High Gain Single-phase Three-level Boost AC-DC Converter with Inherent Output Voltage Balancing

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***Abstract*—This paper presents a high voltage gain single-phase AC-DC converter using a modified three-level boost converter with inherent output voltage balancing. Compared to the conventional three-level boost converter, the proposed converter has a higher voltage gain, thus helping to reduce the converter loss, and requires only one gate driver power supply for low side switches. In addition, the output voltages of the proposed converter are automatically balanced without the help of control algorithm or additional balancing auxiliary circuit, thus simplifying the controller and cost.**

***Index Terms*—High gain, three-level, voltage balancing**

I. Introduction

High voltage gain AC-DC converters have been widely used in many applications such as X-ray systems, HVDC system insulation testing devices and high voltage battery chargers [1], [2]. Isolated or non-isolated converters are commonly used to step up the DC voltage [3]. The conventional isolated AC-DC power converter includes two stages of power converters and isolated transformer. The first stage is conventional power factor correction (PFC) boost converter that convert the AC to DC voltage and the second stage is isolated dc-dc converter. By adjusting the turns ratio of the transformer, the high output DC voltage is achieved. However, the high turns ratio leads to high leakage inductance which causes the voltage spike across the switching devices [4], [5]. Hence, the aforementioned increases the cost and complexity of the system.

None-isolated AC-DC converters are attractive due to single stage boost and simpler controller than two stages [6], [7]. The traditional boost converter can boost to high voltage value but increasing input current ripple and high turn-off current of the power device resulting lower efficiency. Therefore, the conventional three-level boost (TLB) converter shown in Fig. 1 has advantages such as the use of low voltage rating switching devices, small volume of magnetic components, and high efficiency [8]. However, it suffers from unbalanced output capacitor voltages, and isolated voltage sensing circuits are needed to balance the voltages, resulting in increased cost and control complexity [9]. To overcome these aforementioned disadvantages, the proposed converter, shown in Fig. 2, is developed from [10] for dual-output DC-DC applications, and investigated for single-output AC-DC applications in this paper.

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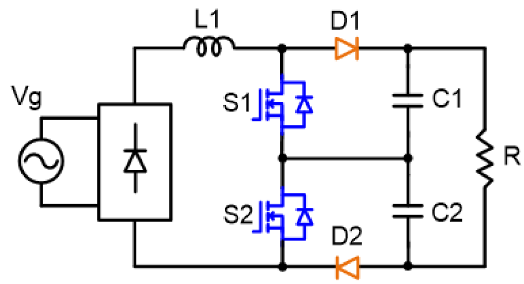


Fig. 1: Conventional three-level boost.

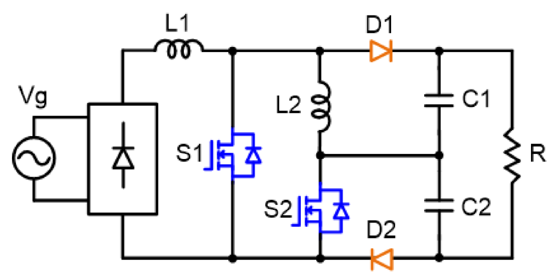


Fig. 2: Proposed converter.

II. Proposed converter

A. Operation Analysis

The equivalent circuit and operation modes of the proposed converter are shown in Figs. 3 and 4, respectively. The AC input voltage is rectified by the diode bridge, and then switches S_1 and S_2 are modulated with a 180-degree phase-shift. The switch duty cycle D higher than 0.5 is analyzed in this paper. For sake of simplicity, the series resistance of inductors and capacitors, diode and switch ON voltage drops are neglected in this analysis.

