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Modelling & Simulation of Solar Photovoltaic Modified Interleaved Buck Converter for Battery Charging Application

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Abstract— ***This paper proposes a new modified interleaved buck converter which can be used where the operating duty cycle is required below 50%. The switching losses and the stress of the switches has been reduced with the IBC and hence the buck conversion efficiency also is increased to 93.3%. The output current ripple is found to be very small with the modified IBC. The operating principles and different modes of operations of the modified IBC are explained in this paper.***

Keywords—Buck converter, interleaved, low switching losses.

NOMENCLATURE

V_L	Inductor voltage in volts
i_L	Inductor current in amps
V_Q	Switch voltage in volts
V_D	Diode voltage in volts
V_S	Supply voltage in volts
V_0	Output voltage in volts
D	Duty cycle in seconds
f_S	Switching frequency in Hz
T_r	Rise time in seconds
T_F	Fall time in seconds
V_{ch}	Voltage drop in converter
P_O	Output power
P_S	Supply power
R_L	Load resistance in ohm
L	Inductance in H
C	Capacitance in farad
I	Cell current
I_{ph}	Photo current by the photo voltaic effect
I_0	Current related to the diode
V	Cell voltage
I	Cell current
R_S	Series resistance
R_P	Parallel resistance
V_t	Temperature voltage
V_g	Gating voltage
I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
I_s	Input current

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I. INTRODUCTION

Due to the fossil fuel exhaustion and environmental problems the renewable energy sources are widely used. In the electric power generation. Hence the photovoltaic source can be used for battery charging. In the conventional IBC the as the switches are connected in parallel the voltage across the switches will be same as the input voltage, so the higher voltage rated components are needed which have generally poor characteristics such as, high ripple current, high on resistance, high cost, so the efficiency will also be very low. To overcome the above said disadvantages the modified IBC has been introduced in which the switches are connected in series, hence the voltage across the switches will be half of the input voltage before turn-on and turn-off [1]. Power processors of the future generation computers will demand very low voltages of about 1 V, with higher output current ripple frequency [2]. The main advantage of the interleaving technique includes the reduced output current ripple and increased efficiency. Therefore to obtain these advantages the interleaving technique is employed in the continuous conduction mode [3]. The high output current can be obtained from the IBC and the main advantage of using the IBC in various applications is that its high efficiency and filter's reduction [4].

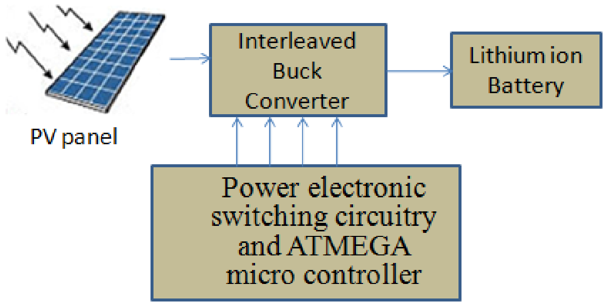


Fig. 1. Block diagram of the PV based modified IBC.

Photovoltaic systems needs a dc/dc power conditioner for its stable operation. The power conditioner will improve the stability operation and the efficiency of the system [5]. The rechargeable batteries are used in many applications such as electric vehicles, uninterruptible power supplies, cell phones, digital cameras and many. Since these appliances consume energy continuously, they need charging circuits for continuous charging. Zero current switching buck converter can be used for efficient charging of batteries. In these method the soft switching technique is used to reduce the switching losses and to increase the reliability for the battery chargers [6].

But the efficiency of the battery charger is low. So to increase the efficiency the twin buck converter has been introduced which consists of two buck converter connected in parallel with an interleaved inductor, with this technique the switching losses is reduced greatly [7]. But the efficiency is not improved. To obtain the high performance of the power converters, the high switching frequency is required, which will cause the switching losses [8]. To overcome the switching losses associated with the conventional buck converter many solutions has been introduced with different techniques [9]-[11]. The switching losses is reduced with the help of the conventional IBC with a single-capacitor turn-off snubber has been introduced in which the switching losses are found to be less [12]. But it consists of many components which increases the cost and the complexity if the converter. Then the IBC with the coupled inductors has been introduced, even though they operate with hard switching, the switching losses is reduced and also it operates with the continuous conduction mode(CCM) [13]. To overcome all this problems the modified IBC has been introduced with the which reduces the stress across the switches. The renewable energy source solar PV is used as the input source in this paper.

