Analysis and design of dual-half bridge converter operating in discontinuous conduction mode

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Abstract Dual-half bridge (DHB) converter is a novel family of phase-shifted full-bridge (PSFB) converter, and it can obtain a significant improvement in conversion efficiency compared to the traditional PSFB converter. However, the main drawback of DHB converter is that only the energy stored in leakage inductor can be used to discharge the junction capacitors of switches. All switches tend to lose zero-voltage switching (ZVS) under light load conditions, which will significantly degrade efficiency. This paper proposes a simple and effective method to extend the ZVS range of DHB converter. By making the DHB converter operating in discontinuous conduction mode (DCM) and widening the dead-time, the energy stored in the magnetizing inductors of transformers can be used to discharge the junction capacitors. Without additional auxiliary components, the ZVS operation under light load conditions can be obtained. Experimental results confirm the validity of proposed method.

Keywords: full-bridge converter, dual-half bridge converter, zero-voltage switching, discontinuous current mode, light load conditions

Classification: Power devices and circuits

1. Introduction

In the traditional phase-shifted full-bridge (PSFB) converter, all the primary switches can achieve zero voltage switching (ZVS) operation by using the parasitic components. Hence, the circuit structure is very simple and high switching frequency can be employed without causing large switching loss, which is beneficial for the improvement of reliability and power density [1, 2, 3, 4, 5, 6]. The PSFB converter is widely adopted for isolated applications, such as renewable power system, server power supply unit and battery charger. However, the PSFB converter has several serious drawbacks. First, the ZVS range of lagging-leg switches is very narrow and the switching loss will increase greatly under light load conditions. Then, the rectified diodes suffer from high voltage stress due to the resonance between leakage inductor of main transformer and junction capacitors of diodes [7]. In addition, the voltage across main transformer is maintained at zero while the primary current is nonzero during the freewheeling interval, which results in the increase of output filter requirement and conduction loss.

In order to overcome the aforementioned drawbacks in the traditional PSFB converter, many novel converters have been proposed. In [8, 9, 10, 11, 12, 13], some auxiliary circuits are

introduced into the PSFB converter. The junction capacitor of primary switch is discharged by these auxiliary circuits instead of the leakage inductor of main transformer. The auxiliary circuits are considered as constant current source during the ZVS transition, thus, the junction capacitors can be discharged completely over the full-load range. However, the auxiliary circuits increase the volume, cost and complexity of PSFB converter. Moreover, the trade-off between the additional power loss caused by the auxiliary circuits and the power loss saved by the ZVS operation should be resolved.

The simplest way to suppress the secondary voltage oscillation is the use of resistor-capacitor-diode (RCD) clamp circuit [14]. The RCD circuit shows a good performance by limiting the peak value of voltage oscillation. However, it cannot prevent the oscillation itself and the power loss caused by resistor degrades the conversion efficiency. In [15, 16, 17, 18, 19], the lossless snubber circuits are implemented to eliminate the voltage oscillation. Power loss of the auxiliary circuit is avoided. In [20, 21], two clamp diodes and a separate inductor are introduced into the primary side of PSFB converter. The peak value of secondary voltage is effectively suppressed by the clamp diodes. But these converters do not deal with the issues of primary circulating current and narrow ZVS range.

In [22, 23, 24, 25], some zero-voltage and zero-current switching (ZVZCS) PSFB converters are proposed to remove circulating current and to extend ZVS range. In these converters, an auxiliary voltage source is introduced into the secondary side or primary side of the traditional converters, which makes the primary current decay to zero during the freewheeling interval. In these ZVZCS converters, the output filter inductor takes part in the ZVS transition of leading-leg and the primary current is maintained at zero when the lagging-leg switches are turned-off. Therefore, the ZVS condition is improved and the primary circulating current is removed. However, during the freewheeling interval, the output power is kept constant by the energy stored in the output filter, which results in high filter requirement.

