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The Effects of Magnetically Coupled Bidirectional Battery Charger and its Performances

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Abstract

Objectives: Batteries have to be charged with constant current when they have very low charge and have to be charged at constant voltage when they have high charge. **Methods/Statistical Analysis:** To take care of the above mentioned objective a bidirectional battery charger is developed which can work as buck converter to boost converter from one direction to another. The buck operation can be used to charge a low voltage battery from a high voltage source and the boost operation is for vice versa. **Findings:** A Magnetically Coupled Bidirectional Battery Charger, the low voltage battery and high voltage battery have smooth and stable transition from Constant Current (CC) to Constant Voltage (CV) that can be achieved using neither control loop nor any extra switches. **Applications/Improvements:** To amplify the dc input voltage to the required high voltage level, an LC-circuit with high quality factor (Q-factor) is employed, in which, to make and break a high current pulse through the inductance, a power switch of MOSFET is employed. Usually, energy is stored in an inductance, when the current is made to flow through the inductance and if this current is cut, then the stored energy in the inductance is transferred to capacitance, which results in a high voltage across the capacitor that is filtered to be used to charge the high voltage batteries.

Keywords: Bidirectional Battery Charger, Buck/Boost Converter, Magnetically Coupled, Quality factor (Q-factor)

1. Introduction

Backup battery is essential for electrical apparatus that provides energy power to load when the input source, typically main power, fails. It depends on their applications, For example., Aircraft emergencies, Burglar alarms, Computers, Telephony and Power stations. Small backup batteries may be primary cells, because rechargeable batteries are kept charged by the primary power supply.

In real time systems, most often, there happens to be more than one battery available in the system, meant for load sharing, backup etc., which may have of different batteries of different voltage levels like 42 V, 14 V etc. A bidirectional battery charger may usually be used to interconnect these different batteries that are meant for either intercharging or redundancy[1-3].

The fundamental block diagram of an optimal bidirectional battery charging system is as illustrated as in Figure.1

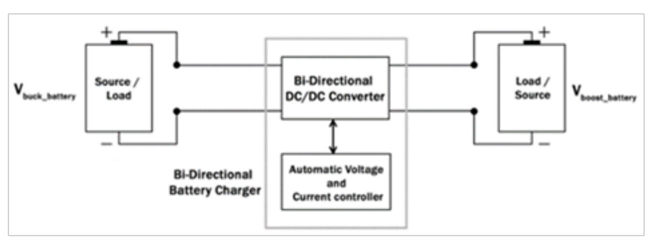

Figure 1. Block diagram for optimal bidirectional battery charging.

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During deep discharge, the optimal charging of a battery can be done by changing it and charge with a constant output voltage near 100% of State Of Charge (SOC).

In between the batteries of Vbuck_battery and Vboost_battery, the bidirectional battery charger is placed that

consists of a bidirectional dc–dc converter with an automatic V I control. The batteries tend to exhibit as a source or a load in complement to each other. That is, if the battery on one side is working as a source, then the other will work as a load and vice versa.

The below given figure 2 shows the real-time implementation circuit[4-10] for the effective realization of the optimal charging algorithms.

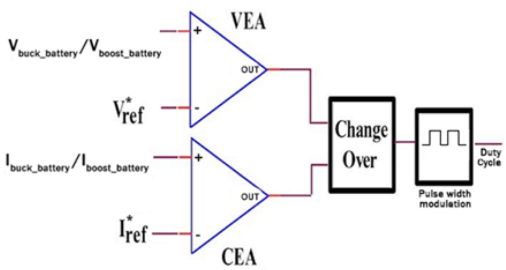

Figure 2. Real-time implementation circuit.

Here the battery current and voltage are accepted as a feedback through changeover switch between the two parallel loops. Pulse Width Modulation (PWM) technique is usually used for controlling the output, when the SOC is low and hence the Current Error Amplifier (CEA) is seemed to be predominant, for the condition while the SOC attains an acceptable level as $V_{ref,}$ for the Voltage Error Amplifier (VEA) that makes to charge and regulate the duty cycle 'D', with a view to normalize the output voltage of the converter.

A bidirectional converter consisting of a coupled inductor has been suggested in this work, wherein the regulation loop is feedback by way of Constant Current (CC) and Constant Voltage (CV). If the transition takes place from CC to CV, then there is every possibility of a ripple-free and automatic transition, without the incorporation of any extra switches or control loop.

