# Novel Zero-Current-Switching (ZCS) PWM Switch Cell Minimizing Additional Conduction Loss

Hang-Seok Choi and B. H. Cho

**Abstract** - This paper proposes a new zero-current switching (ZCS) pulse-width modulation (PWM) switch cell that has no additional conduction loss of the main switch. In this cell, the main switch and the auxiliary switch turn on and turn off under zero current condition. The diodes commutate softly and the reverse recovery problems are alleviated. The conduction loss and the current stress of the main switch are minimized, since the resonating current for the soft switching does not flow through the main switch. Based on the proposed ZCS PWM switch cell, a new family of dc to dc PWM converters is derived. The new family of ZCS PWM converters is suitable for the high power applications employing IGBTs. Among the new family of dc to dc PWM converters, a boost converter was taken as an example and has been analyzed. Design guidelines with a design example are described and verified by experimental results from the 2.5 kW prototype boost converter operating at 40kHz.
**Keywords** – ZCS(zero-current switching), PWM(pulse-width modulation), switch cell

## 1. Introduction

Recently, various kinds of soft switching techniques for switching power converters have been proposed in order to satisfy the ever-increasing requirements for smaller size, lighter weight and higher efficiency. These techniques reduce the switching losses enabling high frequency operation and consequently reduce the overall system size. In general, the soft switching approaches can be classified into two groups; zero voltage switching (ZVS) approaches [1-3] and zero current switching (ZCS) approaches [4-12]. The ZVS approaches are desirable for the majority carrier semiconductor devices such as MOSFET's, since the turn-on loss caused by the output capacitance is large. While, the ZCS approaches are suitable for the minority carrier semiconductor devices such as IGBT's, since the turn-off loss is large due to the current tail characteristics.

These days, IGBT's are replacing MOSFET's for high voltage, high power applications, since IGBT's have higher voltage rating, higher power density, and lower cost compared to MOSFET's. In an effort to increase the switching frequency of IGBT's by reducing switching losses, several kinds of ZCS soft switching techniques have been proposed since the ZCS PWM switch cell was first proposed in [4]. In the approaches proposed in [4] and [5], 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 the approaches proposed in [6], [7] and [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. In the approach proposed in [9], the peak current through the main switch is substantially reduced by using an additional inductor. Unfortunately, this approach is not effective in reducing conduction loss of IGBT, since the on-voltage of IGBTs is almost independent of the current.

This paper proposes a novel ZCS PWM switch cell that improves the drawbacks of the previously proposed ZCS PWM converters. The proposed cell provides ZCS condition for both the main switches and the auxiliary switch. Since the circulating current for the soft switching flows only through the auxiliary circuit, the conduction loss and current stress of the main switch are minimized. The voltage stress of the main diode is reduced by about 15% compared to the previous ZCS PWM switch cell. A new family of dc to dc PWM converters based on the proposed ZCS PWM switch cell is proposed. These converters are suitable for the high power applications employing IGBT's. Among the new family of dc to dc PWM converters, a boost converter was taken as an example and has been analyzed. Design guidelines with a design example are described and verified by experimental results from the 2.5 kW prototype converter operating at 40kHz.

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## 2. The Proposed ZCS PWM Switch Cell

Fig. 1 shows the proposed ZCS PWM switch cell. It consists of two switches S1 and S2, two diodes $D_1$ and $D_2$, two small resonant inductors $L_{r1}$ and $L_{r2}$, and one resonant capacitor $C_r$. S1 is the main switch through which the input current flows while, S2 is the auxiliary switch that handles only a small portion of the output power and is rated at a

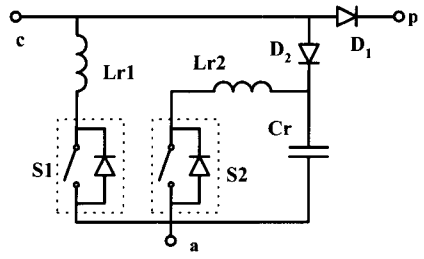


**Fig. 1** The proposed ZCS PWM switch cell

lower average current. In case of the boost type converters, it does not require a floating driver for the auxiliary switch, since the two switches have a common ground.

