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Comparative Study of Interleaved Buck Converters

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Abstract: **An Interleaved Buck Converter (IBC) with continuous input current, extremely low output current ripple, low switching losses and improved step-down conversion ratio is presented in this work. The new interleaved buck converter has lower voltage stress in comparison to the conventional IBC and also can provide a high step-down ratio which makes it a proper choice for high power applications. Also new interleaved buck converter can provide current-sharing between two interleaved modules without using additional current-sharing control method. The new interleaved buck converter is simulated by using MATLAB/Simulink and the experimental results can be obtained.**

Keywords: **Two Phase Interleaved Buck Converter, Continuous Conduction Mode, low switching voltage stress.**

I. INTRODUCTION

Now adays, the tendency to use high performance high step-down DC-DC converters, in applications such as VRMs for microprocessors and battery chargers, has increased [1]. For non-isolated low output current ripple applications, interleaved buck converter (IBC) is an excellent choice due to its simple structure and control. Although, the conventional IBC has some advantages, like current sharing capability between modules, current ripple cancellation and fast transient response, but it suffers from few disadvantages. First of all, voltage stress of switches and diodes of conventional IBC is equal to the input voltage which is an important disadvantage in high input voltage applications. So, high voltage semiconductor devices should be used, where they suffer from high on resistance, high forward voltage drop, high output capacitor and high cost. High voltage across switches and diodes, before turn-on and after turn-off causes high switching losses and high losses related to reverse recovery of diodes [2]. So, a three level buck converter is introduced to reduce voltage stress of its switches and diodes are half of its input voltage but the conversion ratio is still similar to the conventional buck converter.

II. INTERLEAVED BUCK CONVERTER

The conventional interleaved buck converter is shown in Fig.1. This converter having two switches Q_1 and Q_2, diodes D_1 and D_2, and inductors L_1 and L_2 only. The conventional interleaved buck converter has many disadvantages are high ripple current and voltage stress. To overcome the disadvantages of conventional interleaved buck converter, introduce a new interleaved buck converter. The new interleaved buck converter is shown in Fig.2 which suitable for high input voltage, high step-down, non-isolated applications with low output current and continuous input current. It is similar to a three- level buck converter, but the two input capacitors are not connected to each other and also there is an auxiliary inductor at the converter output stage. The two active switches are controlled by two PWM pulses 180 degrees out of phase. The converter has four distinct operating intervals in a switching period. The operating waveforms are shown in Fig.3 and detailed operation modes of the converter also explained.

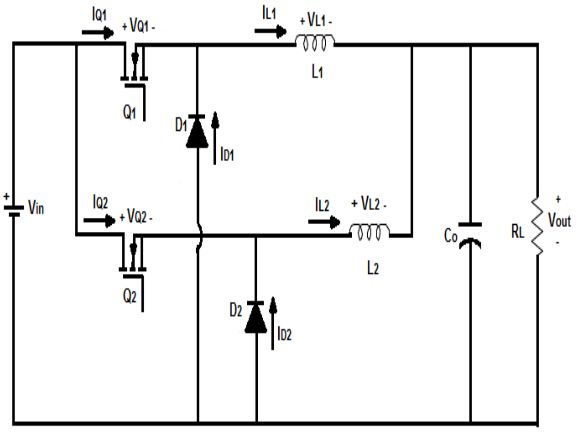


Fig.1. Conventional Interleaved Buck Converter

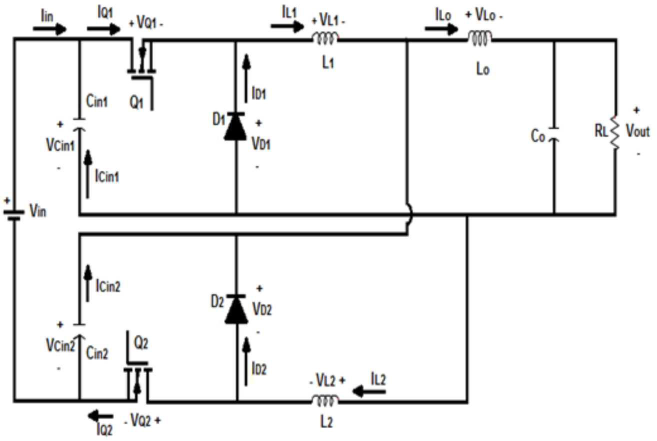


Fig.2. New Interleaved Buck Converter

A. *Modes of Operation:*

(a). Mode 1[$t_0 - t_1$]

