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New Zero-Current-Transition (ZCT) Circuit Cell Without Additional Current Stress

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Abstract **— In this paper, the new zero-current-transition (ZCT) circuit cell is proposed. The main switch is turned-off under the zero current and zero voltage condition, and there is no additional current stress and voltage stress in the main switch and the main diode. The Auxiliary switch is turned-off under the zero voltage condition, and the main diode is turned-on under the zero voltage condition. The resonant current required to obtain the ZCT is small and regenerated to the input voltage source. The operational principles of the boost converter integrated with the proposed ZCT circuit cell is analyzed theoretically and verified by the simulation and experimental result.**

Index terms **— zero-current-transition (ZCT), zero-current-switching (ZCS), zero-voltage-switching (ZVS)**

1. Introduction

Nowadays, the switching frequency of the Switched-Mode-Power-Supply (SMPS) can be increased based on the development of the power semiconductor device. Increasing frequency offers the ability to decrease the size of the reactive components, which the SMPS consists of, such as transformer, inductor, and capacitor. However, the switching loss in the power semiconductor device increases at the high frequency, so the efficiency of the SMPS decreases and the heat sink of the power semiconductor device increases in size. In order to decrease the switching loss in the power semiconductor device, two soft-switching techniques are proposed. One is the zero-voltage-switching (ZVS) and the other is the zero-current-switching (ZCS). The ZVS abbreviates the switching loss at the turn-on, on the other hand, the ZCS abbreviates the switching loss at the turn-off. But under the ZVS the voltage stress of the power semiconductor device is increased, and under the ZCS the current stress of the power semiconductor device is increased. In the result, the conduction loss of the power semiconductor device is increased. In addition, because these soft-switching techniques use the variable frequency control, they are difficult to design and control. To solve these drawbacks of the ZVS and the ZCS, the zero-voltage-transition (ZVT) and the zero-current-transition (ZVS) are proposed.

In the high power SMPS, the insulated gate bipolar transistor (IGBT) is used preferably to MOSFET. The advantages of the IGBT are the high power capability, the low conduction loss, the low cost, and the high voltage durability. However, the fatal disadvantage is the tail current at the turn-off. Therefore, under the ZCT the performance of the SMPS that uses the IGBT can be improved. But, the ZCT proposed in [1-4] has some drawbacks. The resonant current required to obtain the ZCT is large and can cause the significant current stress of the main switch.[1,2] The voltage stress of the main diode can be increased twice due to the resonant voltage.[3,4]

In this paper, the new ZCT circuit cell that does not present the drawbacks mentioned above is proposed. The main switch is turned-off under the zero current and zero voltage condition, and there is no additional current stress and voltage stress in the main switch. The auxiliary switch is turned-off under the zero voltage condition, and the main diode is turned-on under the zero voltage condition. Besides, the resonant current required to obtain the ZCT is small and regenerated to the input voltage source. In section II, the operational principle of the ZCT boost converter (the boost converter integrated with the proposed ZCT circuit cell) is described. In section III, the design guideline and the design example are presented. In section IV, the operation of proposed ZCT circuit cell is verified through the simulation and experimental result on the 200W prototype of the ZCT boost converter. In section V, the conclusion is presented.

2. Principle of Operation

2.1 New ZCT circuit cell

The proposed ZCT circuit cell is presented Fig. 1 and consists of the auxiliary switch, Q_A, the resonant capacitor, C_r, the resonant inductor, L_r, and the blocking diode, D_r.

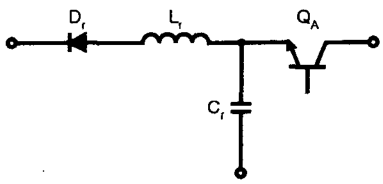

Fig. 1. New ZCT circuit cell

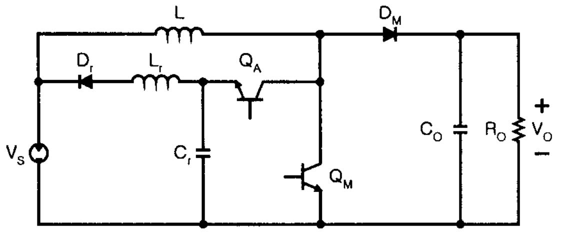

Fig. 2. ZCT Boost Converter

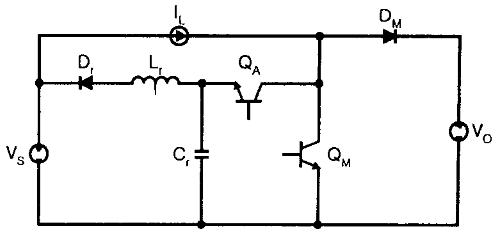

Fig. 3. Equivalent Circuit of ZCT Boost Converter

The main features of the proposed ZCT circuit cell are as follows.

