High Efficiency Current-Doubler Rectifier with Low Output Current Ripple and High Step-Down Voltage Ratio

Chih-Lung Shen, Cheng-Tao Tsai and Yu-En Wu

***Abstract*—This paper presents a current-doubler rectifier with low output current ripple and high step-down voltage ratio. In the proposed rectifier, two extra inductors are introduced to extend the duty ratio of switches which in turn can reduce the peak current through the isolation transformer and lower output current ripple, and two extra diodes are used to provide discharge paths for the two extra inductors. To highlight the merits of the proposed rectifier, its performance indexes, such as voltage gain function, secondary winding peak current of the isolation transformer and output current ripple, are analyzed and compared with the conventional current-doubler rectifier. In this study, a ZVS phase-shift full-bridge converter with the proposed rectifier, input voltage of 400 V, output voltage of 12 V, and full load power of 500 W has been implemented and verified, from which experimental results have shown that 90 % conversion efficiency can be achieved at the full load.**

***Index Terms*—Current-doubler rectifier, ZVS, phase-shift full-bridge converter.**

I. Introduction

PHASE-shift full-bridge dc/dc converters are widely used in medium-high power condition [1]. For low-voltage and high-current applications, power loss at the secondary side of the isolation transformer has a major impact on efficiency. Therefore, proper secondary-side circuit configurations should be designed to reduce the peak current through the secondary winding of the transformer and rectifiers. At the secondary side, forward rectifier, center-tapped rectifier and current-doubler rectifier are commonly chosen for high-current low-voltage applications. Because of its simpler transformer structure, lower inductor current and yielding higher efficiency, the current-doubler rectifier is used more often than the others [2]. However, in high step-down applications, extremely low duty ratio results in high peak current through the isolation transformer winding and switches. Thus, copper loss of the isolation transformer and switch current stress is still very significant, lowering efficiency a lot. To release this shortcoming, a current-tripler rectifier [3] and coupled-inductor current-doubler rectifiers [4],[5] were proposed. Although all of them can reduce the peak current through the secondary winding, the current-tripler rectifier requires triple winding at each side of the transformer, which increases design complexity and needs six active switches to control energy transformation. For the coupled-inductor current-doubler rectifier, leakage inductance problem is a critical issue, which needs extra circuits to suppress ringing.

This paper proposes a high efficiency current-doubler rectifier. Unlike the conventional current-doubler rectifier [6], there are two extra inductors and diodes introduced in the proposed rectifier, as shown in Fig. 1, which can extend duty ratio of the active switches to reduce the peak current through the secondary winding of the transformer and lower output current ripple. The proposed current-doubler rectifier is quite suitable for high step-down voltage ratio and high output current applications.

Section II describes derivation and operational principle of the proposed current-doubler rectifier. Section III demonstrates the benefits of the proposed rectifier and its comparison with the conventional current-doubler rectifier. Simulation and experimental results obtained from a 500 W prototype with the proposed current-doubler rectifier and the full-bridge phase-shift converter are presented in Section IV. Finally, a conclusion is given in Section V.

II. Derivation and Operational Principle

Derivation of the proposed current-doubler rectifier is based on a conventional voltage-quadrupler circuit, as shown in Fig. 2(a). According to duality principle, meshes of the voltage quadrupler are replaced with nodes, and capacitors are replaced with inductors, while diodes are with no change, yielding the proposed current doubler as shown in Fig. 2(b).

Fig. 1 shows the proposed current-doubler rectifier with full-bridge phase-shift converter, in which the L_1 and L_2 are the energy-storage inductors, L_3 and L_4 are the output filter inductors, D_{r1}, D_{r2}, D_{r3} and D_{r4} are the rectifier diodes, and C_o is output filter capacitor. To simplify description of the steady-state operational modes, the full-bridge phase-shift converter will not be discussed in this section. Only is the proposed current-doubler rectifier analyzed and we have the following assumptions:

1) all of the switching devices and diodes are ideal,
2) inductors $L_1 = L_2$ and $L_3 = L_4$, and
3) output filter capacitor C_o is large enough so that it can be treated as a voltage source V_o.

