratio of this circuit. Duty cycle is represented by the (9) and (10) for the buck mode of operation and (11) and (12) for the boost mode of operation.

$$D = \frac{T_{on}}{T} \quad (9)$$

$$V_{BAT} = V_{Cbus} \cdot \frac{T_{on}}{T} = V_{Cbus} \cdot D \quad (10)$$

$$\frac{1}{1-D} = \frac{V_{Cbus}}{V_{BAT}} \leftrightarrow D = -\frac{V_{BAT}}{V_{Cbus}} + 1 \quad (11)$$

$$V_{BAT} = V_{Cbus} \cdot (1 - D) \quad (12)$$

Inductor and DC bus capacitor are essential in the operation of this converter. The inductor act as energy storage element and determine the energy to be released for each chopper side. Inductor also control the source ripple currents and mitigate the higher switching frequency effects. The inductor sizing is based on the higher power level when battery voltage is lower. Equation (13) is for buck mode of operation.

$$L_{Chopper} = \frac{V_{Cbus} - V_{BATnom}}{2.\Delta I_L} \cdot T_{on} \quad (13)$$

Using (9) and (10), equation (14) is obtained:

$$DT = T_{on} \rightarrow \begin{cases} T_{on-min} = \frac{V_{BATmin}}{V_{Cbus}} \cdot T \\ T_{on-max} = \frac{V_{BATmax}}{V_{Cbus}} \cdot T \end{cases} \quad (14)$$

Where,
V_{Cbus} = 325 V,
$V_{BAT_{min}}$ = 75 V,
$V_{BAT_{max}}$ = 127.5 V,
and T = 50 μs. Then the values for T_{on} min and T_{on} max are 12 and 20 μs, respectively (D = 0.24 and D = 0.4). Considering a 1.2 A ripple current (ΔI_L) criterion and the higher T_{on} value (20 μs) on (13) and V_{BATnom}= 96V, then $L_{Chopper}$ value is 1.9 mH.

Equation (15) is used for the operation in boost mode

$$\Delta I_L = \frac{V_{BAT}}{2.L} \cdot DT \leftrightarrow \Delta I_L = \frac{V_{BAT}}{2.L} \cdot T_{on} \quad (15)$$

Equation (16) is obtained by using (9) and (11)

$$DT = T_{on} \rightarrow \begin{cases} T_{on-min} = 1 - \frac{V_{BATmax}}{V_{Cbus}} \cdot T \\ T_{on-max} = 1 - \frac{V_{BATmax}}{V_{Cbus}} \cdot T \end{cases} \quad (16)$$

Where the values of V_{Cbus} , $V_{BAT_{min}}$, $V_{BAT_{max}}$, T , ΔI_L and V_{BATnom} are the same used before. For the buck converter highest value of T_{on} (38 μs) is used then $L_{Chopper}$ = 1.52 mH. Therefore, in a way to behold the worst scenario, a 1.9mH chopper inductor was used.

The DC bus capacitor is used for stabilisation of the DC bus voltage with low ripple. The sizing of the Cbus is made to stabilise the DC bus voltage during $L_{Chopper}$ current regulation. These capacitors will support DCbus demand of energy for long tine than chopper inductor current regulation time (38 μs), because due to load demand controllers cannot attain the desired reference in one switching period (T = 50 μs). Therefore, considering (17) and (18), the maximum *DCbus* current (Imax) is 7.07 A.

$$\mathrm{I_{DCbus-max}} = \frac{\mathrm{P_{max}}}{\mathrm{V_{Cbus}}} \qquad (17)$$

With a 8.13 V *DC bus* voltage ripple and _t = 38 μs. *Cbus* = 33 μF is required for one single T using (18).

$$C_{bus} = I_{max}\,\frac{\Delta t}{\Delta V_{Cbus}} \qquad (18)$$

The final *Cbus* value must be 200 times greater than the one obtained by (18), and therefore a *Cbus* capacitor of 10mF was used.