Fig.4 shows the equivalent circuit of the new IBC in this interval. Prior to this interval both switches are off, the freewheeling diodes are conducting and the input capacitors C_{in1} and C_{in2} are charged. At t_0, Q_1 is turned on, so D_1 turns off. In this interval C_{in2} is charged through V_{in} and L_1, and also C_{in1} is being discharged through L_1-L_o-C_o. In addition, L_1 current is increasing through both of the mentioned current paths. L_2 current is decreasing in this state.

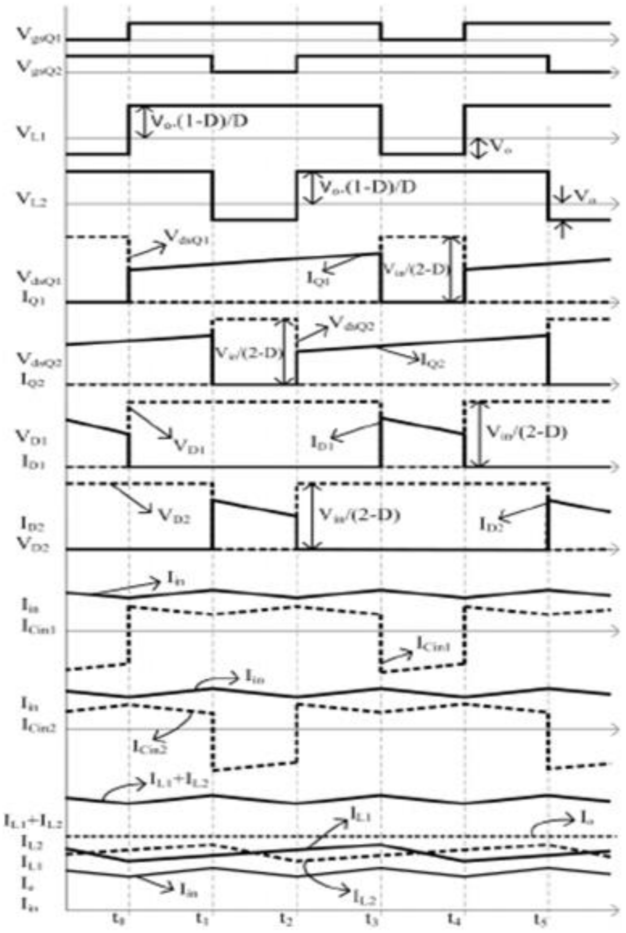


Fig.3. Theoretical Waveforms

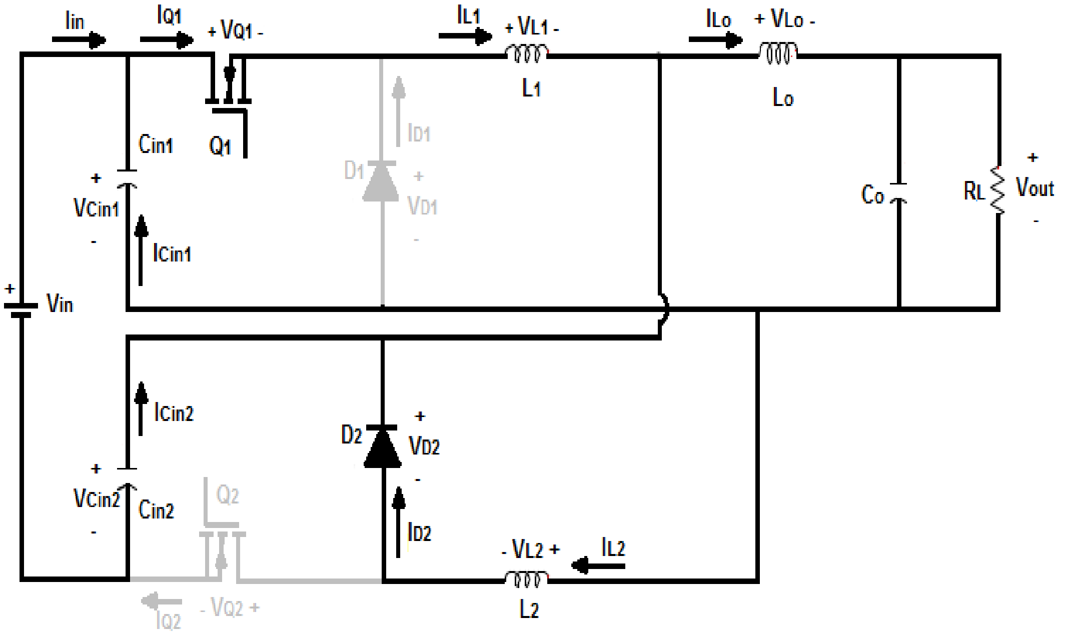


Fig.4. Mode1 (Equivalent circuit)

Voltages and current equation of this interval are as following,

$V_{L1}(t) = V_{Cin1} - V_{out} - V_{Lo}(t) = V_{in} - V_{Cin2}$ (1)

$V_{Lo}(t) = V_{in} + V_{out} - V_{Cin1} - V_{Cin2}$ (2)

$V_{L2}(t) = -V_{out} - V_{Lo}(t)$ (3)

$I_{Lo}(t) = I_{L1} + I_{L2} + I_{in}(t)$ (4)

(b). Mode 2$[t_1 - t_3]$

Fig.5 shows the equivalent circuit of the new IBC in this interval. This interval starts when Q_1 turns off. By turning Q_1 off, L_1 continues it's current and turns D_1 on. Part of the inductor current which was flowing in C_{in1}-L_1-L_o-C_o, continues its path through