Under continuous inductor current operation, eight major operating modes are identified over one switching cycle. Fig. 3 shows conceptual voltage and current waveforms of its key components. D_{eff} and D_{loss} are denoted as the effective and loss duty ratios, respectively. V_{AB} is the voltage across the resonant inductor and the isolation-transformer primary winding, V_{sec} is the voltage across the isolation-transformer secondary winding, i_{sec} is the secondary current, i_{L1} and i_{L2} are the current of the energy inductors, i_{L3} and i_{L4} are the current of the output

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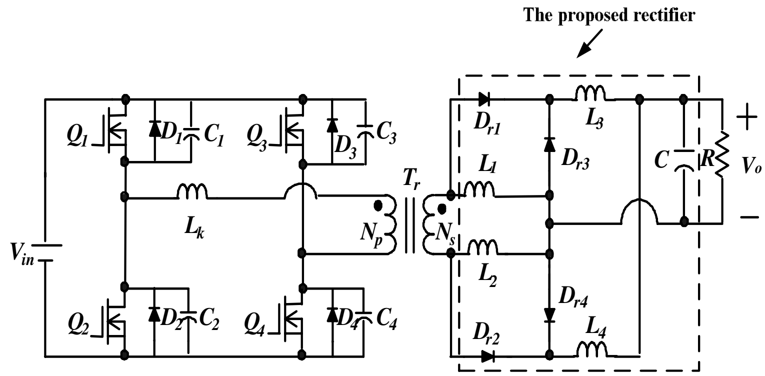
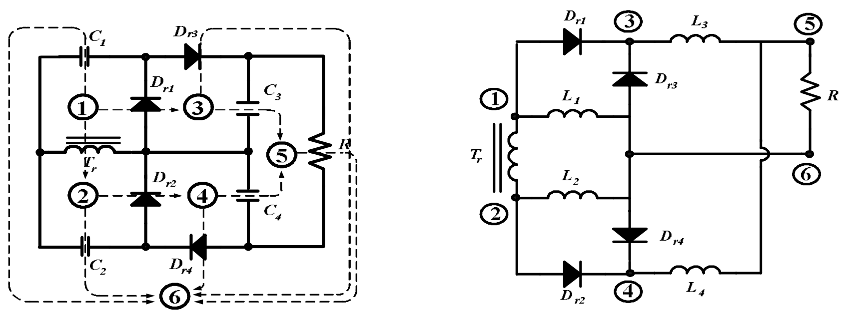


Fig.1. The proposed current-doubler rectifier with full-bridge phase-shift converter.



(a) (b)

Fig. 2. Derivation of the proposed current doubler from a voltage quadrupler based on duality principle: (a)voltage quadrupler, (b) the proposed current-doubler rectifier.

TABLE 1.
COMPARISON BETWEEN THE PROPOSED RECTIFIER AND THE CONVENTIONAL CURRENT-DOUBLER RECTIFIER

	Conventional current doubler	Proposed current doubler
Voltage gain	$\frac{V_o}{V_{\sec}} = D$	$\frac{V_o}{V_{\sec}} = \frac{D}{2}$
Output current ripple	$i_{o(ripple)} = \frac{(1-2D)V_o}{Lf_s}$	$i_{o(ripple)} = \frac{(1-2D)V_o}{2Lf_s}$
Secondary winding peak current of the transformer	$i_{\sec(peak)} = \frac{I_o}{2} + (\frac{V_{\sec} - V_o}{2L})DT_s$	$i_{\sec(peak)} = \frac{I_o}{2} + (\frac{V_{\sec} - V_o}{8L})DT_s$

filter inductors and i_{D1} ~ i_{D4} are the current of the rectifier diodes. Fig. 4 shows equivalent circuits of the operational modes.

Mode 1 **[Fig. 4(a), $t_o \leq t < t_1$] :**

At time t_0, a positive voltage V_{sec} crosses the secondary winding of transformer T_r. First of all, diode D_{r3} is reversely biased and D_{r1}, D_{r2} and D_{r4} are conducting. During this interval, inductor current i_{L3} flowing through the path V_o-L_2-V_{sec}-D_{r1}-L_3 is linearly increased, and inductor currents i_{L1} and i_{L4} are linearly decreased.