- Mode 1: In this mode, S_1 and S_2 are turned-on, $v_{L1} = V_{ir}$, $v_{L2} = 0$, diodes D_1 and D_2 do not conduct, and the load

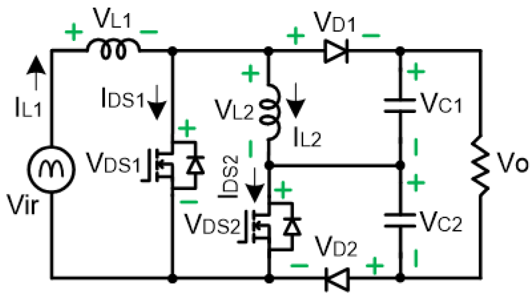


Fig. 3: Equivalent circuit.

current is provided by the output capacitors. Capacitors C_1 and C_2 discharge and charge, respectively.

- Mode 2: S_1 is turned-on while S_2 is turned-off, inductor voltages is expressed as v_{L1} = V_{ir}, v_{L2} = -V_{c2}, diode D_1 does not conduct while diode D_2 conducts. Capacitors C_1 and C_2 discharge.
- Mode 3: Reversed with mode 2, S_1 is turned-off while S_2 is turned-on, v_{L1} = $V_{ir} - V_{c1}$, v_{L2} = V_{c1}, diode D_1 conducts while diode D_2 does not conduct. Capacitors C_1 and C_2 charge and discharge, respectively.

The key waveforms are presented in Fig. 5.

B. Voltage Gain

Applying the flux balance condition for inductor L_1, the theoretical voltage gain of the converter is expressed as:

$$\frac{V_o}{V_{ir}} = \frac{2}{1-D}$$

Where V_o and V_{ir} are the output and input voltages, D is the switch duty cycle and larger than 0.5. Compared to the boost gain of the conventional three-level boost converter, V_o/V_{ir} = 1/(1-D), the proposed converter has double voltage gain as shown in Fig. 6.

The inductors L_1 and L_2 are determined by [10]:

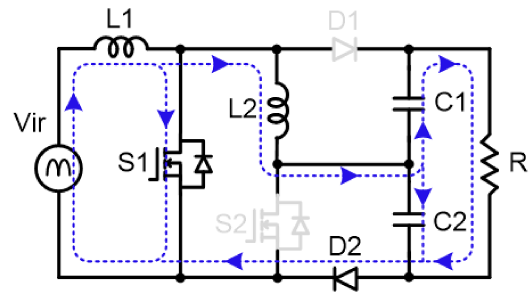
$$L_1 \geq \frac{(1.5-D)(0.5+D)V_o}{8x\% I_{L1} f_s}$$

$$L_2 \geq \frac{(1.5-D)V_o}{2y\% I_{L1} f_s}$$

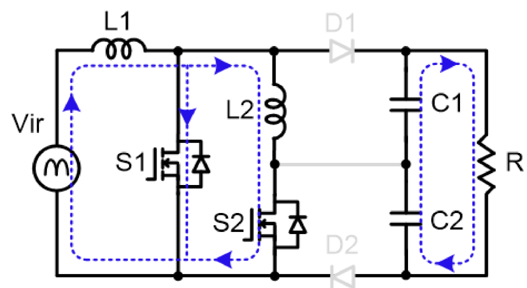
Where x% and y% are current ripple in percentage, f_s is the switching frequency. The inductors are designed at the maximum current.

C. Voltage balancing mechanism

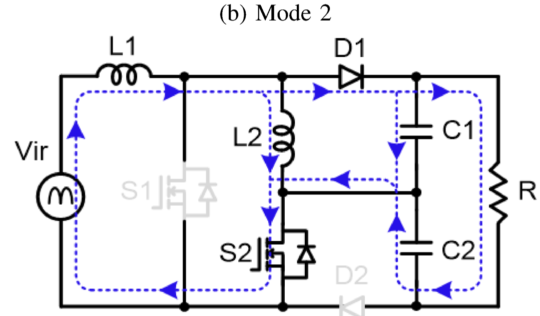
The conventional TLB converter suffers from voltage imbalance because of the inconsistent output capacitance C_1 and C_2, and the mismatch between the duty cycles of switches S_1 and S_2. Thanks to the unique structure of the proposed converter, the flux balance condition of inductor L_2 greatly helps to automatically balance two capacitor voltages without any dedicated voltage balancing algorithm or auxiliary circuit.