D_1-L_1-L_o-C_o, and the other part of L_1 current runs through V_{in}-C_{in1}-D_1-L_1-C_{in2}. So, during this interval, L_1 and L_2 are discharging and C_{in1} and C_{in2} are charging through V_{in}-C_{in1}-D_1-L_1-C_{in2} and V_{in}-C_{in1}-L_2-D_2-C_{in2}.

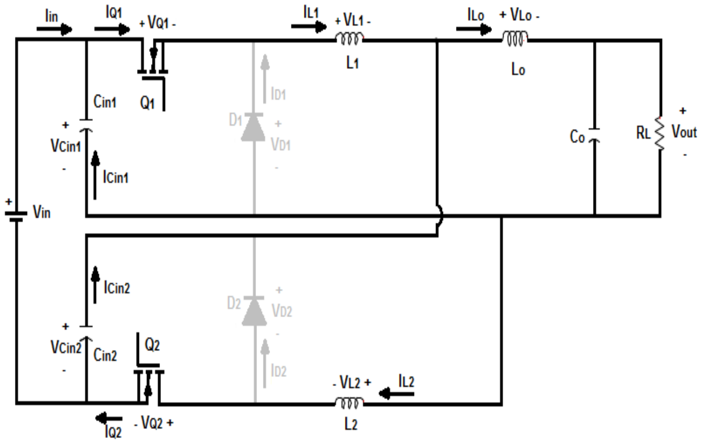


Fig.5. Mode2 (Equivalent circuit)

Using KVL law in D_1-L_1-L_o-C_o and D_2-L_2-L_o-C_o path, V_{L1} and V_{L2} are obtained as following,

$V_{L1}(t) = -V_{out} - V_{Lo}(t)$ (5)

$V_{L2}(t) = -V_{out} - V_{Lo}(t)$ (6)

And for V_{in}-C_{in1}-D_1-L_1-C_{in2} and V_{in}-C_{in1}-L_2-D_2-C_{in2} paths V_{L1} and V_{L2} would be

$V_{L1}(t) = V_{in} - V_{Cin1} - V_{Cin2}$ (7)

$V_{L2}(t) = V_{in} - V_{Cin1} - V_{Cin2}$ (8)

So, V_{Lo} in this interval is

$V_{Lo}(t) = V_{in} + V_{out} - V_{Cin1} - V_{Cin2}$ (9)

As it's obvious, (9) is the same as (2). According to Volt- Second-Balance (VSB), for L_o in one switching period, V_{Lo} is

$V_{Lo}(t) = 0$ (10)

Also from KCL law, $I_{Lo}(t)$ in this interval is

$I_{Lo}(t) = I_{L1} + I_{L2} - I_{in}(t)$ (11)

Due to symmetric operation of two modules in an interleaved buck converter, the operations of interval 3 and interval 4 are similar to those of interval 1 and interval 2.

