Two-Inductor Non-Isolated DC-DC Converter with High Step-Up Voltage Gain

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Abstract

In this paper, an alternative non-isolated DC-DC converter with a high voltage boosting capability is proposed. Two inductors are used and one of them has its flux linkage increases during its charging period to achieve a high step-up voltage gain. Among the three integrated capacitors, one portrays the partial characteristic of the switched-capacitor technique, while the other two are connected in series across the load. With the two switches controlled using the same duty cycle, the proposed topology demonstrates the merits of a higher and wider range of step-up voltage gain when compared with recent topologies. In addition, a reduction in loss is induced and a higher efficiency is ensured with all the voltage stresses constrained within the output voltage. Operation of the proposed converter is analyzed and validated through experimental results obtained with a prototype.

Key words: DC-DC converter, High step-up gain, Non-isolated, Two-inductor

I. INTRODUCTION

There is an ongoing paradigm shift to renewable energy sources to resolve the ever increasing world energy crisis for a sustainable future. The low output voltages [1] and intermittency characteristics [2], [3] of renewable energy sources can be alleviated by various step-up DC-DC converters, where a comprehensive review is summarized in [4].

Two-inductor non-isolated step-up converters have been gaining popularity in recent years owing to their simpler operation and higher step-up voltage gain when compared to conventional boost converters. A simple topology with two active switches is presented in [5]. Its two inductors are charged in parallel during the switched-on period and discharged in series during the switched-off period to achieve a high step-up voltage gain. On the other hand, the authors of [6] advocate an improved three-level-boost (TLB) converter by integrating an additional inductor into a conventional TLB converter to

double the voltage gain. In [7], a combination of a conventional boost converter and a diode-capacitor based single ended primary inductor converter (SEPIC) is presented to increase the step-up voltage gain. Meanwhile, the topologies in [5] and [7] benefit from reduced voltage stresses when compared with conventional boost converters, and the topology in [6] suffers from a voltage stress as high as its output voltage on one of its switches.

Interestingly, the authors of [8] proposed a different way to produce a high voltage gain by introducing two different charging duty-cycles to both of its inductors. A power MOSFET and a diode are added to the topology in [5], where the added switch suffers from a voltage stress equal to its high output voltage. From the analysis in Fig.1, it is obvious that the voltage gain is proportional to λ_2 for a given duty cycle. Considering the volt-seconds balance of the inductor voltage during steady-state operation, λ_2 is equal to λ_1. A lower charging voltage during $D_2 T_s$ results in a reduction of λ_1. Therefore, a decrement in D_2 leads to an increment in the voltage gain. In the case when $D_2 = 0$, the maximum voltage gain is achieved and the topology is equivalent to that in [5]. The increased component count and controller complexity, when compared to topology in [5], make it a less attractive alternative for practical applications. Other techniques using coupled inductor [9] or DC transformer (DCX) [10] are also
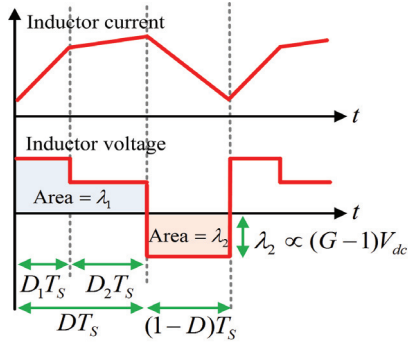
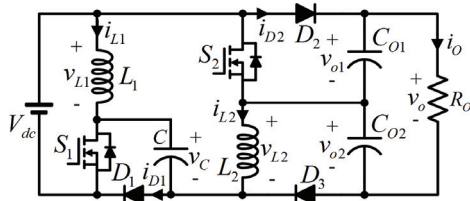Fig. 1. Inductor with two charging duty-cycles [8].

Fig. 2. Circuit diagram of the proposed non-isolated DC-DC converter.

recently explored.

The goal of this paper is to accomplish a novel topology with a high voltage gain by increasing λ_1. While keeping all of the voltage stresses within the output voltage, the established topology exhibits a higher and wider voltage gain than existing two-inductor non-isolated converters. This paper is organized as follows. Section II presents the proposed topology and a comparative analysis with recent two-inductor topologies. Section III discusses simulation results and section IV presents experimental results obtained with a prototype. Finally, section V draws some conclusions.

