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SIMULATION AND IMPLEMENTATION OF AC-DC INTERLEAVED BOOST CONVERTER WITH VOLTAGE MULTIPLIER FOR PHEV

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Abstract

A Plug in hybrid electric vehicle (PHEV) is a hybrid vehicle which employs battery to power up the vehicle motor and it has higher efficiency and low cost compared to the conventional internal combustion engine based vehicle. In PHEV, the charging and discharging of battery is accomplished using a power electronic converter system. This paper focuses on the implementation of an AC-DC interleaved boost converter with voltage multiplier cells for charging of Plug-in Hybrid Electric Vehicle (PHEV). The IBC topology with switched capacitor and coupled inductor is chosen for this work. The proposed AC-DC converter is employed to reduce the ripples at the input and output along with multiplier block to reduce the narrow turn off periods. The output of IBC is fed to a bidirectional DC-DC converter for charging the battery in PHEV. Simulation of the proposed converter is studied in MATLAB. The performance parameters of the converter are computed. Simulation results are verified practically.

Keywords:

IBC, Voltage Multiplier, Bidirectional Converter, Ripple

1. INTRODUCTION

Recently, electric vehicles have gained attention due to high fuel efficiency and low emission. PHEVs and EVs are provided not only with a DC/DC converter which generates electricity for the accessories but also with an AC/DC converter which supplies electric power from a power system at commercial places to an onboard high-voltage battery. The purpose of the AC/DC converter in vehicle charging is to reduce the charging time and to improve the power density so that the space occupied is less [1]. Mainly, the power converters reported in the literature for PHEV charging are larger in size and it is associated with high power loss leading to reduced efficiency [2] [3] [4]. To overcome this problem, this paper presents an AC-DC converter with interleaving concept along with a voltage multiplier unit to enhance the conversion efficiency of the converter.

Voltage multiplier cells are used to reduce the current ripple and to avoid narrow turn-off periods. Interleaved structure is used to distribute the current on the input side and voltage multiplier cells on the output side to achieve a high step-up gain [5]. The diode-capacitor multiplier cells helps to enlarge the voltage conversion ratio and to avoid extreme duty cycles. Here one stage of voltage multiplier cell is utilized to reduce the complexity. The voltage stress on the devices is reduced in this topology. The block diagram of the proposed work is shown in Fig.1.

The output from the IBC is then fed into the bidirectional DC-DC converter. The bi-directional converter acts as a buck converter as the current flows towards the battery and as a boost converter as the current flows out of the battery. The bidirectional DC-DC converter is chosen here instead of unidirectional converter because PHEVs with unidirectional charger can charge but not inject energy into the power grid. A bidirectional charger aids charge from the grid, energy injection back to the grid from the battery, referred to as vehicle-to-grid (V2G) operation mode.

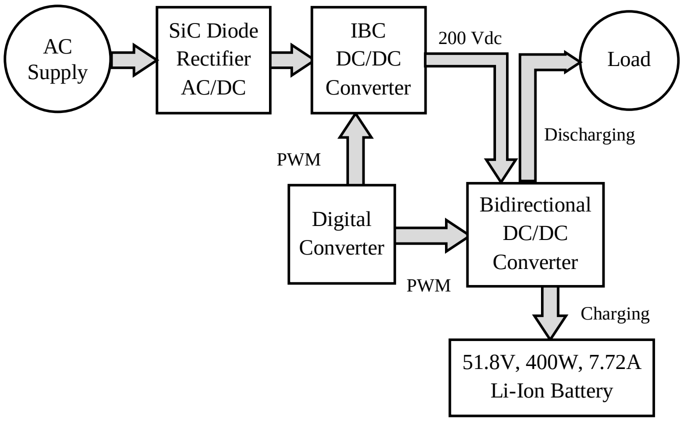

Fig.1. Block diagram of the Proposed Model and power stabilization

So, bidirectional converters are preferred rather than unidirectional converter. The IBC and bidirectional converters are together referred to as the Power Factor Correction unit (PFC). The uniqueness in this model is the usage of interleaving and voltage multiplier cells to enhance the conversion gain and reduces the stress across the switches. The simulation studies of the proposed AC-DC converter are implemented in MATLAB/SIMSCAPE. Simulation results are verified by developing a hardware circuit for the proposed converter.

