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A modified switched-boost DC-DC converter circuit with reduced current stress and output voltage ripple

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Abstract—This paper is aimed to propose an improved boost DC-DC converter, based on the idea of switched-capacitor and switched-boost converters. A modified version of the conventional switched-capacitor switched-boost converter is proposed, particularly suitable for high power applications. The major contributions concern the reduction of the stress in the power components as well as the voltage ripple reduction. Indeed, the current of the switches as well as the current of the diodes are reduced in the proposed converter. Nevertheless, the proposed idea slightly affects the boost factor of the converter. The performance of the proposed step-up DC-DC converter is evaluated through some simulations done in MATLAB.

Index Terms—DC-DC converter, current stress, continuous current, Boost factor.

I. INTRODUCTION

On account of the massive consumption of electrical energy, there is a worldwide growing tendency to utilize the renewable energy resources. Among them, the photovoltaic (PV) system is one of the well-known ideas used in electricity networks, more especially in distribution systems. Although PV can harvest the energy from sun light, its output voltage is low and unregulated. So that, it is necessary to magnify and regulate the output voltage of PV in some applications like grid-connected PV systems. Step-up DC-DC converters can be utilized to simultaneously increase and regulate the output voltage of PVs. Having a high boost factor is favorable for this kind of converters. As a consequence, many researches have been carried out to propose proper converter's topology to achieve high boost factor with a small number of components. The boost factor can be improved using an impedance network in the input side of the converter. Z-source converter is a fine example of this idea [1]. Likewise, active-switched boost converter [2]–[7], adding passive elements into the impedance network [8]–[12], and magnetically coupled inductors [13]–[16] are some approaches to elevate the boost factor. These converters are more particularly concerned by this paper.

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For example, in [2], by combining the switched-capacitor converter and the switched-boost converter, an extended boost switched-capacitor switched-boost converter (SC-SBC) is proposed. The switched-capacitor cells are used in low voltage step-up converter, but due to capacitor switching, the peak current may be high, making them not the most suitable for high power applications. In this paper, the conventional SC-SBC is modified and adapted to be more suitable with higher output power. In comparison with SC-SBC, the proposed converter has the following features:

- Less current stress in active parts,
- Less output voltage ripple.

The principle of operation of the proposed converter is explained and the governing relations are derived. The correctness of the operation is assessed through some simulation results carried out in MATLAB.

II. PROPOSED INVERTER

The conventional SC-SBC is shown in Fig. 1. This converter is derived from the so called switched-capacitor converter. Due to the nature of the switched-capacitor cells, the peak current of the switches is high in SC-SBC, which makes it mainly suitable for low voltage and low power applications. The converter we proposed is shown in Fig. 2. Substituting an inductor for the output diode of SC-SBC makes the proposed topology named “modified SC-SBC” (Fig. 2 (a)). In mode 1, when the switches are turned on, all the diodes are reversed biased. During mode 2, when the switches are forced off, the diodes are conducting. The key waveforms of the proposed converter are shown in Fig. 3. Therefore, the voltage across the inductors in the “modified SC-SBC” can be written as:

$$\begin{cases} v_{L1,on} = V_i + V_{C1} \\ v_{L2,on} = V_i + V_{C1} + V_{C2} - V_{Co} \\ V_{C2} = V_i + V_{C1} \end{cases} \quad (1)$$

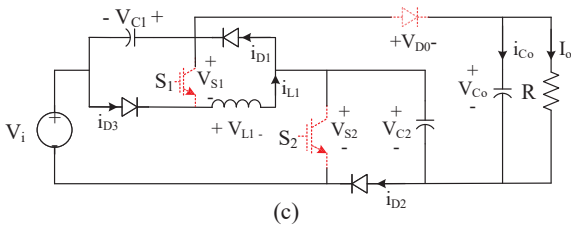
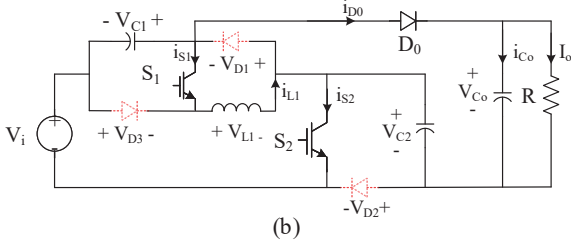
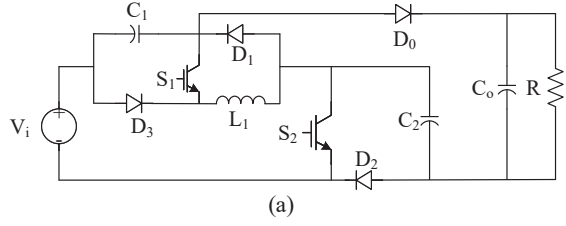


