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Implementation of the Zero Current Transition PWM Boost Converter using Digital Signal Processor

Woo-Cheol Jeong* · Hong-Je Ryoo†

Abstract

There are various solutions for reducing turn-off loss of insulated gate bipolar transistor (IGBT). The 'zero current transition pulse width modulation' (ZCT-PWM) technique is one of them. For ZCT-PWM technique, the gate signal of auxiliary switch, which is synchronized to the gate signal of main switch is needed. This paper describes the implementation of both gate signals which is comprised of the main switch and the auxiliary switch using a digital signal processor (DSP), and 300-W ZCT-PWM boost converter is designed and implemented to verify ZCT technique.

Key Words : IGBT Turn-Off Loss, Soft Switching, Zero Current Transition (ZCT), Digital Signal Processor (DSP)

1. INTRODUCTION

Insulated gate bipolar transistor (IGBT) has excellent high voltage durability against metal-oxide-semiconductor field-effect transistor (MOSFET). Also, the IGBT has a constant collector-source voltage, but the MOSFET increases drain-source voltage as the current increases. Therefore, IGBT is more efficient than MOSFET with high power applications [1]. With these characteristics, IGBT is used in the electric vehicle motor drive, the traction motors in high-speed trains, and medium or high power applications used in renewable energy.

The high frequency switching is preferred to reduce size and weight of filter elements. However, IGBT has some disadvantage in high-frequency driving. Since the IGBT is a minority carrier device, it takes a long time to discharge the energy stored in the minority carrier during turn-off transient. Also, the abrupt collector-source voltage change that occurs during turn-off causes tail current in parasitic inductor of IGBT. Tail current results in a large switching loss. A number of soft-switching PWM and resonant techniques were proposed to overcome disadvantages of the IGBT [2-6]. A zero current switching (ZCS) technique is one of them. The ZCS is the technique that switch is turned off during current through the switch is zero. To

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operate ZCS technique, several resonant converters were proposed [7-13].

One of them, a quasi-resonant converter (QRC) has additional resonant elements for ZCS compared to conventional PWM converter [13]. Resonant elements resonate during operation of PWM converter and create a ZCS condition for the main switch at the turn-off instant. However, high peak current and high rms current flow through the main switch when using the resonance of converter. It causes large conduction loss and high voltage stress is applied to the switches and diodes. In addition, if the load changes to a huge range, the switching frequency also has to be modulated to a wide range, which makes difficult to optimize switching frequency and it may not satisfy ZCS condition. These shortcomings are because resonant elements in QRC belong to main power path.

In this paper, the zero current transition pulse width modulation (ZCT-PWM) converter was investigated and selected to compensate for these shortcomings [14]. The ZCT-PWM has additional shunt resonant circuit to the conventional PWM converter. The ZCT-PWM uses resonance only at switching instant of main IGBT via switching of the auxiliary switch connected to the resonant elements. The ZCT-PWM allows the resonant elements to be separated from the main power path except for switching instant of main IGBT and reduces the resonance time. As a result, have the following advantages:

- Minimize circulation energy
- Less conduction loss
- Less voltage stress on main devices
- Soft turn-off switching regardless of load variation

To test operation of ZCT-PWM technique, a 300-W ZCT-PWM boost converter is designed, simulated, and implemented.

2. OPERATION MODE ANALYSIS

Fig. 1 shows the circuit diagram of ZCT-PWM boost converter. The load is replaced with a constant voltage source assuming that filter capacitor is large enough. The input current is also a constant current because the boost inductor is large enough. Main switch S and rectifier diode D are on the main power path. The topology is similar as the conventional boost PWM converter. However, the ZCT-PWM converter additionally has shunt resonant network which makes a soft switching transition by resonance. This network is defined as 'resonant branch.' The resonant branch consists of the resonant inductor L_r, the resonant capacitor C_r, the auxiliary switch S_1, and the auxiliary diode D_1.