Recently, some dual-half bridge (DHB) converters are proposed [26, 27, 28, 29, 30]. In the primary side of DHB converters, two half-bridge inverters are placed in parallel and are driven in a traditional PS manner. In the secondary side, various rectified structures, such as current doubler rectifier [26, 27], center-tap rectifier (CTR) [28], full-bridge rectifier (FBR) [29] and hybrid rectifier [30], can be adopted to suit for different applications. The DHB converters have the following advantages: (1) the circulating current is removed and the conduction loss can be significantly reduced;

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(2) the primary energy is continuously transferred to the output side and the output filter requirement is reduced. Experimental results have shown that the DHB converters can achieve a significant improvement in conversion efficiency compared to the conventional PSFB converter. The main drawback of DHB converters is that only the energy stored in the leakage inductors can be available to discharge the junction capacitors. Since the available energy is dependent on the load current, all the primary switches tend to lose ZVS operation under light load conditions. In order to further extend the ZVS range of DHB converters, this paper proposes a simple and effective method. By making the DHB converter operating in discontinuous conduction mode (DCM) and widening the dead-time of leading-leg and lagging-leg, the magnetizing inductors can participate in ZVS transitions under light load conditions. Since the energies stored in magnetizing inductors are sufficiently larger than the required ZVS energies, all the primary switches can achieve ZVS operation. The proposed method does not use additional components and it is very simple and cost-effective.

To introduce the proposed method in detail, the DHB converter with FBR is selected in this paper. In Sections 2, the basic operational principle is presented. The performance analysis is given in Section 3. In Section 4, the experimental results on a 1-kW prototype are reported to verify the theory analysis. Finally, some conclusions are given in Section 5.

2. Operational principle

Fig. 1 shows the equivalent circuit of DHB converter with FBR. In the primary side, Q_1 - Q_3 - T_1 - C_B and Q_2 - Q_4 - T_2 - C_B compose the leading and lagging half-bridge inverters, respectively. Two FBRs sharing two low voltage rating diodes are employed in the secondary side. In order to simplify the theory analysis, the following assumptions are made:

(1) the switches are MOSFETs and only parasitic diodes and junction capacitors are considered; (2) the transformers T_1 and T_2 have the same specifications; the leakage inductances and magnetizing inductances are L_k and L_m , respectively; (3) the output filter capacitor C_o and blocking capacitor C_B are considered as constant voltage sources of V_o and $0.5V_{in}$, respectively.

As load current is decreased, the current through output filter inductor will be discontinuous. Fig. 2 shows the key waveforms in DCM operation. V_{in} is input voltage, T_s is switching period. I_m and I_{max} are the maximum currents of magnetizing inductors and output inductor, respectively. The turns ratios $n_p : n_s$ of T_1 and T_2 are $1 : n$. The duty-cycle of rectified voltage is D . The phase-shifted modulation is adopted and the phase-shifted time is $0.5DT_s$. All the

Fig. 1 Simplified equivalent circuit of DHB converter with FBR.

primary switches operate with a constant duty-cycle 50% if dead-time is ignored. Each switching period is divided into two half cycles, $t_0 \sim t_7$ and $t_7 \sim t_{14}$. Due to the symmetry of circuit, only the first half cycle is introduced. This half cycle is divided into seven modes and the corresponding equivalent circuits are shown in Fig. 3.

Mode 1 [$t_0 \sim t_1$]: This mode is defined as duty-cycle interval. Q_1 , Q_4 and D_1 , D_6 are in on-state. The primary voltages of T_1 and T_2 are $0.5V_{in}$. Thus, the magnetizing currents $i_{m1}(t)$ and $i_{m2}(t)$ increase linearly, respectively. The rectified voltage $v_{rec}(t)$ is equal to the sum of the secondary voltages of T_1 and T_2 and its value is nV_{in} . The current of output filter inductor $i_{Lo}(t)$ increase linearly from zero and it is calculated as follow:

Fig. 2 Key waveforms of DHB converter in DCM.