Fig. 1: The conventional SC-SBC [2], (a) circuit topology, (b, c) equivalent circuits in modes 1 and 2.

$$\begin{cases} v_{L1,off} = -V_{C1} \\ v_{L2,off} = V_i + V_{C1} - V_{C_o} \end{cases} \quad (2)$$

Due to the fact that the average voltage on the inductors in steady-state operation is zero, we will have:

$$\frac{1}{T_s} \int_t^{t+T_s} v_{L1}(\tau) d\tau = 0 \quad (3)$$

Therefore

$$\frac{1}{T_s} (v_{L1,on} \cdot DT_s + v_{L1,off} \cdot (1-D)T_s) = 0 \quad (4)$$

where T_s and D are the switching period and switch duty cycle ratio, respectively, with $D = T_{on}/T_s$. Substituting (1) in (4) yields:

$$(V_i + V_{C1})D + (-V_{C1})(1-D) = 0 \quad (5)$$

then we have

$$V_{C1} = \frac{D}{1-2D} V_i \quad (6)$$

Repeating the procedure for L_2 , the following relation is obtained.

$$(2V_i + 2V_{C1} - V_{C_o})D + (V_i + V_{C1} - V_{C_o})(1-D) = 0 \quad (7)$$

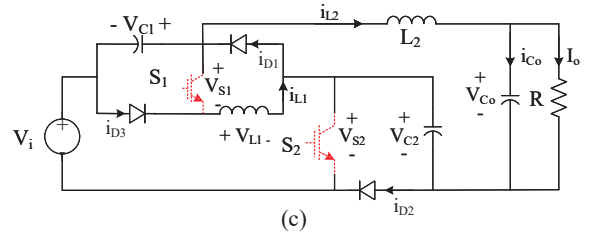
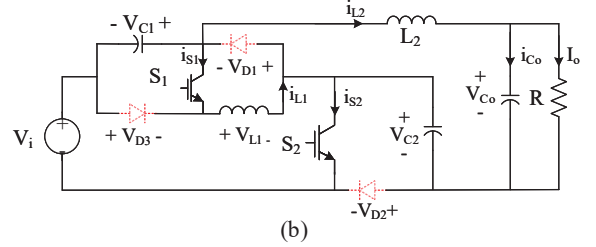
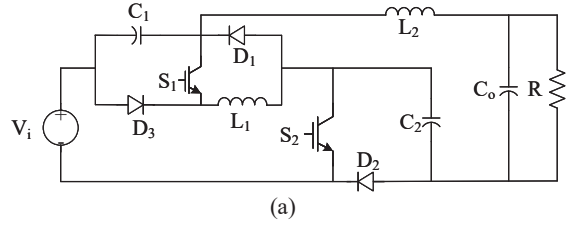


Fig. 2: The modified SC-SBC, (a) circuit topology, (b, c) equivalent circuits in modes 1 and 2.

And after some mathematic manipulations, the following relations can be obtained:

$$\begin{cases} V_{C1} = \frac{D}{1-2D} V_i \\ V_{C2} = \frac{1-D}{1-2D} V_i \\ V_{C_o} = \frac{(1+D)(1-D)}{1-2D} V_i \end{cases} \quad (8)$$

Consequently, the boost factor is :

$$B = \frac{V_{C_o}}{V_i} = \frac{(1+D)(1-D)}{1-2D} \quad (9)$$

The boost factor of the modified SC-SBC is compared with the topology proposed in [2] and shown in Fig. 4.

