MODIFIED INTERLEAVED BUCK CONVERTER IMPLEMENTATION FOR HIGHER STEP-DOWN CONVERSION RATIO

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Abstract: This paper presents Modified Interleaved Buck Converter (MIBC) model which has lower inductor ripple current and higher step-down conversion ratio. This converter is applicable where the input voltage is high and the output voltage is low. Three MOSFETs are connected in series and two coupling capacitors are used in the power path. The converter is working in higher switching frequency and operating duty is below 50%. The proposed MIBC results higher step-down conversion ratio with smaller output current ripple compared with a conventional Interleaved Buck Converter. The converter design, modes of operation, and corresponding simulation results of the proposed MIBC are presented in this paper. The analysis of MIBC is validated by the simulation results of prototype converters with 200V input, 10V/4.3A output.

Keywords: Conversion Ratio, Duty Cycle, Inductor Current Ripple, Modified Interleaved Buck Converter.

Introduction: In applications where high step-down conversion ratio, high output current with lower ripple are necessary, a Modified Interleaved Buck Converter (MIBC) is having a lot of consideration due its simple structure and its reduced control complexity[1]-[6]. However, in the conventional IBC shown in Fig. 1, all semiconductor devices suffer, due to the input voltage and hence, high-voltage devices rated above the input voltage should be used. High-voltage-rated devices have generally poor characteristics such as high cost, high on-resistance, high for-ward voltage drop, severe reverse recovery, etc. In addition, the converter operates under hard switching condition. Thus, the cost becomes high and the efficiency becomes poor. And, for higher power density and better dynamics, it is required that the converter operates at higher switching frequencies [7]. In [8]–[10], three-level buck converters are introduced. The voltage stress is half of the input voltage in the converters. However, so many components are required for the use of IBC. Comparing with conventional IBC, step-down conversion ratio and output inductor current ripple are reduced in MIBC. The Conventional Interleaved Buck Converter which is shown in Fig.1 is having two active switches and a coupling capacitor in its power path.

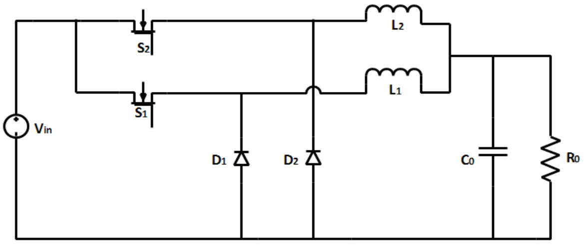

Fig.1. Conventional IBC

In addition, MIBC is implemented with three active switches and two coupling capacitors. The converter acts in continuous conduction mode. If the converter operates under discontinuous conduction mode, all elements will be affected by high current stress and hence conduction loss and core loss of the converter will be increased.

The features of the proposed IBC are similar to those of the IBC in [12]. During the steady state, the voltage stress across all active switches before turn-on or after turn-off is half of the input voltage. The conversion ratio and output current ripple, ripple in inductor current are lower than those of the conventional IBC.

The circuit operations of the proposed Modified IBC are expressed in Section II in detail. The relevant analysis results are presented in Section III. The performance of the proposed IBC is confirmed by the simulation results of prototype converters with 200 V input, 10 V/4.3 A output in Section IV. The conclusion is given in Section V.

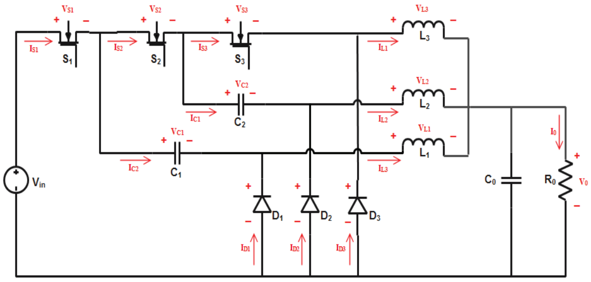

Fig.2. Proposed MIBC

Circuit operations: Fig.2 shows the circuit design of the proposed MIBC. The structure is same as that of a conventional IBC except three active switches are connected in series and two coupling capacitors are employed in the power path. Figs. 3 shows the operating waveforms of the proposed MIBC during steady state condition. The switches S_1, S_2 and S_3 are driven with the phase shift angle of 180°. This is similar to a conventional IBC. Each switching period is divided into six modes. Each mode operation is shown in Fig.4. In order to demonstrate the working principle of the proposed MIBC, some considerations are made as follows:

1) the three inductors L_1, L_2 and L_3 are having the same inductance L;

2) all power semiconducting devices are ideal;

3) the coupling capacitors C_1 and C_2 are considered as the voltage source.