Fig. 3 Equivalent circuits: (a) Mode 1 [$t_0 \sim t_1$]; (b) Mode 2 [$t_1 \sim t_2$]; (c) Mode 3 [$t_2 \sim t_3$]; (d) Mode 4 [$t_3 \sim t_4$]; (e) Mode 5 [$t_4 \sim t_5$]; (f) Mode 6 [$t_5 \sim t_6$]; (g) Mode 7 [$t_6 \sim t_7$].

$$i_{Lo}(t) = \frac{nV_{in} - V_o}{L_o}(t - t_0) \quad (1)$$

Mode 2 [$t_1 \sim t_2$]: Q_1 is turned off at t_1 . The duration of this mode is very narrow and all the currents remain constant. The capacitances are discharged linearly by a constant current source $i_{p1}(t_1)$. $i_{p1}(t_1)$ is equal to $I_m + nI_{max}$. The leading-leg voltage $v_{lea}(t)$, the secondary voltage of T_1 $v_{s1}(t)$, and the rectified voltage $v_{rec}(t)$ decrease from V_{in} , $0.5nV_{in}$, nV_{in} to $0.5V_{in}$, 0 and $0.5nV_{in}$, respectively. At t_2 , $v_{s1}(t)$ falls to zero and diode D_2 starts to conduct.

Mode 3 [$t_2 \sim t_3$]: During this mode, $v_{s1}(t)$ maintains at zero since D_1 and D_2 are simultaneously in conducting state. The resonance of junction capacitances and leakage inductance occurs in the primary side. The leading-leg voltage $v_{lea}(t)$ and current $i_{p1}(t)$ decrease with sinusoidal shape, and they are calculated as follows:

$$v_{lea}(t) = 0.5V_{in} - (nI_{max} + I_m)z \sin \omega(t - t_2) \quad (2)$$

$$i_{p1}(t) = (nI_{max} + I_m) \cos \omega(t - t_2) \quad (3)$$

where $\omega = 1/\sqrt{2C_{oss}L_k}$, $z = \sqrt{L_k/2C_{oss}}$.

The commutation between D_1 and D_2 is progressed, and D_1 current decreases from I_{max} to zero while D_2 current increases from zero to I_{max} . **Mode 3** ends when D_1 current reaches zero at t_3 .

Mode 4 [$t_3 \sim t_4$]: **Mode 4** begins when the commutation between D_1 and D_2 is completed and D_1 is naturally turned-off. During this mode, the secondary current of T_1 is zero and the capacitances of leading-leg switches are discharged by the magnetizing current I_m . The leading-leg voltage $v_{lea}(t)$ decrease linearly from $0.5V_{in}$ to zero. Then, the parasitic diode of Q_3 starts to conduct and Q_3 can be turned on with ZVS.

In summary, the ZVS transition of leading-leg is constituted of three modes (**Mode 2**, **Mode 3** and **Mode 4**). During this interval, the leading-leg voltage $v_{lea}(t)$ and the rectified voltage $v_{rec}(t)$ decrease from V_{in} and nV_{in} to 0 and $0.5nV_{in}$, respectively. On the other hand, the voltages and currents of lagging-leg are considered as constant since the duration is very narrow.

Mode 5 [$t_4 \sim t_5$]: During this mode, the secondary current of T_1 is zero and the primary power is transferred to the secondary side through only T_2 . This mode is called as freewheeling interval. The current of output filter inductor decreases from I_{max} to zero.

$$i_{Lo}(t) = I_{max} - \frac{V_o - 0.5nV_{in}}{L_o}(t - t_4) \quad (4)$$

Mode 6 [$t_5 \sim t_6$]: **Mode 6** begins when $i_{Lo}(t)$ falls to zero at t_5 . Then, all rectified diodes are naturally turned off. The secondary currents of T_1 and T_2 are zero and only the energy stored in the filter capacitor C_o is transferred to the output side. This mode is defined as idle interval.

The junction capacitors of rectified diodes are ignored to simplify the analysis. In fact, the resonance of junction capacitors and output filter inductor occurs in the secondary side during this mode. The resonance voltage is calculated as

$$v_{rec}(t) = V_o - (V_o - 0.5nV_{in}) \cos \omega_s t \quad (5)$$

where $\omega_s = 1/\sqrt{2C_e L_o}$, C_e is the equivalent capacitance of rectified diodes.