III. CURRENT AND VOLTAGE STRESSES

From Fig. 2, it can be seen that the average current of L_2 is equal to the output average current, I_o . In addition, the average current of L_1 is $1/(1-D)$ times than the average current of the source. Knowing that $V_i I_i = V_o I_o = B V_i I_o$ in lossless condition, the source current is expressed as follows:

$$I_i = B I_o = \frac{(1+D)(1-D)}{1-2D} I_o \quad (10)$$

Therefore, the average current stress of inductors are as follows:

TABLE I: Comparison of the average current stress and the average voltage stress in modified SC-SBC and SC-SBC. (* NA: Not Applicable)

Component	Voltage stress		Current stress	
	Modified SC-SBC	SC-SBC [2]	Modified SC-SBC	SC-SBC [2]
C_1	$\frac{D}{1-2D} V_i$	$\frac{D}{1-2D} V_i$	-	-
C_2	$\frac{D}{1-2D} V_i$	$\frac{D}{1-2D} V_i$	-	-
C_o	$\frac{(1-D)(1+D)}{1-2D} V_i$	$\frac{2D}{1-2D} V_i$	-	-
L_1	-	-	$\frac{1+D}{1-2D} I_o$	$\frac{2}{1-2D} I_o$
L_2	-	NA*	I_o	NA
D_1	$\frac{(1-D)}{1-2D} V_i$	$\frac{(1-D)}{1-2D} V_i$	$\frac{D^2-D+1}{1-2D} I_o$	$\frac{1}{1-3D+2D^2} I_o$
D_2	$\frac{(1-D)}{1-2D} V_i$	$\frac{(1-D)}{1-2D} V_i$	I_o	$\frac{1}{1-2D} I_o$
D_3	$\frac{(D)}{1-2D} V_i$	$\frac{(D)}{1-2D} V_i$	$\frac{(1-D)(D+1)}{1-2D} I_o$	$\frac{2}{1-2D} I_o$
D_o	NA	$\frac{(1-D)}{1-2D} V_i$	NA	$\frac{1}{D} I_o$
S_1	$\frac{D}{1-2D}$	$\frac{(D)}{1-2D} V_i$	$D \frac{1+D}{1-2D} I_o$	$\frac{2}{1-2D} I_o$
S_2	$\frac{1-D}{1-2D}$	$\frac{(1-D)}{1-2D} V_i$	$D \frac{2-D}{1-2D} I_o$	$\frac{1}{D(1-2D)} I_o$

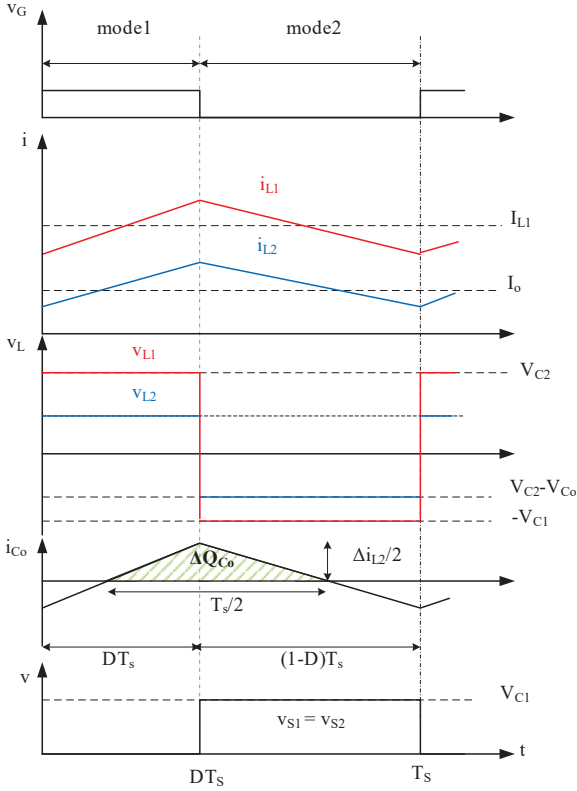


Fig. 3: Waveforms of the modified SC-SBC (V_G is the gate voltage).

$$(11) \quad \begin{cases} I_{L1} = \frac{1}{1-D} I_i = \frac{1+D}{1-2D} I_o \\ I_{L2} = I_o \end{cases}$$