A. Circuit Operation when $D \leq 0.5$

Mode 1 [$t_0 - t_1$]: Mode 1 begins when S_1 is turned ON at t_0. Then, the current of $I_{L1}(t)$, flows through S_1, C_1, and L_1 and hence the coupling capacitor V_{C1} is charged. The current of $I_{L2}(t)$, freewheels through D_2 and the current $I_{L3}(t)$, freewheels through D_3. During this mode, the voltage across $V_{L1}(t)$, is the differences of the input voltage V_S, the voltage of the coupling capacitor V_{C1}, and the output voltage V_O, and its level is positive. Hence, $I_{L1}(t)$ increases linearly from the initial value. The voltage across $V_{L2}(t)$ and the voltage $V_{L3}(t)$ are the negative output voltages. Therefore, $I_{L2}(t)$ and $I_{L3}(t)$ decrease linearly from the initial value. The voltage $V_{S2}(t)$, becomes (2/3) of the input voltage and the voltage $V_{S3}(t)$ is equal to (1/3) of the input voltage. The voltage $V_{D1}(t)$, is equal to the difference of V_S and V_{C1}.

Mode 2 [t_1-t_2]: Mode 2 begins when S_1 is turned OFF at t_1. Then, I_{L1}, I_{L2}, I_{L3} currents freewheel through D_1, D_2 and D_3 respectively. The voltages $V_{L1}(t)$, $V_{L2}(t)$, $V_{L3}(t)$ become the negative output voltage, V_o. Therefore, $I_{L1}(t)$, $I_{L2}(t)$ and $I_{L3}(t)$ decrease linearly. During this mode, the voltage across each switch is $V_S/3$.

Mode 3 [t_2-t_3]: Mode 3 begins when S_2 is turned ON at t_2. The energy stored in the coupling capacitor V_{C1} is discharged and coupling capacitor V_{C2} is charged. The current of $I_{L2}(t)$ flows through S_2, C_2, L_2. The current of inductor $I_{L1}(t)$ freewheels through D_1 and the inductor current $I_{L3}(t)$ freewheels through D_3. During this mode, the voltage $V_{L2}(t)$ is the difference of the coupling capacitor voltages $V_{C1}(t)$, $V_{C2}(t)$ and the output voltage, V_o and its level is positive. Therefore, $I_{L2}(t)$ increases linearly. The voltage $V_{L1}(t)$ and the voltage $V_{L3}(t)$ are the negative voltages. And hence, $I_{L1}(t)$ and $I_{L3}(t)$ decrease linearly from its initial values. The voltage $V_{S1}(t)$ becomes (1/3) of input voltages, V_S and the voltage $V_{S3}(t)$ becomes (2/3) of input voltage, V_S. The voltage $V_{D2}(t)$ is equal to the difference of coupling capacitor voltages $V_{C1}(t)$ and $V_{C2}(t)$

Mode 4 [t_3-t_4]: Mode 4 begins when S_2 is turned OFF at t_3 and its operation is same as that of mode 2.

Mode 5[t_4-t_5]: Mode 5 begins when S_3 is turned ON at t_4. The energy stored in the coupling capacitor V_{C2} is discharged. The current $I_{L3}(t)$ flows through C_2, S_3 and L_3. The inductor current $I_{L1}(t)$ freewheels through D_1 and the inductor current $I_{L2}(t)$ freewheels through

D_2. During this mode, the voltage across $V_{L3}(t)$ is the difference between the coupling capacitor voltage, $V_{C2}(t)$ and the output voltage, V_o and its level is positive. Therefore, $I_{L3}(t)$ increases linearly. The voltage $V_{L1}(t)$ and the voltage $V_{L2}(t)$ are the negative output voltages. And hence, $I_{L1}(t)$ and $I_{L3}(t)$ decrease linearly from its initial values. The voltage $V_{S1}(t)$ is (1/3) of the input voltage,V_S and the voltage $V_{S2}(t)$ is also (1/3) of the input voltage, V_S. The voltage $V_{D3}(t)$ is equal to $V_{C2}(t)$.