(a) Mode 1



(b) Mode 2



(c) Mode 3

Fig. 4: Operation modes a) Mode 1, b) Mode 2 and c) Mode 3.

III. Control Scheme

The control scheme is shown in Fig. 7. There are two control loops including an outer voltage loop for regulating DC output voltage and an inner current loop for controlling unity power factor. The output voltage V_o is feedback and compared with reference voltage. After the PI controller, the reference input current is multiplied with the scaling value of rectifier voltage and compared with the current I_{L1} to have control duty. A feed-forward duty cycle is added to enhance the robustness and stability of the controller. The duty cycles for switches S_1 and S_2 are identical with a 180-degree phase shift.

TABLE I: Electrical parameters

Input voltage (rms, V)	110
Output voltage (V)	1000
Output power (kW)	3
Inductance L_1 (µH)	500
Inductance L_2 (µH)	900
Capacitance C_1, C_2 (µF)	600
Switching frequency (kHz)	50

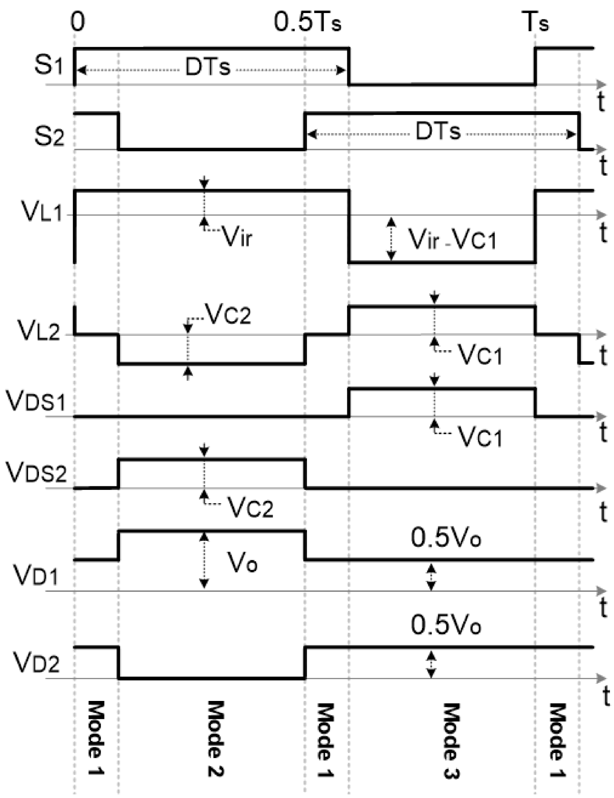


Fig. 5: Key waveforms of the proposed converter.

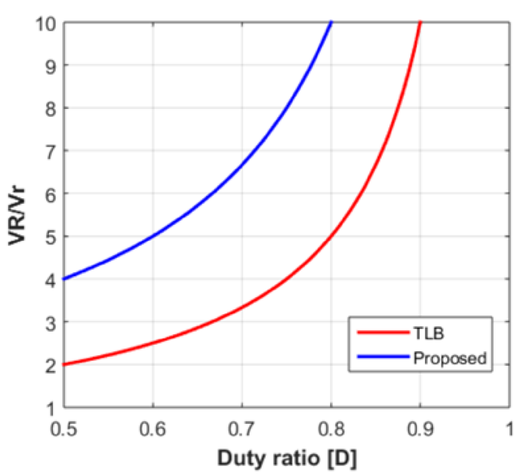


Fig. 6: Gain curves comparison.

IV. Simulation Verification

The electrical parameters are shown in Table I.