The distinctive variables of the proposed system is shown in Figure 3.

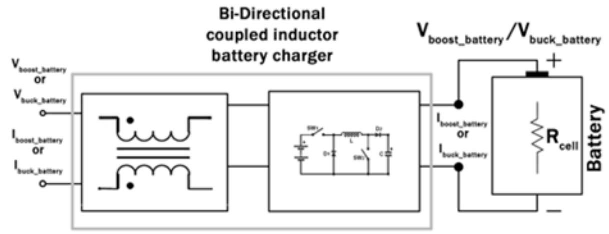

Figure 3. Distinctive variables of the proposed system.

The important thing is the Backup Battery used in Hybrid Electric Vehicle (HEV), since it owes to minimize the footprints of carbon and emission of green house gases. Furthermore, the battery chargers play a pivotal in the arena of making of HEV's. Figure.4 shows the structure of Hybrid Electric Vehicle (HEV).

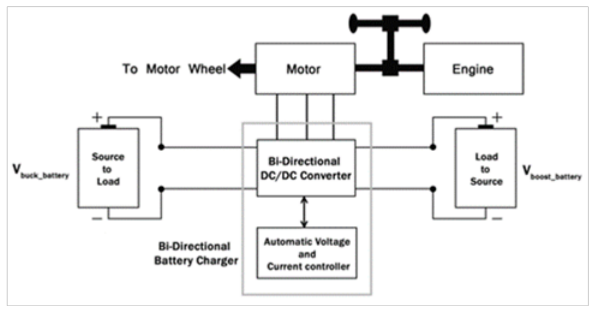

Figure 4. Block Diagram of Hybrid Electric Vehicle.

Advantages of the proposed model:

- Smooth and automatic transition.
- The circuit is always feedback controlled even during the transition from the CC to CV mode of operation.
- It is robust and offers proportional control in case of boost mode of operation that takes into account of coupled inductor and Damping network.
- For the case of boost mode of operation, the right-half plane (RHP) is zero and so be nullified altogether.
- Additional power devices and passive components are not required.
- Highly Efficiency.
- Less complexity.
- Protection circuit is not needed.

Applications of Proposed Model:

- Auxiliary power supplies
- Renewable energy systems

- Hybrid electric vehicles
- Fuel cell-based dc–dc converters
- Battery charged/discharged converters
- Uninterruptible power supplies system.

2. Converter Topology

Of late, there happens to be an overwhelming thrust in the area of research in HEV, owing to its eco-friendliness that also avoids the fast depletion of fossil fuels, besides providing umpteen avenues for energy storage that may be useful for charging/discharging control techniques. A few of bidirectional converter topologies has been analyzed so as to effectively address the energy effective charging and discharging system.Bidirectional magnetically coupled inductor is shown in Figure. 5.

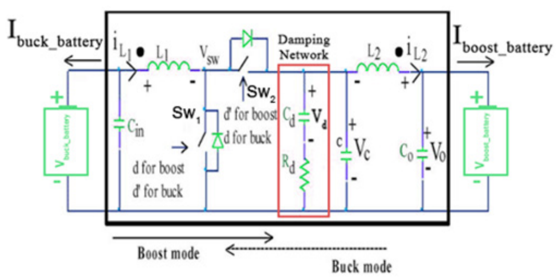

Figure 5. Bidirectional magnetically coupled inductor.

With regard to the myriad topologies existing in the area of converters, the most popular one is transformer-based structures[11-13] and if considered under the non-isolated bidirectional converter, soft-switching converter is said to be more effective and efficient than of the hard-switching converter. Hence, mostly the classical bidirectional buck–boost converter topologies employ soft-switching techniques.

In majority of the practical modern automotive systems, there happens to be the need of employing more number of batteries to be meant towards load sharing and added backup that may usually be ranging from 42 V to 12 V, which may be connected together via a bidirectional battery charger for the needs of interchanging and redundancy. Thus, it can be understood that the bidirectional battery charger can be used for charging any types of battery of any voltages with its optimum charging current requirement.

