

# A New ZVT-PWM DC–DC Converter

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**Abstract**—In this paper, a new active snubber cell that overcomes most of the drawbacks of the normal “zero voltage transition-pulse width modulation” (ZVT-PWM) converter is proposed to contrive a new family of ZVT-PWM converters. A converter with the proposed snubber cell can also operate at light load conditions. All of the semiconductor devices in this converter are turned on and off under exact or near zero voltage switching (ZVS) and/or zero current switching (ZCS). No additional voltage and current stresses on the main switch and main diode occur. Also, the auxiliary switch and auxiliary diodes are subjected to voltage and current values at allowable levels. Moreover, the converter has a simple structure, low cost, and ease of control. A ZVT-PWM boost converter equipped with the proposed snubber cell is analyzed in detail. The predicted operation principles and theoretical analysis of the presented converter are verified with a prototype of a 2 kW and 50 kHz PWM boost converter with insulated gate bipolar transistor (IGBT). In this study, a design procedure of the proposed active snubber cell is also presented. Additionally, at full output power in the proposed soft switching converter, the main switch loss is about 27% and the total circuit loss is about 36% of that in its counterpart hard switching converter, and so the overall efficiency, which is about 91% in the hard switching case, increases to about 97%.

**Index Terms**—Active snubber cells, soft switching, zero current switching, zero current transition, zero voltage switching, zero voltage transition.

## I. INTRODUCTION

**P**ULSE width modulated (PWM) dc–dc converters have been widely used in industry due to their high power density, fast transient response and ease of control. Higher power density and faster transient response can be achieved by increasing switching frequency. However, the more switching frequency increases, the more switching losses and electromagnetic interference (EMI) noise occur. For this reason, the switching frequency can be increased by decreasing the switching losses through circuits called snubber cells [1]–[12]. In literature, there are many types of proposed snubber cells, such as RC/RCD, polarized/nonpolarized, resonant/nonresonant, and active/passive snubbers [1].

In resonant converters, switching losses are significantly reduced by means of the commutations which are realized with either zero voltage switching (ZVS) or zero current switching (ZCS). But, in these types of converters, excessive voltage and current stresses occur, and power density is lower and control is harder than normal PWM converters [3], [4], [6]–[8].

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In recent years, a number of zero voltage transition (ZVT) and zero current transition (ZCT) PWM converters have been proposed by adding resonant active snubbers to conventional PWM converters to combine the desirable features of both resonant and normal PWM techniques [3]–[5], [7]. In these converters, the turn on or off process takes place under ZVS and/or ZCS during a very short period of ZVT or ZCT time provided by a resonance. Consequently, because the resonances occur during very short periods of time, the converter acts as a normal PWM converter during most of the time. However, the on and off states of the PWM operation have a minimum time duration because of the operation features of the snubber components [2], [8].

In the conventional ZVT-PWM converter [2], the main switch is perfectly turned on under ZVS and near ZCS by ZVT with a parallel resonance. The main diode is turned on and off with ZVS. The load current and the reverse recovery current of the main diode and the energy of the resonant capacitor including the parasitic capacitor of the main switch are transferred to the resonant inductor by an auxiliary switch. However, the main switch is turned off with only near ZVS and the auxiliary switch is turned on with near ZCS. Moreover, the operation of the circuit is strongly dependent on line and load conditions. The turn off of the auxiliary switch with soft switching and the transfer of the energy stored in the inductor are very difficult to carry out and require additional circuits. There has been much research in this area to solve these problems [2], [3], [5], [7], [9], [12].

In the normal ZCT-PWM converter [3], the main switch is perfectly turned off under ZCS and ZVS by ZCT with a serial resonance. The auxiliary switch is turned on with near ZCS. The operation of the circuit is very lightly dependent on line and load conditions. However, the main switch is turned on and main diode is turned off simultaneously with hard switching, so that a short circuit occurs at the same time. The prevention of this short circuit causing losses and EMI noise of large magnitudes is very hard to realize. Also, the auxiliary switch is turned off with hard switching, and the parasitic capacitors of the switches discharge through the switches [3], [5].

In addition, most active snubber cells are seriously criticized due to their complexity and thus high cost and difficult control, a large amount of circulating energy and so excessive voltage and current stresses, and also narrow line and load ranges [3], [10].

In recent years, the insulated gate bipolar transistor (IGBT) has been broadly used as a switching device in high power industrial applications. While an IGBT has high switching power, low conduction loss, and low cost, it has relatively high switching loss [2], [3].