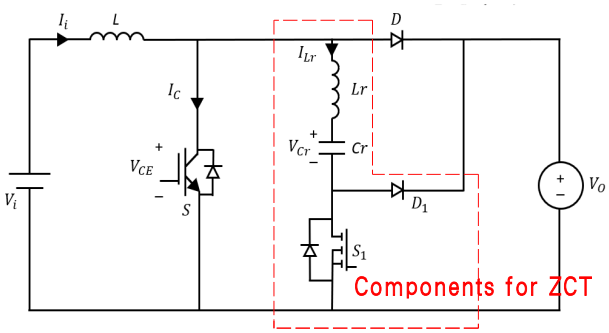

Fig. 1. Circuit diagram of ZCT-PWM boost converter

2.1 Mode 1(T0~T1) : Resonant Stage

Fig. 2 shows waveforms of ZCT-PWM boost converter[14]. Fig. 3 shows equivalent circuit diagrams of each mode. Before Mode 1 starts, the C_r is charged with $-V_{Cr}^{peak}$. The first mode of ZCT-PWM begins when S1 turns on. Resonance of the resonant branch starts and the negative voltage charged in C_r is discharged. The current of L_r is increased. When the resonant current becomes larger than the input current I_i, the reverse body diodes of S is conducted.

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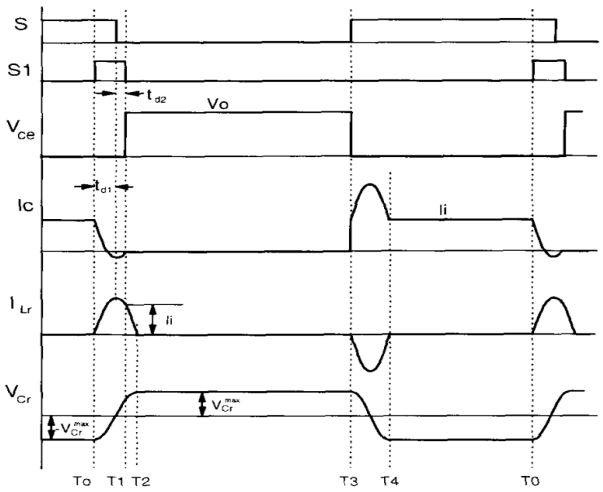

Fig. 2. Waveforms of ZCT-PWM Boost Converter[14]

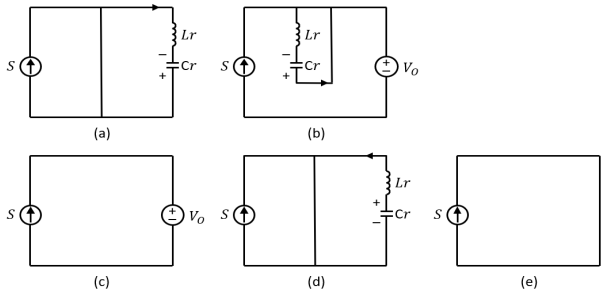

Fig. 3. Equivalent circuits of each mode

Then, main switch satisfies ZCS condition. The ZCS condition is maintained until T1, when the resonance current becomes smaller than I_i again. This is called zero current transition (ZCT). Negative voltage of C_r is discharged and becomes zero during t_{d1}. At this time, the resonant current is the maximum. The t_{d1} is quarter of resonance period ($T_r = 2\pi\sqrt{L_r C_r}$). Maximum resonant current value can be represented by this equation.

$$I_{L_r}^{\max} = \frac{V_{C_r}^{peak}}{Z_r} \left(Z_r = \sqrt{\frac{L_r}{C_r}}\right) \tag{1}$$

The voltage across the entire resonant tank is zero in this mode.

2.2 Mode 2(T1~T2) : Resonant Stage

Mode 2 starts with S_1-off and current flows through D and D_1. The resonant current value of T_1 ($i_{L_r}(T_1)$) is always I_i in steady state operation. If $i_{L_r}(T_1) > I_i$, a mode shown in Fig. 4-(a) is added between Mode 2 and Mode 3. This mode reduces the energy stored in the resonant branch. If $i_{L_r}(T_1) < I_i$, a mode shown Fig. 4-(b) is added between Mode 2 and Mode 3. This mode increases the energy stored in the resonant branch. When these processes are repeated, $i_{L_r}(T_1)$ is always I_i in the steady state operation regardless of the load condition. If $V_{C_r}^{peak} \leq V_o$, resonant capacitor's peak voltage is

$$V_{C_r}^{peak} = \frac{Z_r I_i}{\cos(2\pi T_{d2}/T_r)} \tag{2}$$

t_{d2} is the delay between the turn-off of gate signal of S and S_1. With $\alpha = 2\pi T_{d2}/T_r$, resonant inductor's maximum current is

$$I_{L_r}^{\max} = \frac{I_i}{\cos(\alpha)} \tag{3}$$

If $V_{C_r}^{peak} \leq V_o$ is satisfied, ZCT condition is satisfied regardless of input voltage or load current fluctuation. V_{Cr}^{peak} cannot exceed V_o, since D_1 would conduct during $T_4 - T_0$ if V_{Cr}^{peak} exceed V_o. The voltage across the entire resonant tank voltage is zero in this mode.