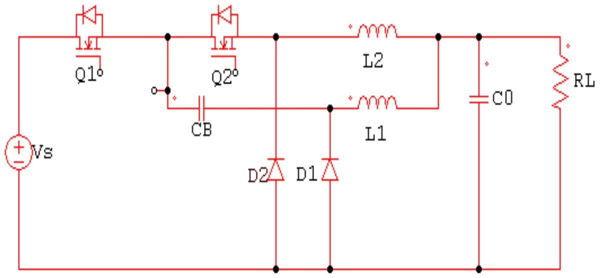


Fig. 2. Modified IBC.

The modified IBC consists of two active switches both are connected in series with each other, which ensures the less switching losses of the converter. This modified IBC is used in the applications where non isolation and the operating duty cycle is less than 50%. The two active switches are operated with the phase shift of 180 degree, the operation of the modified IBC is similar to the conventional IBC but the modified IBC operates with the CCM mode, hence the switching losses are greatly reduced.

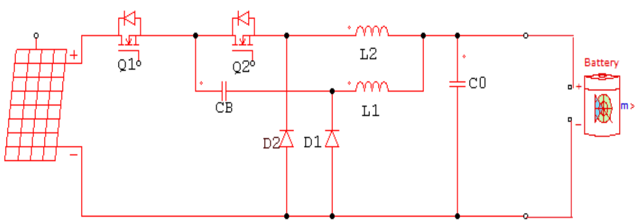


Fig. 3. Proposed PV based Modified IBC for battery charging.

In this paper PV based modified IBC has been introduced for battery charging applications. As the solar energy is abundantly available it can be used for the applications such as battery charging of various kinds of electronic equipments. This can be operated with buck and boost mode and the comparison of the two modes are explained. The different modes of operation of IBC is explained with the section I in detailed. The design and analysis of the modified IBC is explained with the efficiency calculation and the inductor ripple calculation and the stress analysis is also explained in the section II in detailed. The simulink model and the simulation results, with the input voltage as 150 V and the output voltage with 20V is the obtained results of the modified IBC which are explained with the section III. The Conclusion is depicted with the section IV.

II. MODES OF OPERATION

Fig. 3. Shows the Circuit configuration of the modified IBC, it can be operated with the two modes of operation, such as buck mode and boost mode. The switches are operated with the 180 degree mode of operation and hence two states of operation can be explained with four modes in each state. The key operating waveforms of the modified IBC is depicted below. There are four modes, each mode is explained with the operating diagrams.

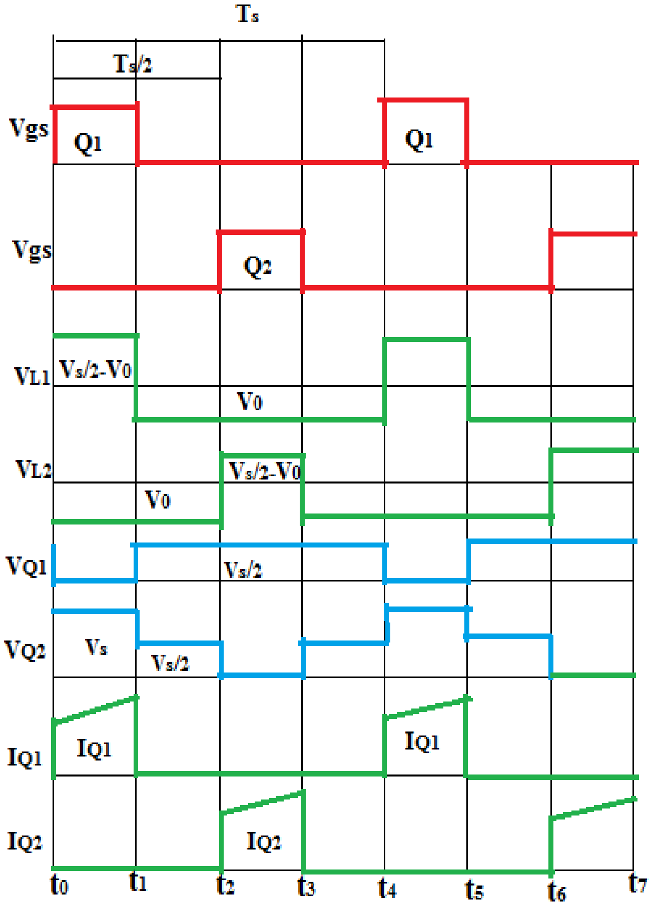
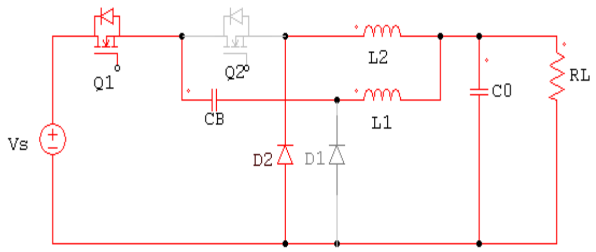


Fig. 4. Key operating waveforms of the Modified IBC

Mode 1 $[t_0 - t_1]$: In mode 1 the switch Q_1 *is* turned on, hence the current is flowing through the Switch Q_1.