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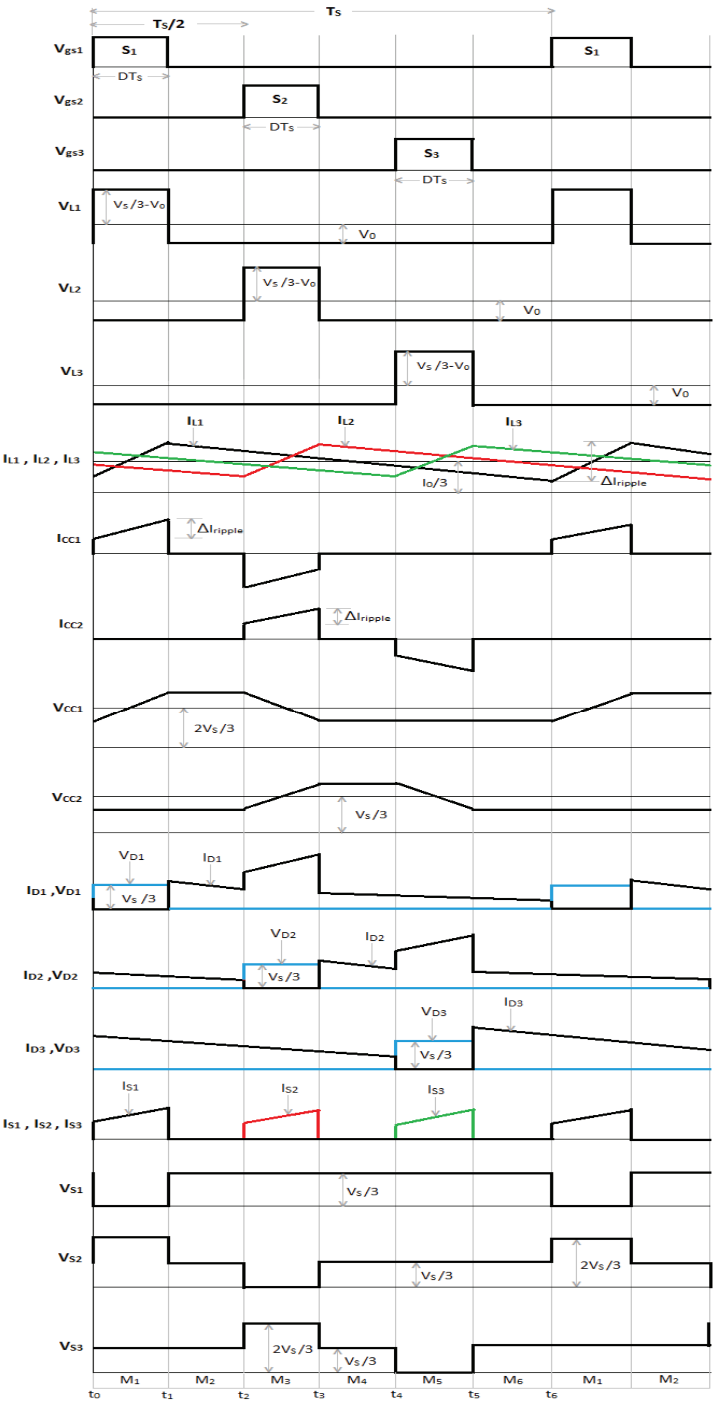
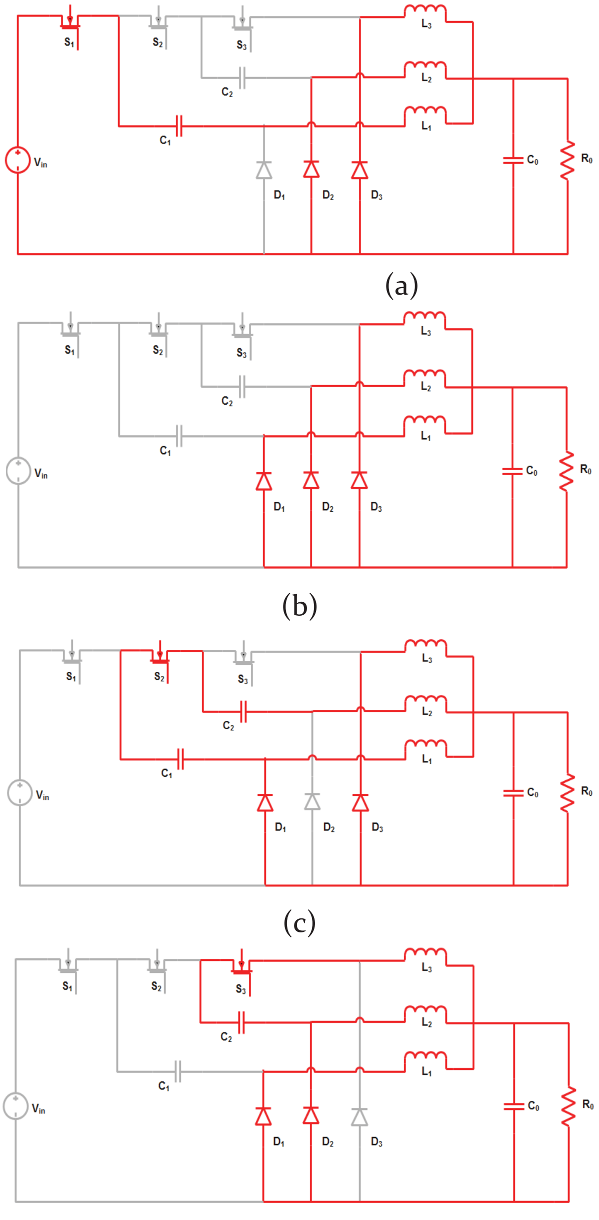


