Research Article

Comparison between Phase-Shift Full-Bridge Converters with Noncoupled and Coupled Current-Doubler Rectifier

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Received 31 July 2013; Accepted 20 October 2013

Academic Editors: G. De Mey, S. A. Mahmoud, and G. Priebe

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This paper presents comparison between phase-shift full-bridge converters with noncoupled and coupled current-doubler rectifier. In high current capability and high step-down voltage conversion, a phase-shift full-bridge converter with a conventional current-doubler rectifier has the common limitations of extremely low duty ratio and high component stresses. To overcome these limitations, a phase-shift full-bridge converter with a noncoupled current-doubler rectifier (NCDR) or a coupled current-doubler rectifier (CCDR) is, respectively, proposed and implemented. In this study, performance analysis and efficiency obtained from a 500 W phase-shift full-bridge converter with two improved current-doubler rectifiers are presented and compared. From their prototypes, experimental results have verified that the phase-shift full-bridge converter with NCDR has optimal duty ratio, lower component stresses, and output current ripple. In component count and efficiency comparison, CCDR has fewer components and higher efficiency at full load condition. For small size and high efficiency requirements, CCDR is relatively suitable for high step-down voltage and high efficiency applications.

1. Introduction

In a decentralized power system, the front end ac/dc converter is generally composed of two stages, in which one is a power factor correction (PFC) and the other is an intermediate dc/dc converter, as shown in Figure 1. Most of PFC circuits adopt a boost converter [1], and an intermediate converter is usually with an isolated version [2]. Using a boost converter can achieve a unity power factory, and using an isolated converter can provide galvanic isolation and high output current. In off-line applications, universal ac voltage is always into dc 400 V as a dc bus by boost converters, and an intermediate dc/dc converter converts it to a low voltage bus of 24 V_{dc} or 12 V_{dc}. Therefore, for high output current and low output voltage applications, an isolated dc/dc converter is usually required.

To achieve low output voltage, high output current, and high efficiency, a phase-shift full-bridge converter with conventional current-doubler rectifier is widely used in medium-high power condition, as shown in Figure 2 [3]. Nevertheless,

it still has several limitations. For example, for high step-down voltage conversion, it requires a transformer with high turns ratio or it has to reduce the duty ratio of the switches. A high turns ratio will result in high duty loss and low conversion efficiency, while a low duty ratio will increase input peak current and component stress [4]. The other limitation is that its large external resonant inductor will induce a large circulation current, which will flow through the primary winding of the transformer and the switches during a freewheeling interval. As a result, conduction loss in the switches and copper loss in the transformer are significant. To release the above-mentioned limitations of the conventional full-bridge converter with current-doubler, many approaches have been conducted [3–7]. However, their high step-down voltage ratio still result in extremely low duty ratio, which will induce high peak current through the secondary winding of the isolation transformer and output filter inductors, increasing copper loss and component stresses [8–12].

To solve the above-mentioned problem, the phase-shift full-bridge converter with NCDR or CCDR is proposed,

FIGURE 1: Two-stage structure of preregulator.

FIGURE 2: The phase-shift full-bridge converter with conventional current-doubler rectifier.

FIGURE 3: The proposed phase-shift full-bridge converter with NCDR.

as shown in Figures 3 and 4 [13]. They can alleviate the drawbacks of extremely low duty ratio and high component stresses. The two proposed improved rectifiers 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 conversion efficiency can be increased significantly. Section 2 describes derivation and operational principle of the two proposed improved current-doubler rectifiers. Section 3 compares the benefits of the two improved current-doubler rectifiers. Power loss and efficiency estimation are described in Section 4. Experimental results obtained from a 500 W phase-shift full-bridge converter with NCDR and CDDR are presented in Section 5. Finally, a conclusion is given in Section 6.