- The main switch, Q_M is turned-off under zero current condition, the auxiliary switch, Q_A is turned-off under zero voltage condition, and the main diode, D_M is turned-on under zero voltage condition.
- There is no additional current stress and voltage stress at the main switch, Q_M.
- The resonant current required to obtain the ZCT is smaller than the peak current of the main inductor and regenerated to the input voltage source.

2.2 Mode analysis

The circuit diagram of the ZCT boost converter is presented in Fig. 2. To simplify the analysis, the follows are assumed.

- All components are ideal.
- The converter is operating in steady - state.
- The inductance of the main inductor, L is large enough to regard the main inductor as the constant current source.
- The capacitance of the output capacitor, C_O is large enough to regard the output capacitor as the constant voltage source.

According to these assumptions, the ZCT boost converter in Fig. 2 is transformed to the equivalent circuit in Fig. 3. The ZCT boost converter operates in six modes as shown in Fig. 4. And the key waveform of the ZCT boost converter is presented in Fig. 5. Prior to t_0, Q_M and Q_A are turned-off, so all the inductor current, I_L flows into the output voltage source, V_O and the resonant capacitor, C_r is charged $-V_{Cr}$.

i) Mode 1: M_1 (t_0~t_1)

Mode 1 begins as Q_M turns on, and the inductor current, I_L flows through Q_M. The ZCT circuit cell does not operate, so C_r holds the initial voltage, $-V_{Cr}$ and no current flows through L_r.

$$i_{Lr}(t) = 0 \tag{1}$$

$$v_{Cr}(t) = -V_{Cr} \tag{2}$$

When Q_A is turned-on, Mode 1 ends.

ii) Mode 2: M_2 (t_1~t_2)

The inductor current, I_L, which flowed through Q_M at Mode 1, flows through Q_A and C_r by the initial voltage of C_r, $-V_{Cr}$ and $v_{Cr}(t)$ increases linearly.

$$i_{Lr}(t) = 0 \tag{3}$$

$$v_{Cr}(t) = \frac{I_L}{C_r}(t - t_1) - V_{Cr} \tag{4}$$

If Q_M is turned-off before $v_{Cr}(t)$ becomes larger than zero, the ZCT of Q_M is obtained. When $v_{Cr}(t)$ reaches V_S, Mode 2 ends.

iii) Mode 3: M_3 (t_2~t_3)

Similarly to Mode 2, the inductor current, I_L flows through Q_A and C_r and $v_{Cr}(t)$ increases. The voltage of C_r is regenerated to the input voltage source, V_S through L_r and D_r, because $v_{Cr}(t)$ is larger than V_S.

$$i_{Lr}(t) = I_L\{1 - \cos w(t - t_2)\} \tag{5}$$

$$v_{Cr}(t) = V_S + I_L Z_r \sin w(t - t_2) \tag{6}$$

$$, where\ w = 1/\sqrt{L_r C_r} \quad and \quad Z_r = \sqrt{L_r / C_r}$$

When $v_{Cr}(t)$ reaches V_O, Mode 3 ends.

iv) Mode 4: M_4 (t_3~t_4)

The inductor current, I_L flows through the output voltage source, V_O. $v_{Cr}(t)$ is clamped to V_O, and $i_{Lr}(t)$ increases linearly by the constant voltage of L_r, (V_O-V_S).

$$i_{Lr}(t) = \frac{V_O - V_S}{L_r}(t - t_3) + i_{Lr}(t_3) \tag{7}$$

$$v_{Cr}(t) = V_O \tag{8}$$

When Q_A is turned-off, Mode 4 ends.

v) Mode 5: M_5 (t_4~t_5)

All the inductor current, I_L flows into the output voltage source, V_O. The voltage of C_r and the current of L_r are regenerated to the input voltage source, V_S through L_r and D_r.

$$i_{Lr}(t) = \frac{V_O - V_S}{Z_r} \sin w(t-t_4) + i_{Lr}(t_4) \cos w(t-t_4) \quad (9)$$

$$v_{Cr}(t) = (V_O - V_S) \cos w(t-t_4) - i_{Lr}(t_4) Z_r \sin w(t-t_4) \quad (10)$$