3. Analysis of AC/DC converter:

AC/DC converter is used in this proposed charger. This AC/DC converter works as rectifier during grid to vehicle operation which coverts he AC supply into Dc supply to charge the battery. This converter works as an inverter during vehicle to grid operation in which DC supply is converted into the AC supply to serve the grid. By using this converter we can achieve the lower voltage ripple and high efficiency. Because it has unipolar PWM method and IGBT with low internal resistance. This converter is controlled by the PWM technique. This PWM controller sends the gate pulses to the converter and decide the in which mode it has to operate.

Controller design of chopper:

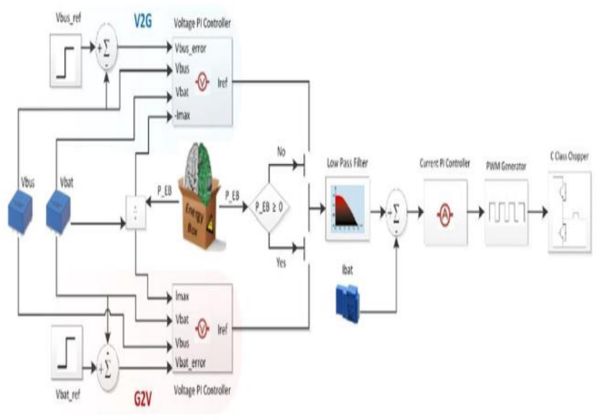

Fig. 2: DC/DC converter controller architecture for V2G and G2V operation modes, respectively.

The design of chopper controller is as shown in the above figure 2. Two modes of operations were implemented one is for G2V and another is for V2G. In this controller two currents will be calculated one is for G2V and another is for V2G. In the both cases Vbus actual voltage is compared with the Vbus measured voltage. Then this error signal is given to the voltage PI controller, battery voltage and current also given to the PI controller. This Pi controller gives a output in the form of current for both G2V and V2G operations. If the power in the energy box is greater than zero then only G2V operation is performed. If energy box power is less than zero then V2G operation is performed. The current signal is given to the current PI controller which converts the current signal into the voltage signal then voltage signal is given to the PWM generator which generates the gate pulses to the chopper. Based on these pulses the DC-DC converter either works as a buck converter or boost converter.

Controller design of AC/DC converter:

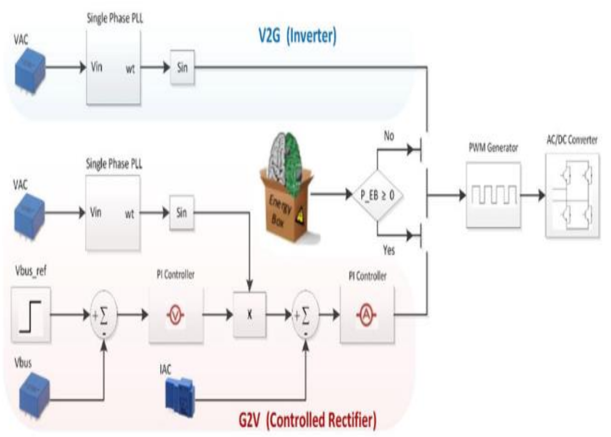

Fig. 3: Architecture of AC/DC converter controller for G2V & V2G mode of operations.

The design of the controller of AC/DC controller is as shown in the above figure 3. In this controller grid voltage and DC bus voltages are compared. To compare the DC voltage with Ac voltage we need phase angle. Vbus gives the magnitude of the voltage and phase angle is calculated by using single phase PLL. Now these signals will come to the decision-making part. When the power in the energy box is greater than the zero then G2V is operated. When power in the energy box is less than zero then V2G is operated. Then the signal is given to the PWM generator which generates the gate pulses to the AC/DC converter. On the basis of these pulses AC/DC converter works as either inverter or rectifier.