As far as the topology of battery charging is concerned, a couple of bidirectional switches embedded with inbuilt body diodes are used in order to get rid of the interruption posed by the inductor current and to protect it from overshoot, a dead time is introduced amongst the switches between the signals of the gates. As the battery current needs to be smoothened, it is desirable to have low-pass filters and hence they are employed on both the input and output sides of the converter, which operates in two modes of operations viz. Buck and Boost modes that are explained as given below;

2.1 Boost Operation

In the boost mode of operation of the converter, it can be seen from the below given illustration that a regulated output voltage V_{boost}_battery and the battery current are found to be variable, wherein it is to be noted that the switch node voltage V_{sw} is zero during D state, i.e., when S1 is ON and S2 is OFF and equals V_{boost}_battery during D' state, i.e., when S1 is OFF and S2 is ON. It is noteworthy that the dc transfer function of the classical boost mode is replicated in this mode of boost operation of the converter.The operation of the converter in the boost mode is presented as in Figure 6.

AV _boost = V_{boost}_battery/V_{buck}_battery =1/D'.

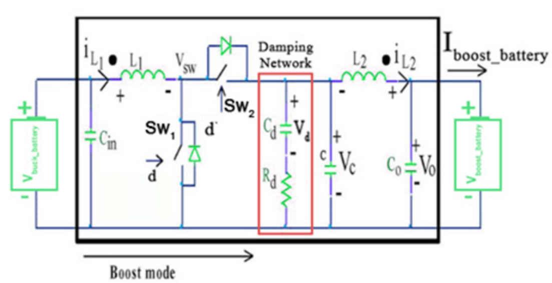

Figure 6. Operation of converter under boost mode.

2.1.1 Working of Boost Operation

When Switch S1 turns ON

When switch S1 turns ON (T=ton) and D2 turns OFF, the LV battery (12V) provides energy to the coupled inductor and the current across it increases linearly. During S1=ton, the previously stored charge in the capacitor is discharged to the HV battery (48V).

When Switch S1 turns OFF

When switch S1 turns OFF (T=toff) and D2 turns ON, the energy stored is transferred to the other winding of the coupled inductor. The capacitor gets charged and the voltage across it increases and to boost the voltage (48V) required by the HV battery.

Switch in ON condition is shown in Figure 7.

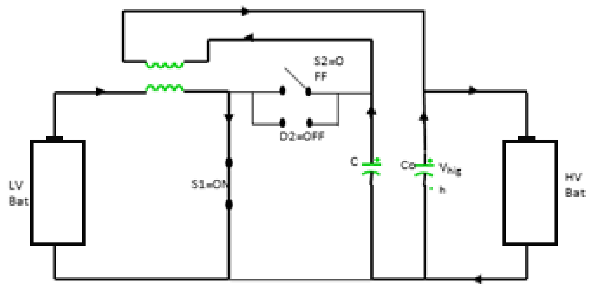

Figure 7. Switch in ON condition.

2.2 Buck Operation

Under the buck mode of operation of the converter, it can be observed that during the D state, when S2 is ON and S1 is OFF, the battery gets charged, by which the current through the inductor iL1 raises and gets such that the switch node voltage Vsw is equal to the input voltage Vboost_battery. On the other hand, during the D' state, when S2 is OFF and S1 is ON, Vboost_batery and the inductor current (IL1) decrease, by when it is to be understood that the switch node voltage Vsw becomes zero. The operation of the converter in the buck mode is presented as in Figure 8.

$$AV\_buck = V_{buck}\_battery/V_{boost}\_battery = D.$$

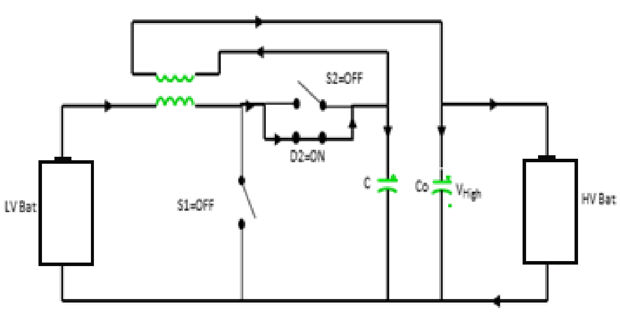

Figure 8. Operation of converter under buck mode.