The simulation results are shown in Figs. 8 and 9. As can be seen in Fig. 8, the output voltage V_o is regulated at 1kV while two capacitor voltages are well balanced at half of the output voltage without dedicated voltage balancing control. The voltage stress of two switches and diode D_2 are equal to half of the output voltage while the voltage stress of diode D_1 is equal to the output voltage. In Fig. 9, the input inductor current I_{L1} is controlled at rectified sinusoidal waveform with

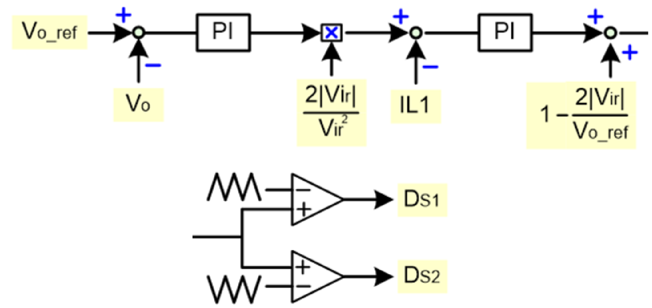


Fig. 7: Feed-forward control for the proposed converter.

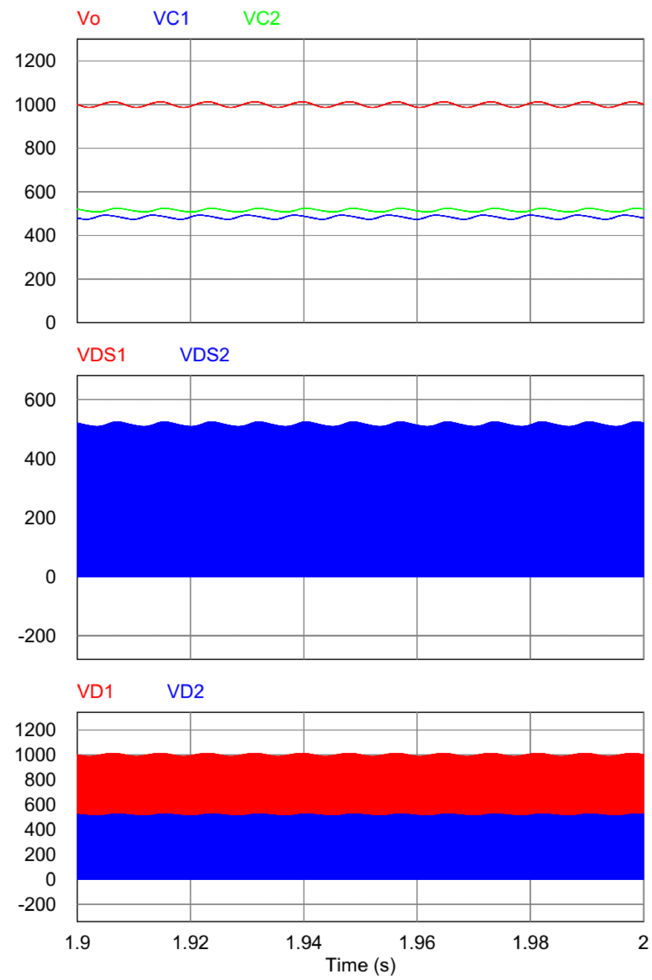


Fig. 8: Top to bottom: Output voltage V_o, capacitor voltages V_{c1}, V_{c2}, switch and diode voltage stress V_{DS1}, V_{DS2}, V_{D1}, V_{D2}.

unity power factor. The current stress of switch S_2 is equal to current I_{L1} while the current stress of switch S_1 and diodes D_1, and D_2 are equal to current I_{L2}.

Fig. 10 shows the simulation results of conventional TLB and the proposed converter when the output voltage are both controlled at 800V under 1% mismatch in duty cycles of switches S_1 and S_2. As can be seen, two capacitor voltages in the TLB converter are unbalanced with a 500V voltage