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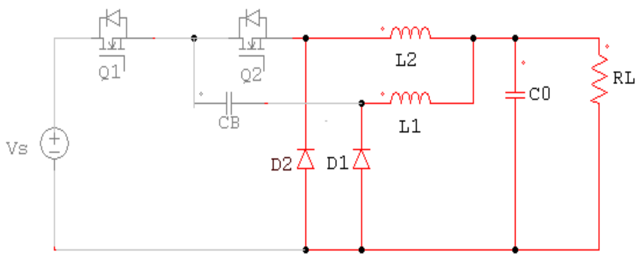
The capacitor is being charged during this time and the diode D_1 is reversed biased during this mode and hence there is no current flow, and the voltage across the inductor L_2 is freewheeled through the diode D_2

$$V_{L1}(t) = V_S - V_{CB} - V_0 \quad (1)$$
$$V_{L2}(t) = -V_0 \quad (2)$$
$$i_{L1}(t) = \frac{V_S - V_{CB} - V_0}{L}(t - t_0) + i_{L1}(t_0) \quad (3)$$
$$i_{L2}(t) = -\frac{V_0}{L}(t - t_0) + i_{L2}(t_0) \quad (4)$$
$$V_{Q2} = V_S \quad (5)$$
$$V_{D1} = V_S - V_{CB} \quad (6)$$
$$V_{CB} \cong V_{CB}(t_0) + \frac{I_0}{2C_B}(t - t_0) \quad (7)$$

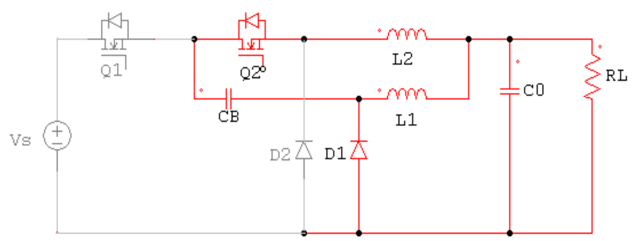
Mode 2 $[t_1 - t_2]$: In the mode 2 the Switch Q_1 is turned off. hence the switch Q_2 is also not turned on, so that the inductors both L_1 and L_2 will freewheel through the diodes D_1 and D_2.



(b)

$$V_{L1}(t) = V_{L2}(t) = -V_0 \quad (8)$$
$$i_{L1}(t) = i_{L1}(t_1) - \frac{V_0}{L}(t - t_1) \quad (9)$$
$$i_{L2}(t) = i_{L2}(t_1) - \frac{V_0}{L}(t - t_1) \quad (10)$$
$$V_{Q_1}(t) = V_S - V_{CB} \quad (11)$$

Mode 3 $[t_2 - t_3]$: In the mode 3 the switch Q_2 is turned ON. But the diode D_2 is turned OFF.

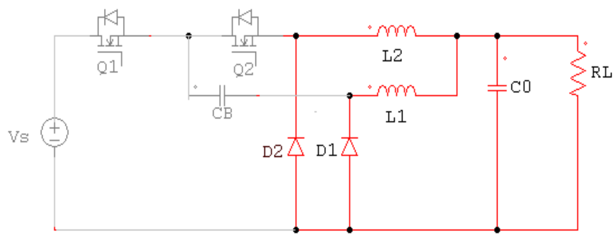


(c)

The inductor L_1 freewheels through the diode D_1. In this mode the V_{CB} is discharged through the switch Q_1.

$$V_{L1}(t) = -V_0 \quad (12)$$
$$V_{L2}(t) = V_{CB} - V_0 \quad (13)$$
$$i_{L1}(t) = -\frac{V_0}{L}(t - t_2) + i_{L1}(t_2) \quad (14)$$
$$i_{L2}(t) = \frac{V_{CB} - V_0}{L}(t - t_2) + i_{L2}(t_2) \quad (15)$$
$$V_{Q_1}(t) = V_S - V_{CB} \quad (16)$$
$$V_{Q_2}(t) = V_{CB} \quad (17)$$
$$V_{CB} \cong V_{CB}(t_2) - \frac{I_0}{2C_B}(t - t_2) \quad (18)$$

Mode 4 $[t_3 - t_4]$: In mode 4 the switch Q_2 is turned OFF and the operation is similar to the mode 2.

