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Design and Implementation of a Modified Cascaded Z-Source High Step-Up Boost Converter for Photovoltaic (PV) Applications

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Abstract. To improve the voltage gain of step-up converters, the cascaded technique is considered as a possible solution in this paper. By considering the concept of cascading two Z-source networks in a conventional boost converter, the proposed topology takes the advantages of both impedance source and cascaded converters. By applying some modifications, the proposed converter provides high voltage gain while the voltage stress of the switch and diodes is still low.

Moreover, the low input current ripple of the converter makes it absolutely appropriate for photovoltaic applications in expanding the lifetime of PV panels. After analyzing the operation principles of the proposed converter, we present the simulation and experimental results of a 100 W prototype to verify the proposed converter performance.

Key words. High step-up converter, impedance source converter, Z-source converter, cascaded technique.

1. Introduction

Power electronics converters are inevitably essential to produce the required voltage and current for different applications. Among different types of renewable energies, solar energy is more popular as a limitless source of energy, which is spread all over the world. Although the output voltage of photovoltaic (PV) cells are relatively low, applying high step-up DC–DC converters can lead to increasing the voltage level without connecting in series numerous PV panels to enhance the operation of photovoltaic systems, especially in low-power applications [1], [2].

Research on high step-up converters in recent years has led to the present diverse topologies that are used to resolve existing drawbacks such as high voltage stress of semiconductor devices, reverse-recovery problem of diodes, and intense spike on switches which mostly appear in conventional boost converters by increasing the duty cycle [3], [4]. Consequently, the topological alteration of the conventional boost converter was proposed by researchers to extend the input-to-output voltage ratio while the circuit operation is enhanced as well. To overcome the drawbacks of boost converters with high efficiency and their simple control scheme, boost converters based on different techniques were proposed by researchers, such as a coupled inductor based boost converter, switched-capacitor based boost converter, cascaded boost converter, and interleaved boost converter [5]. All introduced converters have some weaknesses and strengths that make them restricted for specific applications. A better performance of a high step-up converter may be obtained if it could be possible to apply different techniques in a converter.

Inserting coupled inductors into the DC–DC converters is an effective method to increase the voltage gain by adjusting the turn ratio between the windings in a topology. Although by increasing the leakage inductance, the reverse-recovery problem of diodes can be reduced effectively due to inserting coupled inductors, the leakage energy induces high voltage spikes across the semiconductor switches.

One approach in order to solve this problem is employing a switched-capacitor technique as an active clamp circuit in order to recycle the leakage energy [6]. To reduce the topology complexity and cost, passive clamps are also considered as a possible solution. In [7], a passive clamp was replaced with an active clamp in a flyback converter to enhance the performance of the converter by alleviating the reverse-recovery problem and lowering the circulating current into the clamp circuit. Switched-capacitor converters are able to provide high voltage ratio for high power applications; however, the high input ripple current in these converters make them inappropriate for solar PV applications [5].

In this paper, after elaborating the topology of the proposed converter and investigating the operational modes in Section 2, Finally, Section 3 presents the experimental results of a prototype converter to validate the theoretical analysis.

2. Proposed Converter and Principle of Operation

As it can be seen from Figure 1, the proposed high step-up DC–DC impedance source based boost converter includes two cascaded Z-source networks and two switched-capacitor-inductor cells. The converter hires a single ferrite core with six coupled inductors, which are part of the impedance network and cells. The very high input current ripple and the high voltage stress of the switch are two main problems in this converter. Therefore, some inevitable alterations are required in order to make the converter practically applicable.

Although by adding a capacitor as shown in Figure 2, the voltage stress of the switch clamps at a specific value, the high input current ripple is still considered as a drawback in this converter. The dashed line in Figure 2 represents how the KVL (Kirchhoff's Voltage Law) loop clamps the switch voltage at a specific value. Eventually, the final modification into the converter configuration resulted in obtaining a high step-up converter with low input current ripple and low voltage stress for semiconductor devices.