Fig. 2 shows the previous ZCS PWM switch cell proposed in [4,5] and Fig.3 compares the additional conduction losses of the previous ZCS switch cell and the proposed ZCS switch cell, with respect to a hard switching counterpart. As can be seen in Fig.3, the proposed approach has about 30% reduction in the conduction losses compared to the previous approach. Fig.4 shows the new family of ZCS PWM converters derived using the proposed cell.

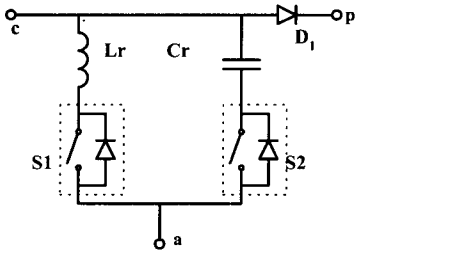


**Fig. 2** The previous ZCS PWM switch cell [4,5]

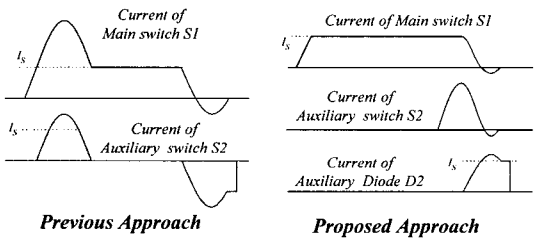


**Fig. 3** Comparison of the additional conduction losses for ZCS

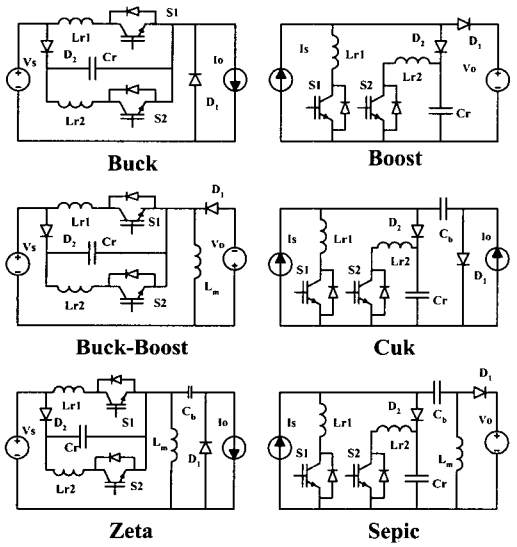


**Fig. 4** New family of ZCS dc-to-dc PWM converters

## 3. Operation Principle

To explain the operation principle of the proposed cell, a boost converter was taken as an example. To analyze the steady state operation, the followings are assumed;

All components and devices are ideal

The input inductor and the output filter capacitor are large enough to be regarded as a constant current source and constant voltage source, respectively during one operating cycle.

The proposed converter has nine operation modes during one switching cycle. The key waveforms and the equivalent circuit of each operation mode are shown in Fig. 5 and 6, respectively.

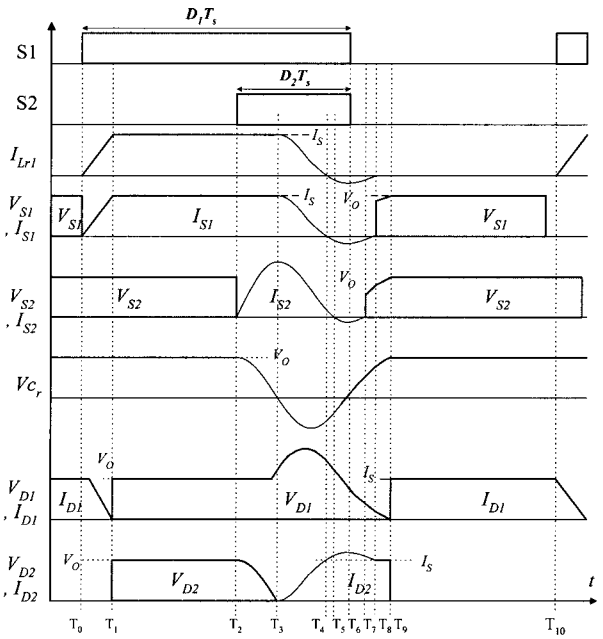


**Fig. 5** Key waveforms of the new ZCS PWM Boost converter

**Mode1 ($T_0$-$T_1$)**: Prior to $T_0$, the input current $I_s$ flows to the output through the ouput rectifier diode D1. At $T_0$, the main switch S1 turns on and the output voltage Vo is applied to the resonant inductor $L_{r1}$. The current through S1 and $L_{r1}$ increases linearly until it reaches the input current $I_s$ at $T_1$.