In this study, a new active snubber cell that overcomes most of the problems of the normal ZVT-PWM converter [2] is proposed to contrive a new family of ZVT-PWM converters. Addi-

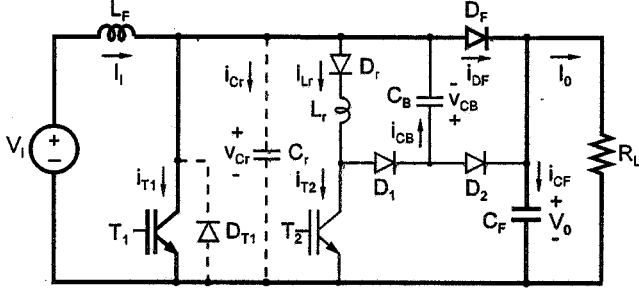


Fig. 1. Circuit scheme of the proposed new ZVT-PWM converter.

tionally, it has a simple structure, low cost, and ease of control. This snubber cell basically consists of an inductor, a capacitor, an auxiliary transistor and two auxiliary diodes. A ZVT-PWM converter with the proposed active snubber cell can also operate at light load conditions. All of the semiconductor devices in this converter are turned on and off under exact or near ZVS and/or ZCS. No additional voltage and current stresses on the main switch and the main diode occur. Also, the voltage and current stresses on the auxiliary components stay at allowable levels. A ZVT-PWM boost converter equipped with the proposed snubber cell is analyzed in detail. The predicted operation principles and theoretical analysis of the proposed converter are verified with a prototype of a 2 kW and 50 kHz IGBT-PWM boost converter.

## II. OPERATION PRINCIPLES AND ANALYSIS

### A. Definitions and Assumptions

The circuit scheme of the proposed new ZVT-PWM boost converter is shown in Fig. 1. The proposed active snubber cell basically consists of a snubber inductor ( $L_r$ ), a resonant capacitor ( $C_B$ ), an auxiliary transistor ( $T_2$ ), and two auxiliary diodes ( $D_1$  and  $D_2$ ). Naturally, the auxiliary transistor  $T_2$  has a lower power rating and is faster than the main transistor  $T_1$ . In the proposed converter, the capacitor  $C_r$  in parallel with  $T_1$  is not required, and the diode  $D_{T1}$  in antiparallel with  $T_1$  may not be used. The diode  $D_r$  in series with  $L_r$  can be used for the same purpose as that in the normal ZVT-PWM converter. The capacitor  $C_r$  can be assumed to be the sum of the parasitic capacitor of  $T_1$  and the other parasitic capacitors incorporating it.

The following assumptions are made to simplify the steady state analysis of the circuit given in Fig. 1 during one switching cycle.

- Input voltage  $V_i$  is constant.
- Output voltage  $V_o$  is constant or output capacitor  $C_F$  is large enough.
- Input current  $I_i$  is constant or main inductor  $L_F$  is large enough.
- Resonant circuits are ideal.
- Main inductor  $L_F$  is much larger than snubber inductor  $L_r$ .
- Voltage drops and parasitic capacitors of semiconductor devices are ignored.
- Reverse recovery time of all diodes except the main diode  $D_F$  is ignored.

### B. Operation Stages

Seven stages occur in the steady state operation of the proposed converter over one switching cycle. The equivalent circuit schemes of these operation stages are given in Fig. 2(a)–(g) respectively. Key waveforms concerning the operation stages are shown in Fig. 3.

1) *Stage 1* [ $t_0 < t < t_2$ ; Fig. 2(a)]: At the beginning of this stage, the main transistor  $T_1$  and the auxiliary transistor  $T_2$  are in the off state. The main diode  $D_F$  is in the on state and conducts the current  $I_i$  of the main inductor  $L_F$ . At the moment  $t = t_0$ , the equations  $i_{T1} = 0$ ,  $i_{T2} = 0$ ,  $i_{Df} = I_i$ ,  $v_{Cr} = V_o$  and  $v_{CB} = 0$  are valid.

