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ZCT Scheme of Push-Pull Forward Converter

Zhang Fanghua Wang Huizhen Yan Yangguang

(College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China)

Abstract: The paper proposes a novel zero-current-transition (ZCT) push-pull forward converter. The auxiliary resonant cell is in parallel with the main circuit and the zero-current-switching (ZCS) range of the main and the auxiliary switches of the proposed converter are entirely achieved. The resonant capacitor achieves high voltage by operating the auxiliary cell. The auxiliary switch turns on before the main switches turn off, the high voltage of resonant capacitor blanks off the rectifier, and then the current of the secondary windings and the primary windings reaches zero. The operation principle of the new ZCT technique is detailed. And the key parameters to realize ZCS are calculated. The simulation and experiment reveal that the above scheme is feasible. A family of ZCT circuit in isolated converters can be developed by the same principle.

Key words: converter/ZCT converter, ZCS/ZCT, push-pull/push-pull forward

The conventional push-pull converter suffers from the flux imbalance of the transformer, and high turn-off voltage spike of the main switches due to the transformer leakage inductance[1]. The push-pull forward (PPF) converter can eliminate the problems in push-pull converter[2,3]. PPF has the following advantages: ① The capacitor clamps the voltage overshoot and recovers the leakage energy; ② The power transformer magnetizes symmetry and has no flux imbalance problem; ③ This topology provides a reduced input current ripple and requires a smaller input filter than in conventional buck type converter.

To reduce switching losses, several kinds of ZCS soft switching techniques have been proposed since the ZCS PWM switch cell was first proposed in Ref. [4]. In Refs. [4 – 6], ZCS of the active switches is achieved by using a resonant inductor in series with the main switch and a resonant capacitor in series with the auxiliary switch. The main drawbacks of the ZCS approaches are high current stress on the active switches and high voltage stress on the diodes. In Refs. [6 – 8], the resonating current for ZCS flows only through the auxiliary circuit, thus the current stress of the main switch is eliminated. However, it presents two power diodes in the power transfer path, which increases conduction losses of the diodes.

This paper proposes a novel ZCT PWM switch cell that improves the previously proposed ZCS PWM converters. The proposed cell provides ZCS condition for both the main switches and the auxiliary switch. Since the resonant current for the soft switching flows only through the auxiliary circuit, the conduction loss and current stress of the main switch are minimized. Design guidelines are described and verified by experimental results from 1?kW, 28.5?V DC input, 75?V DC output prototype converter operating at 100?kHz. The ZCT push-pull forward converter is suitable for the low input voltage and medium power range.

1 Operation Principle

Fig.1 shows the circuit diagram of the proposed ZCT PPF. Where $N_{p_1} = N_{p_2}$, N_s and $n = N_s/N_{p_1}$ represent the winding turns of the primary, the secondary, and the turns ratio of secondary to primary, respectively. The duty ratio D is defined as: $2T_{on}/T_s$, where T_{on} is the on-time of each switch, T_s is the period of one switching cycle. $I_o = V_o/R_L$ is the load current. L_f and C_f are the filter inductor and capacitor, respectively. The diodes D_{a_1} and D_{a_2}, MOSFET S_a, resonant inductor L_r and resonant capacitor C_r constitute the resonant cells shown in the dashed rectangle of Fig.1.

As the detailed operation mode of the push-pull forward converter was mentioned in Ref. [2], we mainly give the principle concerned to the zero-current-switching modes. In one switching cycle, the ZCT PPF has 16 operating modes. The key operating waveforms are given in Fig.2. To analyze the steady state operation, the following assumptions are given[9]: All

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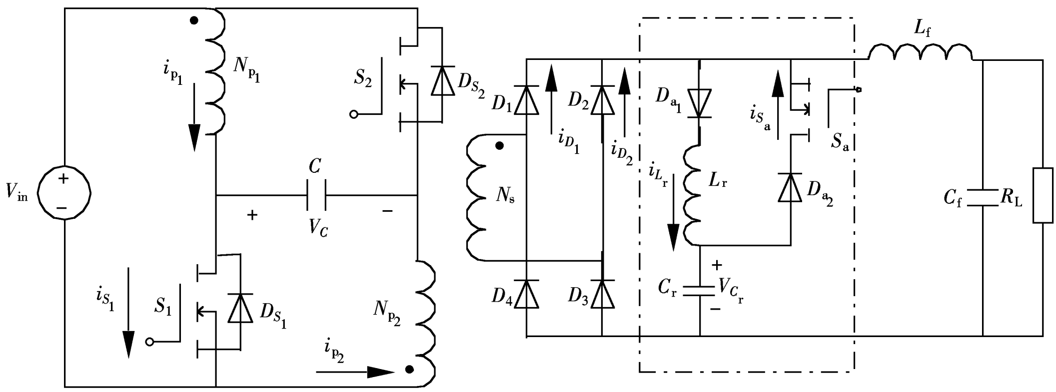