The paper is organized as follows: Section 1 explains the interleaved boost converter with voltage multiplier, section 2 depicts the operation of bi-directional DC-DC converter, section 3 discusses the simulation results, section 4 shows the experimental verification of the proposed AC-DC converter and finally, section 5 provides the conclusion.

2. INTERLEAVED BOOST CONVERTER WITH VOLTAGE MULTIPLIER UNIT

The circuit diagram of the proposed IBC is shown in Fig.2. It shows IBC with diode-capacitor multiplier with an uncontrolled rectifier for converting the AC supply in to a DC for the IBC converter. Voltage multiplier cells are used to reduce the current ripple and to avoid narrow turn-off period. Interleaved structure is used in the input side to distribute the input current and the voltage multiplier is adopted in the output side to achieve a high step-up gain [6] [7] [8]. The stress that is applied on the switches is considerably reduced as the ripple reduces. The diode-capacitor multiplier cells helps to increase the voltage conversion ratio and to avoid extreme duty cycles. The voltage stress on the devices is less in this topology. Here one stage of voltage multiplier cell is employed to reduce the complexity.

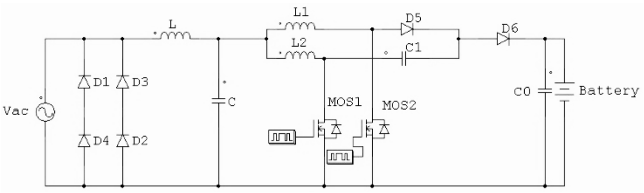

Fig.2. Circuit diagram of AC-DC IBC with voltage multiplier

The operation of the IBC with diode-capacitor can be explained in four modes: In mode-1, as shown in Fig.3, at $t = t_0$, switch S_1 is ON and so diode D_0 is OFF. Switch S_2 is also ON and so D_1 is OFF. Current increases linearly from its minimum value at t_0 and current i_{l2} grows linearly up to its maximum value at t_1. i_{C1} is zero and uc_1 is kept constant. In mode-2, as shown in Fig.4, the gating signal of switch S_2 is removed; thus diode D_1 is ON. Switch S_1 is ON which makes diode D_0 to turn OFF. Current i_{l1} keeps increasing linearly; inductor L_2 charges C_1 and then switch S_2 is gated. Mode-3 operation is similar to that of mode 1. During mode-4, at $t = t_3$, switch S_1 is gated OFF, and diode D_0 is turned ON. The switch S_2 is kept in ON state and current i_{l1} begins to reduce linearly through C_1 which gets discharged as shown in Fig.5. The current i_{l2} increases linearly and the time t_4 is the ending of a switching cycle T_s.

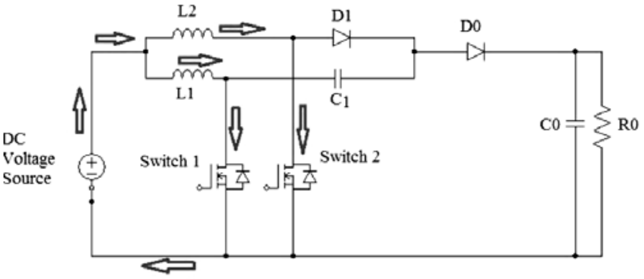

Fig.3. Mode 1 operation of the Proposed Converter

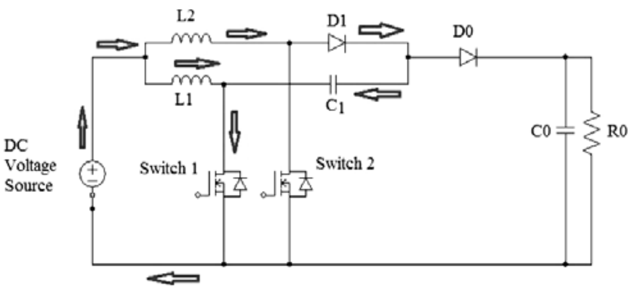

Fig.4. Mode 2 operation of the Proposed Converter

The equations that are required to design the elements of diode-capacitor multiplier are as follows. The conversion ratio here is given by [9] [10],

$$M = \frac{\mu_o}{\mu_{in}} = \frac{n+1}{1-D} \tag{1}$$

where, μ_{in} and μ_o are the input and output voltages and n is the number of the multiplier cells.

