Battery charging in Vehicles using interleaved AC/DC Boost Converter

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***Abstract*- This paper presents a novel, yet simple zero-voltage switching (ZVS) interleaved boost power factor correction (PFC) ac/dc converter used to charge the traction battery of an electric vehicle from the utility mains. The proposed opology consists of a passive auxiliary circuit, placed between two phases of the interleaved front-end boost PFC converter, which provides enough current to charge and discharge the MOSFETs' output capacitors during turn-ON times. Therefore, the MOSFETs are turned ON at zero voltage. The proposed converter maintains ZVS for the universal input voltage (85 to 265 Vrms), which includes a very wide range of duty ratios (0.07–1). In addition, the control system optimizes the amount of reactive current required to guarantee ZVS during the line cycle for different load conditions. This optimization is crucial in this application since the converter may work at very light loads for a long period of time. The simulation results show a considerable increase in efficiency and superior performance of the proposed converter compared to the conventional hard-switched interleaved boost PFC converter.**

***Index Terms*- AC/DC converter, continuous current mode (CCM), dc/dc converter, interleaved boost converter, power factor correction (PFC), zero-current switching (ZCS), zero-voltage switching (ZVS).**

I. INTRODUCTION

Recently the use of the renewable-energy generating system has been increased dramatically due to the exhaustion of fossil fuel and the influence of the environment. The major renewable-energy sources are photovoltaic energy, wind power, solar energy and fuel cell. And, these are systematically accepted for distributed power generation. The unregulated output power of renewable energy sources should be regulated through the power converters, and the power system reliability can beguaranteed depending on the performance of the converters. A dc-dc converter is a high speed switch used to obtain variable dc voltage from a constant dc voltage.The battery Charger/discharger is normally needed as the interface between the equipment and the battery. The boost converter is one of the simplest and most widely used topologies for the battery charger/discharger converter when isolation is not required. The boost converter is used as the battery charger/discharger in the Hybrid Electric vehicles applications. In high power applications, the voltage and current stress can easily go beyond the range that one power device can handle. Instead of paralleling power devices, paralleling power converters is another solution which could be more beneficial.

A typical block diagram of the power conditioning system in an EV is shown in Fig. 1. The high-energy battery pack is typically charged from a utility ac outlet. This energy conversion during the battery charging is performed by an ac/dc converter. Such ac/dc converters, which are used to charge the high-energy battery, usually consist of two stages: front-end boost converter, which performs input PFC and ac/dc conversion, and full-bridge dc/dc converter for battery charging and galvanic isolation. PFC is essential to improve the quality of the input current

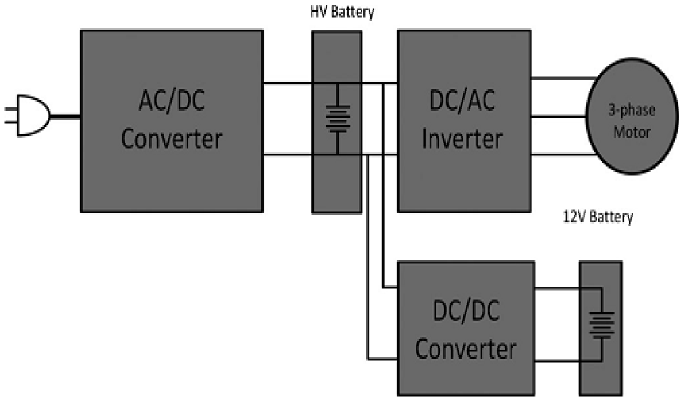

Fig. 1. Block diagram of EV power conditioning system.

Boost converters are generally used to realize input PFC and ac/dc conversion in the front end of an ac/dc converter. But this method is affecting from high switching loss. The main sources of switching losses in boost PFC converters are hard turn -ON of the MOSFET and the reverse recovery of the boost diode during its turn-OFF.

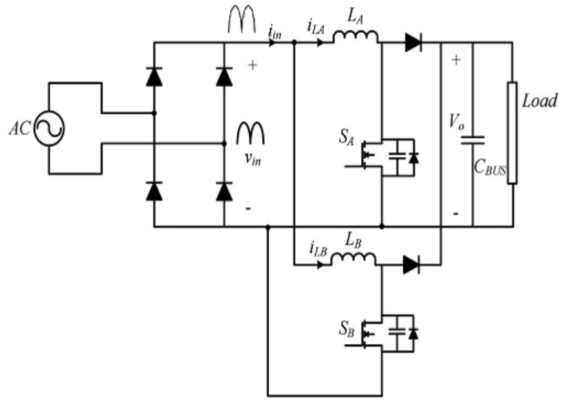

Fig. 2. Interleaved boost PFC schematic.

