

# Boost Type ZVS-PWM Chopper-Fed DC-DC Power Converter with Load-Side Auxiliary Resonant Snubber and Its Performance Evaluations

Koki Ogura\*, Srawouth Chandhaket\*, Tarek Ahmed\* and Mutsuo Nakaoka\*

**Abstract** - This paper presents a high-frequency boost type ZVS-PWM chopper-fed DC-DC power converter with a single active auxiliary edge-resonant snubber at the load stage which can be designed for power conditioners such as solar photovoltaic generation, fuel cell generation, battery and super capacitor energy storages. Its principle operation in steady-state is described in addition to a prototype setup. The experimental results of boost type ZVS-PWM chopper proposed here, are evaluated and verified with a practical design model in terms of its switching voltage and current waveforms, the switching  $v-i$  trajectory and the temperature performance of IGBT module, the actual power conversion efficiency, and the EMI of radiated and conducted emissions, and then discussed and compared with the hard switching scheme from an experimental point of view. Finally, this paper proposes a practical method to suppress parasitic oscillation due to the active auxiliary resonant switch at ZCS turn-off mode transition with the aid of an additional lossless clamping diode loop, and can be reduced the EMI conducted emission.

**Keywords:** DC-DC converter, Active auxiliary edge-resonant snubber, Zero voltage soft switching (ZVS), PWM,  $v-i$  switching trajectory representation, Parasitic oscillation diode clamping loop, EMI noise evaluations

## 1. Introduction

In recent years, the higher efficiency and the more advanced power conversion, energy utilization equipment, a variety of circuit topologies of the soft-switching DC-DC power converter are urgently required. The practical developments of isolated or non-isolated DC-DC power converter using power MOSFETs or IGBTs have attracted special interest in various fields related to the alternative and renewable energy generation and power supplies of small-scale distributed type photovoltaic generation system (PVGS), fuel cell generation system (FCGS) and battery or super capacitor energy storage systems for residential power energy applications, information and telecommunication equipment, and automobile power electronic applications including pure electric vehicle (EV) and hybrid EV systems. Because of the high-frequency switching PWM technologies with the great advances of power semiconductor devices such as power MOSFETs, IGBTs, SITs, in addition to microprocessor control board and the magnetic circuit components of inductor and transformer, the DC-DC power converters have been strongly demanded miniaturization in size, lighter in weight, and high performances (high-speed response, and waveform quality). However, the significant problems for the high-frequency switching

PWM power conversion technologies cause system efficiency reduction due to increased switching losses and snubber circuit losses, the higher  $dv/dt$  and  $di/dt$  electrical surge stresses, high frequency leak current to the ground and EMI noises; radiated emission and conducted emission. For effective and practical solutions, it is presently necessary to use the principles of soft-switching power conversion PWM techniques, which are based on active auxiliary edge resonant snubber[1]-[6] or passive edge resonant snubber[7],[8].

In this paper, the circuit topology of the boost type ZVS-PWM chopper-fed DC-DC power converter with a simple active auxiliary edge-resonant snubber is proposed. The experimental results of boost type ZVS-PWM chopper-fed DC-DC power converter designed for the maximum 3kW output power, and switching frequency 16kHz are presented and discussed, together with comparative operating characteristics of this ZVS-PWM chopper-fed DC-DC power converter and conventional hard switching PWM one. In addition, this paper points out the practical method to protect a large voltage spike due to unnecessary and undersigned parasitic oscillation of the auxiliary resonant active power switch at ZCS turn-off commutation. This parasitic oscillation of this active resonant snubber can be suppressed with the aid of the simple lossless clamping diode connected with the auxiliary resonant snubber which can utilize at the loadside energy processing. Furthermore, the practical effectiveness of this ZVS-PWM chopper-fed DC-

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DC power converter with clamping diode loop is substantially proved on the measured conducted EMI noise from an experimental point of view.

## 2. Boost Type ZVS-PWM Chopper-fed DC-DC Power Converter

### 2.1 Circuit Description

Fig. 1 shows the circuit configuration of the proposed edge-resonant boost type ZVS-PWM chopper-fed DC-DC power converter using IGBTs. This converter is based on the conventional boost type PWM chopper-fed DC-DC power converter, which also includes an active auxiliary resonant snubber circuit composed of a resonant inductor  $L_r$ , a resonant capacitor  $C_r$ , a lossless snubber capacitor  $C_s$ , an auxiliary active power switch  $S_2$  and an auxiliary diode  $D_2$ . This DC-DC power converter is an improved circuit of [1]. The converter circuit proposed in [1] has a problem which the auxiliary switch is turned off under hard switching. However this auxiliary switch in the proposed boost type ZVS-PWM chopper-fed DC-DC power converter can operate ZCS and ZVS under the turn-off transition by adding a resonant capacitor  $C_r$ .