III. SIMULATION MODEL AND RESULTS

In order to verify the operation principle and the theoretical analysis, conventional and new interleaved buck converters are simulated with MATLAB/SIMULINK simulation software and the simulation parameters are listed in Table.1. All switches using in simulation are ideal switches. Switching frequency is taken as 100kHz.

TABLE I: SIMULATION PARAMETERS

Input voltage V_{in}	200 V
Output voltage V_o	24 V
Auxiliary Inductor L_o	5 µH
Input Capacitors C_{in1} & C_{in2}	4.4 µF
Output Capacitor C_o	1 µF
Load Resistor R_L	2.4 Ω

A. *Simulink Model:*

Simulink model of conventional and new interleaved buck converters are shown in Fig.7 and Fig.8. MOSFET's are used as switches. Output voltage, output current ripple and stresses across switches are analyzed from the simulation results.

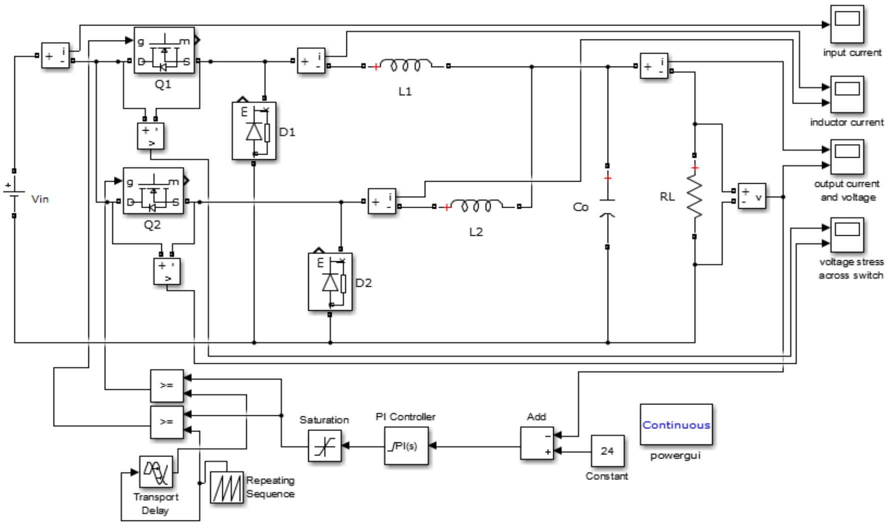


Fig.7. Simulink model of Conventional Interleaved Buck Converter

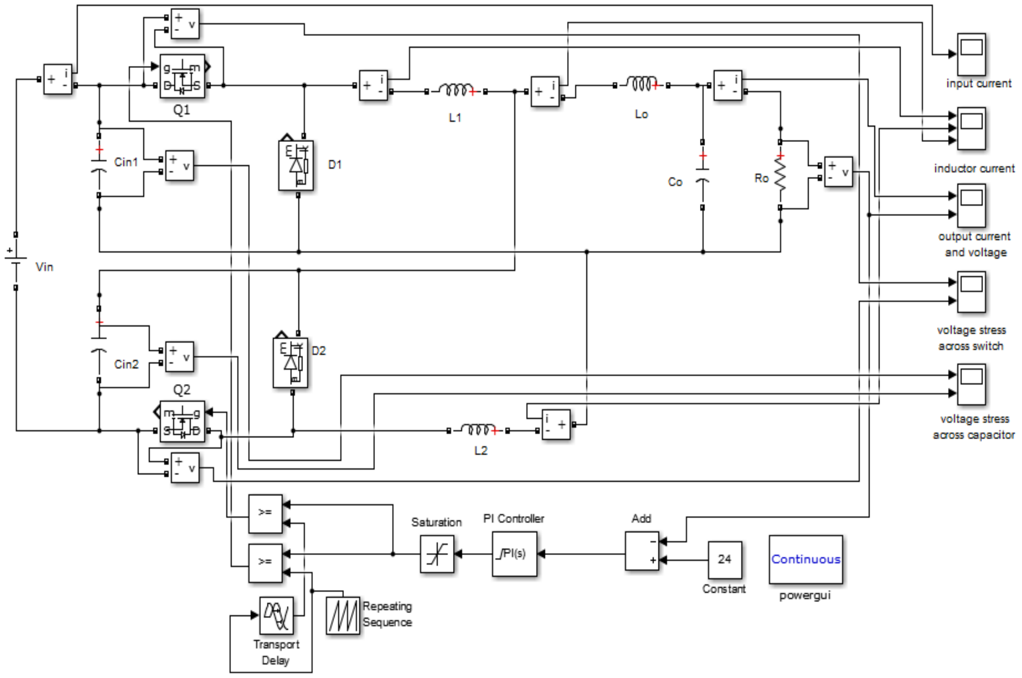


Fig.8. Simulink model of New Interleaved Buck Converter

B. Simulation Results:

Fig.9 shows the switching pulse for both conventional and new interleaved buck converter. The two active switches are controlled by two PWM pulses 180 degrees out of phase. Fig.10 shows that input voltage waveform. Input voltage is given to both converters are 200V. Fig.11 and Fig.12 shows that output voltage waveform of conventional and new interleaved buck converter respectively. For conventional interleaved buck converter, 47.7V is obtained and for new interleaved buck converter, 26.5V is obtained. Fig.13 and Fig.14 shows that inductor current waveform of both conventional and new interleaved buck converter. Fig.15 and Fig.16 shows that input current waveform of conventional and new interleaved buck converter respectively. Input current waveform of new interleaved buck converter is continuous compared to conventional interleaved buck converter. Fig.17 and Fig.18 shows that output current waveform of conventional and new interleaved buck converter respectively. For conventional interleaved buck converter, 19.87A is obtained and for new interleaved buck converter, 11.042A is obtained. Fig.19 and Fig.20 shows that voltage stress across switches for conventional and new interleaved buck converter respectively. Voltage stress across switches in conventional interleaved buck converter is 200V and for new interleaved buck converter is 116V.