2. Derivation of Improved Current-Doubler Rectifiers

With duality method, NCDR can be derived from a voltage-quadrupler circuit, and coupled-doubler can be derived from a voltage-doubler circuits. In the following, derivations of both improved current-doubler rectifiers are described in details.

2.1. Derivation of NCDR. Derivation of NCDR is based on a conventional voltage-quadrupler circuit, as shown in Figure 5(a). According to duality principle, meshes of the voltage quadrupler are replaced with nodes, and capacitors

FIGURE 4: The proposed phase-shift full-bridge converter with CCDD.

FIGURE 5: Derivation of NCDD from a voltage-quadrupler based on duality principle: (a) voltage-quadrupler and (b) NCDD.

are replaced with inductors, while diodes are with no change, yielding the proposed NCDD as shown in Figure 5(b).

2.2. Derivation of CCDD. Similarly, derivation of CCDD is based on a conventional voltage-doubler circuit, as shown in Figure 6(a). According to duality principle, meshes of the voltage doubler are replaced with nodes, and capacitors are replaced with inductors, while diodes are with no change, yielding the conventional current-doubler rectifier as shown in Figure 6(b). Utilizing coupled inductor concept, the output filter inductors can be extended to the coupled ones, as shown in Figure 6(c).

3. Operational Principles of NCDD and CCDD

For NCDD and CCDD, each of which has its own merits and demerits. To have an objective judgment, operational principles of NCDD and CCDD are briefly described as follows.

3.1. Operational Principle of NCDD. In Figure 3, the proposed phase-shift full-bridge converter with NCDD under continuous inductor current operation can be divided into four major operating modes over a half switching cycle. Figure 7

shows conceptual voltage and current waveforms relative to key components of NCDD. D_{eff} and D_{loss} are denoted as the effective and loss duty ratios, respectively. V_{AB} is the voltage across the resonant inductor L_r 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 filter inductors, and $i_{D1} \sim i_{D4}$ are the current of the rectifier diodes. To simplify description of the steady-state operational modes, the phase-shift full-bridge converter will not be discussed in this section. Only the proposed NCDD is analyzed. Under continuous inductor current operation, four major operating modes of the NCDD are identified over a half switching cycle. Figure 8 shows equivalent circuits of the NCDD operational modes.

Mode 1 (Figure 8(a), $t_0 \leq t < t_1$). 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 (Figure 8(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

FIGURE 6: Derivation of CCDD from a voltage-doubler based on duality principle: (a) voltage-doubler, (b) conventional current-doubler rectifier, and (c) CCDD.

FIGURE 7: Key waveforms of the proposed phase-shift full-bridge converter with NCDD.

reversely biased. Inductor current $i_{L_2} = i_{L_3}$ 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 (Figure 8(c), $t_2 \leq t < t_3$). When voltage V_{sec} drops to zero at time t_2 , all of the diodes ($D_{r1} \sim D_{r4}$) are conducting. During this interval, the inductor current i_{L_3} 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_{L_4} flowing through $V_o-D_{r4}-L_4$ are linearly decreased.

Mode 4 (Figure 8(d), $t_3 \leq t < t_4$). 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 $i_{D_{r3}}$ and $i_{D_{r4}}$ have not been commutated completely yet. Therefore, all of the diodes ($D_{r1} \sim D_{r4}$) are maintained conducting, while inductor currents i_{L_3} and i_{L_4} are maintained discharging to the load.

At time t_4 , rectifier diode currents $i_{D_{r3}}$ and $i_{D_{r4}}$ have been commutated completely. Then, a positive voltage V_{sec} crosses the secondary winding of transformer T_r . This ends a half switching cycle operation.