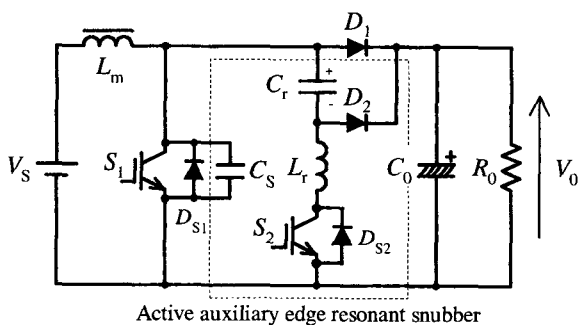


Fig. 1 Zero voltage soft switching boost chopper type DC-DC converter using auxiliary edge resonant snubber

### 2.2 Circuit Operation

The mode transition of boost type ZVS-PWM chopper-fed DC-DC power converter are depicted in Fig. 2. The gate voltage pulse sequences of the main active power switch and the auxiliary active power switch are indicated in Fig. 3, the operating voltage and current waveforms of each component are shown in Fig. 3. The operating principle in mode transitions of this chopper-fed DC-DC power converter is explained as follows;

**Mode 0** The stored energy of the boost inductor  $L_m$  is transferred to the load side. When the auxiliary power switch  $S_2$  is turned on, Mode 0 changes to Mode 1.

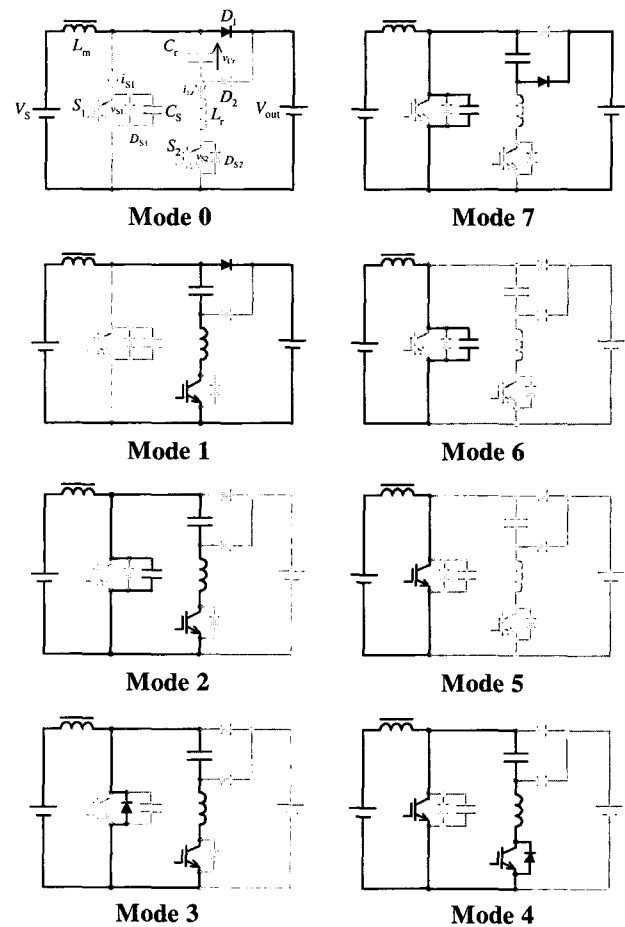


Fig. 2 Mode transitions and equivalent circuits

**Mode 1** When the auxiliary power switch  $S_2$  is turned on with ZCS, the current through the diode  $D_1$  begins to flow the active auxiliary resonant snubber circuit. The current flow through the resonant inductor  $L_r$ , and the resonant capacitor  $C_r$ , and the auxiliary power switch  $S_2$  increases sinusoidally.

**Mode 2** When the diode  $D_1$  is turned off, the current flowing through  $D_1$  commutates through the active auxiliary resonant snubber circuit. The lossless snubber capacitor  $C_s$  connected in parallel with the main power switch  $S_1$  is produced the edge-resonant mode with a resonant inductor  $L_r$  and resonant capacitor  $C_r$ . Therefore, the lossless snubber capacitor  $C_s$  becomes the discharging mode, and the voltages across  $C_s$  drops gradually. Then, Mode 2 changes to Mode 3.