Mode 2 **[Fig. 4(b), $t_1 \leq t < t_2$] :**

At time t_1, the secondary current i_{sec} is equal to inductor current i_{L3}, and diode D_{r2} is reversely biased. Inductor current $i_{L2} = i_{L3}$ flowing through the path V_{sec}-D_{r1}-L_3-V_o-L_2 is linearly increased, while the energy stored in inductor L_1 and L_4 will be released through the rectifier diode D_{r1} and D_{r4} to the load, respectively.

Mode 3 **[Fig. 4(c), $t_2 \leq t < t_3$] :**

When voltage V_{sec} drops to zero at time t_2, all of the diodes (D_{r1} ~ D_{r4}) are conducting. During this interval, the inductor current i_{L3} flowing through two paths V_o-D_{r3}-L_3 and V_o-L_2-V_{sec}-D_{r1}-L_3, and the inductor current i_{L4} flowing through V_o-D_{r4}-L_4 are linearly decreased.

Mode 4 **[Fig. 4(d),** $t_3 \le t < t_4$**] :**

At time t_3, a negative voltage V_{AB} will cross the resonant inductor L_r and the primary winding of transformer T_r, since rectifier diode currents i_{Dr3} and i_{Dr4} have not been commutated completely yet. Therefore, all of the diodes (D_{r1} ~ D_{r4}) are maintained conducting, while inductor currents i_{L3} and i_{L4} are maintained discharging to the load.

At time t_4, rectifier diode currents i_{Dr3} and i_{Dr4} have been commutated completely. Then, a positive voltage V_{sec} crosses the secondary winding of transformer T_r. This ends a half-cycle operation.

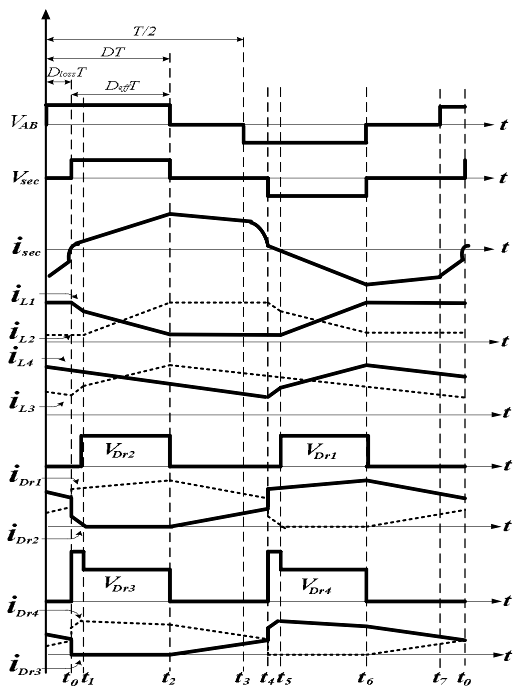


Fig. 3. Key waveforms of the proposed current-doubler rectifier with full-bridge phase-shift converter.

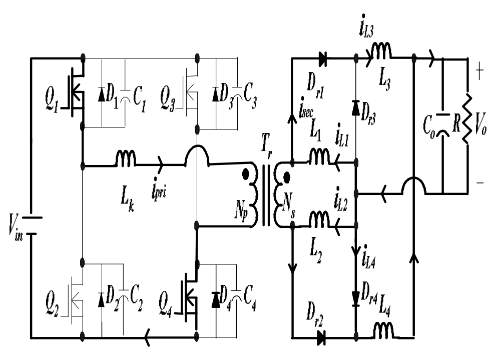


Fig. 4(a)

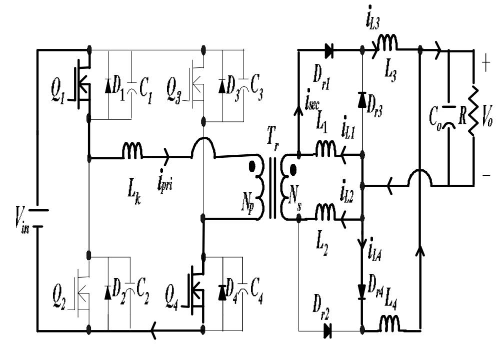


Fig. 4(b)

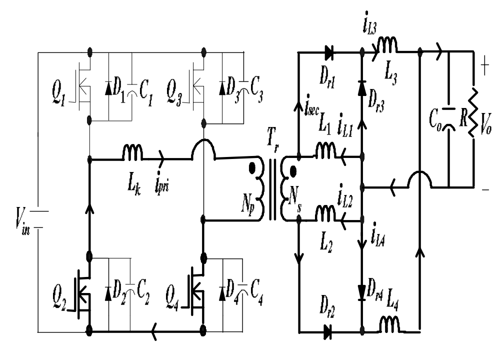


Fig. 4(c)