Fig.1 The proposed ZCS push-pull forward converter

components and devices are ideal; C is large enough to be regarded as a const voltage source; the filter inductor L_f is much larger than the resonant inductor L_r; the output inductor and capacitor are large enough, so L_f, C_f and R_L are regarded as a const current source.

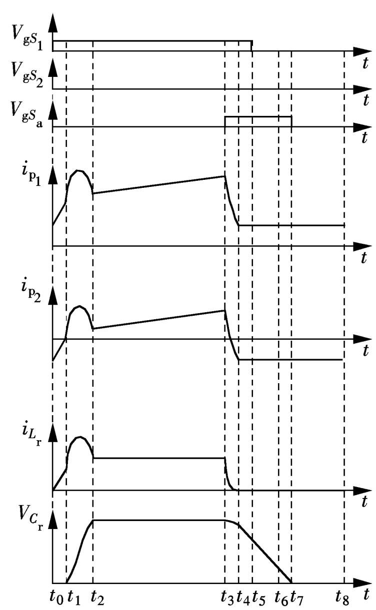

Fig.2 The key waveforms of ZCT PPF

1.1 Mode 1 [t_0, t_1]

Prior to t_0, the main switches S_1 and S_2 in the primary side are all off. The primary current freewheels through V_{in+}-N_{p_1}-C-N_{p_2}-V_{in-}, the current is $I_{av} = \frac{1}{2}nDI_o$, which was proposed in Ref. [2]. The load current and magnetizing current flow through the diodes (D_2, D_3) and (D_1, D_4) equally. At t_0, S_1 turns on, the voltage nV_{in} is applied on the leakage inductance $L_{\sigma s}$, the current i_{D_1} increases linearly with the slope $nV_{in}/L_{\sigma s}$, and the current in D_2, D_4 decreases linearly. Accordingly the current in the primary windings N_{p_1} increases linearly from zero, so the main switch S_1 turns on with snubbed zero-current. Until $I_{D_1} = I_o$, $I_{D_2} = 0$, the mode ends. The duration of this mode is $t_{01} = I_o L_{\sigma s}/(2nV_{in})$. The current in the primary windings N_{p_1} and the rectifier is obtained as

$$i_{D_1}(t) = \frac{1}{2}I_o + \frac{nV_{in}}{L_{\sigma s}}(t - t_0) \tag{1}$$

$$i_{D_2}(t) = \frac{1}{2}I_o - \frac{nV_{in}}{L_{\sigma s}}(t - t_0) \tag{2}$$

$$i_{p_1}(t) = I_{av} + \frac{n}{2}\frac{nV_{in}}{L_{\sigma s}}(t - t_0) \tag{3}$$

$$i_{p_2}(t) = -I_{av} + \frac{n}{2}\frac{nV_{in}}{L_{\sigma s}}(t - t_0) \tag{4}$$

1.2 Mode 2 [t_1, t_2]

Prior to t_1, the current of L_r and the voltage of C_r are all zero. At t_1 the inductive voltage in the secondary is applied on the resonant components L_r and C_r, L_r and C_r begin to resonant. At t_2, the current of resonant inductor equals to zero. As the diode D_{a_1} prevents the current inversely, the resonant is interrupted, and the voltage of C_r equals to $2nV_{in}$, reaches the maximum. The duration of this mode is $t_{12} = \frac{1}{2}T_r = \pi\sqrt{L_r C_r}$. The current through L_r and the voltage of C_r are obtained as

$$i_{L_r}(t) = \frac{nV_{in}}{Z_r}\sin\omega(t - t_1) \tag{5}$$

$$v_{C_r}(t) = nV_{in}[1 - \cos\omega(t - t_1)] \tag{6}$$

The current through the primary windings and the rectifier is

$$i_{D_1}(t) = I_o + \frac{nV_{in}}{Z_r}\sin\omega(t - t_1) \tag{7}$$

$$i_{p_1}(t) = I_{av} + \frac{n}{2}\left(I_o + \frac{nV_{in}}{Z_r}\sin\omega(t - t_1)\right) \tag{8}$$

$$i_{p_2}(t) = -I_{av} + \frac{n}{2}\left(I_o + \frac{nV_{in}}{Z_r}\sin\omega(t - t_1)\right) \tag{9}$$

So the current through the main switch S_1 can be expressed as

$$i_{S_1}(t) = i_{p_1}(t) + i_{p_2}(t) = n\left(I_o + \frac{nV_{in}}{Z_r}\sin\omega(t - t_1)\right) \tag{10}$$

where $Z_r = \sqrt{L_r/C_r}$; $\omega = 1/\sqrt{L_r C_r}$.