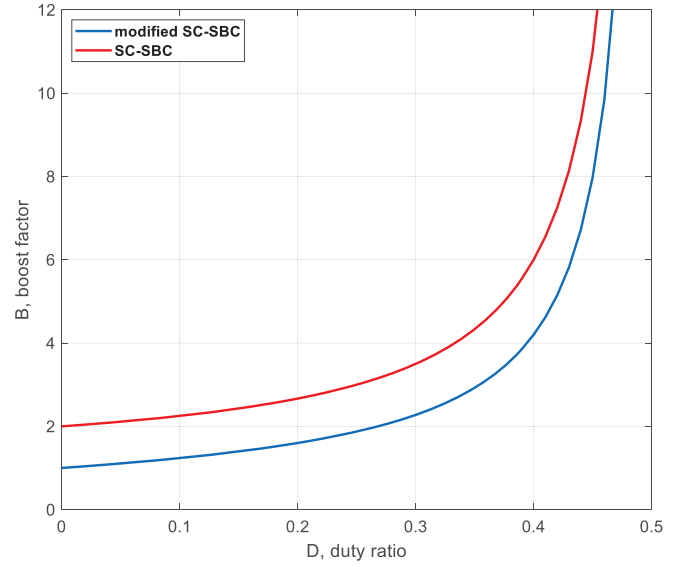


Fig. 4: Boost factor as a function of duty ratio in the two compared topologies.

The average current stress of switches is:

$$(12) \quad \begin{cases} I_{S1} = DI_{L1} = D \frac{1+D}{1-2D} I_o \\ I_{S2} = D(I_{L1} + I_{L2}) = D \frac{2-D}{1-2D} I_o \end{cases}$$

The current and voltage stress of modified SC-SBC and SC-SBC are compared in Table I.

The output voltage ripple in modified SC-SBC can be found using Fig. 3. The average current of L_2 serves the load and the ripple of i_{L2} passes through the output capacitor. So that, knowing the ripple of i_{L2} , the ripple of V_{C_o} can be calculated as follows:

$$\begin{cases} \Delta i_{L2} = \frac{DT_s}{L_2}(2V_i + 2V_{C1} - V_{Co}) \Rightarrow \\ \Delta i_{L2} = \frac{DT_s}{L_2} \frac{(1-D)^2}{1-2D} V_i \\ or \\ \Delta i_{L2} = \frac{DT_s}{L_2} \frac{1-D}{1+D} V_{Co} \end{cases} \quad (13)$$

$$\Delta V_{Co} = \frac{T_s}{2C_o} \frac{\Delta i_{L2}}{2} = \frac{D}{4f_s^2 L_2 C_o} \frac{1-D}{1+D} V_{Co} \quad (14)$$

It can be seen that the output voltage ripple is not dependent on the load for the “modified SC-SBC”, while in SC-SBC, because of the presence of the diode D_o , ΔV_{Co} is dependent on the load.

IV. SIMULATION RESULTS

The parameters used in simulations are summarized in Table II. In Fig. 5 (shown on page 6) the results obtained from simulations are shown for two different conditions. It can be seen that for the same duty ratio the output voltage of the modified SC-SBC is smaller than SC-SBC. To have the same boost factors two different duty ratios should be adjusted for two converters.

TABLE II: Simulation parameters

Parameter	Symbol	Value
Input voltage	V_i	40V
Switching frequency	f_{SW}	30kHz
Inductances	L_1, L_2	1mH
Capacitances	C_1, C_2	330μF
Capacitance	C_o	470μF
Load resistance	R	100Ω

From Fig. 5 it can be found out that for the same duty ratios the modified SC-SBC has smaller boost factor than SC-SBC. However, the peak current in SC-SBC is much higher than improved SC-SBC; therefore, the modified SC-SBC is better suited for the applications which demand higher power and less boost factor. Moreover, the output voltage ripple of the modified SC-SBC is less than SC-SBC and it is independent of the load in modified SC-SBC. This feature is also proper for high power application. All in all, it can be concluded that the modified SC-SBC has less current stress for the switches and diodes and less voltage ripple, all at the expense of a slightly smaller boost factor.

V. CONCLUSION

In this paper, a modified switched-capacitor switched-boost converter (SC-SBC) is proposed, which tackles the problem of high current stress on devices. Moreover, in continuous conduction mode of operation, the output voltage ripple is independent of the load. The principle of operation is presented in detail and a comparison between “modified SC-SBC” and conventional SC-SBC is presented, too. Although the modified SC-SBC has less current stress, one can notice that it has a slightly smaller boost factor than SC-SBC at the same duty ratio. The simulation results proved the theoretical analysis.