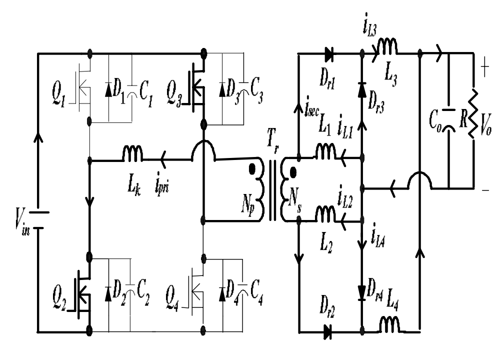


Fig. 4(d)

Fig. 4. Operational modes of the proposed current-doubler rectifier with full-bridge phase-shift converter.

III. Features and Characteristics

This section describes the features and characteristics of the proposed rectifier, which include secondary winding peak current of transformer, voltage gain, and output current ripple.

A. Secondary Winding Peak Current of Transformer

From Fig.3, during one complete switching cycle, the secondary winding peak current $i_{sec(peak)}$ can be expressed as follows:

$$i_{\sec(peak)} = \frac{I_o}{2} + \left(\frac{V_{\sec} - V_o}{8L}\right) DT_s, \qquad (1)$$

where $L = L_1 = L_2 = L_3 = L_4$.

B. Voltage Gain

By applying the volt-second balance principle to the auxiliary inductors and output filter inductors, the voltage gain of the proposed rectifier then can be derived as follows:

$$\frac{V_o}{V_{\sec}} = \frac{D}{2}. \tag{2}$$

C. Output Current Ripple

From Fig. 3, by using the interleaved current of the output inductors L_3 and L_4, the output current ripple can be expressed as:

$$i_{o(ripple)} = \frac{(1-2D)V_o}{2Lf_s}. \tag{3}$$

To objectively judge the merit of the proposed current-doubler rectifier, a circuit comparison between the proposed rectifier and the conventional current-doubler rectifier is summarized in Table 1 and plotted in Fig. 5, assuming that the two current doublers can be operated with identical frequency, the same input and output voltages, and load currents.

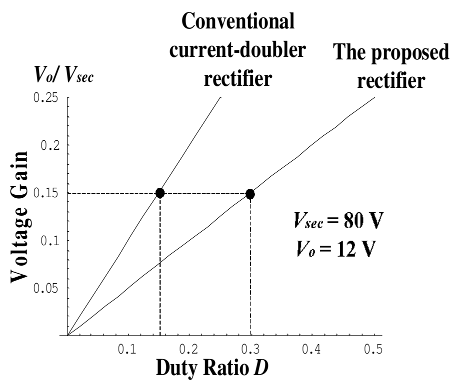


Fig. 5(a)

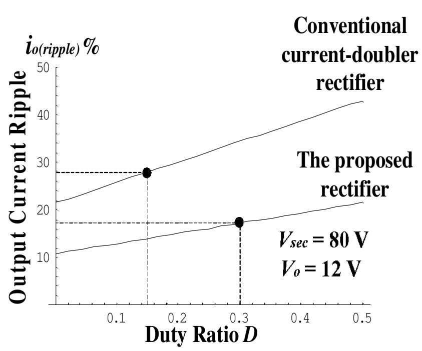


Fig. 5(b)

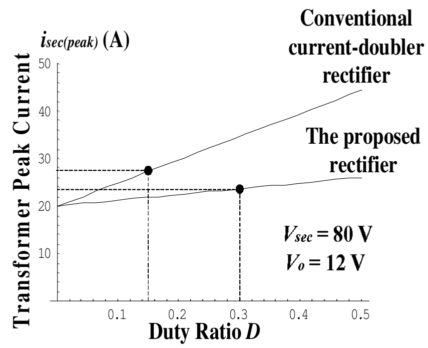


Fig. 5(c)

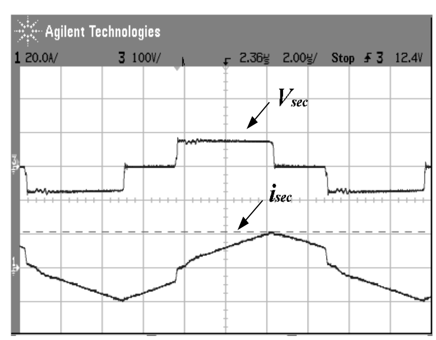
Fig. 5. Performance comparison between the proposed rectifier and the conventional current-doubler rectifier: (a) duty ratio, (b) output current ripple, and (c) secondary peak current of the transformer.