$$I_{S1}(t) = I_{Lr1}(t) = \frac{Vo}{L_{r1}}(t - T_0) \quad (1)$$

**Mode2 ($T_1$-$T_2$)** : The input current flows through S1 and $L_{r1}$. During this mode the ouput diode remains in the OFF state and the voltage of the resonant capacitor $C_r$ is clamped at the output voltage.

**Mode3 ($T_2$-$T_3$)** : At $T_2$, the auxiliary switch turns on and $C_r$ is discharged through the auxiliary switch S2 resonating with auxiliary resonant inductor $L_{r2}$. When $V_{cr}$ reaches zero at $T_3$, diode D2 turns on and this mode ends. The voltage of $C_r$ and the current through the auxiliary switch are obtained as

$$V_{cr}(t) = V_o \cos(w_2(t - T_2)) \tag{2}$$

$$I_{S2}(t) = \frac{V_o}{Z_2}\sin(w_2(t - T_2)) \tag{3}$$

where, $w_2 = \frac{1}{\sqrt{L_{r2}C_r}}$ and $Z_2 = \sqrt{\frac{L_{r2}}{C_r}}$

**Mode4 ($T_3$-$T_4$)** : At $T_3$, D2 begins to conduct and $C_r$ is discharged resonating with $L_{r1}$ and $L_{r2}$. The currents through the main switch and the auxiliary switch decrease, and this mode ends when the current through the main switch reaches zero.

$$V_{cr}(t) = -\frac{V_o}{\sqrt{1 + L_{r2}/L_{r1}}}\sin(w_{eq}(t - T_3)) \tag{4}$$

$$I_{S1}(t) = I_s - \frac{L_{eq}}{L_{r1}} \cdot \frac{V_o}{Z_2}[1 - \cos(w_{eq}(t - T_3))] \tag{5}$$

$$I_{S2}(t) = \frac{V_o}{Z_2} - \frac{L_{eq}}{L_{r2}} \cdot \frac{V_o}{Z_2}[1 - \cos(w_{eq}(t - T_3))] \tag{6}$$

where, $w_{eq} = \frac{1}{\sqrt{L_{eq}C_r}}$ and $L_{eq} = L_{r1} // L_{r2}$

Since D2 is conducting, the voltage of the diode D1 increases as Vcr decreases.

$$V_{D1}(t) = V_0 + \frac{V_o}{\sqrt{1 + L_{r2}/L_{r1}}}\sin(w_{eq}(t - T_3)) \tag{7}$$

**Mode5 ($T_4$-$T_5$)** : At T4, the current through S1 reaches zero and the anti-parallel diode of S1 begins to conduct. This mode ends when the current through S2 reaches zero at $T_5$. Vcr, $V_{D1}$, $I_{S1}$ and $I_{S2}$ are governed by (4), (5) and (6), respectively through mode5 and 6.

**Mode6 ($T_5$-$T_7$)** : The current through S2 reaches zero and the anti-parallel diode of S2 begins to conduct At $T_5$. When the current through the antiparallel diode of S2 goes back to zero, this mode ends. When the currents of S1 and S2 reach their negative peak value at $T_6$, the gate-drive signals for S1 and S2 are disabled at the same time and both the two switches are turned off with zero currents.

**Mode7 ($T_7$-$T_8$)** : $C_r$ is charged by the resonance with $L_{r1}$ and this mode ends when the current through the anti-parallel diode of S1 reaches zero.