At  $t = t_0$ , a turn on signal is applied to the gate of the auxiliary transistor  $T_2$ . The devices  $D_r$  and  $T_2$  are turned on under near ZCS. The rise rate of the current through  $D_r$  and  $T_2$  is limited by the snubber inductor  $L_r$ . During this stage,  $T_2$  current rises and  $D_F$  current falls simultaneously and linearly. For this stage, the following equations can be written generally as

$$i_{L_r} = i_{T_2} = \frac{V_o}{L_r}(t - t_0) \quad (1)$$

$$i_{D_F} = I_i - i_{L_r} = I_i - \frac{V_o}{L_r}(t - t_0). \quad (2)$$

In the interval of this stage, first at  $t = t_1$ ,  $T_2$  current reaches  $I_i$  and  $D_F$  current falls to zero. Then,  $T_2$  current continues to rise and  $D_F$  current continues to fall. As a result, at  $t = t_2$ , the reverse recovery current of  $D_F$  drops to  $-I_{rr}$ , thus the main diode  $D_F$  is turned off under ZVS and this stage finishes. For this stage

$$t_{01} = \frac{L_r}{V_o} I_i \quad (3)$$

$$i_{L_r} = i_{T_2} = I_i + \frac{V_o}{L_r}(t - t_1) \quad (4)$$

$$i_{D_F} = -\frac{V_o}{L_r}(t - t_1) \quad (5)$$

$$I_{L_{r2}} = i_{L_r}(t_2) = i_{T_2}(t_2) = I_i + I_{rr} \quad (6)$$

$$I_{D_{F2}} = i_{D_F}(t_2) = -I_{rr} \quad (7)$$

$$t_{12} = t_{rr} = \frac{L_r}{V_o} I_{rr} \quad (8)$$

can also be written. Here  $I_{rr}$  and  $t_{rr}$  are the reverse recovery current and the reverse recovery time of the main diode  $D_F$  respectively, for the values of  $I_F = I_i$  and  $-di/dt = -V_o/L_r$ . Therefore, at the end of this stage, the main diode  $D_F$  is turned off with ZVS, and the input current  $I_i$  and the reverse recovery current  $I_{rr}$  of the main diode are commutated to the snubber inductor  $L_r$  and the auxiliary transistor  $T_2$ .

2) *Stage 2* [ $t_2 < t < t_3$ ; Fig. 2(b)]: Prior to  $t = t_2$ , the main transistor  $T_1$  and the main diode  $D_F$  are in the off state. The auxiliary transistor  $T_2$  is in the on state and conducts the current  $I_i + I_{rr}$ . At the instant  $t = t_2$ ,  $i_{T1} = 0$ ,  $i_{T2} = I_i + I_{rr}$ ,  $i_{D_F} = 0$ ,  $v_{Cr} = V_o$  and  $v_{CB} = 0$  are valid.

At the moment  $t = t_2$ , a parallel resonance between  $L_r$  and  $C_r$  starts to resonate via the resonant path  $C_r - D_r - L_r - T_2$  under the input current  $I_i$  and with the initial current  $I_{L_{r2}}$  of