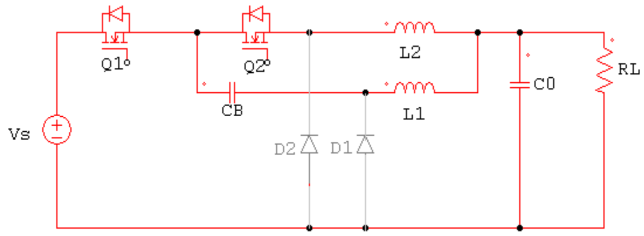


(d)

$$V_{L1}(t) = V_{L2}(t) = -V_0 \quad (19)$$
$$i_{L1}(t) = i_{L1}(t_1) - \frac{V_0}{L}(t - t_1) \quad (20)$$
$$i_{L2}(t) = i_{L2}(t_1) - \frac{V_0}{L}(t - t_1) \quad (21)$$
$$V_{Q_1}(t) = V_S - V_{CB} \quad (22)$$

A. Boost operation when D≥0.5

Mode 1 $[t_0 - t_1]$: In mode 1 the switches Q_1 and Q_2 are turned ON and hence both the diodes are reverse biased, so there is no current flow through the diodes.



(e)

$$V_{L1}(t) = V_S - V_{CB} - V_0 \quad (23)$$
$$V_{L2}(t) = V_S - V_0$$

(24)

$$V_{Q_1}(t) = V_S - V_{CB} \quad (25)$$
$$V_{Q_2}(t) = V_B \quad (26)$$

Mode 2 $[t_0 - t_1]$: In mode 2 the switch Q_1 *is* turned on, hence the current is flowing through the Switch Q_1. This is same as mode 1 when *D≦0.5.*

Mode 3 $[t_2 - t_3]$: In mode 3 the switch Q_1 *is* turned on, hence the current is flowing through the Switch Q_1. This is same as mode 1 when *D≦0.5.*

Mode 4 $[t_3 - t_4]$: This is same with as the mode 3 when *D≦0.5.* In boost mode both the switches Q_1 and Q_2 will experience high current and hence the stress also will increase in this boost mode. So the modified IBC can be used only for buck mode.

Fig. 5. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 1 in boost operation.

III. DESIGN ANALYSIS

A. *Duty cycle*

The voltage of the coupling capacitor can be expressed as,

$$V_{CB} = \frac{V_S}{2} \quad (27)$$

This equation shows that the capacitor is designed to allow the half of the input voltage.

$$M = \frac{V_0}{V_S} = \frac{D}{2} \quad (28)$$
$$V_0 = \frac{D}{2} * V_S \quad (29)$$

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B. *Efficiency*

The efficiency can be calculated by using the formula as,

$$n = \frac{Load\ power\ (Output\ power)}{Supply\ power\ (Input\ power)}$$

The load power can be calculated by using the formula as,

$$P_0 = \frac{\partial (V_S - V_{ch})^2}{R} \quad (30)$$

The supply power can be obtained by using the formula as,

$$P_S = \frac{1}{T}\int_0^{\partial T} V_S \left(\frac{V_S - V_{ch}}{R}\right) dt \quad (31)$$

C. *Stress analysis results*

The stress analysis results are shown in above table which proves that the less amount of stress is found at the modified IBC. The formulas for the stress analysis can be obtained by referring [12] and [13].

TABLE I
STRESS ANALYSIS RESULTS

Items	Modified IBC	Traditional IBC	Less stress found at
Voltage stress of Q_1	$0.5V_s$	V_s	Modified IBC
Voltage stress of Q_2	V_s	V_s	Equal
Peak current stress of Q_1 & Q_2	$\frac{I_o}{2} + \frac{1}{2}\frac{0.5V_s - V_o}{L}(DT_s)$	$\frac{I_o}{2} + \frac{1}{4}\frac{V_s - V_o}{L}(DT_s)$	Modified IBC
RMS current stress of Q_1 & Q_2	$\frac{I_o}{2}\sqrt{2D}$	$\frac{I_o}{2}\sqrt{\frac{D}{2}}$	Traditional IBC
Average current stress of D_1	$\frac{I_o}{2}(1-D)$	$\frac{I_o}{2}(1-\frac{D}{2})$	Modified IBC
Average current stress of D_2	$\frac{I_o}{2}$	$\frac{I_o}{2}(1-\frac{D}{2})$	Traditional IBC