The value of inductors and capacitors are,

$$L = \frac{V_{in} D}{\Delta I_L f_s} \tag{2}$$

where, V_{in} is the input voltage, f_S is the switching frequency and ΔI_L is the ripple content in the inductor current.

$$C = \frac{DV_o T}{R\Delta V_o} \tag{3}$$

where, V_o is the output voltage is the time period is the resistance, ΔV_o is the ripple of the output voltage and D is the duty ratio.

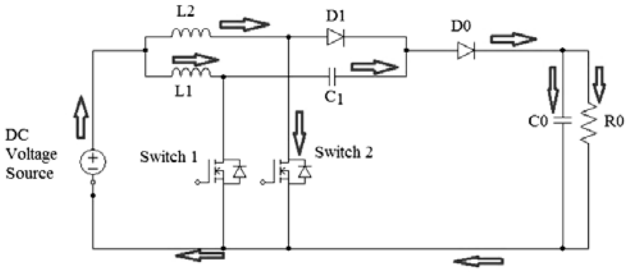

Fig.5. Mode 4 operation of the Proposed Converter

The simulation of IBC was carried out in MATLAB as shown in Fig.6 based on the design values and the parameters are shown in Table.1.

Table.1. Simulation Parameters

Parameters	**Values**
Duty Ratio	0.6
Input Voltage (AC)	40V
Frequency (f_s)	50kHz
Capacitor	40uF
Inductor	640uH

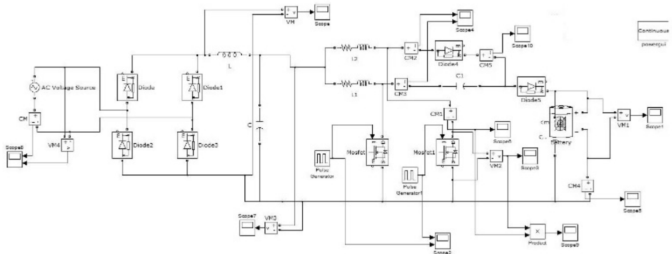

Fig.6. Simulation model of the proposed IBC

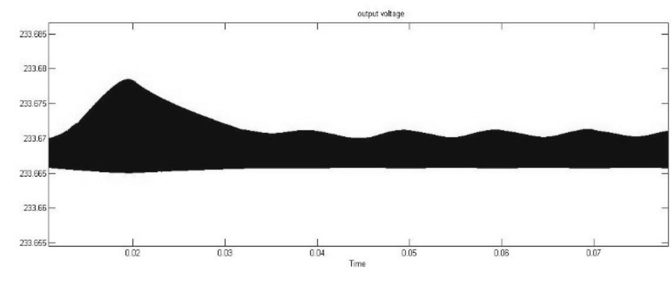

Fig.7. Output Waveform

Simulation of the IBC with the three different topologies with the uncontrolled rectifier was performed in MATLAB and a comparison study was carried out as shown in Table.2.

Table.2. Comparison of IBC with the three multiplier topologies

Topologies	**Output Voltage Ripple**	**Supply Current THD (%)**	**Supply Distortion Factor**	**Supply Power Factor**
Uncontrolled Rectifier with IBC	0.002567	50.67	0.8920	0.9238
Uncontrolled Rectifier with Diode Capacitor Multiplier	0.00342	37.97	0.9348	0.891
Uncontrolled Rectifier with Switched Capacitor and Coupled Inductor	0.001283	38.10	0.9344	0.9238

The results have shown that the uncontrolled rectifier when used with the IBC with diode-capacitor multiplier gives the least value of supply current THD and output voltage ripple. The values of the losses like inductor loss, diode loss and conduction loss in switches in the model was calculated [11]. The value of average and RMS current for the switch, diode and inductor was calculated as shown in Table.3. The diode loss calculation is shown in the Table.4 and the inductor loss calculation is shown in the Table.5.