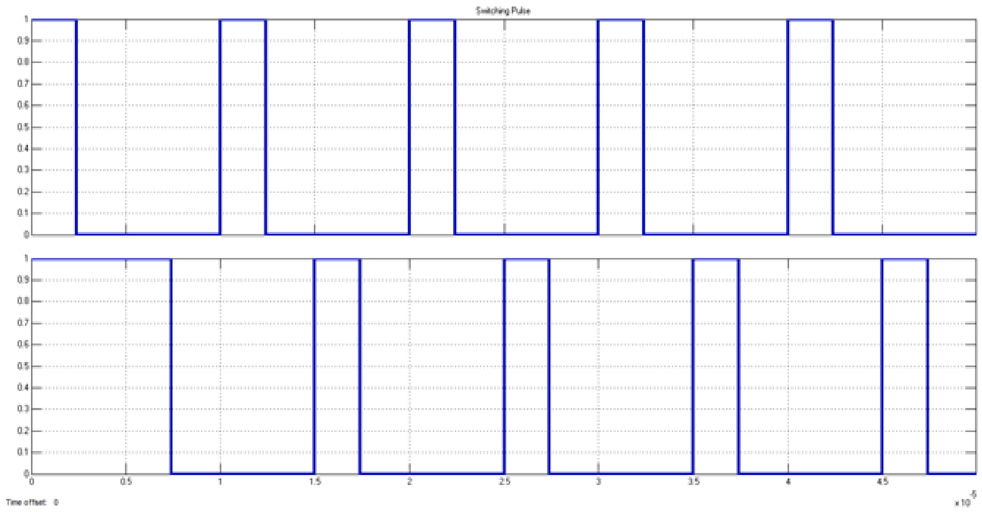


Fig.9. Switching Pulse

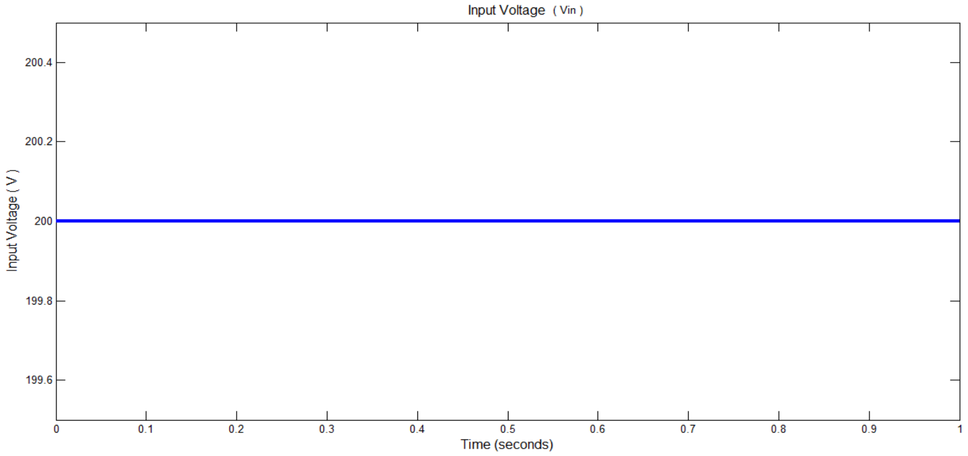


Fig.10. Input Voltage Waveform of CIBC and NIBC