Fig. 3. Operating waveforms of the proposed MIBC when $D \leq 0.5$

Mode 6[t_5-t_6]: Mode 6 begins when S_3 is turned OFF at t_5 and its operation is same as that of mode 2.



(a)

(b)

(c)

(d)

Fig.4 Operating circuits of the proposed MIBC when D ≤ 0.5.
(a) Mode 1. (b) Mode 2 or 4 or 6. (c) Mode 3. (d) Mode5.

Relevant Analysis:

A. DC Conversion Ratio

By using the principle of Inductor volt-second-balance (VSB) [11], the DC conversion ratio of the proposed MIBC can be derived.When D ≤ 0.5, the follwing equations can be obtained from the VSB of L_1, L_2 and L_3, respectively

$(V_S - V_{C1} - V_o)\, DT_S = (1 - D)\, V_oT_S$

$(V_{C1} - V_{C2} - V_o)\, DT_S = (1 - D)\, V_oT_S$

$(V_{C2} - V_o)\, DT_S = (1 - D)\, V_oT_S$

By solving equations (1), (2) and (3), the dc convertion ratio, M of MIBC can be obtained as follows:

$$M = V_o / V_S = D / 3$$

B. Inductor Ripple Current

When $D \le 0.5$, the inductor ripple current can be expressed as,

$$\Delta I_{ripple} = (0.33V_S - V_o)\, DT_S / L$$

Or

$$\Delta I_{ripple} = (1- D)\, V_oT_S / L$$

Simulation results and analysis: For the proposed MIBC, the parameter specifications are shown next.

1) Switching Frequency: $F_S = 65KHz$
2) Input Voltage: $V_S = 200V$
3) Output Voltage: $V_o = 10V$
4) Output Current : $I_o = 4.3A$
5) Output Ripple Voltage,
$V_{oripple}$ = below 0.025V
6) Inductor Ripple Current,
$I_{Lripple}$ = below 1A

By using MATLAB simulink, the simulations results have been obtained.

Table I

Results Obtained For Buck Converters

MODELS	V_{OUT}	I_{OUT}	ΔI_L	M
Normal Buck Converter	≈98V	≈40A	≈8A	0.49
Interleaved Buck Converter	≈24V	≈10A	≈3A	0.12
Proposed Modified IBC	≈10V	≈4.3A	≈1.4A	0.05

The simulation results obtained for various buck converters are given in table I and the simulation waveforms of input voltage, output voltage, output current and inductor current for Modified Interleaved Buck Converter are shown in Fig.5

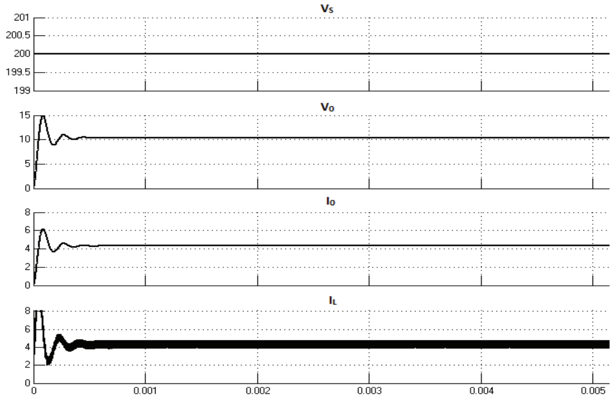


Fig.5.Simulation waveforms of the proposed MIBC

Conclusion: A Modified Interleaved Buck Converter is proposed in this paper. It is having a simple structure and the main advantage of the proposed MIBC is that in open loop even higher step-down conversion ratio is obtained. The voltage stress across the switches is reduced considerably when the operating duty is below 50%. The ripple current of each inductor and the output ripple current of the converter are very low compared with conventional IBC. Without using any cotroller even lower output voltage is achieved and the complexity of the converter is low. Therefore, the proposed MIBC bocomes smart choice in applications where higher step-down convertersion ratio with high input voltage, nonisolation, high output current with lower ripple, and low cost are required.

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