Table.3. Calculation of average and RMS values of currents

Boost inductor RMS current	$I_{L\text{-}rms}$	$\frac{5\sqrt{3}}{12}\frac{P_o}{V_{PK}}=\frac{5\sqrt{3}}{12}\times\frac{53}{40}=0.9562A$
Boost diode average current	$I_{D\text{-}ave}$	$\frac{P_o}{2V_o}=\frac{53}{2\times 233}=0.1137A$
Boost diode RMS current	$I_{D\text{-}rms}$	$\frac{P_o}{2V_o}=\frac{53}{2\times 233}=0.1137A$
Boost switch RMS current	$I_{Q\text{-}rms}$	$\frac{I_{PK}}{4\sqrt{\prod V_o}}\sqrt{2\prod V_o^2-4V_{PK}V_o+\prod V_{PK}^2}=0.2A$

where,

P_o - the power output,

V_o - Output voltage,

V_{PK} - Peak value of the input voltage and

I_{PK} - Peak value of input current.

Table.4. Diode loss calculation

$P_{RD}=R_D\times I_{RMS}$ $P_{VF}=V_F\times I_{avg}$	$P_{cond}=P_{rd}+P_{vf}$ = 0.003820+0.23877 =0.24259 W	$P_{diode}=R_{trr}+I_{cond}$ = 0.24259 W (P_{trr} is negligible)

where, P_{trr} - power loss during the reverse recovery time, P_{cond} - Power loss during conduction, P_{diode} – Losses in the diode, P_{rd} – Equivalent resistance drop and P_{vf} - Forward voltage drop loss.

Table.5. Inductor loss calculation

$P_{inductor}=P_{fe}+P_{cu}$ = 0.17874 W	$P_{fe}+(P_{mlcs}\times V_{me})/1000$ = (4.8901 × 8.320)/1000 = 0.04068 W	$P_{cu}=R_{mL}\times I_{rms}^2$ = (0.9562)^2 × 0.151 = 0.13806 W

where,

$P_{inductor}$ - Power loss in the inductor,

P_{fe} - Core loss,

P_{cu} - Copper loss,

P_{mlcs} - Core loss of the cross section,

V_{me} - Volume of the inductor,

R_{mL} - Resistance of the inductor and

I_{rms} - RMS value of inductor current.