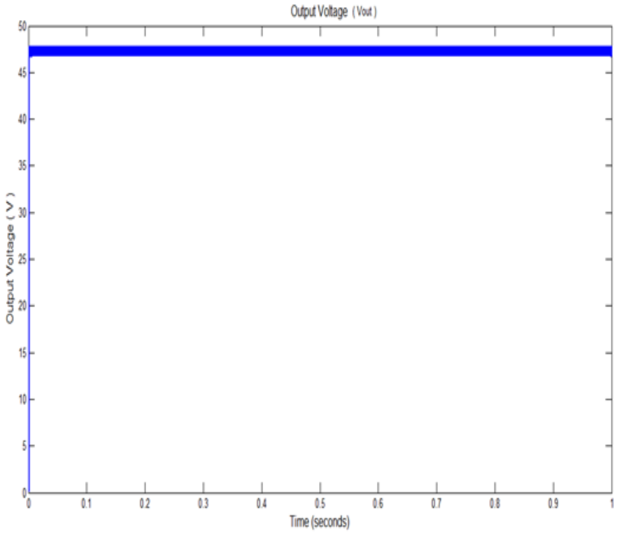


Fig.11. Output Voltage Waveform of CIBC

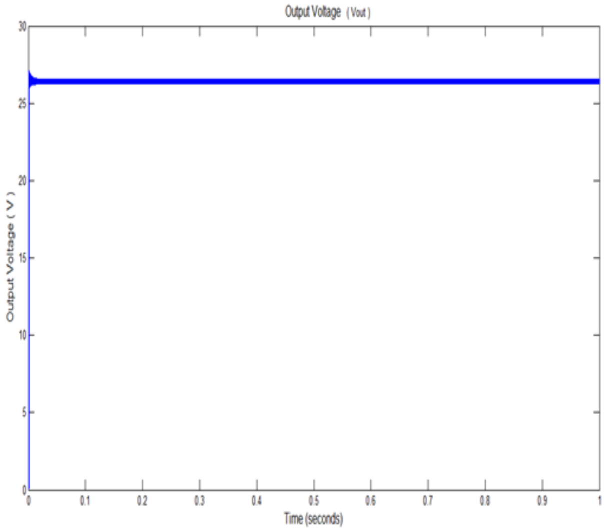
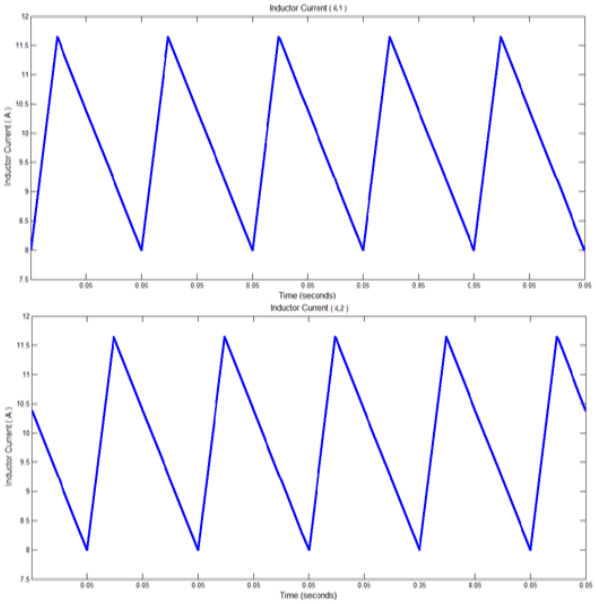