3.2. Operational Principle of CCDD. In Figure 4, each coupled inductor individually functions as a tapped inductor or a transformer during one switching cycle. In other words, the upper coupled-inductor is charged during the charging period, which functions as a tapped inductor, while the lower coupled-inductor functions as a transformer. Therefore, Figure 4 can be redrawn as shown in Figure 9. The proposed phase-shift full-bridge converter with CCDD under continuous inductor current operation can be divided into three major operating modes over a half switching cycle. Figure 10 shows conceptual voltage and current waveforms relative to key components of the converter. D_{eff} and D_{loss} are denoted as the effective and lost 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_L and V_L are the current and voltage of the coupled-inductor winding n_1 , i_{D_r} and V_{D_r} are the current and voltage of the rectifier diode, and i_o is the output current. The circuit operation is explained as follows.

Mode 1 (Figure 11(a), $t_0 \leq t < t_1$). At time t_0 , currents $i_{D_{r1}}$ and $i_{D_{r2}}$ are commutated completely. Then, a positive voltage V_{sec} crosses the secondary winding of transformer T_r ; diode D_{r1} is reversely biased, and inductor current i_{L_1} flowing through the path of $V_o-D_{r2}-L_{22}-V_{sec}-L_{11}-L_1$ increases linearly. During this interval, the energy stored in inductor L_{22} will be released to the load through coupled inductor L_2 , and inductor current i_{L_2} flowing through the path of V_o-D_{r2} is decreased. Meanwhile, inductors L_{11} and L_1 function as

FIGURE 10: Key waveforms of phase-shift full-bridge converter with CCDR.

winding peak current of transformer, voltage gain, and output current ripple.

4.1. Performance of NCDR. From Figures 3 and 7, during one complete switching cycle, the secondary winding peak current $i_{\text{sec(peak)}}$ can be expressed as follows:

$$i_{\text{sec(peak)}} = \frac{I_o}{2} + \frac{(V_{\text{sec}} - V_o)}{8Lf_s}, \quad (1)$$

where $L = L_1 = L_2 = L_3 = L_4$, V_{sec} is secondary voltage of transformer, and the voltage stresses of free-wheeling diodes can be expressed as follows:

$$\begin{aligned} V_{D_{r1}} = V_{D_{r2}} &= \frac{V_{\text{sec}} + V_o}{2}, \\ V_{D_{r3}} = V_{D_{r4}} &= \frac{V_{\text{sec}} - V_o}{2}, \end{aligned} \quad (2)$$

where V_o is output voltage. 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:

$$\frac{V_o}{V_{\text{sec}}} = \frac{D}{2}, \quad (3)$$

where D is duty ratio of power switches. From Figure 7 again, by using the interleaved current of the output inductors L_3 and L_4 , the output current ripple can be expressed:

$$i_{o(\text{ripple})} = \frac{(1 - 2D)V_o}{2Lf_s}, \quad (4)$$

where f_s is switching frequency of power switches.

4.2. Performance of CCDR. From Figures 9 and 10, during one complete switching cycle, the secondary winding peak current $i_{\text{sec(peak)}}$ can be expressed as follows:

$$i_{\text{sec(peak)}} = \left(\frac{V_{\text{sec}} - nV_o}{n^2L} \right) DT_S \left(\frac{n_2}{n_1} \right) - \frac{V_o}{L}, \quad (5)$$

where $L = L_1 = L_2$, and the voltage stresses of free-wheeling diodes can be expressed as follows:

$$V_{D_{r1}} = V_{D_{r2}} = \frac{V_{\text{sec}}}{n}, \quad (6)$$

where $n = (n_1 + n_2)/n_1$ is turns ratio of coupled inductors. 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:

$$\frac{V_o}{V_{\text{sec}}} = \frac{2D}{n(1+n)}. \quad (7)$$

FIGURE 11: Equivalent circuit modes of the CCDR operating over a half switching cycle.

TABLE 1: Comparison between NCDR and CCDR.