**Mode8 ($T_8$-$T_9$)** : The input current flows through D2 charging Cr, and the voltage of Cr increases linearly until it reaches Vo at $T_9$.

$$V_{cr}(t) = V_{cr}(T_8) + \frac{I_s}{C_r}(t - T_8) \tag{8}$$

**Mode9 ($T_9$-$T_{10}$)** : When the $V_{cr}$ reaches Vo, D2 turns off and D1 begins to conduct. Since the voltage of Cr is clamped at Vo, D2 turns off with zero voltage. During this mode, Is flows to the output through D1.

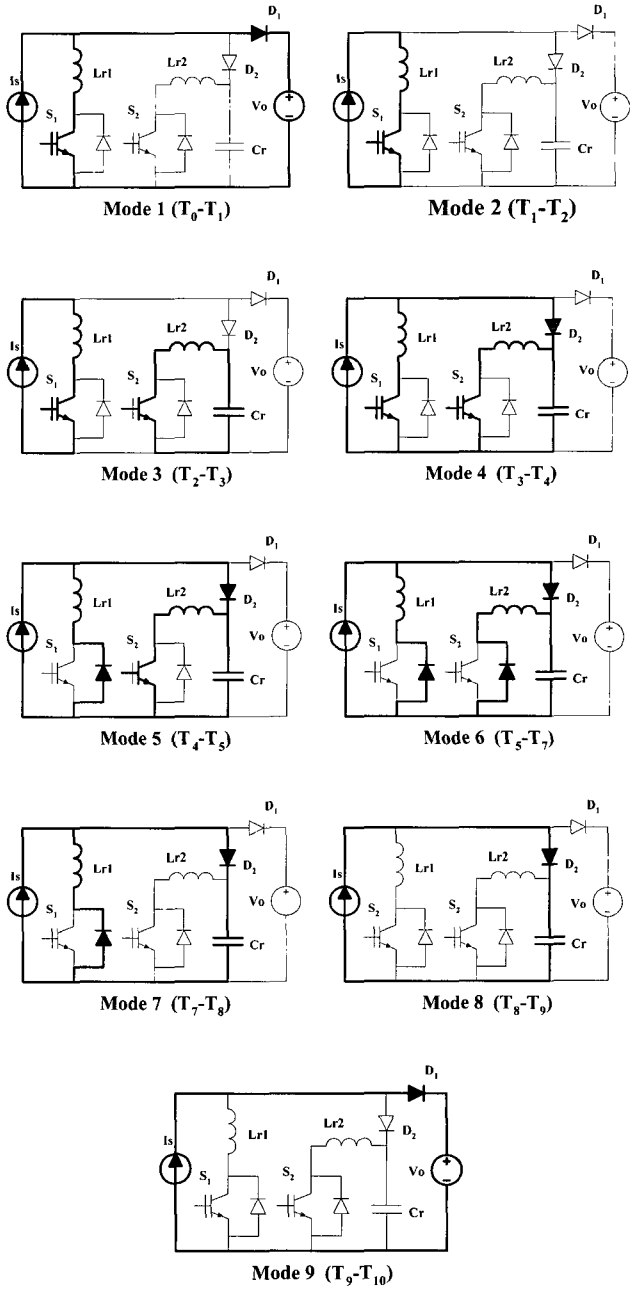


**Fig. 6** Operation modes

## 4. Topology Variations

An alternative circuit variation to reduce the number of resonant inductors is shown in Fig.7 [12]. In the cell shown in Fig.7, one resonant inductor is used and other circuit operations are very similar with the proposed ZCS PWM switch cell. It also has no additional conduction loss in the main switch. Fig.8 shows alternative ZCS PWM boost converter derived using the cell in Fig.7. Contrary to the proposed cell in Fig.1, it requires floating gate driver since the two switches do not share common ground, and the voltage stress of the output diode $D_1$ is twice of the output voltage.