In high power applications, interleaving continuous current mode(CCM) PFC boost stages, as shown in Fig. 2, is a very commonapproach to effectively decrease the inductor footprint and volume as well as the output capacitor current ripple .Commonly, these auxiliary circuitsconsist of a combination of passive components such as smallinductors and capacitors and additional active components such as MOSFETs and diodes.

II. BACKGROUND SURVEY

Previously proposed single stage AC-DC full bridge converter have the following drawbacks :

1) The current source converter with boost inductor connected to the input of the full bridge circuit, they lack an energy storage capacitor across the primary side DC bus. It causes the output voltage to have a large low frequency 120-HZ ripple.

2) Some converters have two converter stages and thus have the cost and complexity associated with two stage converters.

3) Resonant converter that must be controlled using different switching frequency control, which makes it difficult to optimize the design.

The interleaved boost converter is explained by Y.-J. Lee, A. Khaligh, and A. Emadi. The type of converters is AC/DC and DC/DC boost interleaved converters which are used in plug-in vehicles and hybrid electrical vehicles. The energy storage system for automotive applications are explained by S. M. Lukic, J. Cao, R. C. Bansal, F. Rodriguez, and A. Emadi.

T. Nussbaumer, K. Raggl, and J.W.Kolar explained about the Power Factor Correction(PFC) for interleaved single-phase boost circuits. The coupled inductor characterization for interleaved boost converter is explained by H. Kosai, S. McNeal, B. Jordan, J. Scofield, B. Ray, and Z. Turgut. To reduce conduction losses in a zero voltage boost converters the soft switching auxiliary circuit is employed. These auxiliary circuit is explained by N. Jain, P. Jain, and G. Joos.

The control system used in a ZVS interleaved boost Ac/Dc converter for hybrid electrical vehicles are explained by M. Pahlevaninezhad, J.Drobnik, P. Jain, and A. Bakhshai with reference of A load adaptive control approach for a zero voltage switching DC/DC converter used for electric vehicles.

The design and modeling of a supercapacitors as peak power unit for hybrid electrical vehicles is explained by J.M Timmermans, P. Zadora, J. Cheng, Y. Van Mierlo, and Ph. Lataire. The analysis and implementation of a high efficiency, interleaved current fed full bridge converter for fuel cell system is explained by Xin KONG and A. KHA.

Seong-Jeub Jeon, Gyu-Hyeong Cho is explained about A Zero-Voltage and Zero-Current Switching Full Bridge DC-DC Converter With Transformer Isolation. A planar transformer used in step up and step down the voltages in between the converters.

A. STEADY-STATEANALYSIS OF THE ZVS INTERLEAVED BOOST PFC CONVERTER

The power circuit of the ZVS interleaved boost PFC converter. In this converter, two boost converters operate with 180°phase shift in order to reduce the input current rippleof the converter. This 180°phase shift can be used to provide reactive current for realizing ZVS for power MOSFETs. This auxiliary circuit consists of a HF inductor and a dc-blocking capacitor. Since there may be a slight difference between the duty ratios of the two phases, this dc-blocking capacitor is necessary to eliminate any dc current arising from the mismatch of the duty ratios of the main switches in the practical circuit.

Fig.3 shows the key waveforms of the converter for D >0.5. According to this figure, there are eight operating modes in one switching cycle of the converter. The operating modes are explained as follows.

Mode I ($t_0 < t < t_1$): This mode starts when the gate pulse is applied to S_{A1} . Once the voltage is applied to the gate, S_{A1} is turned ON under zero voltage. Since S_{A1} and S_{B1} are ON during this interval, the voltage across the auxiliary inductor is zero.

Thus, the current through the auxiliary circuit remains constant at $I_{Aux,p}$. During this interval, the switch S_{A1} current, i_{SA1} , is given by:

$$i_{SA1}(t) = I_V - I_{Aux,p} - \frac{v_{in}}{L_A}(t - t_0) \quad ....1$$

Since the two phases have 180◦ phase shift, the value of t_1 is given

$$t_1 - t_0 = (D - 0.5)T_S. \;.... (2)$$

Therefore, the duty ratio is given by

$$D = (t_1 - t_0)\, f_s + (1/2) \quad ...... (3)$$

Inserting (2) into (1), the value of the switch current is calculated At t_1

$$I_1 = I_V - I_{Aux,p}(t) - \frac{v_{in}}{2L_A f_s} - \frac{v_{in}^2}{L_A f_s V_o} \;.. (4)$$

This mode ends once the gate voltage has been removed from S_{B1}.