2.2.1 Working of Buck Operation

When Switch S2 turns ON:

When S2 turns ON, the source (HV bat) is connected to the load (LV bat). The current flows through the inductor and capacitors to charge LV battery.

Switch is in ON condition is shown in Figure 9.

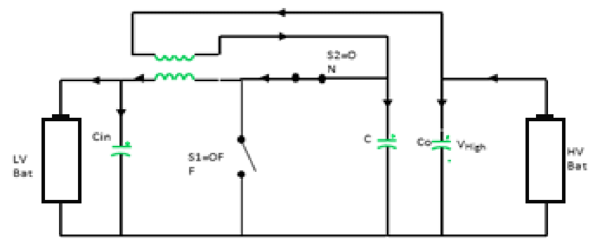

Figure 9. Switch is in ON condition.

When Switch S2 turns OFF

When S2 turns OFF, the source (HV bat) is disconnected from the load (LV bat). The current flow to the LV battery from HV battery is also terminated. Thus the voltage to the load (LV bat) is chopped to maintain the required voltage (12V) across it.

Switch is in OFF condition is shown in Figure 10.

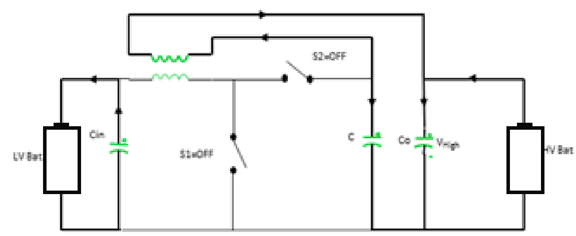

Figure 10. Switch is in OFF condition.

2.3 Design Procedure for Damping Network

The need for damping network in the electrical drive systems, which include static converters. The converters deform loads for the power system network and at the same time they deform energy sources for the electric motor. So, the main reason is to employ the damping network input filters for the Pulse Width Modulation (PWM).

The other reasons to employ the damping network input filters are to keep away the interferences caused by electromagnetic waves by the concerned power converter upon the other systems of electrical and electronic significance, so as to stay away from the disturbances owing to electromagnetic noises by the operation of the converters to spread to the surroundings.

Though, there may be enumerous types of damped input filter, the simplest methodology out of them all is that to add a resistor R_d in parallel with the capacitor C_d, which is supposedly the very cost effective and the easiest amongst of all, as well. The value of output impedance goes maximum at the resonant frequency, whose value equals to that of the resistance $R_{d.}$

However, the intricacy in the optimum design of the damping network is posed by the size of the capacitor $C_{d.}$ and hence it should be skilfully traded off between the size of the damping network C_d as against the damping to be achieved. Further, it is to be noted that the inequality constraint as given below must be addressed, if such an identical converter characteristic is to be obtained upon both the input and output sides of the converter, be provided with or without filter.

The inequality constraint is coined as;

$$|Zs(j\omega)| <<< (R / D^2) \quad (1)$$

Where,

$|Zs(j\omega)|$ represents the value of the impedance of output filter, the duty ratio under steady-state is identifiable by D and R stands for the load resistance.

The value of R_d at resonant frequency is given by;

$$R_d = Q(L_1 / C)^{1/2} \quad (2)$$

Where,

$$Q = ((2+k)\ (4+3k) / 2k^2(4+k))^{½} \quad (3)$$

$$K = C_d / C \quad (4)$$

And thus from the above equations, it can be derived for the optimum damping network.

3. Feedback-Clamped Control System

Under the proposed system of boost operation employing the feedback-clamped control circuit, the VEA and CEA are being cascaded and the output of the VEA connects to the variable voltage feedback-clamping circuit. It can be inferred that the output of the VEA exceeds the value of V_{clamp} at a point when the battery is deeply

discharged. The below given figure shows the feedback clamped control system, as in figure 11.

In case of buck mode, the input voltage is$V_{boost_battery}$ and the feedback shall be $V_{buck\_battery}$, for otherwise that the feedback-clamped circuit operation remains as the same. Thus, the Feedback-clamped loop for boost-operation is illustrated through figure. 12, as given below.