	NCDR	CCDR
Voltage gain	$\frac{V_o}{V_{sec}} = \frac{D}{2}$	$\frac{V_o}{V_{sec}} = \frac{2D}{n(1+n)}$
Output current ripple	$i_{o(ripple)} = \frac{(1-2D)V_o}{2Lf_s}$	$i_{o(ripple)} = \left[\frac{(1+n)}{2} - 2D \right] \frac{V_o}{Lf_s}$
Diode voltage stress	$V_{Dr1} = V_{Dr2} = \frac{V_{sec} + V_o}{2}$	$V_{Dr1} = V_{Dr2} = \frac{V_{sec}}{n}$
Peak current of transformer secondary winding	$i_{sec(peak)} = \frac{I_o}{2} + \left(\frac{V_{sec} - V_o}{2L} \right) DT_s$	$i_{sec(peak)} = \left(\frac{V_{sec} - nV_o}{n^2L} \right) DT_s \left(\frac{n_2}{n_1} \right) - \frac{V_o}{L}$

From Figure 10 again, by combining the currents of i_{L1} and i_{L2} , output current ripple can be determined as

$$i_{o(ripple)} = \left[\frac{(1+n)}{2} - 2D \right] \frac{V_o}{Lf_s}. \quad (8)$$

To objectively judge the merits and demerits of NCDR and CCDR, their performances are compared as summarized in Table 1 and Figure 12, assuming that the two improved current-doubler rectifiers can be operated with identical frequency, the same input and output voltages, and load currents.

5. Experimental Results

To verify the performance of NCDR and CCDR, two sets of 500 W prototypes with phase-shift full-bridge converters were built (see Figures 13 and 14). The specifications are listed as follows:

- (i) input voltage V_{in} : 400 V_{dc},
- (ii) output current I_o : 42 A,
- (iii) output voltage V_o : 12 V_{dc}.

FIGURE 12: Performance comparison between NCDR and CCDR: (a) duty ratio, (b) output current ripple, and (c) secondary peak current of the transformer.

FIGURE 13: Experimental circuit of the phase-shift full-bridge converter with NCDR.

FIGURE 14: Experimental circuit of the proposed phase-shift full-bridge converter with CCDR.

FIGURE 15: Measured waveforms of the secondary voltage and current of the transformer: (a) NCDR and (b) CCDR.

FIGURE 16: Measured waveforms of output filter inductor current i_{L1} and i_{L2} : (a) NCDR and (b) CCDR.

- (iv) output power P_o : 500 W,
- (v) switching frequency f_s : 100 kHz.

Figure 15 shows measured transformer waveforms of NCDR and CCDR under full load condition. From these measured waveforms, it can be seen that NCDR and CCDR can be extended duty ratio. Comparing between NCDR and

CCDR, the NCDR has a wide duty ratio. Figure 16 shows waveforms of output filter inductors L_3 and L_4 for NCDR and CCDR, from which it can be seen that NCDR has lower inductor current ripple. Figure 17 shows waveforms of full-load output current, from which it can be seen that NCDR has lower output current ripple. Figure 18 shows the comparison of efficiency measurements between NCDR and CCDR, from

FIGURE 17: Measured output current i_o waveforms: (a) NCDR and (b) CCDR.

FIGURE 18: Efficiency comparison between NCDR and CCDR associated with phase-shift full-bridge converters.

which it can be seen that CCDR can achieve higher efficiency at heavy load and can reach as high as 91%. The reason behind is that NCDR is used with four inductors resulting in low conversion efficiency.

6. Conclusions

In this paper, the proposed phase-shift full-bridge converter with NCDR and CCDR under 500 W has been implemented. The NCDR has the merits of extended duty ratio, lower output current ripple, and lower rectifier diodes voltage stresses, which can reduce the peak current through the isolation transformer and switches. However, in comparison between efficiency of NCDR and CCDR, the NCDR has lower efficiency at full load condition. The reason behind is that NCDR is used with four inductors resulting in low conversion efficiency. For small size and high efficiency requirements, CCDR is relatively suitable for high step-down voltage and high power conversion applications.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgment

This work was supported by the National Science Council, Taiwan, under Grant no. NSC102-2221-E-167-024.

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