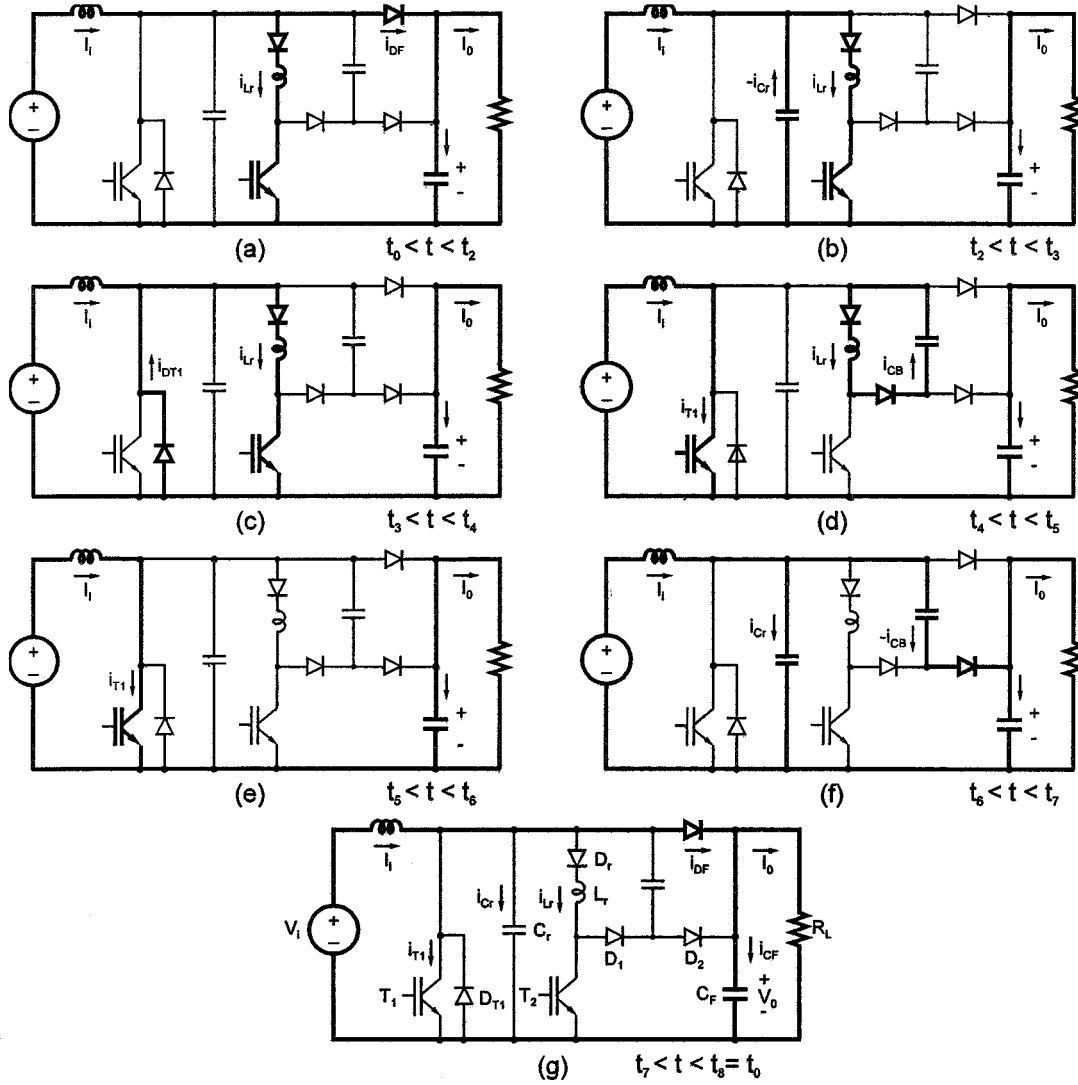


Fig. 2. Equivalent circuit schemes of the operation stages in the proposed soft switching converter.

the inductor  $L_r$ . The following equations are obtained for this resonance:

$$i_{L_r} = i_{T_2} = I_i + I_{rr} \cos \omega_1(t - t_2) + \frac{V_o}{Z_1} \sin \omega_1(t - t_2) \quad (9)$$

$$v_{C_r} = v_{T_1} = V_o \cos \omega_1(t - t_2) - Z_1 I_{rr} \sin \omega_1(t - t_2). \quad (10)$$

At  $t = t_3$ , the transfer of the energy stored in the capacitor  $C_r$  to the inductor  $L_r$  is completed, and  $\mu_{C_r}$  becomes 0. The current and energy values of the inductor  $L_r$  reach their maximum levels at the same time. From (9) and (10)

$$I_{L_r \max} = I_i + \sqrt{V_o^2 + Z_1^2 I_{rr}^2} / Z_1 \quad (11)$$

$$W_{L_r \max} = \frac{1}{2} L_r I_{L_r \max}^2 = \frac{1}{2} L_r (I_i + I_{rr})^2 + \frac{1}{2} C_r V_o^2 \quad (12)$$

$$t_{23} = \sqrt{L_r C_r} \arctg \frac{V_o}{Z_1 I_{rr}} \quad (13)$$

are derived. In these equations

$$\omega_1 = 1/\sqrt{L_r C_r} \quad (14)$$

$$Z_1 = \sqrt{L_r / C_r} \quad (15)$$

are valid. It should be noted that the capacitor  $C_r$  includes the parasitic capacitors of the main transistor  $T_1$ , the main diode  $D_F$ , and the auxiliary diodes  $D_1$  and  $D_2$  in this stage. The parasitic capacitors of  $T_1$  and  $D_1$  are discharged from  $V_o$  to zero, and the others are charged from zero to  $V_o$ . Moreover, in the proposed converter, an additional capacitor  $C_r$  is not required, or the capacitor  $C_r$  can be assumed to be the sum of these parasitic capacitors.

3) Stage 3 [ $t_3 < t < t_4$ : Fig. 2(c)]: Before this stage, only the auxiliary transistor  $T_2$  is in the on state and conducts the maximum current of the inductor  $L_r$ . At  $t = t_3$ ,  $i_{T_1} = 0$ ,  $i_{T_2} = I_{L_r \max}$ ,  $i_{D_F} = 0$ ,  $v_{C_r} = 0$  and  $v_{C_B} = 0$  are valid.