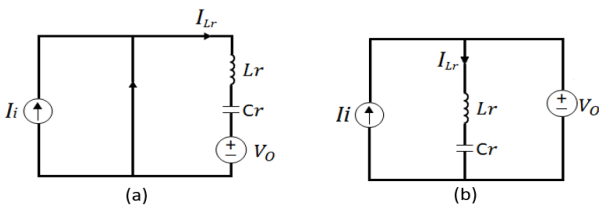

Fig. 4. Equivalent circuits of additional mode (a) $i_{L_r}(T_1) > I_i$ (b) $i_{L_r}(T_1) < I_i$

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2.3 Mode 3(T2~T3) : Conventional Boost Stage

After $i_{L_r}=0$ on T_2, it operates as the power transfer mode of the conventional boost converter. At this mode, the resonance branch doesn't belong to the main power path. The current through the entire resonant is zero in this mode.

2.4 Mode 4(T3~T4) : Resonant Stage

Mode 4 is for the inductor voltage second balance of L_r and the capacitor ampere second balance of C_r. The current through main switch reaches maximum in this mode. The voltage across the entire resonant tank is zero in this mode.

2.5 Mode 5(T4~T5) : Conventional Boost Stage

Mode 5 starts when the resonance current is 0. This mode operates as the power transfer mode of the conventional boost converter. In this mode, resonant branch doesn't belong to the main power path and the current through the entire resonant tank is zero.

In steady state operation, energy transfer between resonant branch and main power path is zero, because the voltage or current of the entire resonant tank is zero for each mode. The circulating energy is very small since the resonant stage is very short compared to the QRC. Additionally, there is no voltage ringing phenomenon at turn-off of main switch because the current of the semiconductor device doesn't change rapidly. Therefore, the voltage stress on the power transistor and the rectifier diode is small. On the other hand, the conduction loss of ZCT-PWM converter is similar to conventional PWM converter because peak current and rms current of ZCT-PWM converter similar to conventional PWM converter.

3. Design and Implementation of 300-W ZCT-PWM Boost Converter

To examine ZCT-PWM technique, 300-W ZCT-PWM boost converter is designed. This boost converter is regulated at 200 V output with 100 V input.

3.1 Resonant Branch Design

We use Eqs. (1), (2), and (3) to design L_r and C_r of the resonant branch. In order to use the above equations, $V_{C_r} \leq V_o$ must be satisfied. In the ideal case, the constant input current is used in the above equations, but in practical case, the input side has a small current ripple even if the boost inductor is large. The current at the turn-off of the main switch (I_{Soff}) is used as I_i in practice because the reason for using resonant branch is to solve the problem that occurs when the main switch (IGBT) turns-off. Fig. 5-(a) is a conventional boost converter circuit diagram that uses PSIM software to measure I_{Soff}. Fig. 5-(b) shows the waveform of the current through main switch S (i_S) and the gate signal of S. Table 1 is the specification of the design. Specification is the same as the target ZCT-PWM converter except the resonant branch.

Simulation shows $I_{Soff}=3.62A$ in conventional boost converter. MATLAB codes were used to obtain L_r and C_r that satisfy eqs. (2), (3) and $V_{C_r}^{peak} \leq V_o$.

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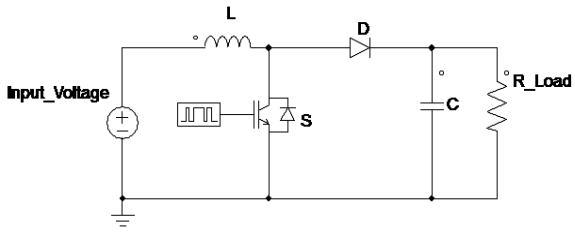
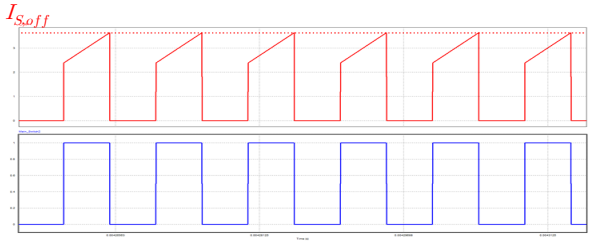


(a)



(b)