IV. SIMULATION RESULTS

The simulation is carried out by using the MATLAB/SIMULINK. The solar PV equations are as follows,

$$I_{ph} = I_D + I_{Rp} + I \quad (32)$$

$$I = I_{ph} - I_D + I_{Rp} \quad (33)$$

$$I = I_{ph} - I_0\left[exp\left(\frac{V+IR_s}{V_T}\right) - 1\right] - \frac{V+IR_s}{R_P} \quad (34)$$

TABLE II
SIMULATION PARAMETRS

Input voltage	150V
Output voltage	20V
Input current	2A
Output current	24A
Inductance value	100micro H
Switching frequency	65KHz
Short-circuit current of Solar PV, Isc	7.34A
Open-circuit voltage, Voc	0.6V

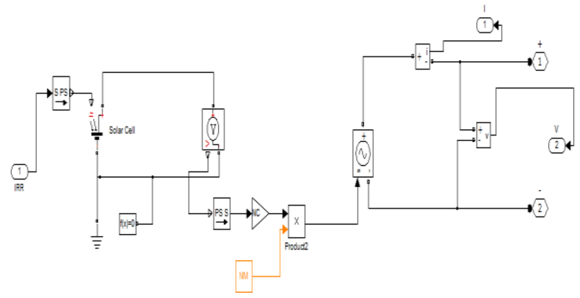


Fig. 6. Simulink model of the solar photovoltaic panel.

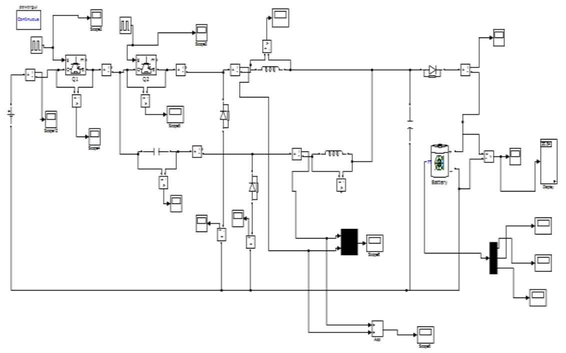


Fig. 7. Simulink model of the modified IBC

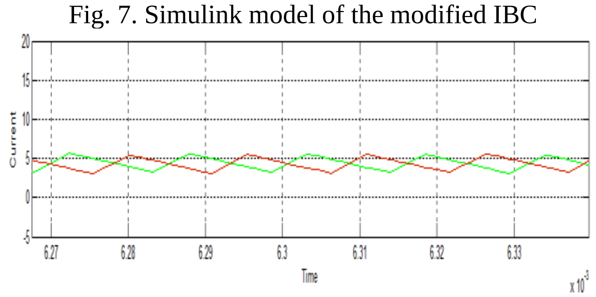
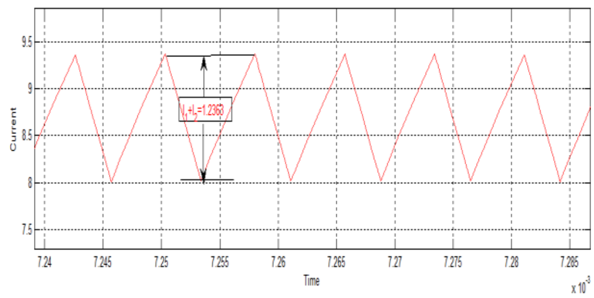


Fig. 8. (a) Ripple Current of modified IBC



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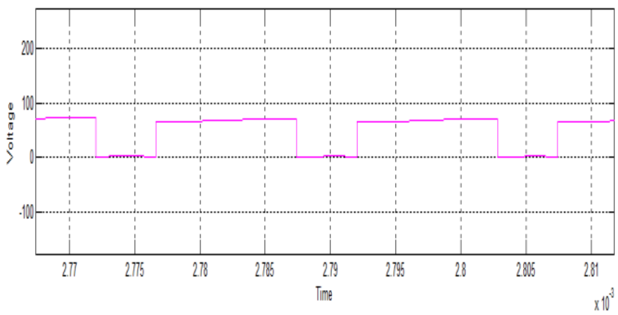