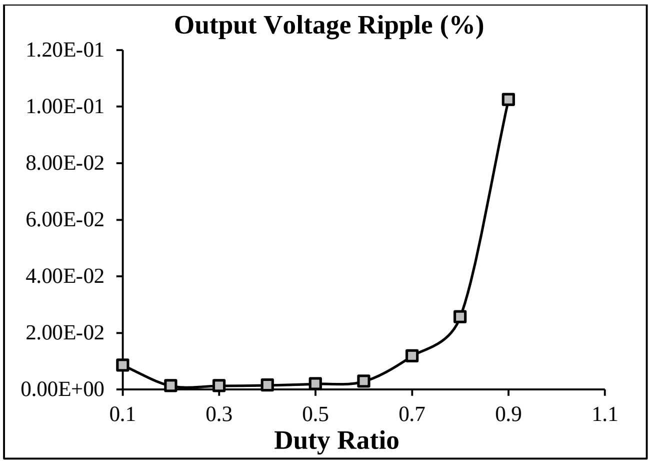

Fig.8. Duty ratio vs. Output voltage ripple

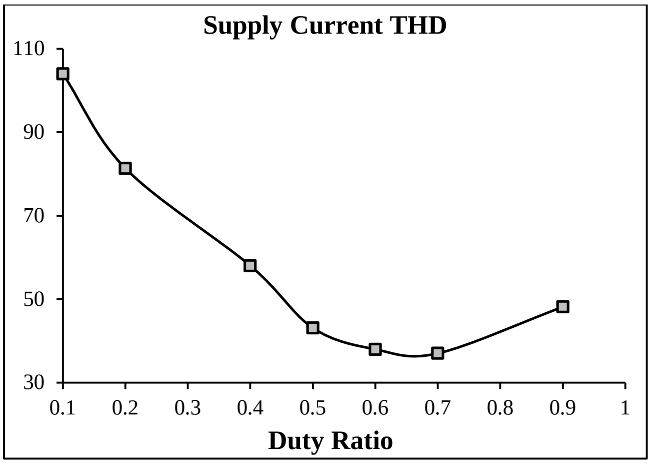

Fig.9. Duty ratio vs. supply current THD

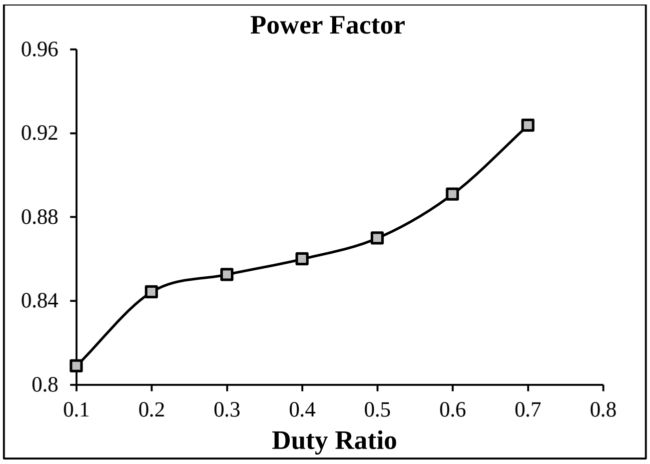

Fig.10. Duty ratio vs. Power factor

A graphical analysis of IBC with the diode-capacitor multiplier was done between the duty ratio and the output voltage ripple, duty ratio and supply current THD and duty ratio and the power factor was done and they are shown in the Fig.8 - Fig.10 respectively.

The graphs have shown that for a duty ratio of 0.6 that output voltage ripple, supply current THD and the power factor is minimum compared to a duty ratio of 0.5. For a duty ratio of 0.7 it is much better, but we have considered duty ratio to be 0.6 because the complexity increases as the duty ratio increases.

3. BIDIRECTIONAL DC-DC CONVERTER

The bidirectional dc-dc converter is also called a buck- boost converter. This converter has the capability of making the input DC voltage to boost or buck depending on the Pulse Width Modulation and switching [12]. The conversion of the voltage may occur in any direction. The use of a bi-directional dc-dc converter in motor drives devoted to EVs allows control of both motoring and regenerative braking operations. The bidirectional dc-dc converter can be operated in a total of four modes, each of them allowing the stepping of battery voltage level either up or down. Either from buck to boost or from boost to buck, any type of conversion can be done by varying the modulation index. That is why this type of converter is needed in electric vehicles; plug in hybrid vehicles, and fuel cell vehicles. Bi-directional converters may reduce the cost; it may improve efficiency and also improves the performance of the system. In the electric vehicle applications, an additional energy storage battery absorbs the regenerated energy fed back by the electric machine. With the ability to reverse the direction of the current and power flow of the system, the bidirectional dc-dc converters are being used vastly to achieve power transfer between two dc power sources in either direction. The bidirectional dc-dc converter is shown in Fig.11.

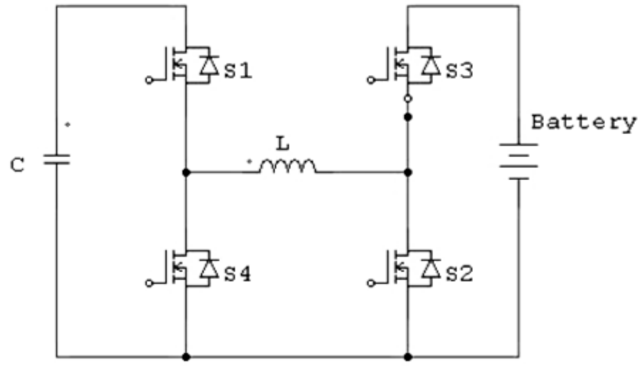

Fig.11. Bidirectional DC-DC Converter

In the topology, the bidirectional function can be divided into two modes as,

i. Buck mode while charging and
ii. Boost mode while discharging

Switch S_1 will be turned on during charging mode as shown in Fig.12 and the DC-DC converter will work as a buck converter while charging the battery pack. During the charging mode switch S_1 will be turned on and anti-parallel diode S_3 and S_4 will be working as freewheeling diode. In this period of time switch S_1 will charge the inductor. In the next cycle switch S_1 will be turned off and anti-parallel diode S_3 and S_4 will charge the battery.