Mode II ($t_1 < t < t_1$): This mode is the dead time between the phase B MOSFETs. During this interval, the auxiliary circuit current charges the output capacitance of S_{B1} and discharges the output capacitance of S_{B2}. In this mode, the average voltage across the boost inductance L_B is zero. Therefore, the current through L_B remains constant at its peak value. The voltage across the auxiliary inductor is given by:

$$v_{AUX}(t) = -\frac{V_o}{t_2 - t_1}(t - t_1) ...... (5)$$

Thus, the current through auxiliary circuit is given by:

$$i_{AUX}(t) = I_{AUX,p} - \frac{V_o}{2(t_2 - t_1)L_{AUX}}(t - t_1)^2 \;.....(6)$$

$t_2 - t_1 = t_d$ is the dead time between S_{B1} and S_{B2} . During this period, the output capacitors of the MOSFETs should fully charge and discharge in order to guarantee ZVS for S_{B1} and S_{B2}. Thus, the dead time is calculated as follows

$$I_p + I_{Aux,p} - \frac{V_o}{2L_{AUX}} t_d = 2C_{So}\frac{V_o}{t_d} .... (7)$$

$$t_d = \frac{(I_p + I_{Aux,p})L_{AUX}}{V_o} + \sqrt{\frac{(I_p + I_{AUX})^2 L_{Aux,p}{}^2 - 4C_{So}L_{AUX}V_o{}^2}{V_o{}^2}} \quad (8)$$

the current through switch S_{A1} is calculated as follows:

$$i_{SA1}(t) = I_V + I_{Aux,p} - - \frac{v_{in}}{L_A}(t - t_o) + \frac{V_o}{2t_d L_{AUX}}(t - t_1)^2 \quad ..... (9)$$

This mode ends when the output capacitors completely charged and discharged. The switch current i_{SA1} at this point is given by:

$$I_2 = I_V - I_{Aux,p} - \frac{v_{in}}{L_A}(t_d + t_1 - t_o) + \frac{V_o}{2L_{AUX}} t_d \quad .... \quad (10)$$

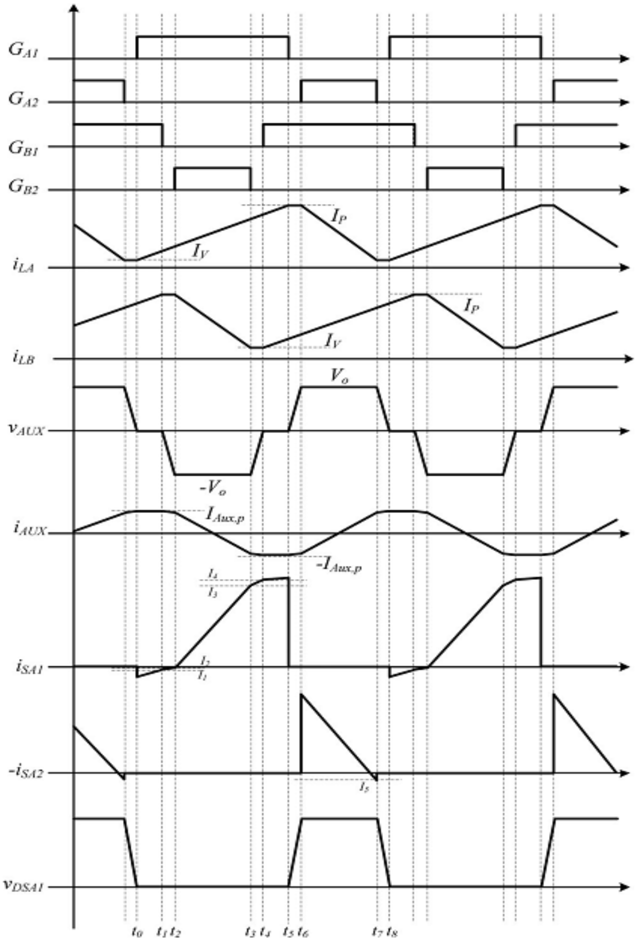

Fig. 3. Key waveforms of the converter forD>0.5.

Mode III ($t_2 < t < t_3$): Once the output capacitors of S_{B1} and S_{B2} have been charged and discharged completely, the gate signal of S_{B2} is applied and S_{B2} is turned ON under ZVS.

During this interval, the voltage across the auxiliary circuit is $-V_o$. The current through the auxiliary inductor, inductor L_A and switch S_{A1} , is given by:

$$i_{AUX,p} = I_{Aux,p} - \frac{V_o}{2L_{AUX}} t_d - \frac{V_o}{L_{AUX}}(t - t_2) \;\dots\dots (11)$$

$$i_{LA}(t) = I_V + \frac{v_{in}}{L_A}(t - t_o) \dots\dots (12)$$

$$i_{SA1}(t) = I_V - I_{Aux,p} - \frac{v_{in}}{L_A}(t - t_o) + \frac{V_o}{2L_{AUX}} t_d - \frac{V_o}{L_{AUX}}(t - t_2) \dots \qquad (13)$$

This mode ends once the gate signal of S_{B2} has become zero ($t_3 = t_0 + 0.5\, T_s - t_d$). The value of i_{SA1} at this point is given by:

$$I_3(t) = I_V - I_{Aux,p}(t) + \frac{v_{in}}{2L_A f_s} - \frac{V_{in}}{L_A} t_d + \frac{V_o}{2L_{AUX}} t_d + \frac{V_o}{f_s\, L_{AUX}}(1 - D) - \frac{2V_o}{L_{AUX}} t_d \dots\dots (14)$$