Simulation Model:

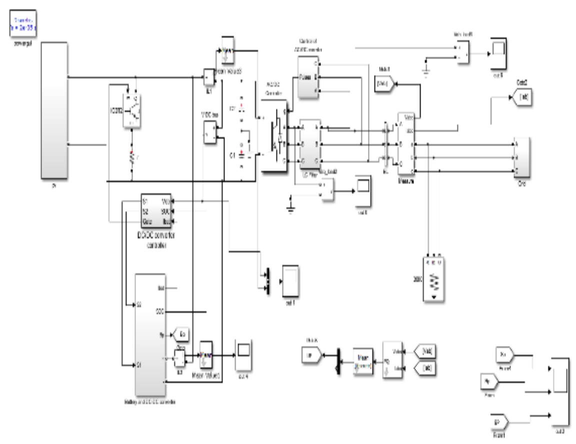

Fig. 4: Simulation model of proposed charger

The simulation diagram for hybrid electrical vehicle with v2g and g2v is verified in MATLAB/Simulink environment. Figure 4 shows the simulation diagram for grid interfaced hybrid vehicle. And fig 5 shows the grid input voltage and current

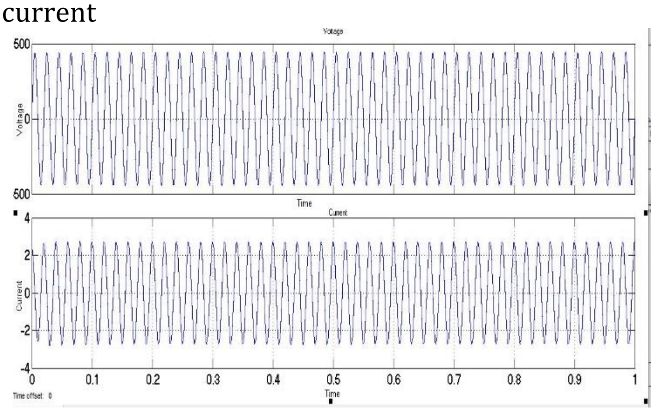

Fig. 5: Input voltage and current of Grid

4. Simulation Results:

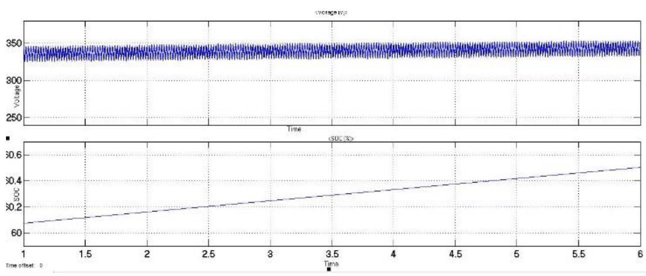

Fig. 6: Wavefrom for Battery Voltage and SOC during G2V

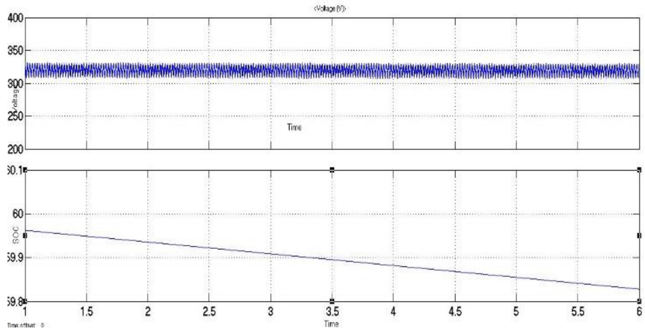

Fig. 7: Wavefrom for Battery Voltage and SOC during V2G

The experimental results obtained for voltage and state of charge of battery during G2V and V2G are presented in Figs. 6 and Fig. 7 Full charger power profile and corresponding battery SoC evolution. Fig. 8 shows the output of the inverter without using LC filter and with using LC filter which is used to reduce spikes in the wavefom.