**Mode 3** When the voltage across the snubber capacitor  $C_s$  becomes zero, the anti-parallel diode  $D_{S1}$  of the main power switch  $S_1$  is naturally turned on. As a result, the main power switch  $S_1$  can achieve ZVS and ZCS hybrid soft commutation in a turn-on transition when current flow through the anti-parallel diode  $D_{S1}$  decreases and naturally shifts to the main power switch  $S_1$  by giving the gate voltage signal of the main power switch  $S_1$  while  $D_{S1}$  is turned on.

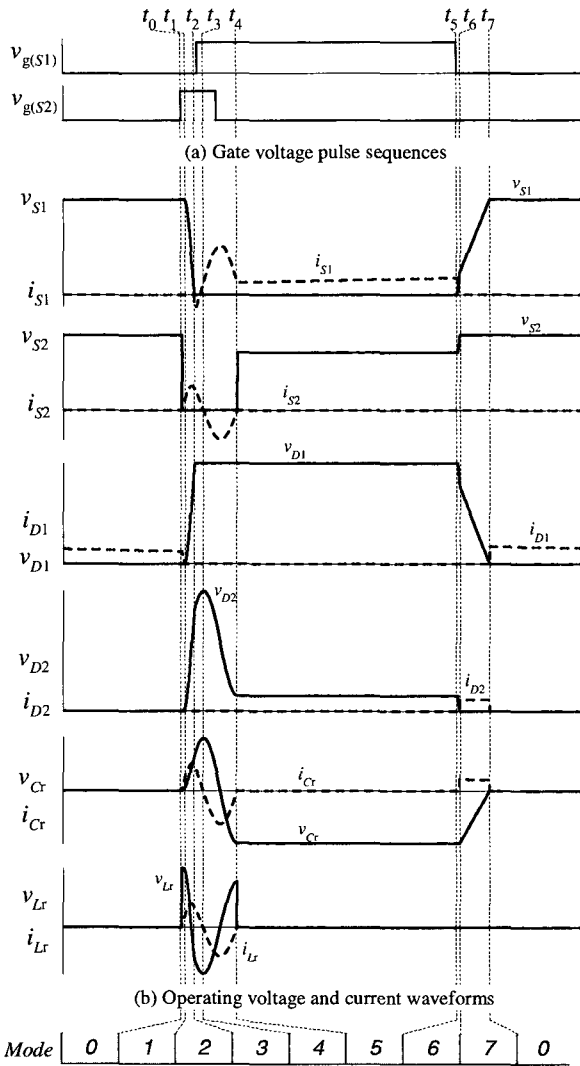


Fig. 3 Gate pulse sequences and typical operating waveforms

**Mode 4** When the current of the main power switch  $S_1$  becomes bigger than the current flowing through a boost inductor  $L_m$ , the diode  $D_{S2}$  in anti-parallel with the auxiliary power switch  $S_2$  is naturally turned on, and the current flowing through  $S_2$  begins to commute to the anti-parallel diode  $D_{S2}$ . By turning the gate voltage pulse signal delivered to the auxiliary power switch  $S_2$  during this period, an auxiliary power switch  $S_2$  can achieve complete ZVS and ZCS hybrid soft commutation under the turn-off transition when the current flowing through the auxiliary power switch  $S_2$  shifts exactly.

**Mode 5** When the auxiliary power switch  $S_2$  is turned off, the resonant current flowing through the inductor  $L_r$  and the capacitor  $C_r$  becomes zero; all the circuit operations are identical to the conduction state of the conventional boost type PWM chopper-fed DC-DC power converter.

**Mode 6** When the main power switch  $S_1$  is turned off with ZVS, the current flowing through the boost inductor  $L_m$  flows through the snubber capacitor  $C_s$ . Therefore, the

lossless snubber capacitor  $C_s$  becomes its charging mode, and the voltages across the lossless capacitor  $C_s$  increases gradually.

**Mode 7** When the voltage across the lossless snubber capacitor  $C_s$  becomes larger than the sum of the voltage across the resonant capacitor  $C_r$  and the output voltage  $V_o$ , the auxiliary diode  $D_2$  is turned on. When the voltage across the lossless snubber capacitor  $C_s$  equals to the output average voltage  $V_o$  and the voltage across the auxiliary resonant capacitor  $C_r$  becomes zero, the diode  $D_2$  is naturally turned off. At the same time, the diode  $D_1$  is turned on and Mode 7 shifts to Mode 0.

This boost type ZVS-PWM chopper-fed DC-DC power converter repeats cyclically the steady-state operation described above.

### 3. Experimental Results and Performance Evaluations

#### 3.1 Design Specifications and Switching Operating Waveforms

The experimental design specifications and circuit parameter of the boost type ZVS-PWM chopper-fed DC-DC power converter with a single active auxiliary edge-resonant snubber is listed in Table 1.