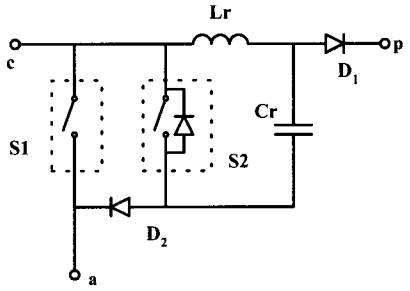


**Fig. 7** Alternative circuit variation [12]

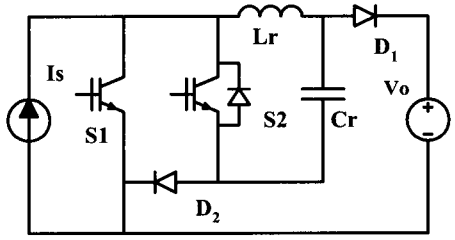


**Fig. 8** Alternative ZCS PWM boost converter [12]

## 5. Design Procedure and Example

Fig.9 shows the detailed current waveforms of S1 and S2 when they turn off. In order to achieve ZCS for the two switches, $I_{S1}$ and $I_{S2}$ given by (5) and (6) should reduce to zero during the time interval from $T_4$ to $T_6$. From (5) and (6), the following conditions are obtained;

$$K_1 = \frac{I_{p1}}{I_s^*} = \frac{2V_o L_{r2}}{Z_2 I_s^* (L_{r1} + L_{r2})} > 1 \tag{9}$$

$$K_2 = \frac{I_{p2}}{V_o / Z_2} = \frac{2L_{r1}}{L_{r1} + L_{r2}} > 1 \tag{10}$$

where, $I_{p1} = \frac{2V_o}{Z_2}\frac{L_{eq}}{L_{r1}}$ , $I_{p2} = \frac{2V_o}{Z_2}\frac{L_{eq}}{L_{r2}}$ and $I_s^*$ is the peak value of the input current.

To minimize the circulating current, $K_1$, $K_2$ should be chosen as small as possible satisfying (9) and (10).

The proper turn-off time for S1 and S2 is when $I_{S1}$ and $I_{S2}$ reach their negative peak values, and the on-time for the auxiliary switch is given by

$$D_2 T_S = \frac{1}{2}\pi\sqrt{L_{r2}C_r} + \pi\sqrt{L_{eq}C_r} \tag{11}$$

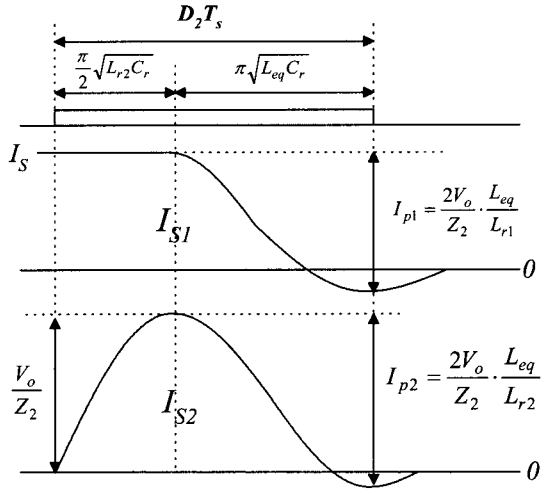


**Fig. 9** The detailed ZCS waveforms

Thus, $D_2T_s$ is only determined by the resonant parameters and independent of the input and output conditions.

The voltage stress of the output rectifier diode is below $2V_o$, since the two resonant inductors decrease the current charging Cr as in (5) and (6). The maximum voltage of the rectifier diode $D_1$ is given by

$$V_{D_1}^{\max} = (1 + \sqrt{\frac{L_{r1}}{L_{r1} + L_{r2}}}) \cdot V_o \tag{12}$$

By setting the value of Lr1 close to Lr2, the voltage stress of D1 can be minimized.

***Design example***

The specifications of the boost example are as follows;
Vs=220V, Vo=400V, Po=2.5kW, fs=40kHz

1. The peak of the input current is

$$I_s^* = \frac{P_o}{\eta V_s} \cong 12A \tag{13}$$

2. By setting $D_2$=0.1, $K_1$=$K_2$=1.15, from (9), (10) and (11) the values of the $L_{r1}$,$L_{r2}$ and $C_r$ are obtained as; $L_{r1}$=28μH, $L_{r2}$=22μH, Cr=34nF, and $V_{D1}$=699 V

The power stage circuit is shown in Fig.10 and the main parameters are summarized in Table I. To prevent ringing of the voltages of the active switches, a simple clamp circuit is used as shown by the dashed line in Fig.10 [11]. The clamp circuit consists of a low voltage zener diode in series with the clamp diode. The voltages of the switches are

clamped to a voltage slightly higher than the output voltage. A small saturable core is used to suppress the parasitic oscillation between the resonant inductor and the parasitic capacitance during the main switch is turned on.