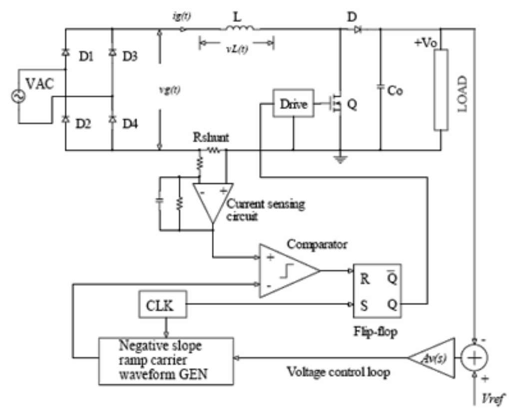

Figure 11. Feedback Clamped Control System.

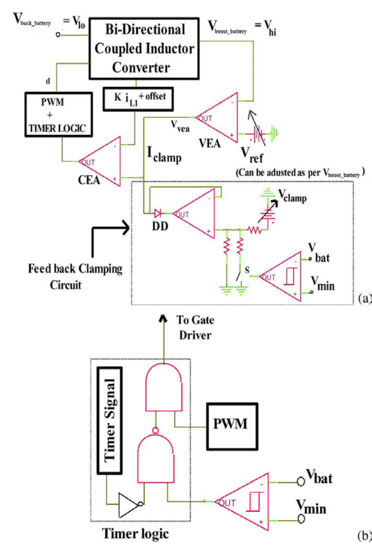

Figure 12. Feedback-clamped loop for boost operation.

4. Large-Signal Dynamics

While giving a step change in the reference voltage, the large signal behavior of the circuit can be deemed to be realized. In the event of a step-up, S_1 is turned on by the control loop, over a long period. Thus, it is noteworthy that the value of I_{L2}goes very low and that of $V_{boost\_battery}$ goes for multiple cycles, in the case of boost operation that tracks the step-up change. If there is a change of step-down, then for the same step change[16-19], switch S_2 gets turned on. The real-time realization of the proposed charger in the case of boost mode of operation, is as shown below;

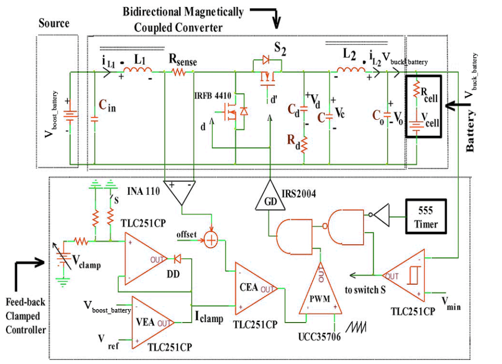

Figure 13. Realization of the proposed charger under boost mode of operation.

5. Verification

List of Parameters with their Attributes

Part/Parameters	Attributes	Manufacturer
Low voltage battery	12V	
High voltage battery	48V	
Mutual Inductance (L_1, L_2)	$L_1 = 500e^{-6}$ H $L_2 = 1500e^{-6}$ H	
Damping Network (C_d, R_d)	$C_d = 57e^{-6}$ F $R_d = 3\ \Omega$	
Input Capacitance (C_{in})	$C_{in} = 100e^{-6}$ F	
Output Capacitance (C_{out})	$C_{out} = 100e^{-6}$ F	
Capacitance (C)	$C = 3e^{-6}$ F	
Resistances	$R_1 = R_2 = 0.001\ \Omega$	
Battery-type		Lead-acid
Gate Driver		IRS2004 (IR corp.)

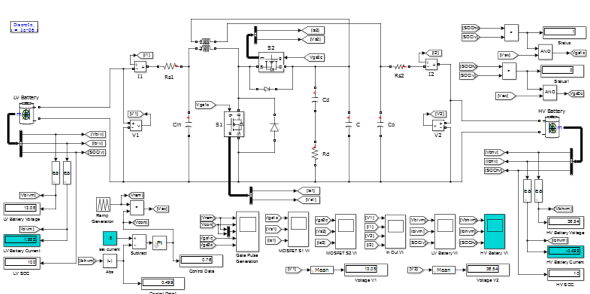

Figure 14. Simulink model of boost mode.

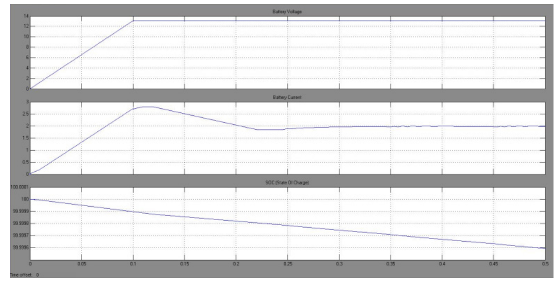

Figure 15. Output for Low voltage battery.