Mode IV ($t_3 < t < t_4$): During this mode, the output capacitor of S_{B2} is charging from zero to V_o and the output capacitor of S_{B1} is discharging from V_o to zero. This period is actually the dead time between S_{B2} and S_{B1} ($t_3 < t < t_4$). The auxiliary inductor current, the boost inductor current, and the switch current, during this mode, is given by:

$$i_{AUX}(t) = I_{Aux,p} + \frac{3V_o}{2L_{AUX}} t_d - \frac{V_o}{f_s\, L_{AUX}}(1 - D) - \frac{V_o}{2t_d L_{AUX}}(t - t_3)^2 \dots\dots\dots \quad (15)$$

$$i_{LA}(t) = I_V + \frac{v_{in}}{L_A}(t - t_o) \dots (16)$$

$$i_{SA1}(t) = I_V - I_{Aux,p} - \frac{v_{in}}{L_A}(t - t_o) + \frac{V_o}{2L_{AUX}} t_d + \frac{V_o}{L_{AUX}}(t - t_2) \dots\dots \quad (17)$$

This mode ends once the gate signal is applied to S_{B1}. The value of i_{SA1} at this instant is given by:

$$I_3(t) = I_V - I_{Aux,p}(t) + \frac{v_{in}}{2L_A f_s} + \frac{V_o}{L_{AUX}} t_d + \frac{V_o}{f_s\, L_{AUX}}(1 - D) \dots\dots (18)$$

Mode V ($t_4 < t < t_5$): This mode starts when the gate signal is applied to S_{B1}. Once the gate has been applied, S_{B1} is turned ON under ZVS. Since S_{A1} and S_{B1} are ON during this period, the voltage across the auxiliary inductor is zero; hence, the auxiliary inductor current remains constant at its peak value, $I_{Aux,p}$. The boost inductor current and the switch current, during this mode, are given by:

$$i_{LA}(t) = I_V + \frac{v_{in}}{L_A}(t - t_o) \dots\dots (19)$$

$$i_{SA1}(t) = I_V + I_{Aux,p} - \frac{v_{in}}{L_A}(t - t_o) \qquad (20)$$

This mode ends once the gate signal is removed from S_{A1} . The value of i_{SA1} at this time is given by:

$$i_{SA1}(t) = I_V + I_{Aux,p} - \frac{v_{in}}{f_s L_A} D \dots\dots \quad (21)$$

Mode VI ($t_5 < t < t_6$): During this mode, the output capacitor of S_{A1} is charging from zero to Vo and the output capacitor of S_{A2} is discharging from Vo to zero. This period is actually the dead time between S_{A1} and S_{A2} ($t_6 - t_5 = t_d$). In this period, the current through the boost inductor L_A remains constant at its peak value. The auxiliary inductor current i_{AUX} is given by:

$$i_{AUX}(t) = -I_{Aux,p} + \frac{V_o}{2t_d L_{AUX}}(t - t_5)^2 \dots\dots (22)$$

This mode ends once the output capacitors have completely been charged and discharged.

Mode VII ($t_6 < t < t_7$): During this mode, the voltage across the auxiliary circuit is V_o ; hence, the current through the auxiliary circuit is given by:

$$i_{AUX}(t) = -I_{Aux,p} + \frac{V_o}{2L_{AUX}} t_d + \frac{V_o}{L_{AUX}}(t - t_6) \quad \dots\dots\dots\dots \qquad (23)$$

During this mode, the MOSFET channel S_{A2} is conducting the current to the output. The current through this switch is given by:

$$i_{SA2}(t) = I_{Aux,p} - \frac{V_o}{2L_{AUX}} t_d + \frac{V_o}{L_{AUX}}(t - t_6) + \frac{v_{in} - V_o}{L_A}(t - t_6) \quad \text{... (24)}$$

The peak value of this current is given by:

$$I_5(t) = -I_{Aux,p} + \frac{V_o}{2L_{AUX}} t_d + I_p \quad \text{... (25)}$$

This mode ends when i_{SA2} reaches zero. Thus t_7 is given by:

$$t_7 = t_6 + \frac{I_{Aux,p} - (\frac{V_o}{2L_{AUX}} t_d)}{(\frac{V_o}{L_{AUX}}) + (v_{in} - \frac{V_o}{L_A})} \quad . (26).$$

Mode VIII ($t_7 < t < t_8$): During this mode, the output capacitor of S_{A1} is discharging from V_o to zero and the output capacitor of S_{A2} is charging from zero to V_o. In this mode, the current through L_A is at its minimum value I_V and the excess current from the auxiliary circuit charges and discharges the output capacitors. The auxiliary inductor current is given by:

$$i_{AUX}(t) = -I_{Aux,p} + \frac{V_o}{2L_{AUX}} t_d + \frac{V_o}{L_{AUX}} \frac{I_{Aux,p} - (\frac{V_o}{2L_{AUX}} t_d)}{(\frac{V_o}{L_{AUX}}) + (v_{in} - \frac{V_o}{L_A})} + \frac{V_o}{2L_{AUX}}(t - t_7)^2$$

…….(27)

Since this mode is the dead time between S_{A1} and S_{A2}, $t_8 = t_7 + t_d$. This mode ends once the output capacitors have been charged and discharged completely.