**Table 1** Utilized components and parameters

| Components | Parameters |
|---|---|
| Lf | PE22EC90-Z , 2mH |
| Lr1, Lr2 | PQ2620, 28μH / PQ2620, 22μH |
| Cr | 34 nF ,polypropylene capacitor |
| Co | 450V/ 470 μF, electrolytic capacitor |
| S1 | IRGPC40UD2 (600V, 20A) |
| S2 | IRG4BC30UD2 (600V, 12A) |
| D1 | DSEI30-10A(1000V, 30A) |
| D2 | MUR860(600V, 8A) |

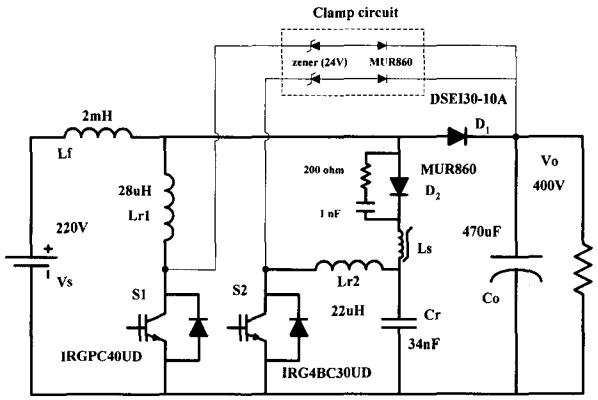


**Fig. 10** Implemented circuit of the new ZCS PWM Boost converter

## 6. Experimental Results

Fig.11 and Fig.12 show the current and voltage waveforms of the main switch and the auxiliary switch at full load, respectively. The main switch and the auxiliary switch turn on and turn off with zero currents. Fig.13 and Fig.14 show the current and voltage waveforms of the output diode and the auxiliary diode at full load, respectively. The output diode turns off softly by the resonance inductor $L_{r1}$ and the reverse recovery is reduced. The voltage stress of the output diode is about 700V as designed. The auxiliary diode turns off with zero voltage and reverse recovery loss is eliminated.

Fig.15 shows the efficiency curves versus output power with different approaches. The efficiencies were measured using Voltech power analyzer (PM3300). For a proper comparison, the resonant components of the previous ZCS approach are determined to have the same resonant energy with the proposed approach, i.e. Cr=34nF and Lr=22uH. The proposed approach shows better efficiency than the previous ZCS approach and the maximum efficiency is 97.8%. As the load level decreases, the efficiencies of the ZCS schemes drop since the resonant energy is constant, which is the common characteristic of the ZCS approaches.