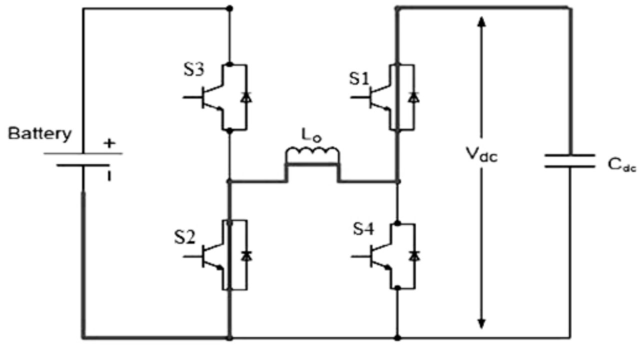

Fig.12. Circuit while charging

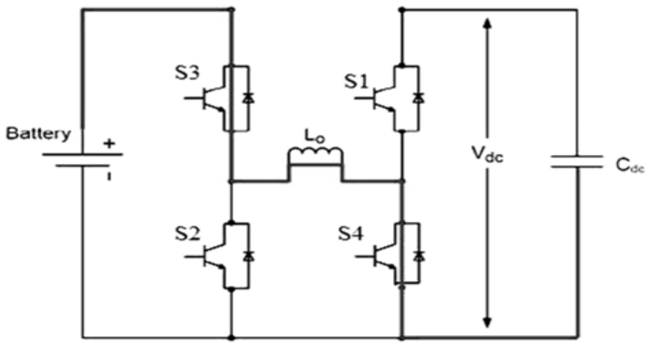

Fig.13. Circuit while discharging

In discharging operation the buck-boost converter circuit state is shown in Fig.13, when the switch S_4 is on or off and S_3 is always on. When the switch S_4 is in conduction state, the battery and capacitor C supply energy respectively to the inductor L and to the machine load. When the switch S_4 is off, the diode D_2 is direct biased and the output capacitor C_2 and the load receive energy from the inductor. Thereby, the voltage V_0 at the output capacitor terminals can be regulated accordingly by adjusting the duty-cycle of the switch S_1. The automatic control in simulation for the charging and discharging was done using time clock. The switches to the pulses used in the simulation are shown in Fig.14.

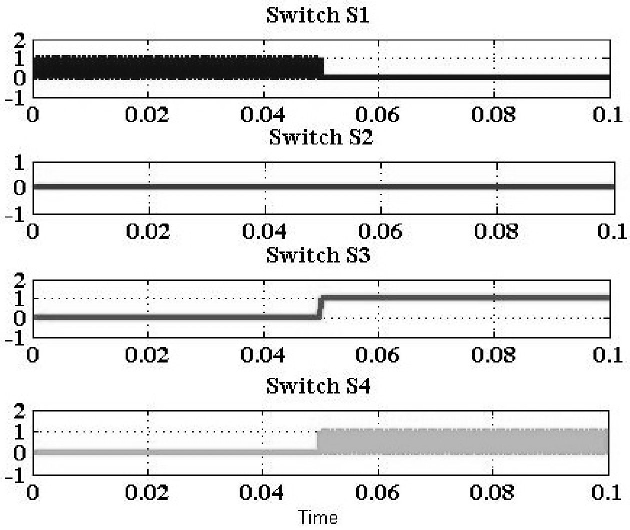

Fig.14 Pulses for the Switches

It shows that while charging the battery the switch S_1 is ON and OFF and while discharging the switch S_3 is ON and switch S_4 is ON and OFF. The Fig.15 shows the SOC and the battery voltage during the two modes of operation. The battery voltage is around 51.8V.

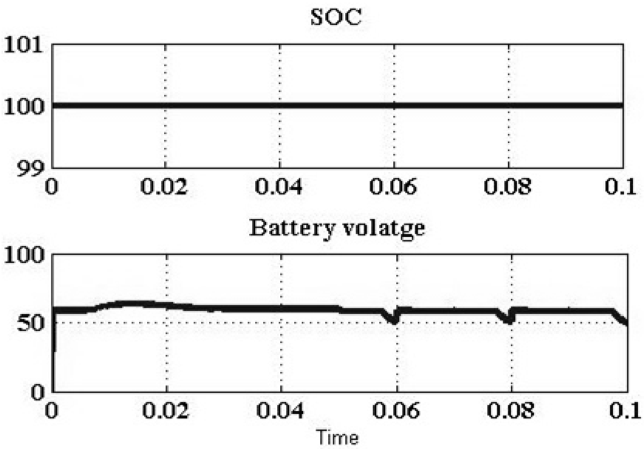

Fig.15 SOC and Battery voltage

The Fig.16 shows the output of the IBC while charging and discharging of the battery. It is around 130V while charging and goes beyond 200V while discharging where in the capacitor discharges.