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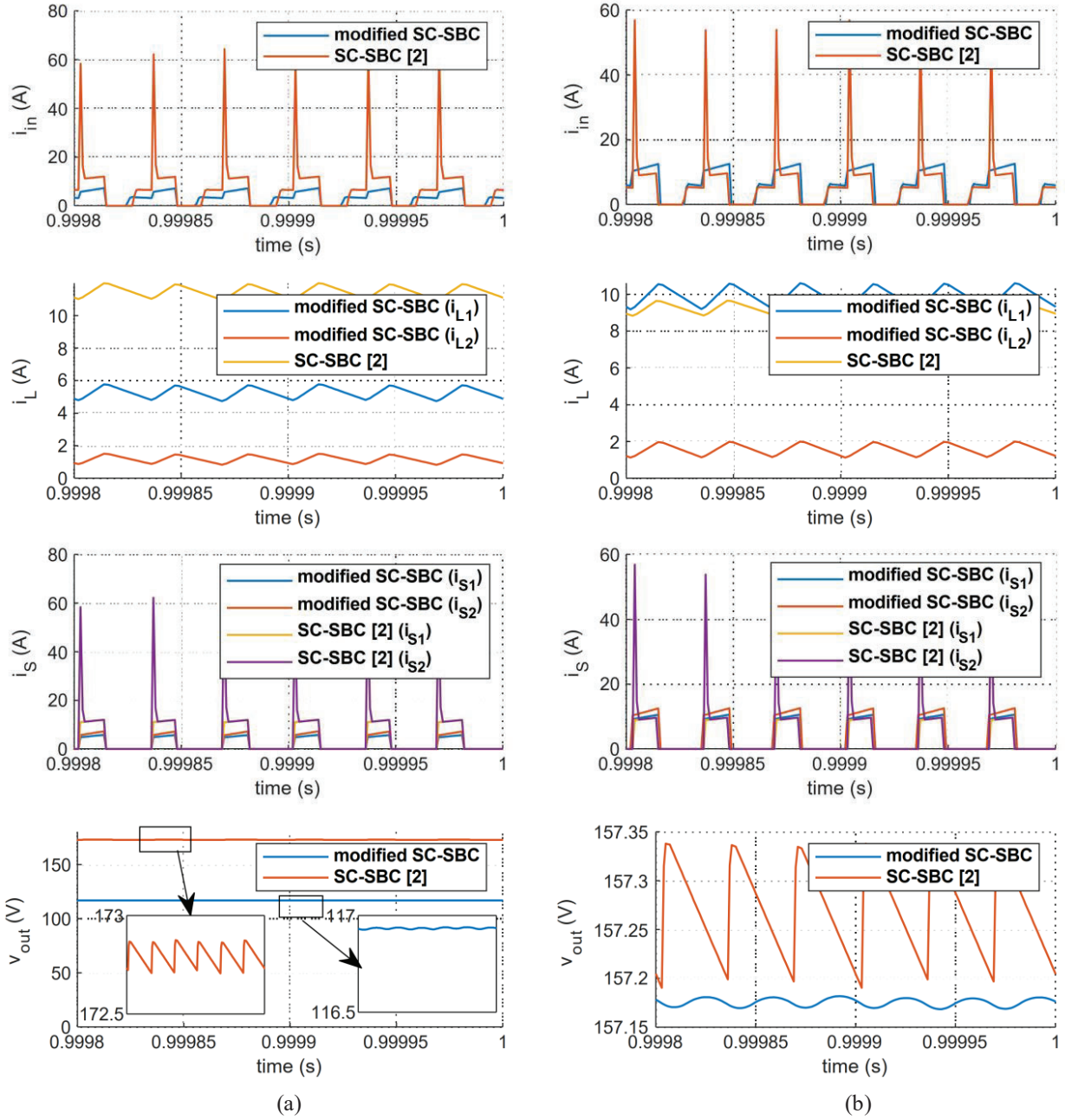


Fig. 5: Simulation results, (a) $D=0.35$, (b) the same boost factor (adjusting of the D ratio), $B=4$. The figures from up to down are input current, the currents through the inductors, the currents crossing the switches, and the output voltage.