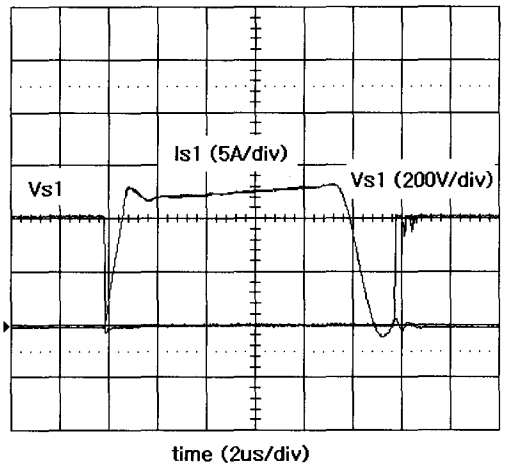


**Fig. 11** Voltage and Current waveforms of S1

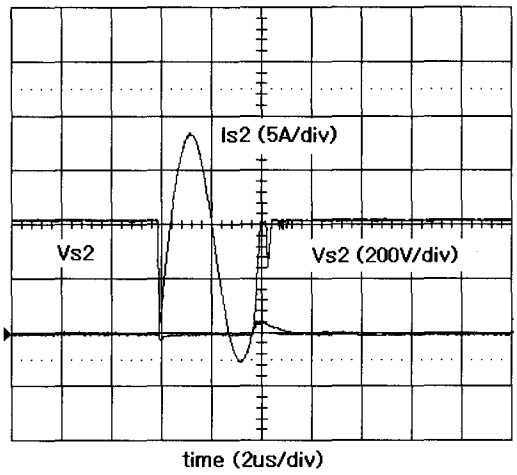


**Fig. 12** Voltage and Current waveforms of S2

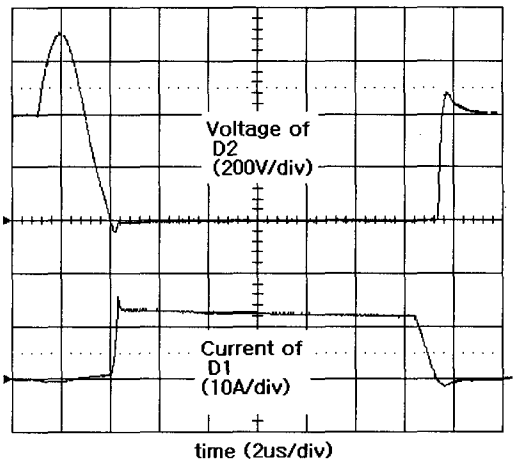


**Fig. 13** Voltage and Current waveform of D1

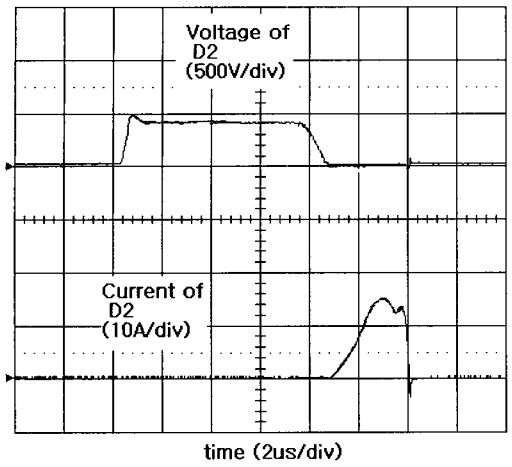


**Fig. 14** Voltage and Current waveform of D2

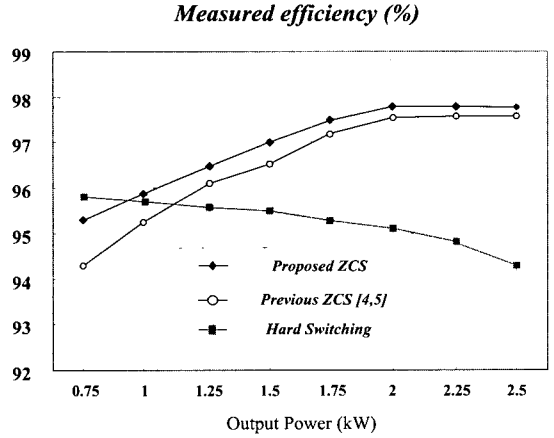


**Fig. 15** Measured efficiency

However, the proposed scheme has higher efficiency than the hard switching approach down to the 30% load, since the additional conduction loss is minimized.

## 7. Conclusion

This paper has presented a novel zero-current switching (ZCS) pulse-width modulation (PWM) switch cell minimizing the additional conduction loss for ZCS. The proposed cell provides zero current switching conditions for the main switch and the auxiliary switch. The diodes are softly commutated and the reverse recovery problems are alleviated. The conduction loss and current stress of the main switch are minimized since the resonating current flows only through the auxiliary circuit. Based on the proposed soft commutation cell, a new family of dc to dc PWM converters was derived. The new family of ZCS PWM converters is suitable for the high power applications employing IGBT's. A boost converter was taken as an example and has been analyzed. Design guidelines with a design example are illustrated. Experimental results from the 2.5 kW, 40kHz prototype ZCS boost converter employing IGBT's are presented and compared with that of hard-switching and previous ZCS schemes.

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