II. PROPOSED NON-ISOLATED DC-DC CONVERTER

The proposed converter topology is constituted by two switches S_1 and S_2, a capacitor C, two inductors L_1 and L_2, three diodes D_1, D_2 and D_3, and two output capacitors C_{O1} and C_{O2}, as depicted in Fig. 2.

The two series-connected output capacitors are used to enhance the step-up gain, while C is used to absorb the energy from L_1 before it is transferred to C_{O2} and L_2. Note that the incorporation of C is inspired by the switched-capacitor technique. Compared with topologies where only one output capacitor involved, the adoption of two output capacitors efficiently reduces the voltage stress on each capacitor. Key waveforms and equivalent circuits for the continuous inductor current are illustrated in Fig. 3 and Fig. 4, respectively. Note that the two switches are controlled by the same duty cycle, while L_2 is charged to the sum voltage across C and V_{dc} in order to increase λ_1 for further voltage boosting.
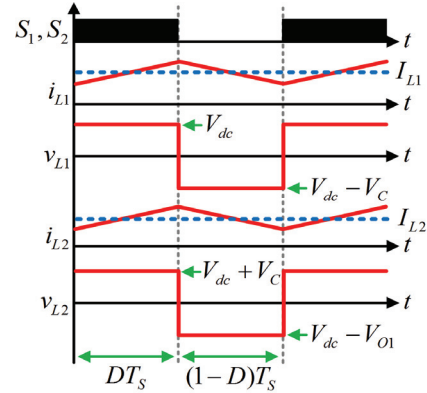

Fig. 3. Key waveforms of the proposed non-isolated DC-DC converter.
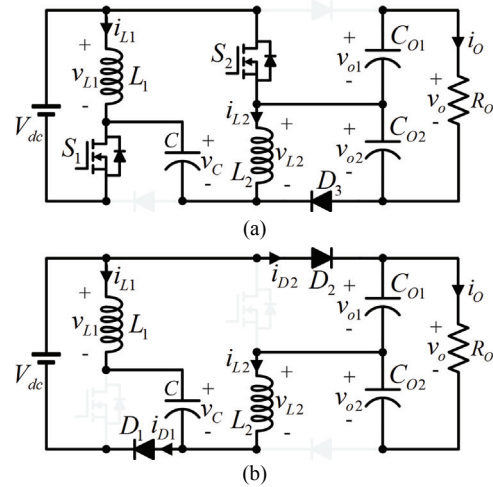

(a)

(b)

Fig. 4. Equivalent circuits of the proposed non-isolated DC-DC converter with a continuous inductor current. (a) Mode 1. (b) Mode 2.

Considering the volt-seconds balance of the inductors during steady-state operation, the following equations can be derived:

$$V_C = \frac{1}{(1-D)}V_{dc} \tag{1}$$

$$V_{O1} = \frac{1}{(1-D)^2}V_{dc} \tag{2}$$

where V_{dc} is the input voltage, D is the duty-cycle, V_C is the average voltage of C, and V_{O1} is the average voltage of C_{O1}. Referring to mode 1, shown in Fig. 4(a), the average voltage of C_{O2} is equal to the sum of V_{dc} and V_C. Thus, it is written as:

$$V_{O2} = \frac{2-D}{1-D}V_{dc} \tag{3}$$

The total average voltage across C_{O1} and C_{O2} is given as:

$$V_O = \frac{D^2 - 3D + 3}{(1-D)^2}V_{dc} \tag{4}$$

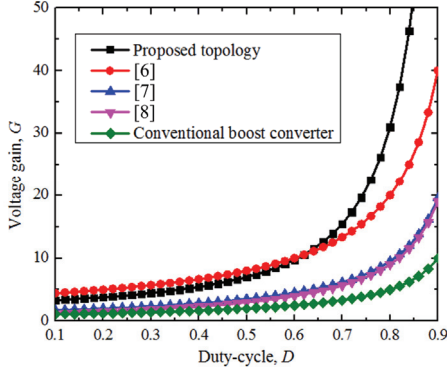The average inductor currents flowing through L_1 and L_2 are:

Fig. 5. Voltage gain comparison with recently presented two-inductor non-isolated DC-DC converters.
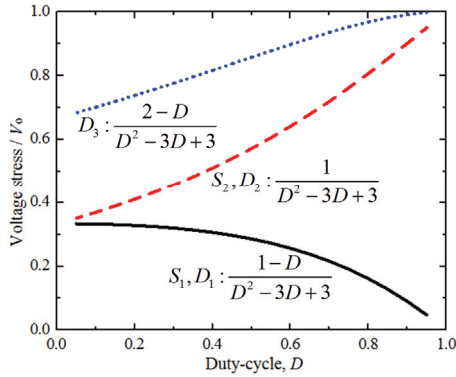

Fig. 6. Voltage stresses on the switches and diodes.

$$I_{L1} = I_{dc} - \frac{(2-D)}{(1-D)} I_O \qquad (5)$$

$$I_{L2} = \frac{I_O}{(1-D)} \qquad (6)$$

where I_{dc} is the average input current, I_O is the average output current, I_{L1} is the average current of L_1, and I_{L2} is the average current of L_2. Considering the boundary condition for the inductor current, the minimum inductances for both of the inductors are given by:

$$L_{1,min} = \frac{DV_{dc}}{2f_S \left[I_{dc} - \frac{(2-D)}{(1-D)} I_O \right]} \qquad (7)$$

$$L_{2,min} = \frac{D(2-D)V_{dc}}{2f_S I_O} \qquad (8)$$

where f_S is the switching frequency, and $L_{1,min}$ and $L_{2,min}$ are the respective minimum inductances for L_1 and L_2, which guarantee continuous current.

The step-up voltage gains, as a function of duty-cycles for various DC-DC converters, are compared in Fig. 5. Existing two-inductor converters demonstrate better step-up capabilities when benchmarked with a conventional boost converter. However, the proposed topology offers the highest and widest step-up voltage gain among all of them. In addition, Fig. 6
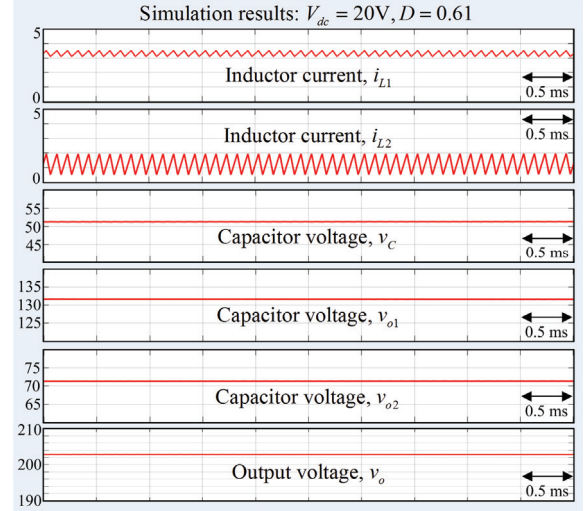

Fig. 7. Simulated waveforms of the proposed DC-DC converter.

shows that the voltage stresses of all the switches and diodes of the proposed topology are less than the output voltage. This guarantees the added benefits of low power loss and high efficiency.

III. SIMULATION RESULTS

To verify the operation of the proposed topology, simulations were conducted. The inductor current, capacitor voltage and output voltage are depicted in Fig. 7. A voltage boost gain of 10 is achieved at D = 0.61. In addition, the voltage across each of the capacitors is in good agreement with the theoretical analysis in (1)-(3).

IV. EXPERIMENTAL RESULTS

The experimental prototype depicted in Fig. 8 was tested to further verify the operation of the proposed DC-DC converter. The specifications of the experimental prototype are summarized in Table I. The limited bandwidth of the current probe restricts the operating switching frequency to 10 kHz. Open-loop control was implemented by using a function generator to generate a PWM signal. The duty-cycle was manually adjusted to produce an output voltage of 200V.