Figure 3 shows the modified proposed high step-up impedance source converter with an equivalent circuit of coupled inductors. The proposed converter is composed of a single switch Q_1; one diode D_1 in the impedance network; two diodes in the cells D_2 and D_3; and one output diode D4; six coupled inductors L_1, L_2, L_3, L_4, L_5, and L_6; four capacitors C_1, C_2, C_3, and C_4 in the impedance network; two switched-capacitors C_5 and C_6; and the output capacitor C_7.

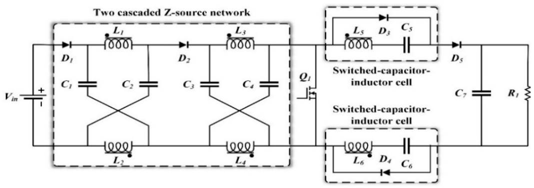

Fig. 1. Two cascaded Z-source high step-up converter.

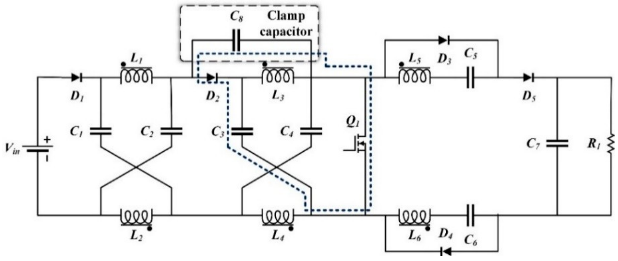

Fig. 2. Modified converter by a clamp capacitor.

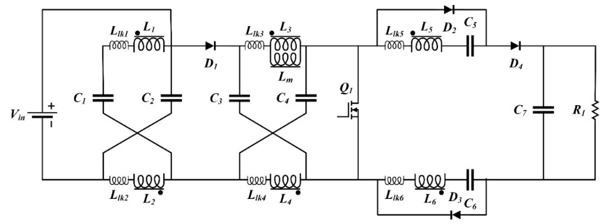

Fig. 3. Circuit diagram of proposed converter with equivalent circuit of coupled inductors.

The converter has four time intervals within a switching cycle in the steady state operation. Figure 4 illustrates the equivalent circuits for each operating interval; the capacitor C_2 can be considered not in the circuit due to being in parallel with input voltage source, and Figure 5 is provided to show the theoretical waveforms of the proposed converter. To simplify the steady state analysis, the following assumptions are made:

- The converter operates in continuous conduction mode (CCM).
- The switch, diodes, and all inductors and capacitors are assumed ideal.
- The magnetizing inductance is large enough to ignore its current ripple.
- The leakage inductances of all windings are equal.
- The output capacitor C_7 is large enough to make the output voltage practically constant.
- The switching capacitors C_5 and C_6 are equal.