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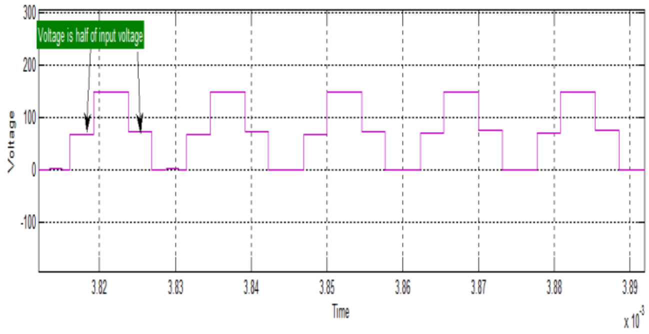

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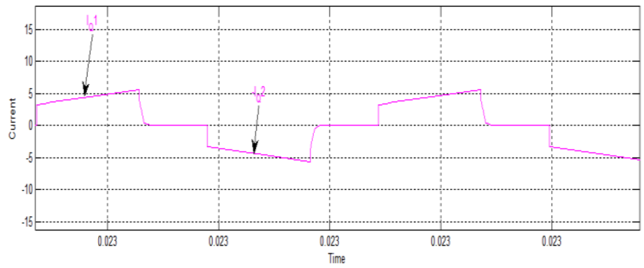

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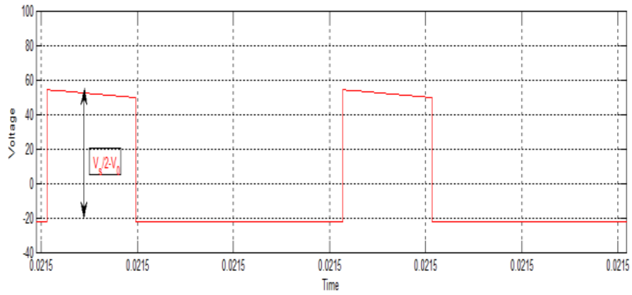

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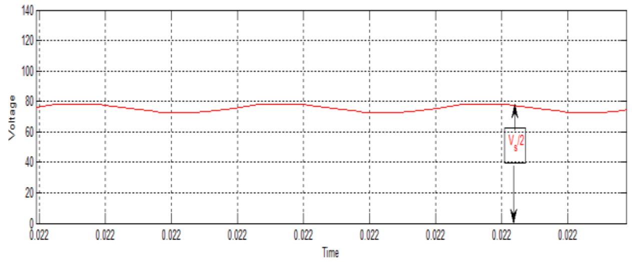

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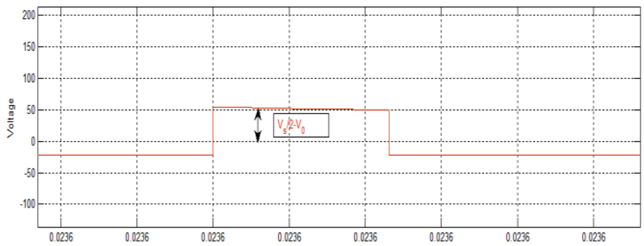

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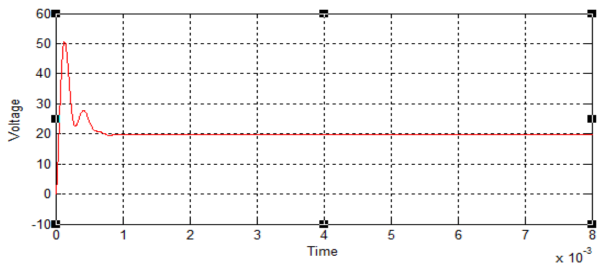

(h)

Fig. 9. (a) Reduced inductor current ripple. (b) Voltage through the Switch 1. (c) Half of the input voltage through the switch 2. (d) Current through the switch 1 and switch 2. (e) Voltage across the inductor V_{L1} . (f) Voltage across the coupling capacitor V_{CB}. (g) Voltage across the inductor V_{L2}. (h) Output voltage V_0.

V.CONCLUSION

This paper has introduced the new modified IBC which has very less stress across the switches, is main advantage. The voltage across the switches is half of the input voltage before turn-on and after turn and after turn on. The output voltage of the modified IBC is found to be 20v but the conventional IBC has 39v with same input as 150v. So the buck conversion efficiency of the modified IBC is found to be 93.33%. The inductor current ripple is also found to be very less of about 1.2 A. These all features made this suitable for battery charging and for the future generation computers which requires voltage of about 1V.

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