Mode 7 [$t_6 \sim t_7$]: **Mode 7** begins when Q_4 is turned off at t_6 . The secondary currents are continuously maintained at zero. The junction capacitors of Q_2 and Q_4 are charged by the magnetizing current of T_2 . The lagging-leg voltage $v_{lag}(t)$ increases linearly. At t_7 , $v_{lag}(t)$ increases to V_{in} and the parasitic diode of Q_2 starts to conduct. Then, Q_2 can be turned on with zero voltage. At the end of this mode, D_3 and D_4 start to conduct and the secondary currents increase linearly from zero. The primary power is transferred to the output side through T_1 and T_2 .

3. ZVS conditions

As described in the previous section, the ZVS transition of leading-leg switches is constituted of three modes (**Mode 2**, **Mode 3** and **Mode 4**) when the DHB converter operates in DCM. During **Mode 2**, the output filter inductor is reflected into the primary side and the leading-leg voltage decreases linearly from V_{in} to $0.5V_{in}$. During **Mode 3**, the secondary winding of T_1 is shorted and the junction capacitors of switches are discharged by the energy stored in the leakage inductor of T_1 . During **Mode 4**, the secondary current of T_1 is maintained at zero and the junction capacitors are discharged by the magnetizing current. At the end of **Mode 4**, the leading-leg voltage falls to zero and the ZVS operation can be achieved.

According to the relevant analysis results in [25], the ZVS transition of leading-leg is constituted of two modes in continuous conduction mode (CCM). At first, the leading-leg voltage decreases linearly from V_{in} to $0.5V_{in}$ due to the existence of output filter inductor. Then, the remaining voltage across the junction capacitors is discharged by the leakage inductor of transformer. In the view of energy, the ZVS condition of leading-leg switches is represented as

$$\frac{1}{2}L_k(nI_o)^2 > \frac{4}{3}C_{oss}(0.5V_{in})^2 \quad (6)$$

When the DHB converter operates in DCM, the secondary currents of transformers are maintained at zero and the junction capacitors are mainly charged by the magnetizing inductor during the ZVS transition of lagging-leg. The lagging-leg voltage increases linearly from 0 to V_{in} . On the other hand, if the DHB operates in CCM, the current of output inductor is nonzero and rectified diodes keep conducting during the ZVS transition. The secondary windings of transformers are shorted by the rectified diodes. Therefore, only the energy stored in the leakage inductors can be used to charge junction capacitors. The ZVS condition of lagging-leg switches in CCM is represented as

$$L_k(nI_o + I_m)^2 > \frac{4}{3}C_{oss}V_{in}^2 \quad (7)$$

From (6) and (7), it can be noted that the available energy charging or discharging the junction capacitors is dependent on the energy stored in leakage inductors, which is directly decided by the load current. Therefore, all the primary switches tend to lose ZVS operation under light load conditions if the DHB converter operates in CCM. This is in contrast to the fact that the available energy is mainly stored in the magnetizing inductors if the DHB converter

operates in DCM. Since the magnetizing inductance is large enough, the available energy is also sufficiently larger than the required ZVS energy.

The peak value of magnetizing current is calculated as follow:

$$I_m = \frac{V_{in} T_s}{8L_m} \quad (8)$$

I_m is independent on load current. Based on the aforementioned analysis, the junction capacitors of switches are mainly discharged or charged by the magnetizing current I_m when the DHB converter operates in DCM. Therefore, the ZVS conditions of lagging-leg switches and leading-leg switches are also independent on the load conditions and a full ZVS range can be achieved. It should be noted that the value of magnetizing current is usually very small and the dead-time are widened to ensure that capacitors are charged or discharged completely by the magnetizing current [31].

4. Design example and experimental results

In order to verify the theory analysis of DHB converter operating in DCM, an experimental prototype converter is built with the following specifications: input voltage $V_{in} = 320\sim 400$ V; output voltage $V_o = 100$ V; switching frequency $f_s = 50$ kHz; maximum load current $I_o = 10$ A.

Main transformers: Based on the window-area product of magnetic core required for the maximum power capacity, PQ3535 is selected as the core of transformers. When input voltage is the minimum and the corresponding maximum duty-cycle is preset 0.9, the turns ratio can be calculated according to the voltage gain of DHB converter in CCM, and its value is 0.34.