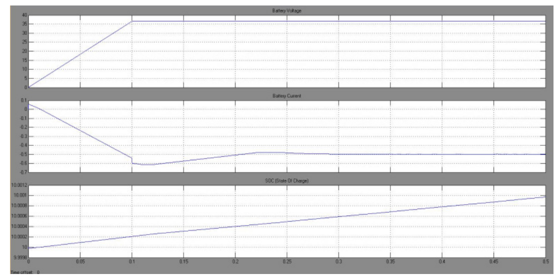

Figure 16. Output for High voltage battery.

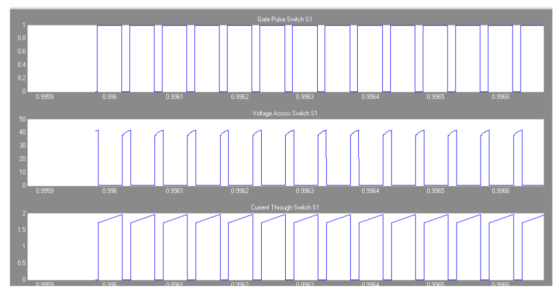

Figure 17. Output for Mosfet1.

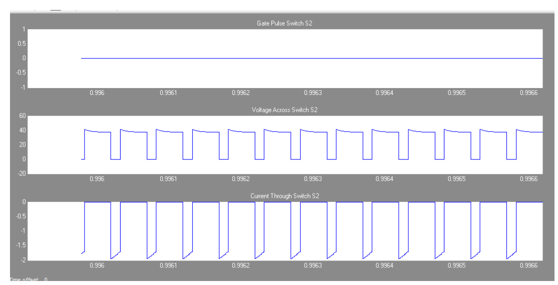

Figure 18. Output for Mosfet2.

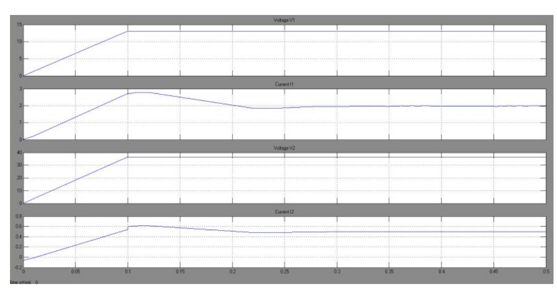

Figure 19. Output for Voltage and Current.

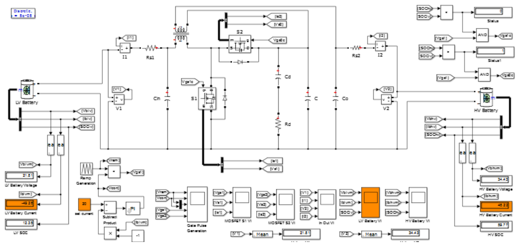

Figure 20. Output for Low voltage battery.

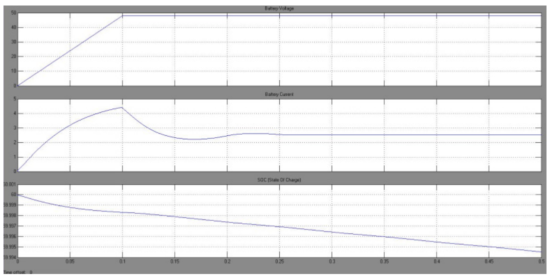

Figure 21. Output for High voltage battery.

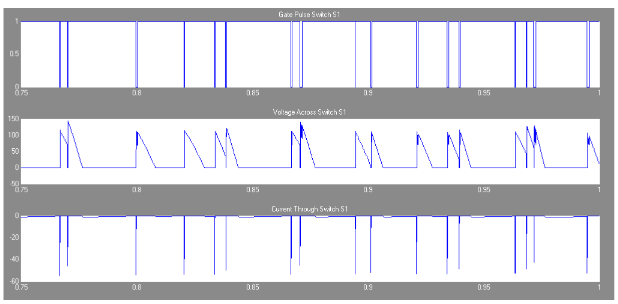

Figure 22. Output for Mosfet1.