Table 1 Design specifications and circuit parameters

DC Input Voltage	$V_s$	200V	Snubber Capacitor	$C_s$	33nF
DC Output Voltage	$V_o$	380V	Resonant Inductor	$L_r$	7.6μH
Switching Frequency	$f_s$	16kHz	Resonant Capacitor	$C_r$	121nF
Output Capacitor	$C_o$	8,200μF	Boost Inductor	$L_b$	1.02mH

(Remarks)

Power Switching Devices

. IGBT [ $S_1, S_2$ ] – Mitsubishi CM75DU-24H

. Diode [ $D_1$ ] – Toshiba 30JL2C41

. Diode [ $D_2$ ] – Hitachi DFM30F12

Fig. 4 (a) illustrates the voltage and current operating waveforms and its  $v-i$  trajectory in case of turn-on commutation of the main power switch  $S_1$  of the hard switching boost type PWM chopper-fed DC-DC power converter in the hard switching. Fig. 4 (b) illustrates the voltage and current operating waveforms and its  $v-i$  trajectory in case of turn-on commutation of the main power switch  $S_1$  of the ZVS-PWM one in the soft switching. From the voltage and current waveforms in Fig. 4 (a) under a condition of a hard switching commutation, the higher  $dv/dt$  and rapid  $di/dt$  characteristics as well as voltage surge and current surge can be observed. Moreover, taking a look at the  $v-i$  trajectory in Fig. 4 (a), it spread out over the first quadrant and the second quadrant area. Therefore, it is based on the in-

censement of the electrical switching stresses for IGBT used in the converter, and increase of the switching power loss and EMI noises. However, switching waveforms in Fig. 4 (b) under a condition of soft-switching commutation, the softened  $dv/dt$  and  $di/dt$ , and the suppression of the voltage surge and current surge can be achieved. Observing the  $v-i$  trajectory in Fig. 4 (b), it goes along the voltage axis and current axis of the main power switching device, so the ideal soft switching operation can be achieved without the switching losses at turn-on transition. Therefore, under the soft-switching scheme, the switching power losses, voltage surge and current surge don't occur because the switching can be achieved under a condition of ZVS and ZCS.

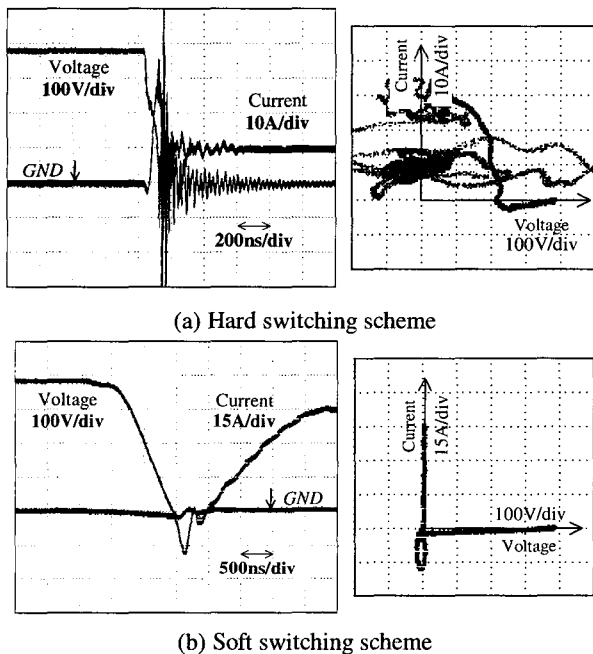


Fig. 4 Voltage and current waveforms and  $v-i$  trajectory in case of turn-on transition of main power switch  $S_1$

Fig. 5 (a) shows the voltage and current operating waveforms and its  $v-i$  trajectory in case of turn-off switching commutation in the hard switching. Fig. 5 (b) illustrates the voltage and current operating waveforms and its  $v-i$  trajectory in case of turn-off switching commutation in the soft-switching. From the voltage and current switching waveforms at turn-off commutation as depicted in Fig. 5 (a) under the hard switching commutation, there is overlapped region of voltage and current switching waveforms. Moreover, observing the  $v-i$  trajectory in Fig. 5 (a), it spreads out in the first quadrant in the  $v-i$  plane. Therefore, this concerns with increase of the switching power losses. Therefore, in Fig. 5 (b) under soft switching commutation, except for the overlapping period of the switching voltage and falling current during the turn-off period and tail current during the tail period of IGBT, there is no overlapping region. And taking a look at the  $v-i$  trajectory illustrated in

Fig. 5 (b), it is nearly moving along the voltage axis and current axis of  $v-i$  plane. Therefore, under a soft-switching PWM scheme, the switching power losses of the power switch can be lowered as compared with that of the hard switching PWM scheme.