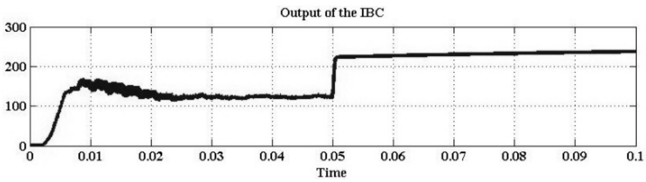

Fig.16 Output of the IBC

The Fig.17 shows the motor side parameters like the motor voltage and the pulse to the switches during the two modes of operation.

Thus the buck-boost operation of the bidirectional converter was obtained and the control was established.

4. HARDWARE IMPLEMENTATION

The pulses to the switches were obtained using the driver circuit for which the pulse was provided with the help of the 555 timer circuit. The IBC circuit with the diode capacitor multiplier was then implemented and the result was obtained. The output of the IBC network was then fed into the bidirectional dc-dc converter for the buck-boost operation to be established. The gate of each switch is triggered using pulse produced by the driver circuit. The gating circuit that was implemented in hardware is shown in Fig.18 and the pulse was generated for a switching frequency of 50 kHz. Pulses that were obtained are shown in Fig.19 and Fig.20.

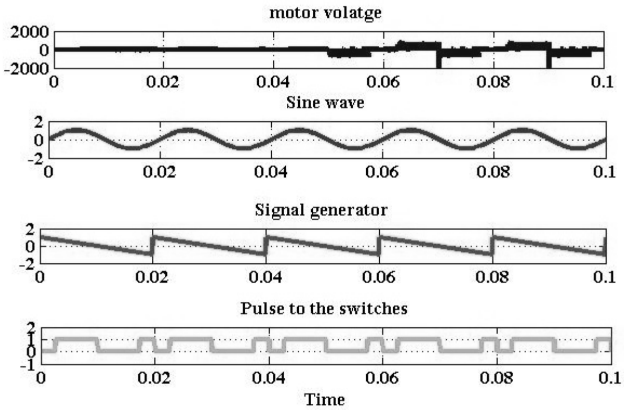

Fig.17. Motor side parameters

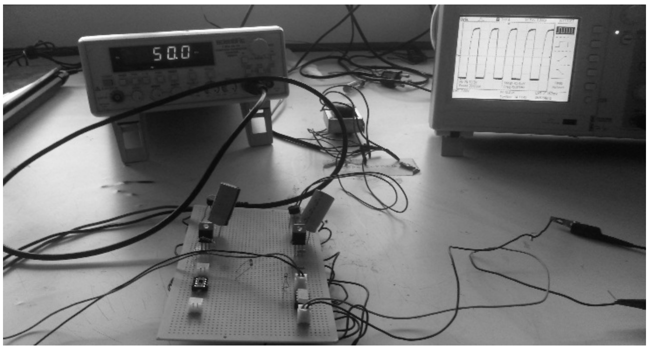

Fig.18. Hardware implementation of the gating circuit

The output of this driver circuit is used to supply pulse to the switches of the IBC network. The IBC with diode capacitor multiplier circuit was implemented and the hardware circuit is shown in Fig.20.