Fig. 5. 300-W 100 V/200 V conventional boost converter (a) Circuit diagram using PSIM (b) i_S(red) and gate signal of main switch(blue)

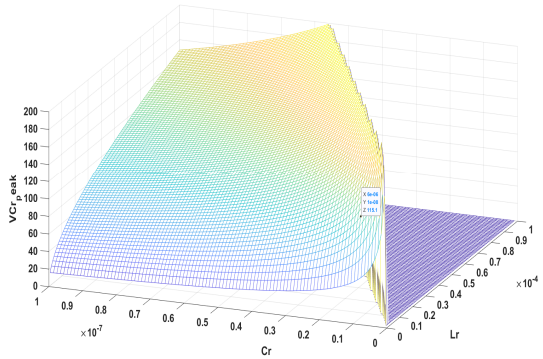
Table 1. Conventional boost converter design specification

Input voltage	100V
Boost inductor inductance	400μH
Output capacitor capacitance	300μF
Load resistance	133Ω
Output voltage	200V
Output power	300W

Fig. 6 is a three-dimensional graph with $L_r, C_r, V_{C_r,peak}$ as x,y,z axis. The range of each axis is $1\,\mu H \le L_r \le 100\,\mu H$, $1\,nF \le C_r \le 100\,nF$, $0 \le V_{C_r,peak} \le 200\,V$. The reason for $T_{d2} = 0.11 * T_r$ is to make $I_{Lr}^{\max}$ 30 % larger than I_i in equation (3). It is better to design so that $V_{C_r,peak}$ isn't too large because parasitic inductance or capacitance may cause additional resonance. Also, the smaller the T_r, the shorter the resonant stage $(t_{d1}+t_{d2})$ and the advantages of ZCT-PWM can be maximized. Considering these conditions, one point in the graph $(6\,\mu H, 10\,nF, 115\,V)$ is selected. L_r used $6\,\mu H, 17\,turns$ air core inductor to prevent saturation, and C_r used $10\,nF$ film capacitor.

```
Lr=[1E-06:0.1E-06:10E-06];
Cr=[1E-09:1E-09:100E-09];


[Lr,Cr]=meshgrid(Lr,Cr);
Tr=2*pi.*sqrt(Lr.*Cr);
Zr=sqrt(Lr./Cr);
Ii=3.62;
Td2=0.11.*Tr;

VCr_peak = Ii*sqrt(Lr./Cr)./cos(2*pi.*Td2./Tr);


VCr_peak(VCr_peak<0)=0;
VCr_peak(VCr_peak>200)=0;


mesh(Lr,Cr,VCr_peak);
```

(a)



(b)

Fig. 6. Resonant components design (a) MATLAB code for design (b) $L_r - C_r - V_{C_r,peak}$ 3D graph

3.2 Simulation of 300-W ZCT-PWM Boost Converter

Fig. 7 shows a PSIM model of 300-W ZCT-PWM boost converter. The specifications of the converter are given in Table 2. Fig. 8 is a simulation waveforms. Simulation results show that when the

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main switch is switched off, the resonant current is larger than the boost inductor current and the reverse current flows through main switch. As a result, the ZCT condition is satisfied.

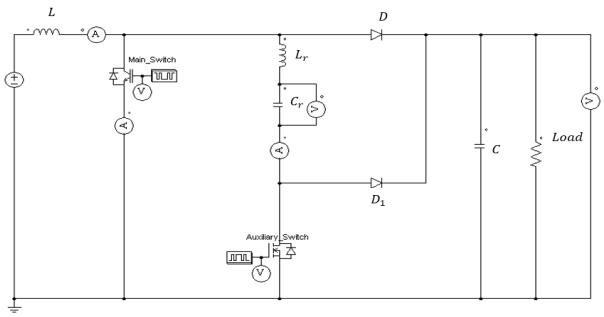

Fig. 7. PSIM model of 300-W ZCT-PWM boost converter

Table 2. 300-W ZCT-PWM boost converter design specification

V_i	100V
L	400μH
C	300μF
L_r	6μH
C_r	10nF
R	133Ω
V_o	200V
P_o	300W

3.3 Gate Signal of Main Switch and Auxiliary Switch Using DSP

To operate ZCT-PWM boost converter, the 50% duty, 100 kHz main switch gate signal and 100 kHz auxiliary switch gate signal which is turned on by t_{d1} before turn-off of main switch and turned off t_{d2} later than the turn-off of the main switch are required. The algorithm for the implementation of the auxiliary switch gate signal is Fig. 9. The 'ePWM1' provides the gate signal to the main