Just after  $v_{C_r}$  becomes 0 at  $t = t_3$ , the antiparallel diode  $D_{T_1}$  of the main transistor  $T_1$  is turned on, and it conducts the excess

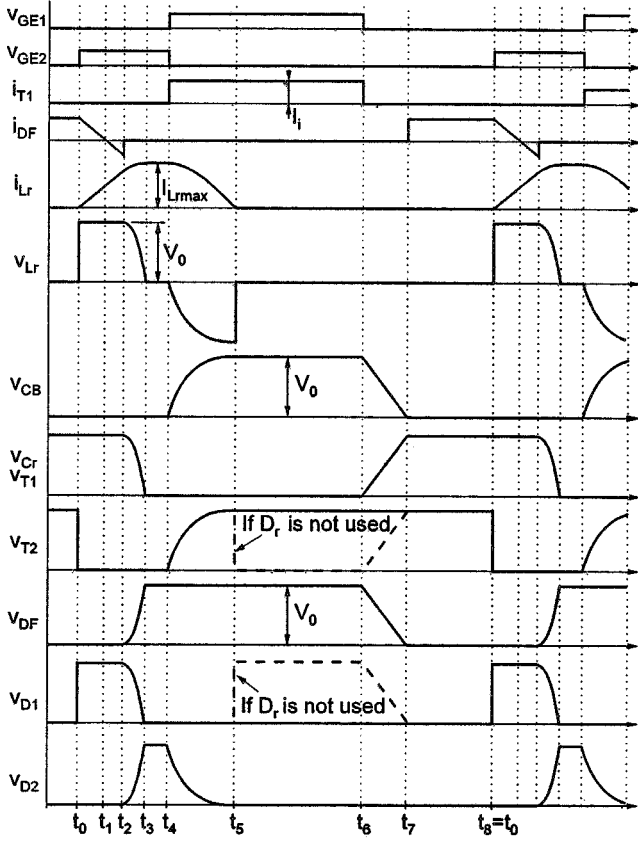


Fig. 3. Key waveforms concerning the operation stages in the proposed soft switching converter.

of the inductor  $L_r$  current from the input current  $I_i$  during this stage. For this stage

$$i_{L_r} = i_{T_2} = I_{L_r \max} \quad (16)$$

$$i_{D_{T_1}} = I_{L_r \max} - I_i \quad (17)$$

can be written. The duration of this stage, in which  $D_{T_1}$  is in the on state, provides basically zero voltage transition (ZVT) for the main transistor  $T_1$ . Whereas the diode  $D_{T_1}$  is required in the normal ZVT-PWM converter, it is not needed, and the following stage can be started directly at  $t_3$  in the proposed converter.

4) Stage 4 [ $t_4 < t < t_5$ ; Fig. 2(d)]: At the beginning of this stage,  $i_{T_1} = 0$ ,  $i_{T_2} = I_{L_r \max}$ ,  $i_{D_F} = 0$ ,  $v_{C_r} = 0$  and  $v_{C_B} = 0$  are valid.

At  $t = t_4$ , a turn on signal is applied to the gate of the main transistor  $T_1$  and the gate signal of the auxiliary transistor  $T_2$  is removed simultaneously. At the same time,  $T_1$  is turned on with ZVS and begins to conduct the current  $I_i$ , and  $T_2$  is turned off with near ZVS through  $C_B$ . A serial resonance between  $L_r$  and  $C_B$  starts to resonate by the way of  $L_r - D_1 - C_B - D_r$  under the maximum inductor current  $I_{L_r \max}$ . Here, the auxiliary diode  $D_1$  is turned on with ZVS at  $t_4$ . For this resonance, the following equations are derived:

$$i_{L_r} = i_{D_1} = I_{L_r \max} \cos \omega_2(t - t_4) \quad (18)$$

$$v_{C_B} = v_{T_2} = Z_2 I_{L_r \max} \sin \omega_2(t - t_4). \quad (19)$$

During this stage the energy stored in inductor  $L_r$  is transferred to the capacitor  $C_B$ . If it is assumed that the capacitor