III. PROPOSED SYSTEM COFIGURATION

Fig. 4 shows the block diagram of the proposed control system. The proposed control system includes an external voltage loop, internal current loop, and a switching frequency control loop. Therefore, a frequency loop is added to the control system to optimize the circulating current of the auxiliary circuit based on the load and duty ratio of the converter. At heavy loads, the frequency is lower to provide more reactive current in the auxiliary circuit to overcome higher values of IV and charge and discharge the output capacitors. Whereas at light loads, the frequency is higher to reduce the auxiliary circuit current in order to avoid any extra circulating current between the two phases.

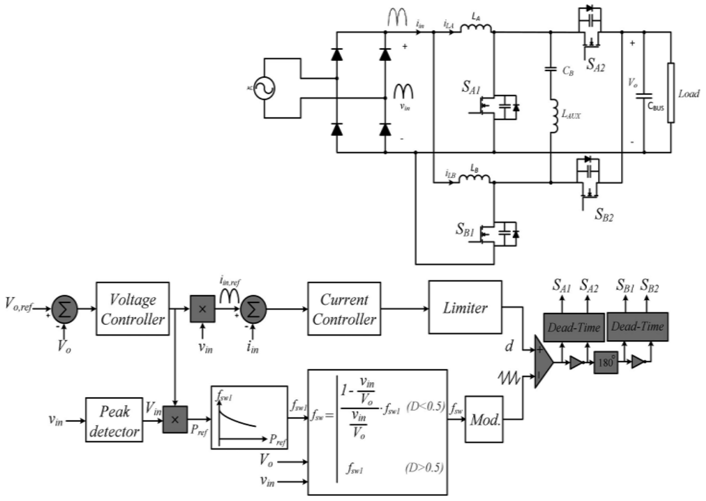

Fig. 4. Control system block diagram.

Owing to the change of frequency, the circulating current is optimized for a very wide range of operation. Since the converter is used to charge the traction battery, there is actually a need for very wide range of operating conditions and the converter has to work at very light loads for a long period of time. The peak value of the auxiliary inductor current is maximum at the peak value of the input voltage, and as the input voltage decreases to zero, the peak value of the auxiliary inductor decreases to zero. Such load-adaptive switching frequency variation has been proved to increase efficiency in ZVS converters.

IV. SIMULATION RESULTS

In this section we are discussing about the simulation model of ZVS interleaved boost PFC converter circuit.