Magnetizing inductor: The specified value of magnetizing inductor is designed by adjusting the gap of magnetic core. A wide ZVS range can be achieved by reducing the magnetizing inductance and increasing the magnetizing current. In spite of using a small magnetizing inductance, the primary current stress will not increase significantly because the average value of magnetizing current is zero within a half period and its contribution to the total RMS current can be ignored. In this paper, the maximum magnetizing current is selected as 0.5 A. The magnetizing inductance is determined from (8) and its value is 1.5 mH.

Output filter inductor: The output filter inductor is designed based on the waveform of rectified voltage and its value is calculated as follows

$$L_o = \frac{V_o}{4f_s \Delta I_o} \frac{D(1-D)}{1+D} \quad (9)$$

where ΔI_o is the current ripple of output filter inductor.

The current ripple has a significant effect on the performance of DHB converter since it decides the critical point between CCM and DCM. According to the ZVS conditions of DHB converter, the ZVS range can be extended by increasing ΔI_o , which results in high current stress. A trade-off should be made in the design process. Generally, ΔI_o is set around 30% of maximum load current. In this paper, ΔI_o is selected as 3 A. Then, the value of output filter inductor can be calculated based on (9), and it is 25 μ H.

The voltage and current stresses of rectified diodes and

Fig. 4 Experimental waveforms of DHB converter in DCM. (a) Leading-leg; (b) lagging-leg; (c) secondary side.

primary switches can be obtained by calculating the maximum values as follows:

$$I_{D1-6(max)} = I_{o(max)} + \Delta I_o = 13 \text{ A} \quad (10)$$

$$V_{D1,3,4,6(max)} = nV_{in} = 136 \text{ V} \quad (11)$$

$$V_{D2,5(max)} = 0.5nV_{in} = 68 \text{ V} \quad (12)$$

$$V_{Q1-4(max)} = V_{in(max)} = 400 \text{ V} \quad (13)$$

$$I_{Q1-4(max)} = n(I_{o(max)} + \Delta I_o) + I_m = 4.9 \text{ A} \quad (14)$$

Based on the aforementioned values, D_1 , D_3 , D_4 , D_6 are selected as MBR20200CT (200 V, 20 A) and D_2 , D_5 are selected as MBR20150CT (150 V, 20 A). The primary switches are selected as STW10NK60Z (600 V, 10 A).

Fig. 4 shows the key experimental waveforms of DHB converter operating in DCM. The leading current i_{p1} increases linearly during the duty-cycle interval and it falls quickly from the maximum value to the magnetizing current during the ZVS transition. The lagging current i_{p2} contains three slopes during one half cycle. As shown in Fig. 4(c), during the duty-cycle interval, the rectified voltage v_{rec} is nV_{in} and the current of filter inductor i_{Lo} increases linearly. During the freewheeling interval, v_{rec} is $0.5nV_{in}$ and i_{Lo} decreases linearly. When i_{Lo} falls to zero, the resonance between junction capacitors of rectified diodes and output filter inductor occurs in the secondary power path. The experimental results coincide well with the theory waveforms described in Fig. 2.

Fig. 5 and Fig. 6 show the ZVS waveforms of leading-leg and lagging-leg switches under light load conditions, respectively. As shown in Fig. 5 and Fig. 6, although the reflected current of output filter inductor falls to zero during the ZVS transitions, all the switches can still achieve ZVS operation by using the magnetizing current to discharge the junction capacitors.

5. Conclusion

This paper proposes a practical and simple way to extend the ZVS range of DHB converter. By making the DHB converter operating in DCM and widening the dead time of leading-leg

Fig. 5 ZVS waveforms of leading switches under light load conditions. (a) 1% of full load; (b) 10% of full load; (c) 30% of full load.

Fig. 6 ZVS waveforms of lagging switches under light load conditions. (a) 1% of full load; (b) 10% of full load; (c) 30% of full load.

and lagging-leg, the magnetizing inductors can be used to participate in the ZVS transitions. Since the energy stored in the magnetizing inductor is sufficiently larger than the required ZVS energy and they are independent on the load conditions, the ZVS operation can be achieved under light load conditions without additional components. The validity of proposed method is confirmed by the experimental results.

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