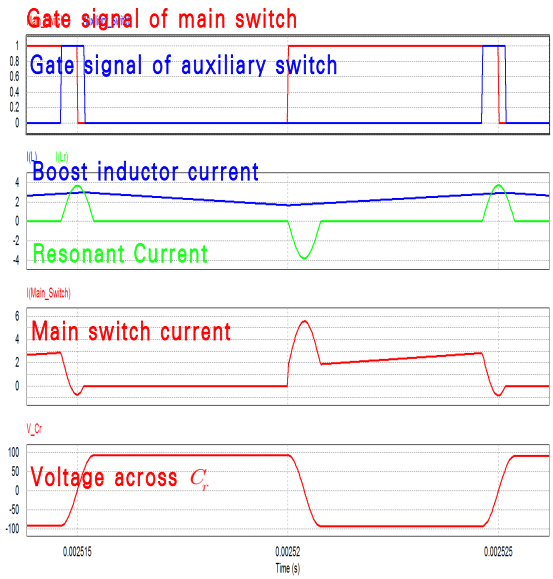

Fig. 8. Simulation results of 300-W ZCT-PWM boost converter

switch, the 'ePWM2' provides the gate signal to the auxiliary switch. At the algorithm, ePWM1_CMPB = $(t_{S,on} - t_{d1}) \times TBCLK$ and $t_{S,on}$ is the length of the time which the main switch is on state. If the TBCTR of ePWM1 equals ePWM1_CMPB, a synchronization signal is sent to the lower ePWM module(ePWM2). When the synchronization signal is arrived, TBCTR of ePWM2 is initialized to 0, and the output of ePWM2 becomes high. And if the TBCTR of ePWM2 equals to ePWM2_CMPA(= $(t_{d1} + t_{d2}) \times TBCLK$), the output of ePWM2 becomes low. Using the resonant period T_r of the resonant branch designed in this paper, $t_{d1} = 385ns$, $t_{d2} = 169ns$.

The output of the DSP is connected to the switch through the gate driver. The gate driver is configured using IXDD404, which is capable of 2-input/2-output. The boost converter's main switch is adjacent to the ground. Therefore, isolation transformer is not needed for the gate driver.

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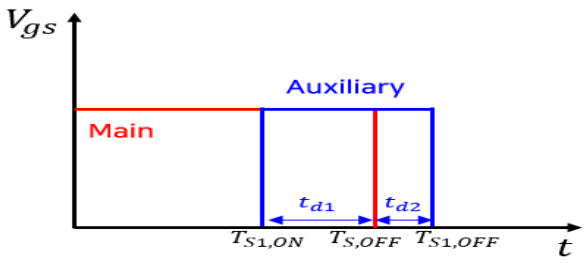


Fig. 9. ZCT-PWM gate signal

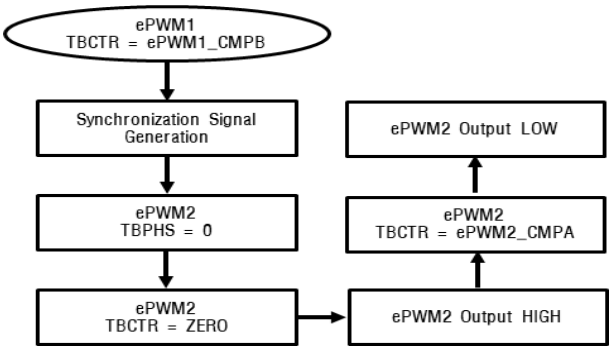
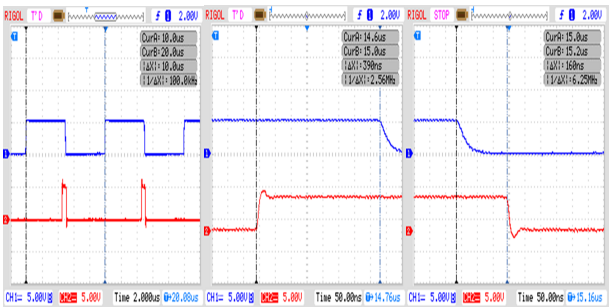


Fig. 10. Gate Signal Algorithm

Fig. 11 are the gate signal waveform obtained from actual experiments. The blue waveform is gate signal of main switch and the red waveform is gate signal of auxiliary switch. Fig. 11-(a) shows that experimental switching frequency is 100 kHz. Fig. 11-(b) shows that experimental $t_{d1} = 390ns$ and Fig. 11-(c) shows that experimental $t_{d2} = 160ns$. The difference between the design values and experimental values of t_{d1} and t_{d2} is negligible.