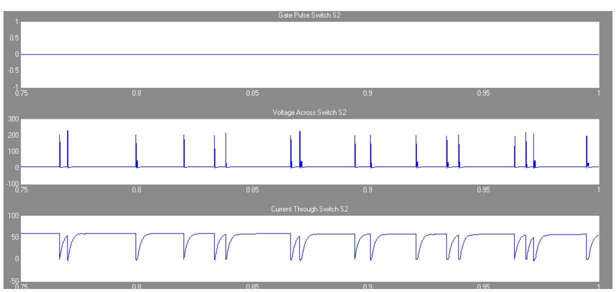

Figure 23. Output for Mosfet2.

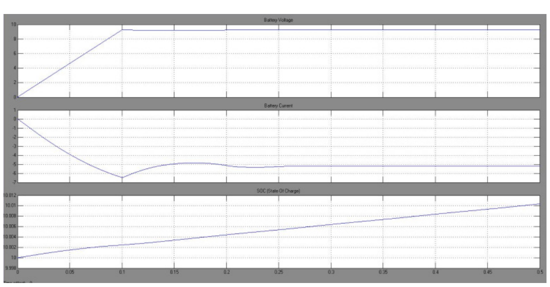

Figure 24. Output for Voltage and Current.

5.1 Proportional Integral Control (PI)

The PI Controller produces a control signal (Vcon) based on the difference between the set current and the battery currents. The control pulses to the switches are varied depending on the control signal to achieve the desired output.

Closed loop PI control logic is shown in Figure 25

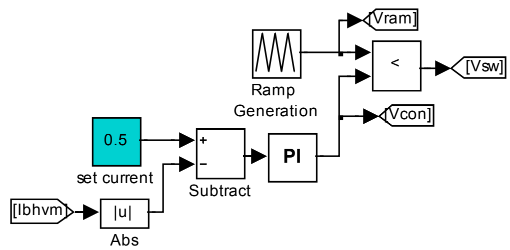

Figure 25. Closed loop PI control logic.

5.2 Gate Pulse Generation

A repeating sequence (ramp generation) is employed to generate a triangular/ramp signal with equal slope on either side at 100 kHz frequency. The peak value of ramp is set at 1 Volt. The actual value and set value is compared and an error signal is generated and this error is fed to PID Control unit to generate a control signal in the range 0 to 1 Volt. It is usually in practice that the two slopes of triangular pulses compare the control signal, so as to generate the low-to-high transition and high-to-low transition of the gate pulse.

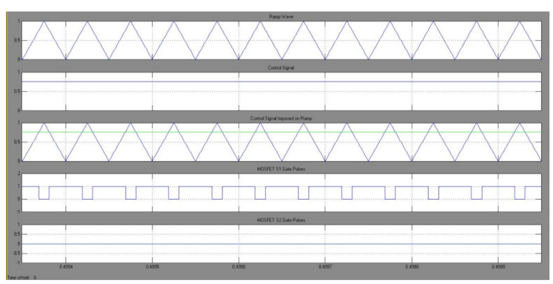

Figure 26. Output for Gate pulse generation.

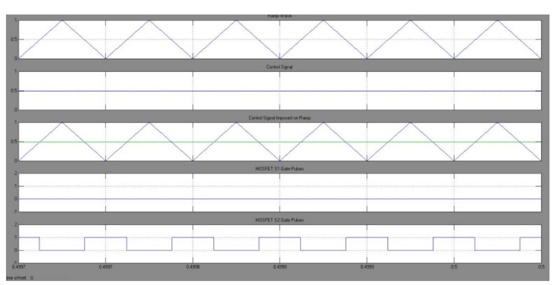

Figure 27. Output for Gate pulse generation.

6. Conclusion

Thus, in this work, it has been well established with the prototype models of implementation that demonstrate how smooth and stable transition can be guaranteed from constant current to constant voltage for a magnetically coupled bidirectional battery charger, associated with a low and high voltage batteries, without using any extra switches or control loop[20-23]. This paper also paves way for the scopes of future research in terms of design and disposition of the controller, with an electronics environment and the possibilities of its compatability towards a variety of other converter typologies, as well

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