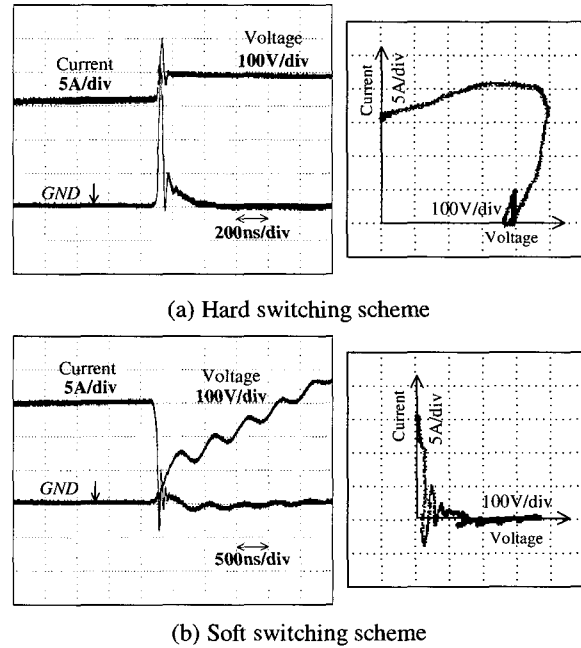


Fig. 5 Voltage and current waveforms and  $v-i$  trajectory in case of turn-off transition of main power switch  $S_1$

### 3.2 Temperature Characteristics of Main Power Switch

A small pin hole is made under the metal bottom side of IGBT as the main switch  $S_1$  power module package as shown in Fig. 6, and the tip of the K-type thermocouple probe is tightly inserted into the central portion of the IGBT module. The measured temperature of the IGBT module package under a both operating conditions of the hard switching (H-SW) and soft-switching (S-SW) PWM schemes is depicted in Fig. 7.

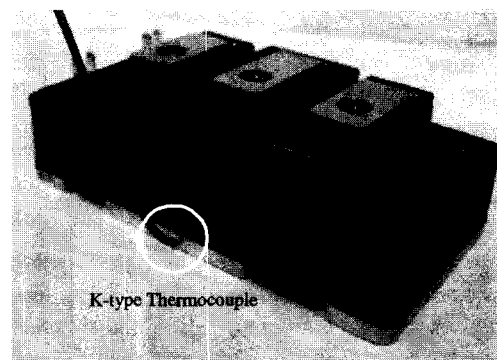


Fig. 6 Temperature measurement of IGBT module using K-type thermocouple

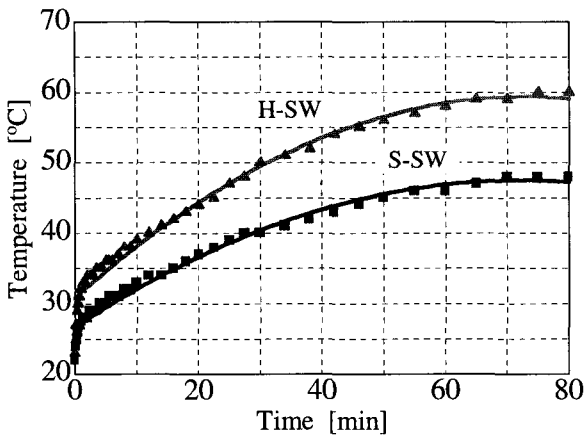


Fig. 7 Temperature measurement of IGBT module

As shown in Fig. 7, after 80 minutes of operation, the temperature of IGBT under hard switching scheme is 60°C, but the temperature under soft-switching scheme is 48°C. So soft-switching reduced temperature about 12°C as compared with hard switching scheme. From these results, the downsizing of the cooling equipment can be substantially achieved, because the switching power losses of the main power switch  $S_1$  can be sufficiently reduced with using ZVS-PWM scheme.

### 3.3 Actual Power Conversion Efficiency Characteristics

The actual power conversion efficiency of hard switching boost type PWM chopper-fed DC-DC Power converter and soft switching ZVS-PWM type can be respectively measured by using the digital power meter. As the results in Fig. 8, the actual efficiency of the soft switching is higher than that of hard switching for the required output power range. Especially, for 3kW breadboard setup, the actual conversion efficiency of soft-switching PWM scheme achieves up to 97.8%. And moreover, for high frequency switching, this power circuit can achieve higher efficiency characteristics.