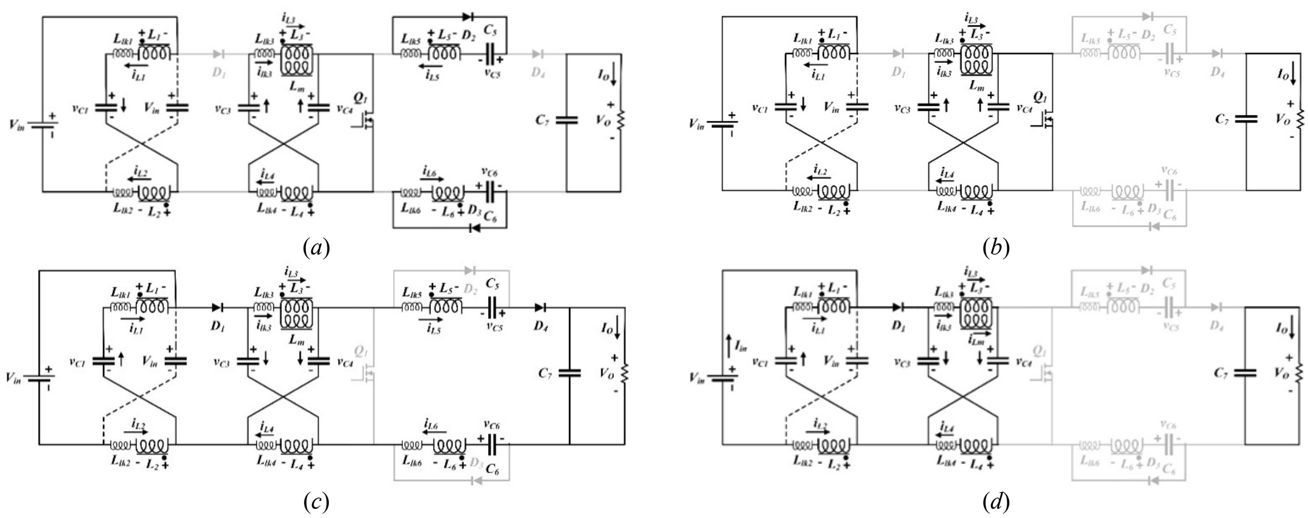

Fig. 4. Equivalent circuits of the proposed converter for each operation mode: (*a*) interval 1, (*b*) interval 2, (*c*) interval 3, (*d*) interval 4.

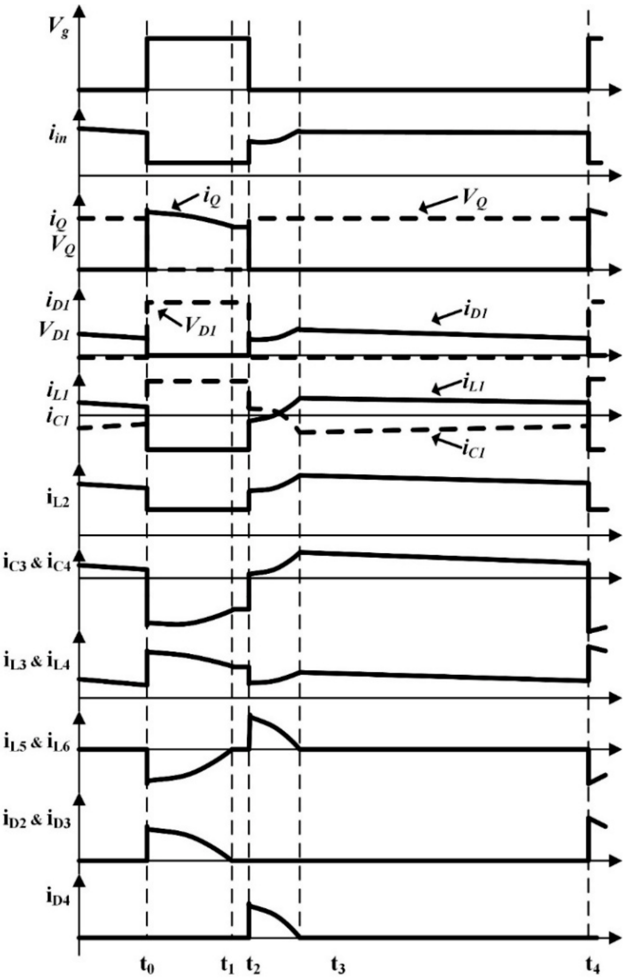

Fig. 5. Theoretical waveforms of the proposed converter.

3. Experimental Results

To compare the performance of the proposed converter in practice, a real prototype of the converter was implemented, and experimental results are provided in order to verify the theoretical analysis. Figure 6 shows the real implemented prototype. The implemented converter operated at 50 kHz to convert the 25-V input voltage to 300 V with a nominal power of 100 W for the load.