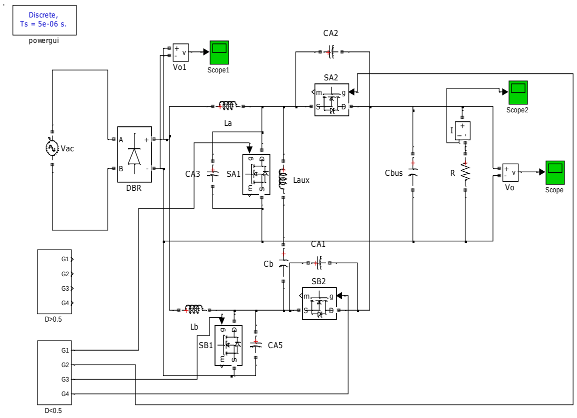

Fig.5. Simulink model for ZVS interleaved boost PFC circuit for D < 0.5

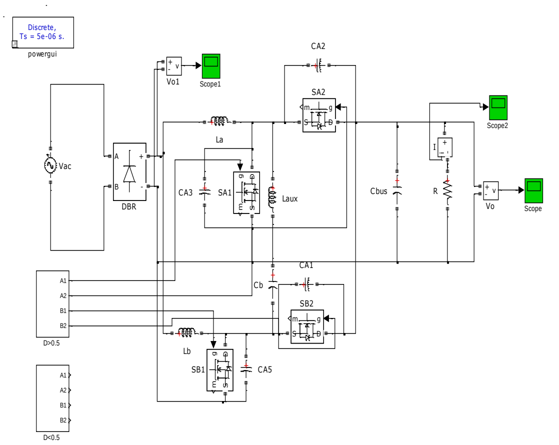

Fig.6. Simulink model for ZVS interleaved boost PFC circuit for D **> 0.5**

By using MATLAB/SIMULINK software, the simulation of the entire system has been carried out.The following fig 5 and 6 shows the block diagram for ZVS interleaved boost PFC converter for D < 0.5 and D > 0.5. From the circuit AC input voltage Vac given to the Diode Bridge Rectifier (DBR). It converts AC voltage into DC voltage. Scope1 shows the DBR output voltage. The output of the DBR connected to the ZVS interleaved boost converter through an inductor. The connections of MOSFETs in the converter circuit shown in fig.5 The gating pulses to the MOSFETs (switches) are given by pulse generator. These ZVS interleaved boost converter operates for two duty ratio ranges. Those are (1) D < 0.5 and (2) D>0.5. The MOSFET switches are turned ON when the voltage equal to zero. So it is called “Zero Voltage Switching”.

Then the power factor is less. The capacitor across MOSFET gives leading current and resultant phase angle becomes less. So the power factor becomes more. These improved power factor boost voltage is connected to the load. Across the load we placed a capacitor to reduce the ripples. The scope2 shows the current in the load and scope shows the voltage across the load (i.e. output voltage) which is high when compared with the input voltage.

The following fig.7 shows diode bridge rectifier (DBR) output voltage. Because of DBR is the uncontrollable rectifier the output voltage is not pure dc. So the output gives with ripples. The voltage peaks are varies from 80V to 100V.

The following fig.8 shows the output voltage of ZVS interleaved boost PFC converter at the load terminal for D < 0.5. At this lower duty ratio the output voltage is also low. The following figure shows the output voltage as 160V.

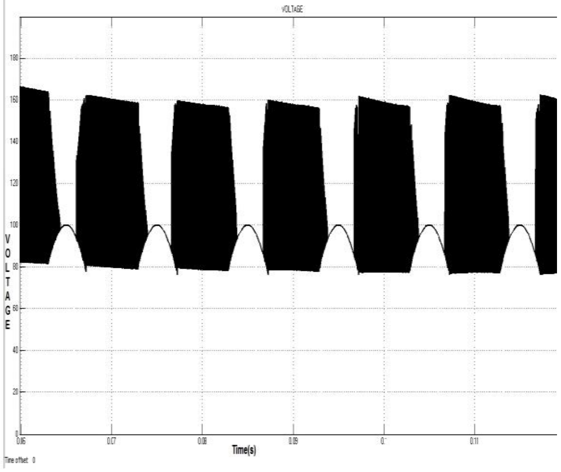

Fig.7. output voltage of the diode bridge rectifier

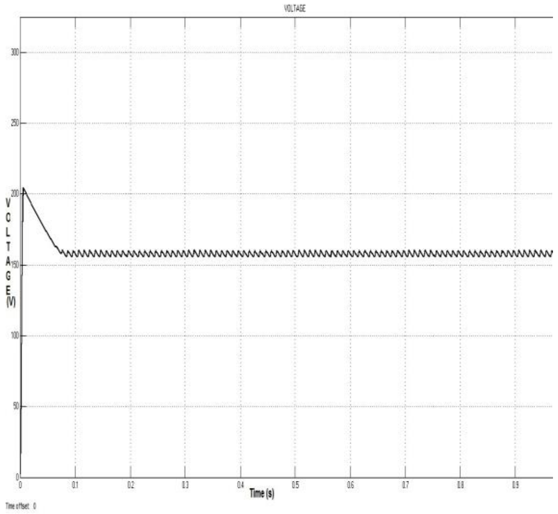

Fig.8 output voltage at the load terminal (D < 0.5)

The fig. 9 shows the output current of ZVS interleaved boost PFC converter at the load terminal for D < 0.5. At this lesser duty ratio the current in the load is also low. From the figure we observing that the output current is 3.2A.

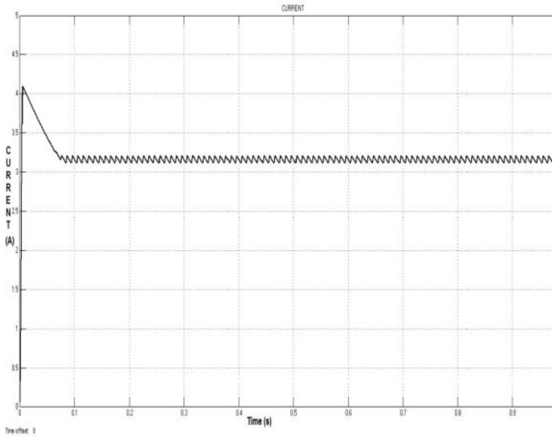

Fig. 9 Output current at the load terminal (D < 0.5)

The fig.10 shows the output voltage of ZVS interleaved boost PFC converter at the load terminal for D > 0.5. For the higher duty ratio (D >0.5) the output voltage is also high when compare with the lower duty ratio (D<0.5). For D > 0.5 the output voltage is 230V.