Fig.12. Output Voltage Waveform of NIBC



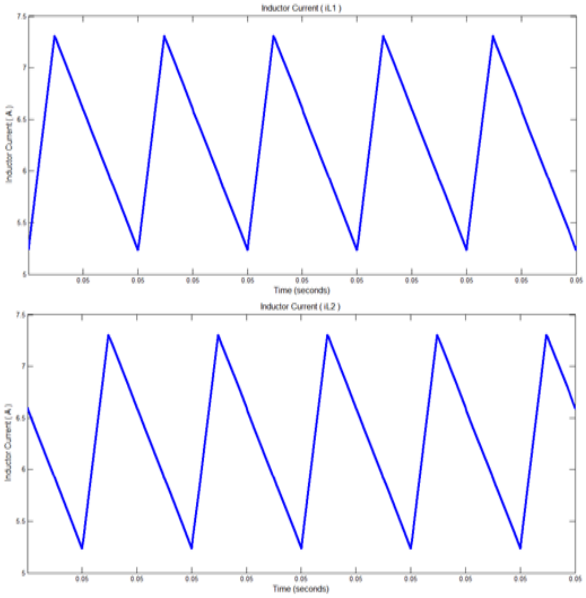


Fig.13. Inductor Current of CIBC **Fig.14. Inductor Current of NIBC**

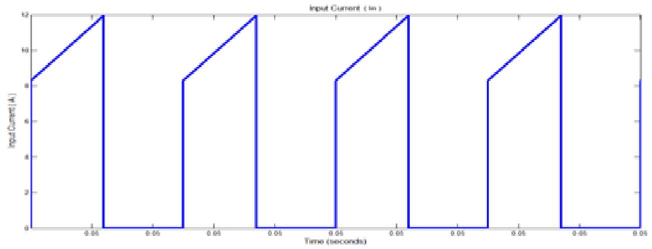


Fig.15. Input Current Waveform of CIBC

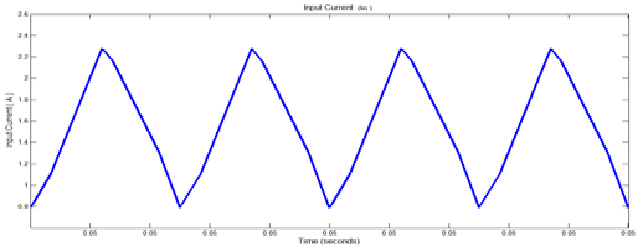


Fig.16. Input Current Waveform of NIBC

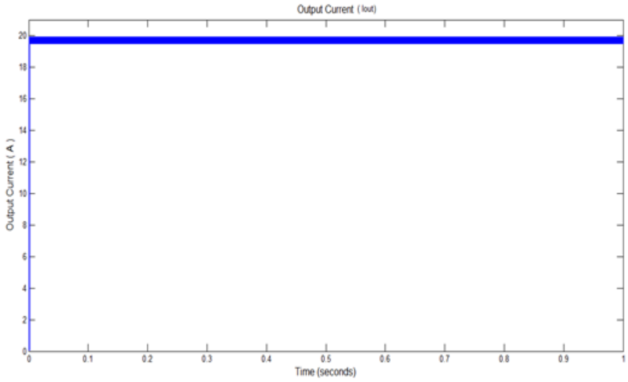


Fig.17. Output Current Waveform of CIBC

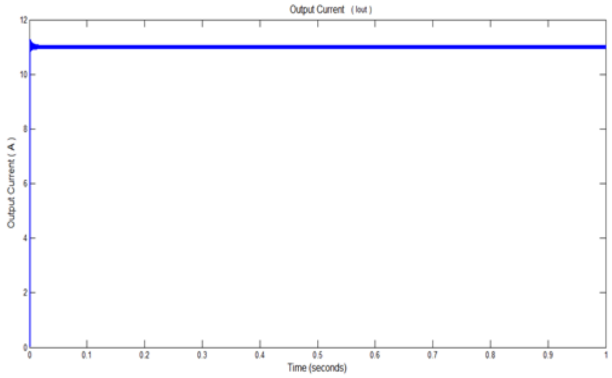


Fig.18. Output Current Waveform of NIBC

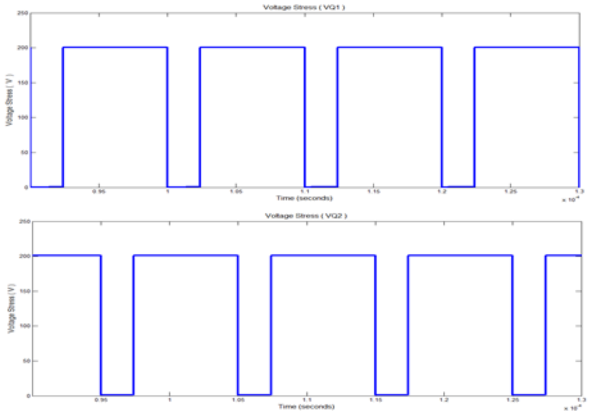


Fig.19. Voltage Stress of Switches in CIBC

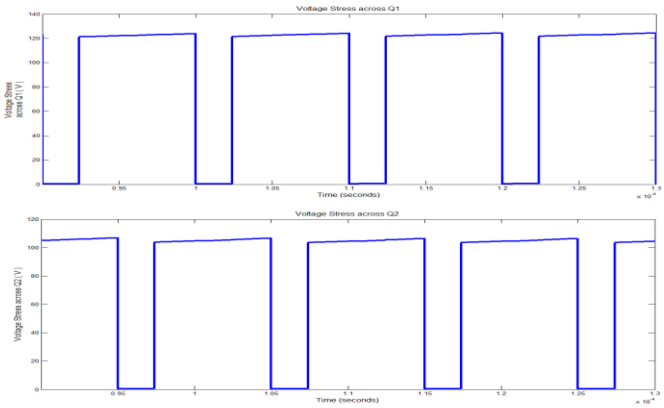


Fig.20. Voltage Stress of Switches in NIBC

TABLE II: COMPARATIVE STUDY

Parameters	Conventional IBC	New IBC
Output Voltage	47.7 V	26.5 V
Voltage Stress across Switch	200 V	116 V
Output Current Ripple	0.335 A	0.084 A
Output Voltage Ripple	0.850 V	0.084 A
Input Current	Discontinuous	Continuous
Stepdown Conversion Ratio	0.24	0.13

Table II shows that comparative study of conventional and new interleaved buck converter. Output voltage is reduced by 44.4%. Voltage stress across Q_1 & Q_2 decreased by 42% for both switches. Output current ripple of new interleaved buck converter is reduced by 74.92%. Voltage conversion ratio is improved by 45.83%. And also, input current of new interleaved buck converter is continuous compared to conventional interleaved buck converter.

IV. CONCLUSIONS

An interleaved DC-DC step down converter for low output voltage and high output current suitable for VRM application is presented here. The paper explains clearly the operating principle of two phases IBC with equivalent circuits. The new interleaved buck converter has many advantages like improved step-down conversion ratio, extremely low output current ripple and low switching losses. Also, the voltage stress of semiconductor components in the new interleaved buck converter is much smaller than the conventional interleaved buck converter. All these benefits are obtained without applying any additional voltage or current stress on the components.

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