The voltage of C_r is charged to the initial voltage of C_r, $-V_{Cr}$ by the resonance of L_r and C_r.

$$v_{Cr}(t_5) = -V_{Cr} = -\sqrt{(V_O - V_S)^2 + \{i_{Lr}(t_4) Z_r\}^2} + V_S \quad (11)$$

When $i_{Lr}(t)$ reaches 0, Mode 5 ends.

vi) Mode 6: M_6 (t_5~t_6)

All the inductor current, I_L flows into the output voltage source, V_O. The ZCT circuit cell does not operate.

$$i_{Lr}(t) = 0 \quad (12)$$

$$v_{Cr}(t) = -V_{Cr} \quad (13)$$

When Q_A is turned-on, Mode 1 ends.

3. Design Guideline and Design Example

In this section, the design guideline and a design example of how to determine the component values of the ZCT boost converter are given.

The design specification is defined as follows.

- Input voltage: V_S = 50V
- Output voltage: V_O = 200V
- Output power: P_O = 200W
- Predicted efficiency: = 0.95 (95%)
- Switching Frequency: f_s = 100kHz

i) Calculate I_L at output power, P_O.

$$I_L = \frac{P_O}{V_S \cdot \eta} \quad (14)$$

$$I_L = \frac{200}{50 \times 0.95} = 4.2A$$

ii) Select the desired negative initial voltage of C_r, V_{Cr}.

$$V_{Q_A,\max} = V_O + V_{C_r} \quad (15)$$

$$V_{D_r,\max} = V_S + V_{C_r} \quad (16)$$

$$V_{Q_A,\max} = 200 + V_{C_r} \le 400V$$

$$V_{D_r,\max} = 50 + V_{C_r} \le 200V$$

Select V_{Cr} =130V.

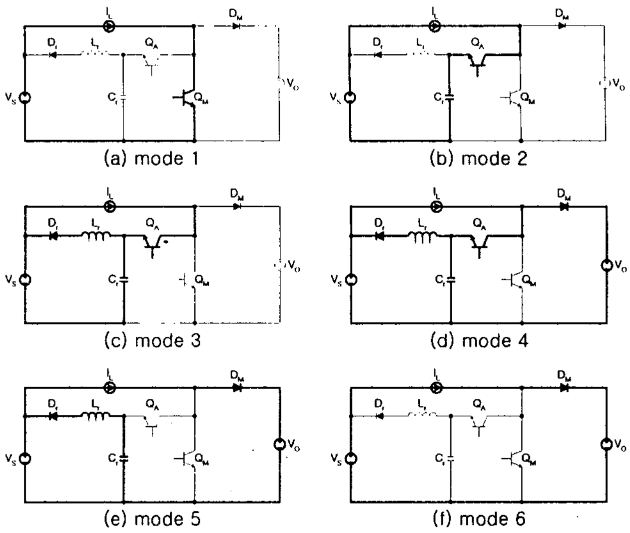

Fig. 4. Operation Modes

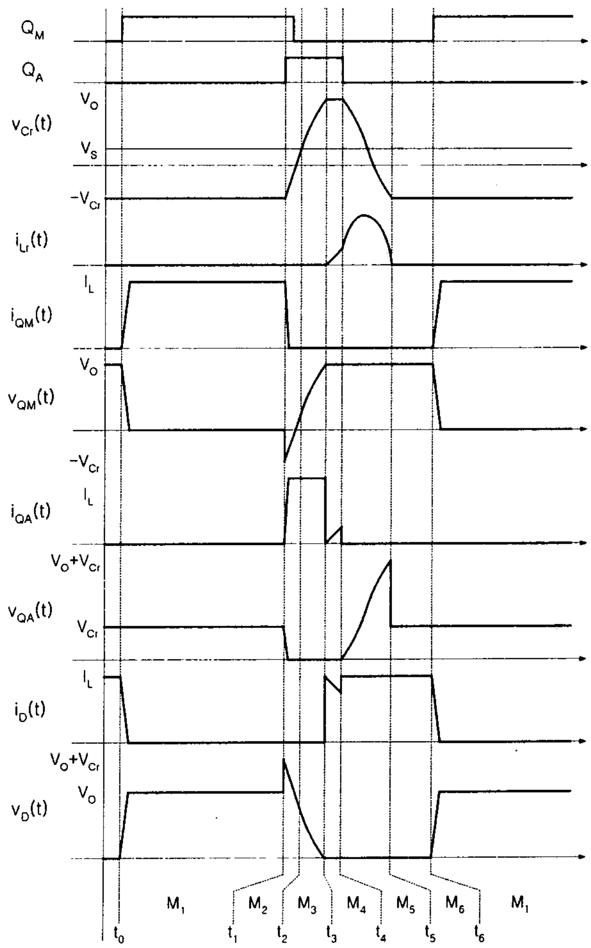

Fig. 5. Key Waveform of ZCT Boost Converter

iii) Calculate the characteristic impedance of L_r and C_r, Z_r required to obtain the selected V_{Cr}. The values of V_{Cr} as a function of Z_r are shown in Fig. 6.