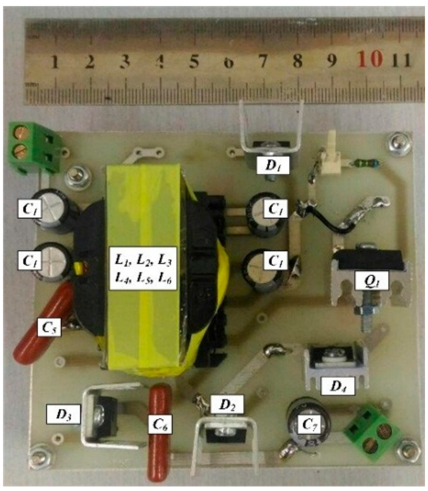

Fig. 6. Implemented prototype of the proposed cascaded Z-source high step-up boost converter.

Table I reports the parameters of the designed converter. The drain-to-source breakdown voltage of the selected MOSFET was much lower than the output voltage, and therefore a low R_{DS} of the MOSFET resulted in low conduction power loss.

Table I. - Important parameters of the implemented prototype.

Parameters	Value
Input voltage V_{in}	25 V
Output voltage V_o	300 V
Output power P_o	100 W
Switching frequency (f_{sw})	50 kHz
Switch Q	IRFP3710
Input diode D_1	MUR880
Diodes D_2, D_3, D_4	MUR460
Coupled inductors core L_1, L_2, L_3, L_4, L_5, L_6	380 µH
Turns of ($L_1 \ldots L_6$)	90 turns
Turns ratio n	1
Z-source network capacitors (C_1, C_2, C_3 and C_4)	15 µF/100 V
Switched capacitors C_6, C_7	560 nF/100 V
Output capacitors C_8	10 µF/400 V

Experimental waveforms of the implemented prototype are illustrated in Figures from 7 to 11. The input current and voltage of the converter are shown in Figure 7; the low input current ripple can be observed in this figure. In addition, Figure 8 shows the voltage and current of diode D_1; the voltage and current waveforms of the switch are shown in Figure 9. Moreover, it can be seen that regarding the output voltage of 300 V, which is illustrated in Figure 11, the stress voltage of MOSFET is 100 V. Finally, the voltage and current of diode D4 can be seen in Figure 10.

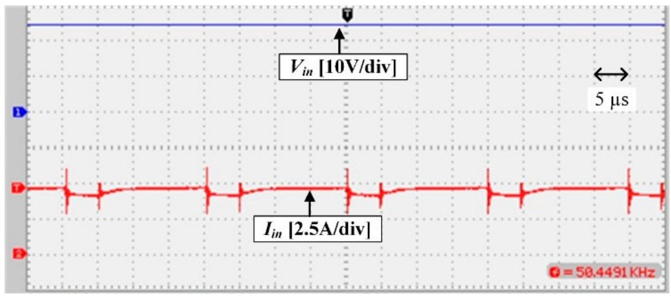

Fig. 7. Input voltage and current waveforms of the modified cascaded Z-source high step-up boost converter.

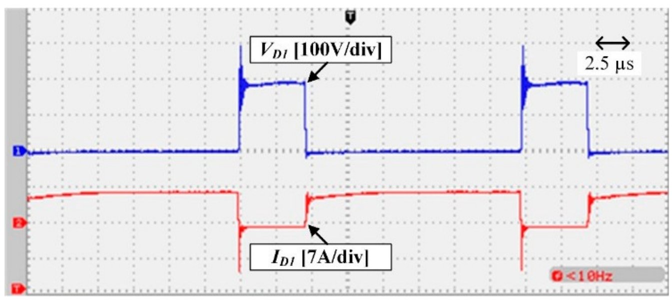

Fig. 8. Voltage and current waveforms of the diode D_1 of the modified cascaded Z-source high step-up boost converter.