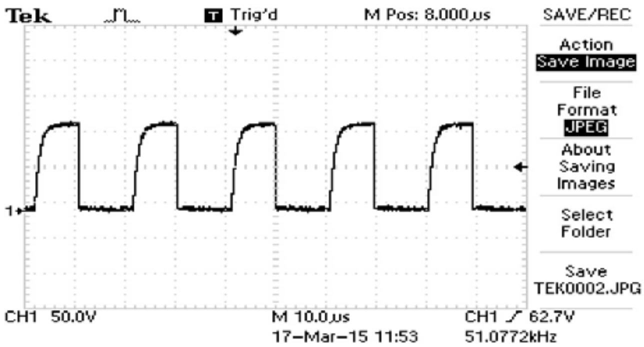

Fig.19. Pulse obtained using 555 timer

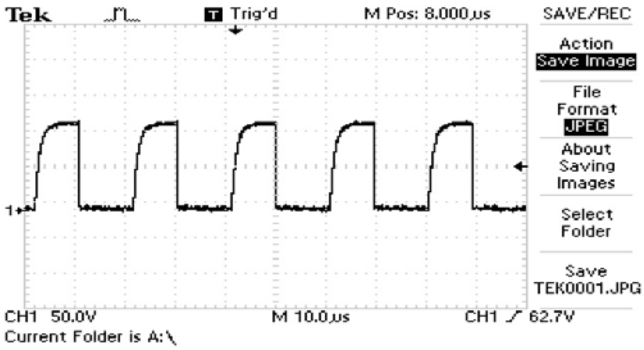

Fig.20. Pulse with 180^0 phase shift

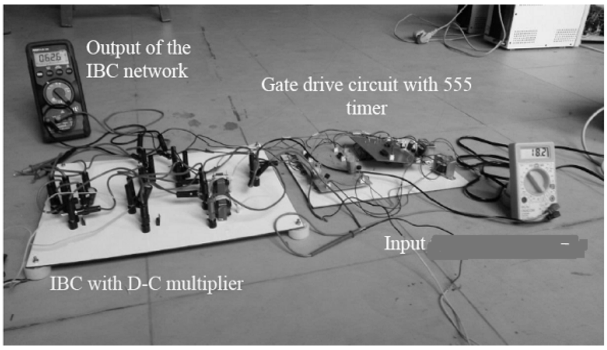

Fig.21. IBC with diode-capacitor multiplier

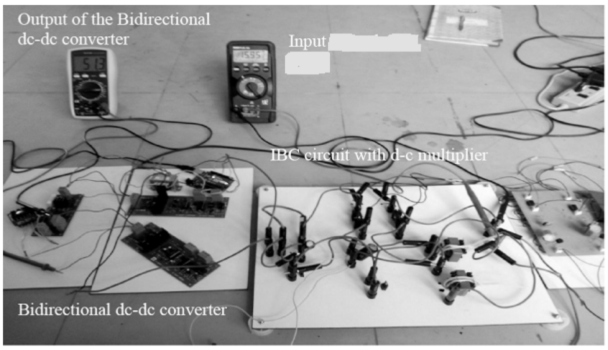

Fig.22. Output of Bidirectional DC-DC converter in Buck mode

The output from the IBC with diode-capacitor multiplier was given as input to the bidirectional dc-dc converter. The pulse that is to be fed to one switch of the circuit is obtained using the Arduino board. The bidirectional dc-dc converter was made to operate in buck mode with one switch in operation. The Fig.21 and Fig.22 shows the input and the output of the bidirectional dc-dc converter. The Fig.23 shows the output of the IBC circuit and the output of the bidirectional dc-dc converter.

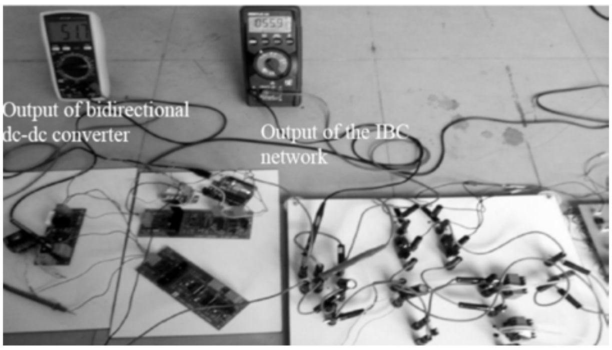

Fig.23. Circuit showing the output of the IBC and the output of the bidirectional dc-dc converter

The Table.6 shows the RMS and dc values of the output voltage of the IBC circuit.

Table.6. Values of Vrms and Vdc

Vrms	Vdc
54.9	54.9

The value of ripple in the output voltage is found to be 1.11 as in Table.7.

Table.7. Values of output voltage ripple of IBC from PQ analyser

Vac	Vavg	Vpk	Vrpl	CF
0.6	54.4	55.1	1.1	1.02

Thus the output was obtained from the bidirectional converter in buck mode as the voltage was reduced from 56V to 51V.

5. CONCLUSION

In this paper, AC-DC interleaved boost converter with voltage multiplier unit was studied and analyzed. The performance parameters like output voltage ripple, input current ripple are analyzed and it is found that the proposed IBC is better compared to the conventional for the battery charging of the PHEV. A loss calculation for the proposed model is also studied. The hardware implementation of the IBC with diode-capacitor multiplier and bidirectional converter was implemented and the results were obtained. Simulation results were verified practically. Hence, AC-DC interleaved boost converter with voltage multiplier is a better one for charging of PHEV.

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