1.3 Mode 3 $[t_2, t_3]$

In this period, the voltage of C_r maintains the voltage of $2nV_{in}$, and the current through the secondary windings is the load current. $i_{p_1}(t) = I_{av} + \frac{n}{2}I_o$, $i_{p_2}(t) = -I_{av} + \frac{n}{2}I_o$.

1.4 Mode 4 $[t_3, t_4]$

At t_3, S_a turns on with zero-current, C_r and the leakage inductance begin to resonant, i_{D_1} decreases until it reaches zero at t_4. The voltage of C_r is

$$V_{C_r}(t_4) = nV_{in}[1 + \sqrt{1 - (Z_1 I_o/(nV_{in}))^2}] \tag{11}$$

The current through the rectifier and the auxiliary switch S_a is obtained as

$$i_{D_1}(t) = I_o - \frac{nV_{in}}{Z_1}\sin\omega_1(t - t_3) \tag{12}$$

$$i_{S_a}(t) = \frac{nV_{in}}{Z_1}\sin\omega_1(t - t_3) \tag{13}$$

The voltage of the resonant capacitor is: $V_{C_r}(t) = nV_{in}[1 + \cos\omega_1(t - t_3)]$.

And the duration of this mode is

$$t_{34} = \frac{1}{\omega_1}\arcsin\left(\frac{Z_1 I_o}{nV_{in}}\right) \tag{15}$$

where $Z_1 = \sqrt{L_{\sigma s}/C_r}$; $\omega_1 = 1/\sqrt{L_{\sigma s} C_r}$.

1.5 Modes 5 and 6 $[t_4, t_6]$

The resonant capacitor is discharged through S_a, and the discharge current equals to the load current I_o, and no energy is transferred to the secondary windings from the primary at this mode. The voltage of C_r is: $v_{C_r}(t) = V_{C_r}(t_4) - \frac{I_o}{C_r}(t - t_4)$. The main switch S_1 can be turned off with zero-current at t_5. At t_6, the voltage of C_r reaches zero. The duration from t_4 to t_6 is

$$t_{46} = C_r V_{C_r}(t_4)/I_o \tag{16}$$

1.6 Modes 7 and 8 $[t_6, t_8]$

The rectifier continues the load current from the moment t_6. The auxiliary switch S_a can be turned off with zero-voltage and zero-current. At t_8, the main switch S_2 turns on with zero-current snubber, and the next half cycle begins.

2 Design Guidelines

2.1 L_r and C_r

The next three factors restrict the value of the resonant components.

The resonant impedance is large enough to deduce the current stress caused by resonance. Generally,

$$nV_{in}/Z_r = (1/2 \text{ to } 3/4)I_{omax} \tag{17}$$

This is a merit of ZCT scheme, which means the increased resonant current can be less than the maximum load current. So the current stress of the main switches is less than that in ZCS scheme.

The resonant cycle should be short enough to minimize its impact on the pulse-width-modulation control. Generally, $T_s = (6 \text{ to } 15)T_r$.

The duration of C_r discharging ($[t_4, t_6]$) is large enough to easily control the main switches turn off with zero-current, i.e. $t_{46\min} = C_r V_{C_r}(t_4)/I_{omax}$ should be large enough.

2.2 Semiconductors

From Eqs.(7) and (17), the maximum current through the rectifiers is obtained as

$$I_{D_1\max} = I_{omax} + \frac{nV_{in}}{Z_r} = \left(\frac{3}{2} \text{ to } \frac{7}{4}\right)I_{omax}.$$

From Eq.(10), the current stress of the main switches is $I_{smax} = \left(\frac{3}{2} \text{ to } \frac{7}{4}\right)nI_{omax}$.

Because the resonant cycle is very short, the root-mean-square (RMS) current value of the rectifier diodes increases little. But the voltage stress of the rectifier is 2 times of original value.