Fig. 9 shows waveforms captured when the input voltage was 20V. The duty-cycle was set to approximately 0.62 to generate an output voltage of 200V. The measured step-up voltage gain of 10 is slightly less than its theoretical value of 10.6. Both of the inductor currents are continuous with a steeper slope on i_{L2} during the charging period (DT_S). This indicates that L_2 is charged with a higher voltage to increase λ_1. This is done to enhance the voltage boosting capability. This experiment was repeated at an input voltage of 60V with the duty-cycle was set to 0.1. Fig. 10 reveals that the measured and calculated step-up gains are approximately the same, i.e. 3.33 and 3.35, respectively.
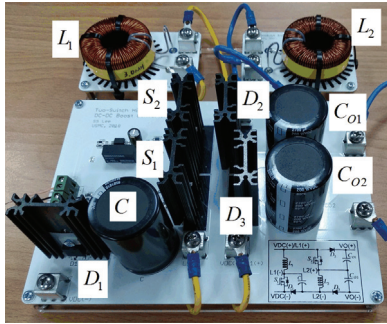
Fig. 8. Experimental prototype.

TABLE I
PROTOTYPE SPECIFICATIONS AND COMPONENT RATINGS

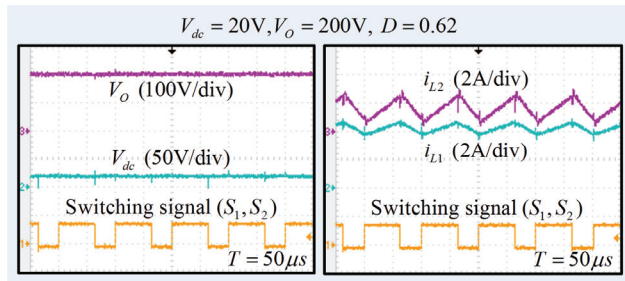| Parameter	Value
Input voltage, V_{dc}	20V – 60V
Output voltage, V_O	200V
Switching frequency, f_S	10kHz
Capacitor (C, C_{O1}, C_{O2})	2700μF
Inductor (L_1, L_2)	3mH
Power MOSFET (S_1, S_2)	C2M0080120D
Diode (D_1, D_2, D_3)	C3D08065A

Fig. 9. Experimental waveforms at an input voltage of 20V.
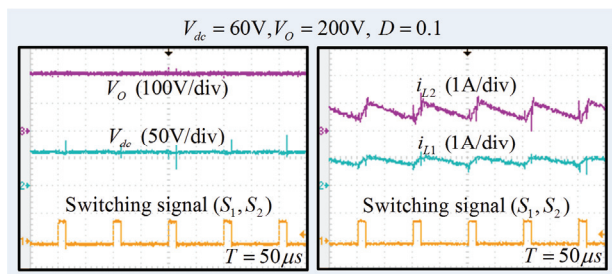

Fig. 10. Experimental waveforms at an input voltage of 60V.
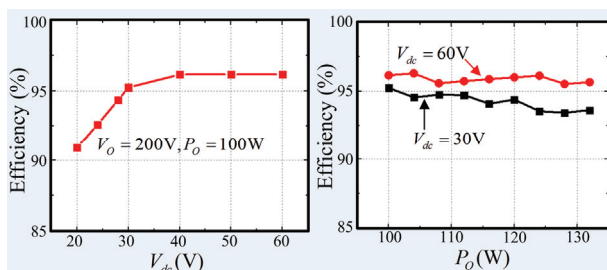

Fig. 11. Efficiency of the experimental prototype.

Experiments were then conducted to study the efficiency of the prototype at different input voltages and different output powers, as shown in Fig. 11. Considering a fixed output power of 100W, it can be seen that the efficiency increased with the input voltage, and that it was recorded well above 95% for an input voltage beyond 30V. The measured efficiencies for output power ranges from 100W to 130W, on the other hand, centers around 95% for an input voltage of either 60V or 30V.

V. CONCLUSION

This paper establishes a new two-inductor non-isolated DC-DC converter that features a high voltage boosting capability, a wide voltage gain range, and low voltage stress across switches and diodes. It is superior to recent topologies in view of its higher and wider range of step-up voltage gain. Good agreement between the theoretical analysis and experiments verified the conceptual validity and operation of the proposed topology. The peak efficiency of the proposed topology exceeds 95%. Therefore, it could be an interesting alternative for DC-DC power conversion systems.

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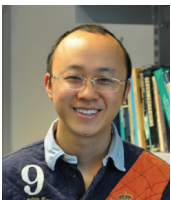
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