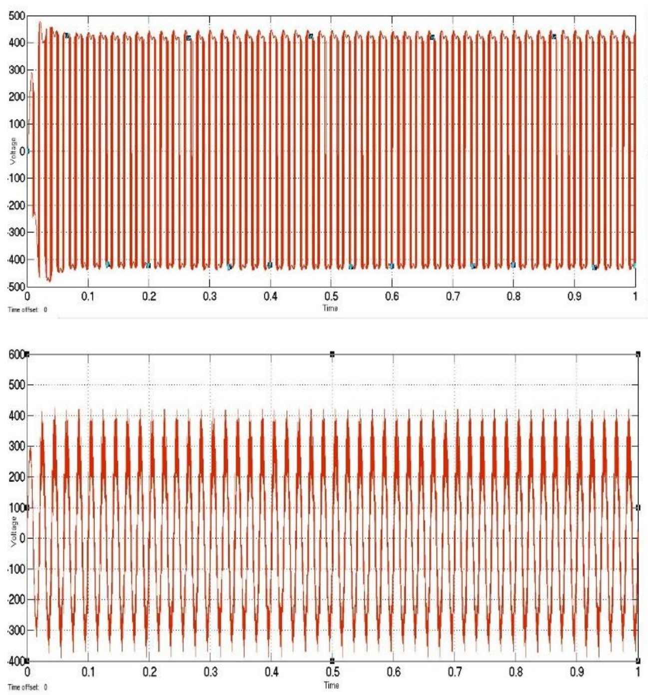

Fig. 8: Wavefrom for output of Inverter without and with LC filter

The simulation diagram for PV based hybrid electrical vehicle with v2g and g2v is verified in MATLAB/Simulink environment. Results of powers are shown in fig 9 for G2V operation and fig.10 shows the results of powers for V2G operation.

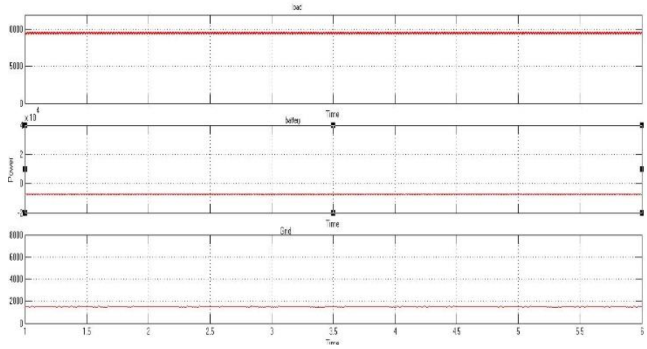

Fig. 9: Wavefrom for PV,Battery andGrid Powers during G2V operation

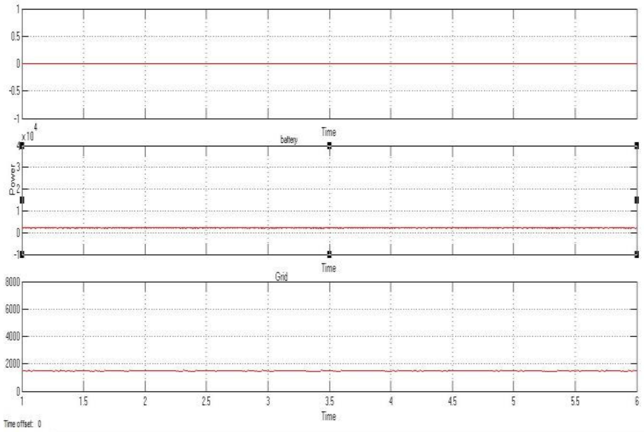

Fig. 10: Wavefrom for PV,Battery andGrid Powers during G2V operation

5. Conclusion:

This paper proposes a PV based bidirectional PEV (or stationary battery) charger topology, which allows enhancing the capabilities of a joint operation of storage and an autonomous EMS in a residential setting, with potential benefits for end-users and utilities/system operator. The PEV role as load or power supplier is also emphasized. This charger is adjustable for charging or discharging operations using a power level provided by the EMS, instead of minimizing the charging time by using only the maximum power level. Since the charger is power flexible and bidirectional, its power electronics topology allows performing charge/discharge operations at different power levels, which benefits the integrated power allocation and scheduling among all residential loads. The cosumer just needs to indicate the instant he/she needs the vehicle and the EMS determines the optimal charging according to that requirement and the information from other loads and price signals from the grid. The validation of the proposed charger has been performed using MATLAB simulink. The simulation results presented shows an adequate interaction between the charger and an autonomous EMS, in which the stipulated power limits are fulfilled and the PQ impact on the interconnection point lies within the international standards for both operation modes (G2V and V2G). This methodology can be used also for higher power and is compatible with any battery chemistry and its particular voltage, current and depth of discharge limits.

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