### 3.4 EMI Testing of Radiated Emissions

The performance of radiated emission measured by EMC bilog antenna (30MHz~1GHz) in the shielded anechoic chamber shown in Fig. 9. Observing from the results in Fig. 10, soft switching has the lower noise level compare to the hard switching for all over the frequency range. Especially, the noise level for the maximum 37.1 [dBμV/m] can be reduced at 230MHz. It is more effective to use the boost type ZVS-PWM chopper-fed DC-DC power converter with active auxiliary resonant snubber to suppress the radiated emission.

### 3.5 EMI Testing of Conducted Emissions

The measuring result of conducted emission is measured with using the line impedance stabilization network (LISN) shown in Fig. 11[9],[10]. According to the results shown in Fig. 12, soft switching is lower noise level compare to the hard switching all over the frequency range except for around 1.8MHz, 2.7MHz and 5.5MHz. Especially over 6MHz, soft switching can be excellent performance compared with hard switching. It is effective to use a soft-switching PWM scheme with active auxiliary resonant snubber to suppress the conducted emission.

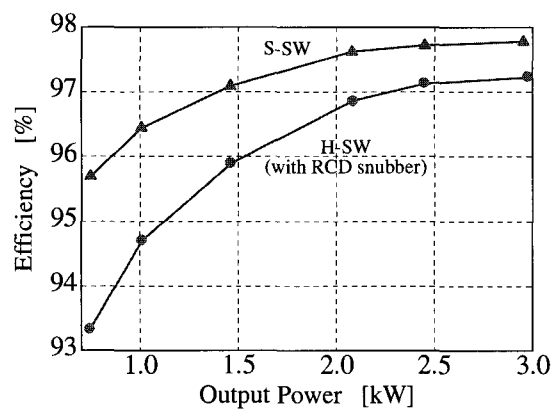


Fig. 8 Output power vs. actual efficiency characteristics

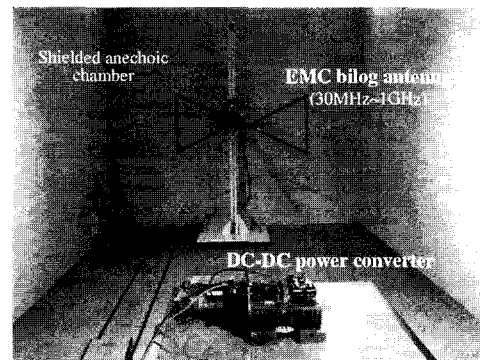


Fig. 9 Facility for measuring radiated emission

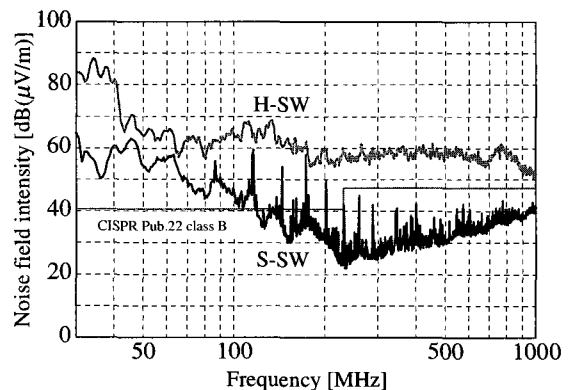


Fig. 10 Noise measurement of radiated EMI

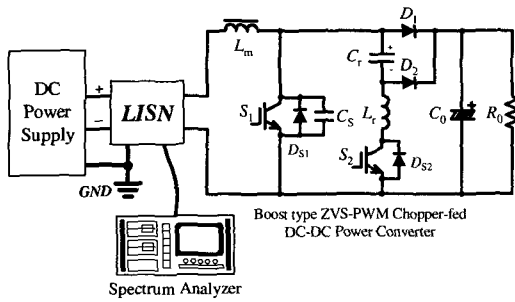


Fig. 11 Measurement of conducted emission

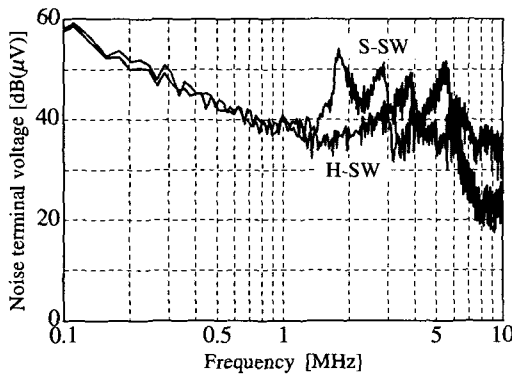


Fig. 12 Noise measurement of conducted EMI

#### 4. Parasitic Oscillation of Auxiliary Power Switch at ZCS Turn-off

##### 4.1 Generation of Parasitic Oscillation

Fig. 13 depicts a parasitic oscillation phenomenon at the voltage across the auxiliary power switch  $S_2$  and its current waveforms at ZCS turn-off. This means that the quality factor of edge resonant circuit is high, and the element of dissipation is substantially small. The peak surge voltage across the auxiliary power switch  $S_2$  becomes about 900V, so the power semiconductor device protection of the auxiliary power switch from a surge voltage is a significant problem.

Before the auxiliary power switch  $S_2$  is turned off, the resonant current flowing through  $S_2$  has naturally commutate to the antiparallel diode  $D_{S2}$ . During this interval, the gate voltage pulse signal of the auxiliary power switch  $S_2$  has to be turned off. Presently, the resonant current flowing through the antiparallel diode  $D_{S2}$  becomes zero if the diode  $D_{S2}$  is ideal. But in fact, the resonant current is not suppressed, and the reverse recovery current flowing through  $D_{S2}$  appears when changes from forward-directional bias to the reverse-directional bias.