(a) $T_S = 10us$ (b) $t_{d1} = 390ns$ (c) $t_{d2} = 160ns$

Fig. 11. Experimental waveforms of gate signal

3.4 Experimental Results

Applying the designed parameter examined through the simulation, 300-W ZCT-PWM boost converter was implemented. Fig. 12 is the entire experimental system : Converter, DSP board, SMPS, and Load resistor. SMPS was used to power DSP board and gate driver.

Fig. 13 is the experimental waveform that shows gate signal of main switch, auxiliary switch, boost inductor current, and resonant current. As designed, it can be seen that the resonant current is greater than the boost inductor current when the main switch is turned off. Therefore IGBT's ZCT condition is satisfied.

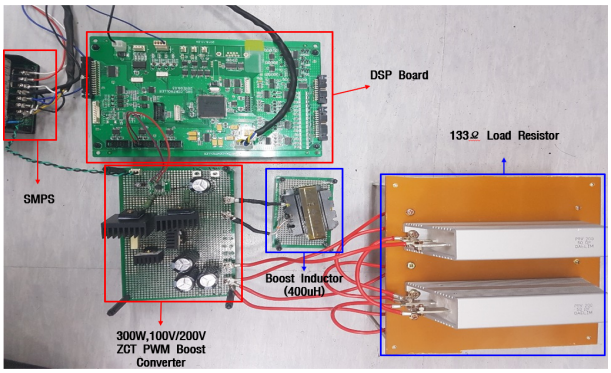


Fig. 12. Entire experimental system

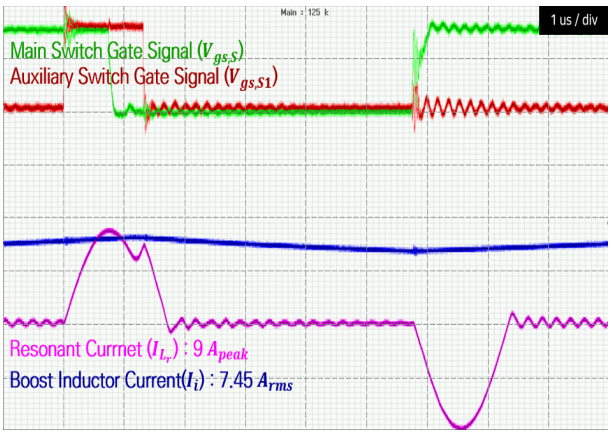


Fig. 13. Experimental waveform

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4. Conclusion

IGBT has been widely used in high-power applications as it improves switching speed, reduces challenge losses, and becomes cheaper. However, IGBT is not used at high frequencies because of large turn-off loss.

The resonant converter was proposed to reduce turn-off loss of the IGBT using ZCS technique. But, resonant converter has large circulating energy, has limited load range to satisfy ZCS condition, and gives high voltage/current stress to semiconductor devices.

In this paper, we investigated and selected ZCT-PWM technique to overcome these shortcomings and designed and implemented 300-W ZCT-PWM boost converter. ZCT-PWM constitutes shunt resonance branch instead of the resonant elements which is in main power path. If the on-off state of the auxiliary switch in this resonant branch is properly designed, resonance is used only in the vicinity of the turn-off instant of the main switch and creates the zero current transition condition. Turn-off loss of main switch is zero in ZCT condition. Although resonance is used, ZCT-PWM topology has small circulating energy, soft switching is possible regardless of load condition and voltage/current stress applied to semiconductor devices is low. This is because resonance is used for only a very short period compared to entire operation period of the converter (remaining period is the same as the operation mode of the conventional PWM converter) and resonant elements don't belong to the main power path.

In order to drive the ZCT-PWM, gate signal of main switch and the gate signal of auxiliary switch have specific associations with the turn-off instant of the main switch. This gate signals could be generated by DSP.

Resonance branch parameters were designed taking into account peak resonance current and required resonance times. Using the parameters, the 300-W ZCT-PWM boost converter was implemented and experimental result shows that theoretical ZCT technique is actually possible.

The ZCT-PWM technique is expected to be used for the following needs:

- When soft switching turn-off of power switch is required.
- When low voltage/current stress condition is required for power switches and diodes.
- When reducing circulating energy is required.
- When soft switching condition is required in large load range.

Acknowledgement

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