IV. Simulation and Experimental Results

To verify the performance of the proposed current-doubler rectifier, a 500 W prototype of a ZVS full-bridge phase-shift converter with the proposed rectifier was built. Its specifications are listed as follows:

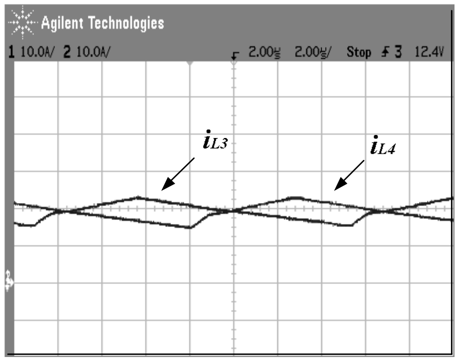
- input voltage: 400 V_{dc}
- output voltage: 12 V_{dc}
- output current: 40 A
- switching frequency: 75 kHz

Fig. 6 shows measured waveforms of the secondary voltage and current under full load condition. Fig. 7 shows measured current waveforms of inductors L_3 and L_4, from which it can be seen that inductors L_3 and L_4 can achieve balanced interleaving currents. Fig. 8 shows measured output current, from which it can be seen that output current ripple is pretty low. Fig. 9 shows the comparison of efficiency measurements between the proposed current-doubler rectifier and conventional current-doubler rectifier, from which it can be seen that the proposed current-doubler rectifier can achieve higher efficiency at heavy load and can reach as high as 90 %.



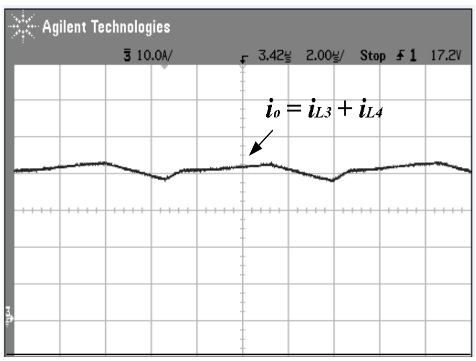
(V_{sec}: 100V/div, i_{sec}: 20A/div, Time: 2µs/div).

Fig. 6. Measured waveforms of the secondary voltage and current of the transformer.



(i_{L3}: 10A/div, i_{L4}: 10A/div, Time: 2µs/div)

Fig. 7. Measured waveforms of inductor currents i_{L3} and i_{L4}.



(i_o: 10A/div, Time: 2µs/div).

Fig. 8. Measured waveforms of output current i_o under full load condition.

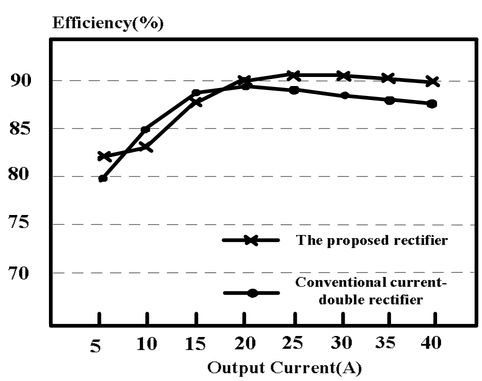


Fig. 9. Efficiency comparison between the proposed and the conventional current doublers associated with ZVS full-bridge converters.

V. Conclusions

In this paper, a current-doubler rectifier with low output current ripple and high step-down voltage ratio has been proposed and analyzed. The proposed rectifier has the merits of low output current ripple and extended duty ratio, which can reduce the peak current through the isolation transformer, the conduction loss of the switches and the copper loss of the isolation transformer. Experimental results have verified that the proposed rectifier can achieve high efficiency over a wide load range. It is relatively suitable for high step-down voltage ratio and high output current applications.

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