The recombination and diffusion of the minority carrier is to be generated when the current direction changed into the reverse direction from the forward direction. Due to the

rapid direction change of current with a higher  $di/dt$ , a resonant inductor  $L_r$  connected to the auxiliary power switch  $S_2$  in series induces a large voltage from the steep  $di/dt$ . So the voltage across the auxiliary power switch  $S_2$  induces a large voltage, too. The voltage and current waveforms of the resonant inductor  $L_r$  at this time are shown in Fig. 14. The energy stored into that resonant inductor decreases with continuing resonant oscillation between the resonant inductor and the resultant parasitic capacitance including diffusion capacitance and junction capacitance of the antiparallel diode  $D_{S2}$  in addition to the capacitance  $C_{CE}$ (see Fig. 15). Observing this oscillation frequency by using the synchroscope, the frequency is about 2.7MHz. As compared with the results of synchroscope and the results of conducted emission shown in Fig. 12, it is proved that the fundamental frequency (about 2.7MHz) and the twice of frequency (about 5.4MHz) appear as a spectrum due to this oscillation.

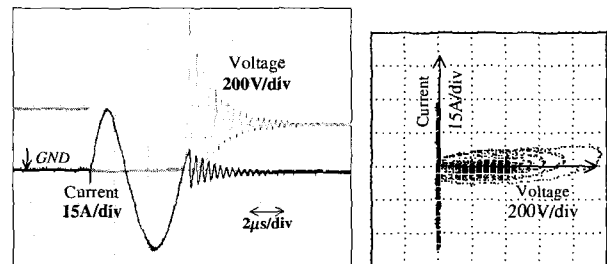


Fig. 3 Voltage and current waveforms and v-i trajectory of auxiliary switch  $S_2$

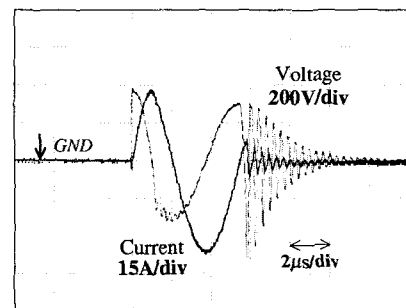
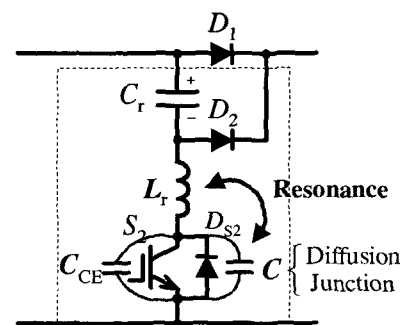


Fig. 14 Voltage and current waveforms of resonant inductor



Active auxiliary edge resonant snubber

Fig. 15 Parasitic oscillation principle

### 4.2 Suppression Method of Parasitic Oscillation

As for suppressing the parasitic oscillation, the clamping diode loop in the boost type ZVS-PWM chopper-fed DC-DC power converter is added as illustrated in Fig. 16. This clamping diode with lossless snubber is naturally turned on when the voltage across the auxiliary power switch  $S_2$  is higher than a voltage of the output DC port. Therefore, with using clamping diode loop can suppress the peak voltage across the auxiliary power switch  $S_2$  less than the output voltage. And this snubber energy is used effectively at the output side, so that lossless snubber can be implemented.