3 Experimental Results

A prototype (V_{in} = 21?V to 34?V, V_{out} = 75?V, and P_o = 1?000?W) was built to evaluate the performance of ZCT PPF DC-DC converter. The switching frequency of main switches is 100?kHz. Fig. 3 and Fig.4 are the key waveforms of the converter when the load current is 10?A. Fig.3 shows the voltage and current waveforms of the resonant capacitor C_r and the secondary windings N_{P_1}. The four channels in Fig. 3 are as follows. ① The voltage of grid and source of S_1, V_{gS_1}; ② The voltage of grid and source of auxiliary switch S_a, V_{gS_a}; ③ The voltage of resonant capacitor, V_{C_r}; ④ The current through secondary side i_s. Fig.4 shows the voltage and current waveforms of the diode D_1 and the resonant current through L_r. The four channels in Fig.4 are as follows: ① The voltage of grid and source of S_1, V_{gS_1}; ② The voltage of grid and source of auxiliary switch S_a, V_{gS_a}; ③ The voltage of diode D_1, V_{D_1}; ④ The current through the resonant inductor, i_{L_r}. The current through secondary windings increases linearly with snubbed when S_1 turns on and it reaches zero before the main switch S_1 turns off. So the main switches turn on

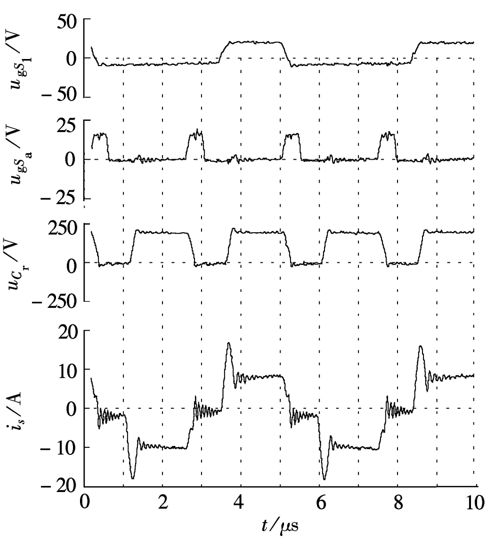

Fig.3 The voltage and current waveforms of the resonant capacitor C_r and the secondary windings N_s

with snubber zero-current and turn off with zero-current. The experimental waveforms verify the theoretical analysis.

4 Conclusion

The paper proposes a novel zero-current-transition (ZCT) push-pull forward converter. The auxiliary cell is in parallel with the main circuit and the zero-current-switching (ZCS) range of the main and the auxiliary switches of the proposed converter are entirely achieved by operating the auxiliary cell. The high voltage of the resonant capacitor blanks off the output of the rectifier before the main switches turn off, so the current through the main switches reaches zero before they turn off. The experimental results reveal that the scheme is feasible. A family of ZCT circuit in isolated

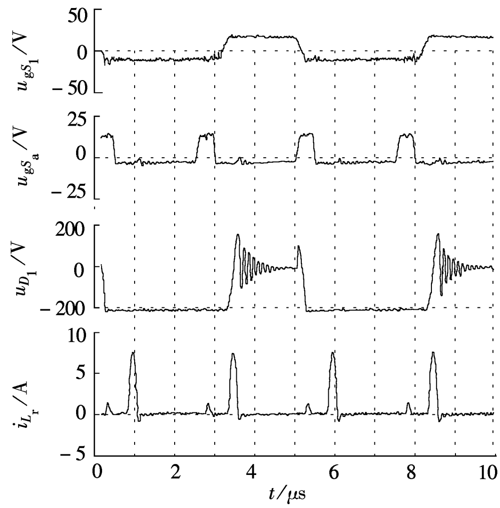

Fig.4 The voltage and current waveforms of the diode D_1 and the resonant current through L_r

converters can be developed by the same principle.

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推挽正激电路的 ZCT 方案

张方华　王慧贞　严仰光

（南京航空航天大学自动化学院，南京 210016）

摘　要　在 ZCS 推挽正激电路的基础上增加 2 个单向导通二极管,把谐振电感移出主回路,实现了电路主开关管和辅助开关管的零电流转换开关(ZCT).通过理论分析和样机研制证明了这种方案的可行性.通过谐振电容的高电压来封锁副边整流桥输出,使原边电流在主开关管关断以前降到零,这种思想可以应用到其他的有变压器隔离的电路拓扑中.

关键词　变换器/零电流转换变换器，ZCS/ZCT，推挽/推挽正激

中图分类号　TM46