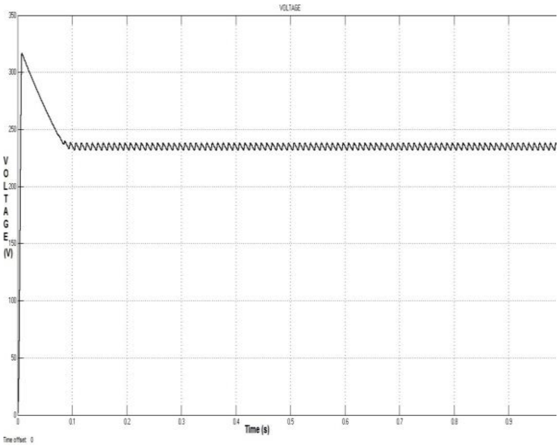

Fig.10 output voltage at the load terminal (D > 0.5)

The fig.11. shows output current of ZVS interleaved boost PFC converter at the load terminal for duty ratio(D>0.5). For the higher duty ratio(D>0.5) the output current is also high when compare with the lower duty ratio(D<0.5). For D > 0.5 the output curent is 4.6A.

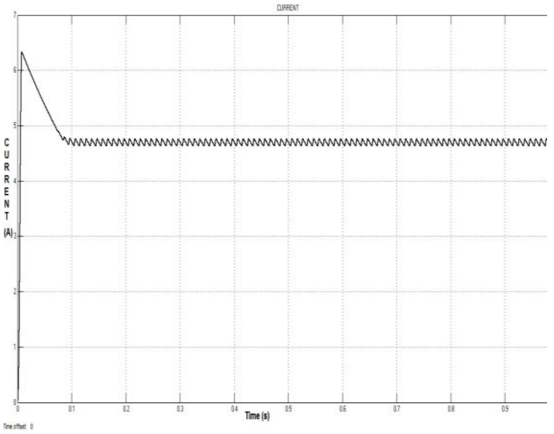

Fig.11 Output current at the load terminal (D > 0.5)

The following fig.12 shows the output voltage at the load terminal with controlling circuit. To control the output voltage it compare with the reference voltage $V_{ref.}$=450V. By using the control circuit it gives high voltage when compare with without control as shown in fig.9. For controlled circuit the output voltage is 360V.

The following fig.13 shows Supercapacitor voltage and currents waveforms. Supercapacitor voltage gives oscillations during charging and discharging period.

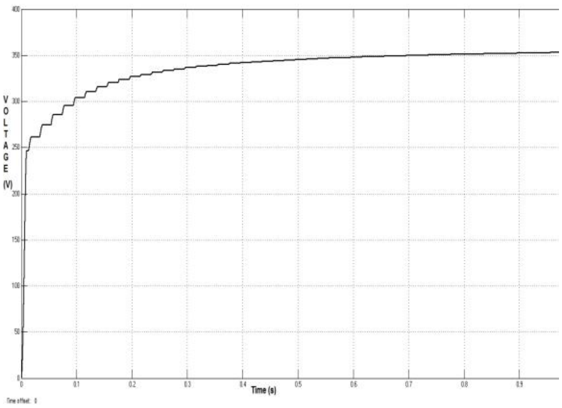

Fig.12. output voltage at load terminal with controlling circuit

After fully charged it will settled at a constant voltage *i*.e. 43V. According to charging and discharging of supercapacitor the current wave form also follows positive and negative cycles respectively as shown in fig.13. After fully charging of supercapacitor it settled at 13A.

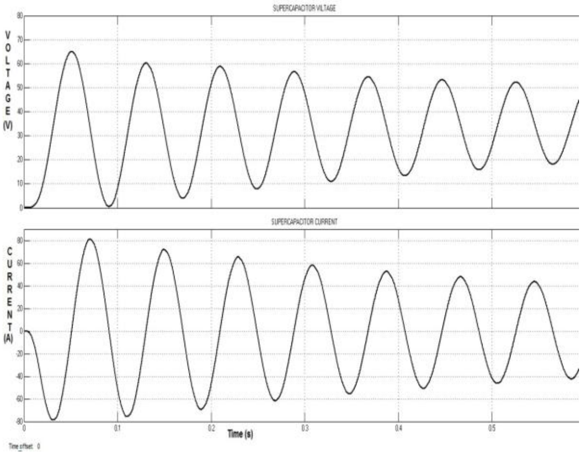

Fig.13 Voltage and current across the supercapacitor

The following fig.14 and fig.15 shows the planar transformer primary and secondary voltages. Planar transformer having the turns ratio m=3. The input voltage is step up by 3 times (m=3).