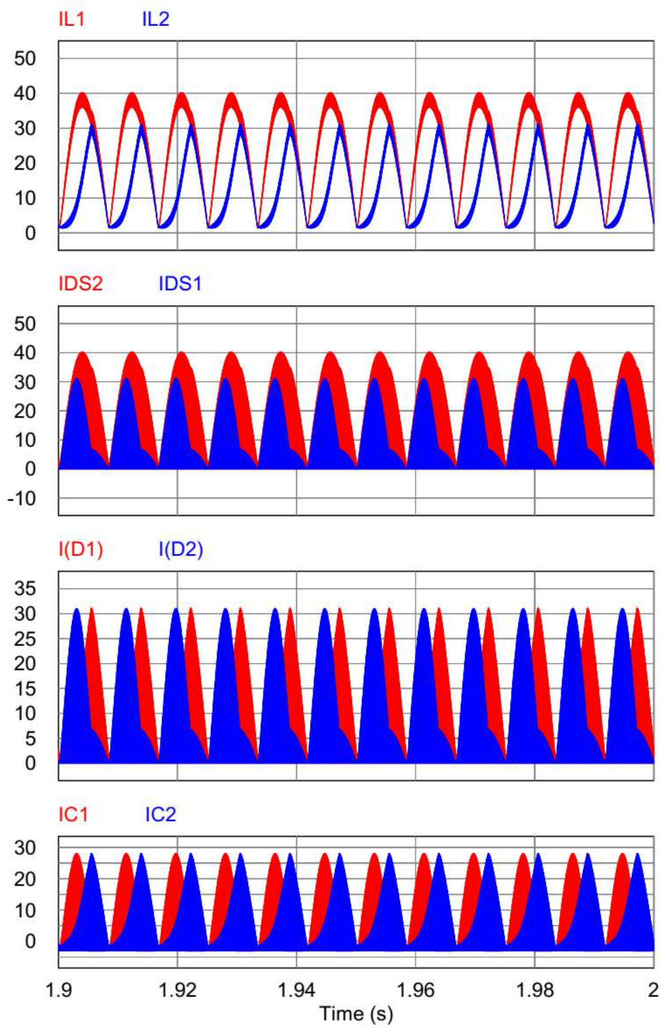


Fig. 9: Top to bottom: Inductor currents I_{L1}, I_{L2}; switch, diode and capacitor current stress I_{DS1}, I_{DS2}, I_{D1}, I_{D2}, I_{C1}, I_{C2}.

difference. However, in the proposed converter, the capacitor voltages are well balanced.

Conclusion

This paper presents a high voltage gain single-phase AC-DC converter with inherent output voltage balance. Compared to the conventional TBL, the proposed converter has higher voltage gain, and the output capacitor voltages are automatically balanced without additional voltage balancing control or auxiliary circuit. In addition, only one gate driver power supply for low side switches is needed. The simulation results show the effectiveness of the proposed structure.

Acknowledgment

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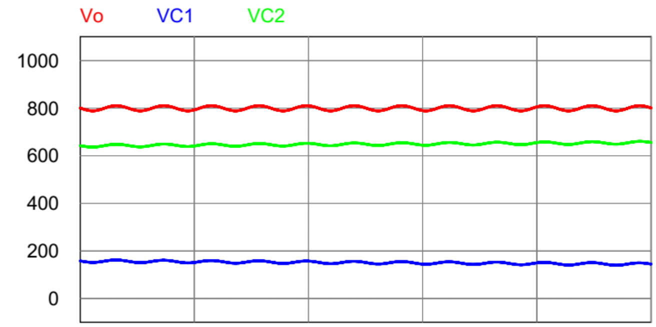
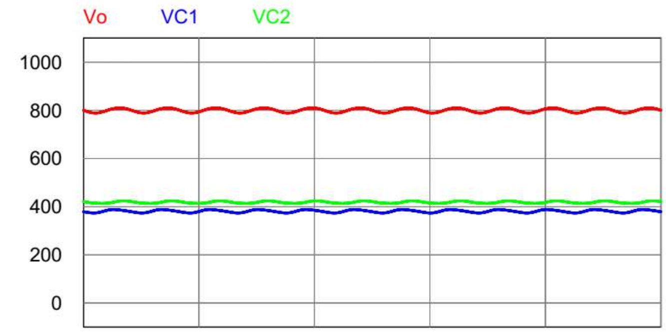


(a) TLB converter



(b) Proposed converter

Fig. 10: Output voltage, capacitor voltage waveforms of a) TLB and b) proposed converter under 1% mismatch in the gate signal of switches S_1 and S_2.

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