$$V_{Cr} = \sqrt{(V_O - V_S)^2 + \left[Z_r \left\{ I_L - \sqrt{I_L^2 - \{(V_O - V_S)/Z_r\}^2} \right\} \right]^2} - V_S \quad (17)$$

Select $Z_r = 44.7\Omega$.

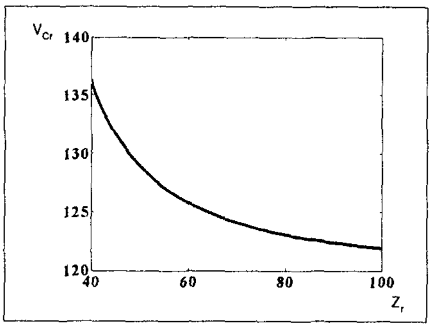

Fig. 6. Values of V_{Cr} as a function of Z_r

iii) Select the resonant period of L_r and C_r, T_r.

$$0.01T_S \le T_r \le 0.1T_S \quad (18)$$

$$, where \quad T_S : switching\ period$$

$$0.1u\sec \le T_r \le 1u\sec$$

iv) Calculate the values of L_r and C_r from Z_r and T_r.

$$L_r = \frac{Z_r T_r}{2\pi} \quad (19)$$

$$C_r = \frac{T_r}{2\pi Z_r} \quad (20)$$

$$L_r = 20uH$$

$$C_r = 10nF$$

v) Calculate the duty cycle of the auxiliary switch, Q_A, d and the time required to obtain the ZCT, T_{ZCT}.

$$d = \frac{1}{T_S}\left\{ \frac{C_r}{I_L}(V_S + V_{C_r}) + \sqrt{L_r C_r}\sin^{-1}\left(\frac{V_O - V_S}{Z_r I_L} \right) \right\} \quad (21)$$

$$T_{ZCT} = \frac{C_r}{I_L} V_{C_r} \quad (22)$$

$$d = 0.0343$$

$$T_{ZCT} = 0.095u\sec$$

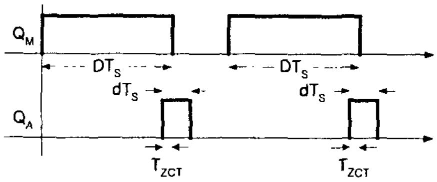

Fig. 7. Gate Signal of Main Switch and Auxiliary Switch

4. Simulation and Experimental Results

Following the design example shown in the preceding section, the 200W ZCT boost converter has been simulated with PSIM using the ideal components, and the prototype has been implemented to verify the operation and the performance of the proposed ZCT circuit cell. The design specification is presented in Table 1. The circuit used in the experiment is presented in Fig. 8 and the circuit parameters are shown in Table 2. The Auxiliary Inductor, L_A is added to reduce the resonance of the parasitic inductor and capacitor.