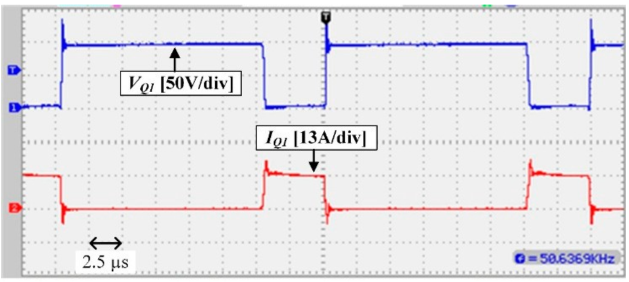

Fig. 9. Voltage and current waveforms of the switch Q of the modified cascaded Z-source high step-up boost converter.

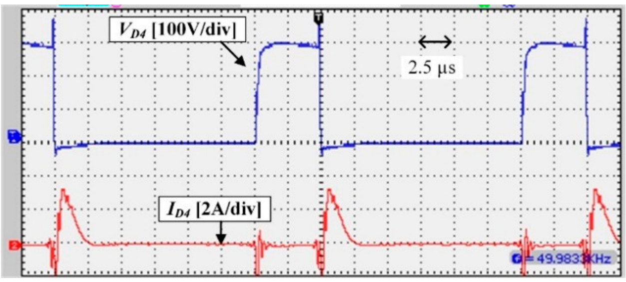

Fig. 10. Voltage and current waveforms of the diode D_4 of the modified cascaded Z-source high step-up boost converter.

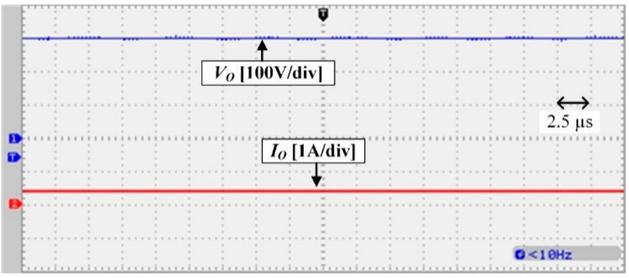

Fig. 11. Output voltage and current waveforms of the modified cascaded Z-source high step-up boost converter.

The efficiency of the proposed converter was calculated by measuring the input and output current and voltage of the converter by means of DC current and voltage meters, respectively. Figure 12 shows the efficiency of the implemented proposed converter from 50 % to 100 % of a full load condition and it is compared with the converter in [8]. As it can be observed, by increasing the output power, conduction losses increase as well and lead to dropping the efficiency slightly. Moreover, under a full load condition, the measured efficiency is 93%.

4. Conclusion

Among the different step-up techniques that were applied on boost converters in order to improve the input-to-output voltage ratio, the cascaded technique was chosen in this paper in order to cascade two Z-source networks and take advantage of both the cascade and impedance source converters. All inductors were coupled together in the proposed converter; therefore, the voltage gain increased only by utilizing a single core in the proposed configuration. A low duty cycle of the switch lead to reducing the reverse-recovery problem of the output diode significantly and results in enhancing the efficiency due to a reduction of power loss of the converter switches; i.e., the transistor and diodes.

Furthermore, diodes D_2, D_3, and D_4 turn off under a ZCS condition. The low input current ripple of this converter makes it appropriate to apply in renewable energy sources. A laboratory prototype of the proposed converter in order to justify the theoretic analysis was built, and experimental waveforms were presented for a 100 W output power converter.

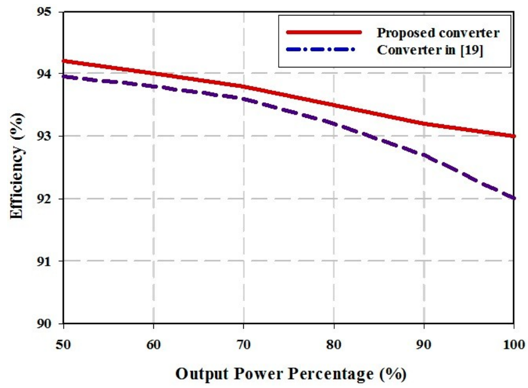

Fig. 12. Efficiency plot of the implemented prototype under different load conditions.

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