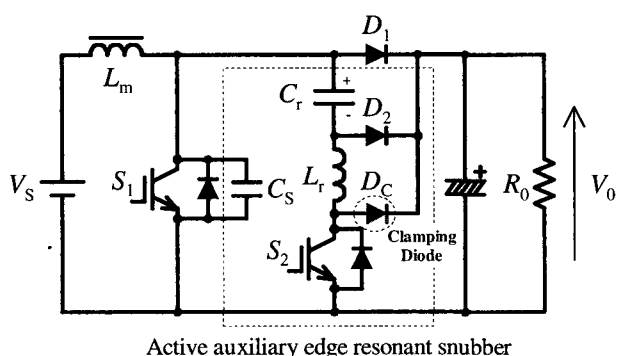


Fig. 16 Boost type ZVS-PWM chopper-fed DC-DC Power converter with an additional clamping diode  $D_c$

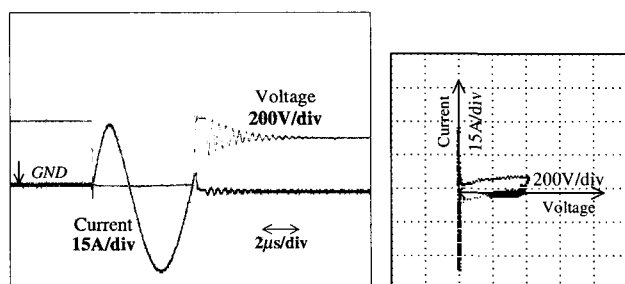


Fig. 17 Voltage and current waveforms and  $v-i$  trajectory of auxiliary switch  $S_2$  with a clamping diode

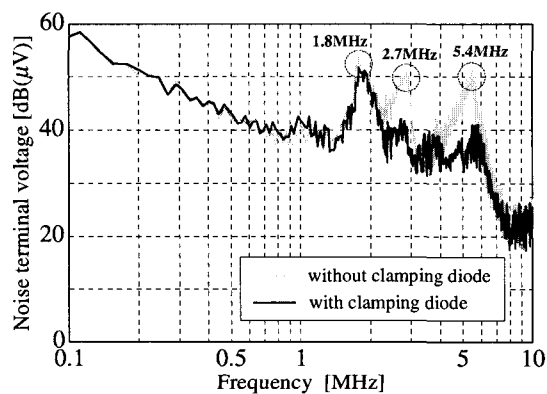


Fig. 18 Comparative noise measurement of conducted EMI with a clamping diode and without clamping diode

The voltage and current operating waveforms of the auxiliary power switch  $S_2$  in case of adding a clamping diode are represented in Fig. 17. As shown in Fig. 17, a large oscillation in Fig. 13 disappears, and the surge voltage is effectively suppressed. Therefore, the over voltage across the auxiliary power switch  $S_2$  can be reduced positively. Fig. 18 illustrates the measured result of conducted emission in case of using the clamping diode loop. According to Fig. 18, the noise level can reduce  $5\text{dB}\mu\text{V}\sim 10\text{dB}\mu\text{V}$  around 2.7MHz and 5.5MHz, therefore, excellent results are obtained for the suppression of the conducted emission.

### 5. Conclusion

In this paper, boost type ZVS-PWM chopper-fed DC-DC power converter with a load side single active auxiliary resonant snubber has introduced for the power interface of the solar photovoltaic or fuel cell power conditioner. The feasible characteristics of this boost type ZVS-PWM chopper-fed DC-DC power converter using IGBTs is compared with the conventional hard switching PWM one on the basis of the voltage and current waveforms, switching  $v-i$  trajectory, measured temperature of IGBT module package, actual power conversion efficiency, and EMI test data. In addition to these, this paper also discussed the problem of ZCS turn-off of the auxiliary active power switch, and suggested to reduce the unnecessary parasitic oscillation with using lossless clamping diode loop. In terms of the measured voltage and current operating waveforms and EMI conducted emission, the diode clamping diode loop to suppress this high-frequency parasitic oscillation is suggested and presented herein.

### Acknowledgements

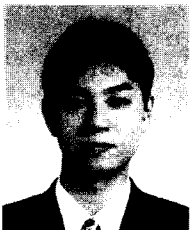
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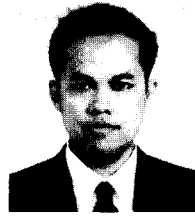
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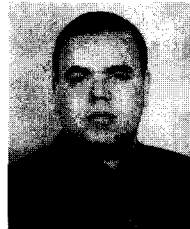
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