Table 1. Design Specification

V_S	50V	V_O	200V
P_O	200W	f_S	100kHz

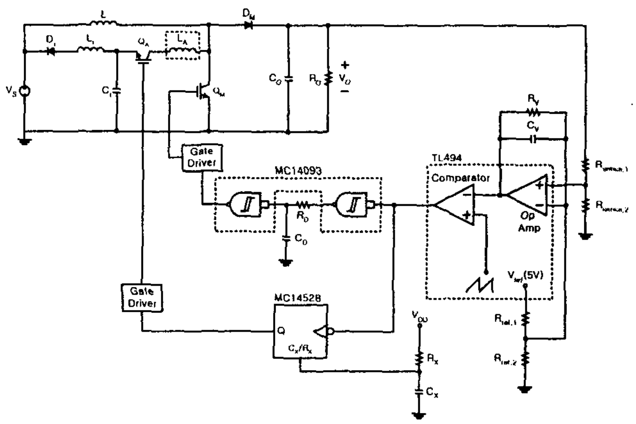

Fig. 8. Circuit used in the experiment

Table 2. Circuit Parameters

Q_M	IRG4PC50W (600V, 55A, 2.3V)	C_D	100pF
Q_A	IRG4PC50W (600V, 55A, 2.3V)	C_X	1nF
D_M	15ETH03 (300V, 15A, 40ns)	R_O	400Ω (ELECTRIC LOAD)
D_r	15ETH03 (300V, 15A, 40ns)	$R_{sense,1}$	240kΩ
L	1mH (PQ2625, 41turn)	$R_{sense,2}$	30kΩ
L_r	20uH (PQ2020, 23turn)	$R_{ref,1}$	20kΩ
L_A	4uH	$R_{ref,2}$	20kΩ
C_O	47uF, 250V, 2EA	R_V	100kΩ
C_r	10nF, 630V	R_D	1.3kΩ
C_v	1uF	R_X	270kΩ

The key waveform of the experiment is shown Fig. 9 and confirms the analysis mentioned previously. Like in the design example, V_{Cr} is 130V. The voltage stress of the auxiliary switch, Q_A is 330V. The peak current of the main switch, Q_M is 6A, and the peak resonant current is 4A. The voltage peak of D_M is reduced from (V_O+V_{Cr}) to V_O by adding the auxiliary inductor, L_A.

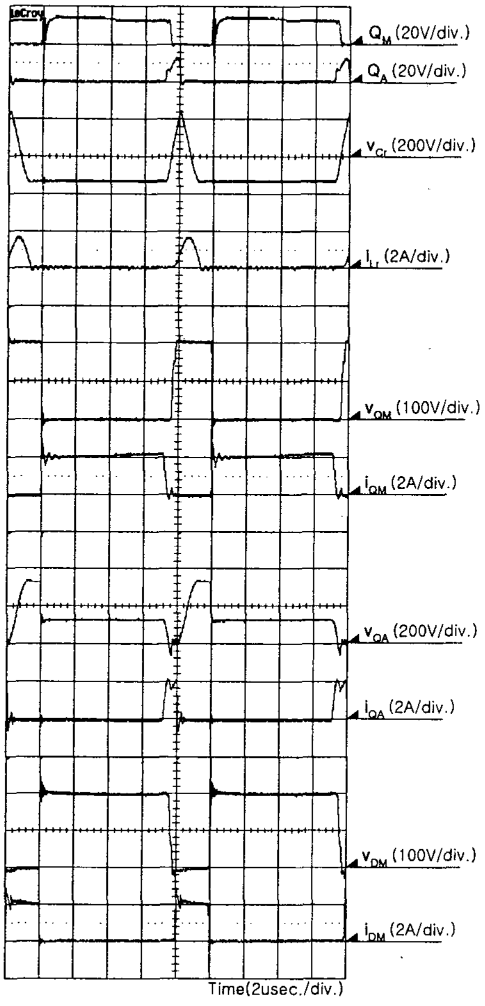

Fig. 9. Key Waveform of Experiment

Fig. 10 shows the voltage and current of the switching device, the main switch, Q_M, the auxiliary switch, Q_A, and the main diode, D_M. Q_M is turned-off under zero current condition, Q_A is turned-off under zero voltage condition, and D_M is turned-on under zero voltage condition. There is no additional current and voltage stress at the main switch and the main diode.

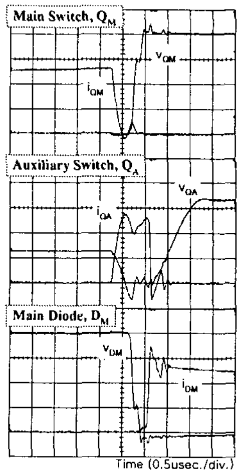

Fig. 10. Zoomed Waveform of Switching Device

5. Conclusions

The new ZCT circuit cell is proposed in this paper. The operational principle of the ZCT boost converter (the boost converter integrated with the proposed ZCT circuit cell) is described. The design guideline and the design example are presented. The operation of proposed ZCT circuit cell is verified through the simulation and experimental result on the 200W prototype of the ZCT boost converter. The main switch is turned-off under the zero current and zero voltage condition, and there is no additional current stress and voltage stress in the main switch. The auxiliary switch is turned-off under the zero voltage condition, and the main diode is turned-on under the zero voltage condition. The resonant current required to obtain the ZCT is small than the peak current of the main switch and regenerated to the input voltage source.

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