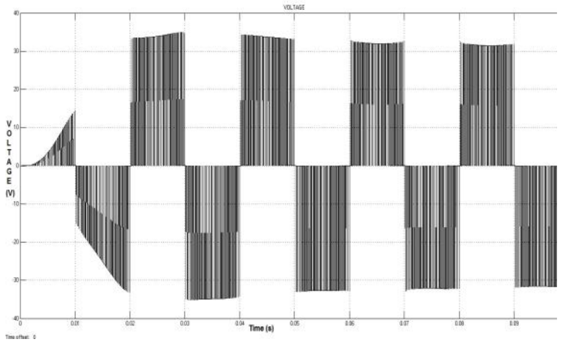

Fig.14 Planar transformer Primary voltage

The primary voltage of planar transformer is 35V. This primary voltage is step up to m (=3) times. i.e. 105V. The secondery voltage of planar transformer shown.

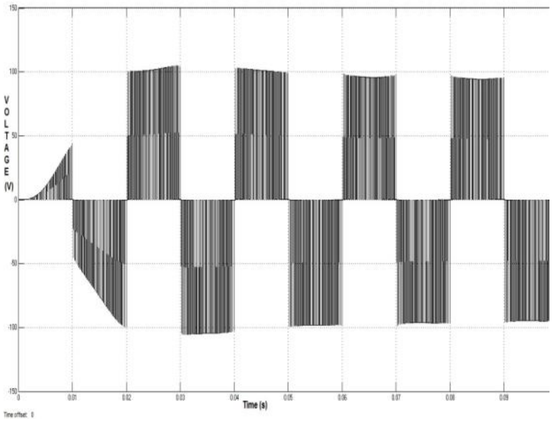

Fig.15 Planar transformer secondary Voltage

The following fig.16 shows the dc motor torque and armature current. In dc motor the torque and armature currents are in proportional. From the figure we observe that torque waveform follows proportionall with the armature current waveform.

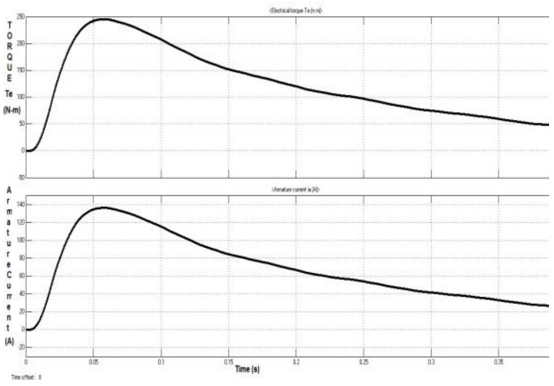

Fig.16 DC motor torque and Armature current

The following fig.17 shows load terminal voltage and current waveforms. The voltage at load terminal is 95V. At starting of hybrid vehivles it draws more current as shown in figure.

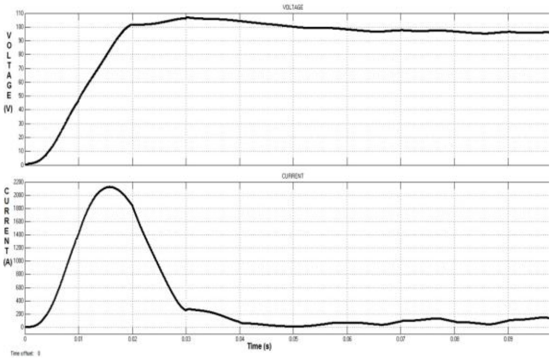

Fig.18 Voltage and current at the Load terminal

By using supercapacitor across the load then less ripple output voltage is produced at Diode Bridge Rectifier(DBR) as shown in fig.19.

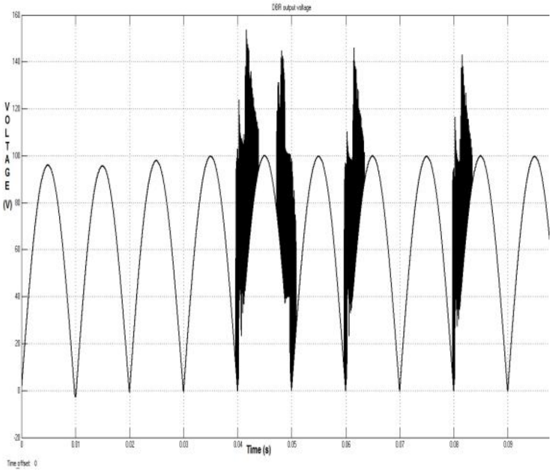

Fig.19 DBR output voltage with supercapacitor

V. CONCLUSION

The super capacitor power management of a Electrical Vehicle is explained by using multi boost and multi full bridge converters through a planer Transformer. An Interleaved boost PFC converter provides soft switching for the power MOSFETs, through an auxiliary circuit. The auxiliary circuit provides reactive current during the transition times of MOSFETs to charge and discharge the output capacitors of the MOSFETs. At the starting of Electrical vehicle it draws more current. This causes unstable operation to the system. This extra current is provided by using the Supercapacitor power. Then the system maintain the stability.

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