$C_B$  is charged from zero to exactly  $V_o$  with the transfer of all the energy in inductor  $L_r$ , from the equations above

$$V_{C_{B_3}} = v_{C_B}(t_5) = V_{C_B \max} = Z_2 I_{L_r \max} = V_o \quad (20)$$

$$t_{45} = \frac{\pi}{2} \sqrt{L_r C_B} \quad (21)$$

$$\frac{1}{2} L_r I_{L_r \max}^2 = \frac{1}{2} C_B V_{C_B \max}^2 = \frac{1}{2} C_B V_o^2 \quad (22)$$

are obtained. If the value of  $C_B$  is smaller than the value above,  $C_B$  is charged up to  $V_o$  again and the excess energy is transferred to the load. If  $C_B$  is larger than the value above, the voltage of  $C_B$  does not reach  $V_o$ . In the equations above

$$\omega_2 = 1/\sqrt{L_r C_B} \quad (23)$$

$$Z_2 = \sqrt{L_r/C_B} \quad (24)$$

are valid. The capacitor  $C_B$  limits the growth rate of  $T_2$  voltage in this stage. Thus,  $T_2$  is turned off under near ZVS. Moreover, the parasitic capacitors of  $T_2$  and  $D_2$  incorporate the capacitor  $C_B$  in this stage.

At  $t = t_5$ , as soon as the inductor current  $i_{L_r}$  drops to zero, the auxiliary diodes  $D_r$  and  $D_1$  are turned off under near ZCS through  $L_r$ , and this stage stops.

5) Stage 5 [ $t_5 < t < t_6$ ; Fig. 2(e)]: During this stage, the main transistor  $T_1$  continues to conduct the input current  $I_i$  and the snubber circuit is not active. The duration of this stage is a large part of the on state duration of the normal PWM converter and is determined by the PWM control. For this stage

$$i_{T_1} = I_i \quad (25)$$

can be written.

6) Stage 6 [ $t_6 < t < t_7$ ; Fig. 2(f)]: Before this stage,  $i_{T_1} = I_i$ ,  $i_{T_2} = 0$ ,  $i_{D_F} = 0$ ,  $v_{C_r} = 0$  and  $v_{C_B} = V_o$  are valid. At  $t = t_6$ , when the gate signal of the main transistor  $T_1$  is removed, the main transistor  $T_1$  is turned off under near ZVS and the auxiliary diode  $D_2$  is turned on with ZVS because of the capacitor  $C_B$  charged to  $V_o$ . During this stage,  $C_r$  is charged and  $C_B$  is discharged. At instant  $t_7$ , when  $C_r$  voltage reaches  $V_o$  and  $C_B$  voltage falls to zero simultaneously, the main diode  $D_F$  is turned on with ZVS and the auxiliary diode  $D_2$  is turned off with ZVS, and this stage finishes. In this case

$$v_{C_r} = v_{T_1} = V_o - v_{C_B} = \frac{I_i}{C_r + C_B}(t - t_6) \quad (26)$$

$$t_{67} = \frac{C_r + C_B}{I_i} V_{C_B \max} = \frac{C_r + C_B}{I_i} V_o \quad (27)$$

are found. In this stage,  $C_B$  restricts the rise rate of  $T_1$  voltage. Thus,  $T_1$  is turned off under near ZVS. Additionally, the parasitic capacitor of  $D_F$  incorporates the capacitors  $C_r$  and  $C_B$  in this stage.

It should be noted that if the load current is decreased,  $C_B$  voltage does not reach  $V_o$  in the interval  $(t_4 - t_5)$ . Consequently, the snubber effect of  $C_B$  decreases proportionally in the interval  $(t_6 - t_7)$ , but the duration of this stage  $t_{67}$  does not vary. This feature provides operation at light load conditions for the proposed converter.

7) Stage 7 [ $t_7 < t < t_8$ ; Fig. 2(g)]: During this stage, the main diode  $D_F$  continues conducting the input current  $I_i$  and the snubber circuit is not active. The duration of this stage is

a large part of the off state duration of the conventional PWM converter and is determined by the PWM control. For this stage

$$i_{D_F} = I_i \quad (28)$$

can be written.

Therefore, at the moment  $t = t_s$ , one switching cycle is completed and another switching cycle starts.

### III. DESIGN PROCEDURE

The following design procedure, which is developed by considering the design procedures presented before [5], [7], is based not only on the soft switching turn on and turn off requirements of the main transistor  $T_1$ , the main diode  $D_F$  and the auxiliary transistor  $T_2$ , but also the transfer of the snubber energy to the load.

- 1) Snubber inductor  $L_r$  is selected to allow a current rise rate to be the maximum input current at most, within three times the nominal reverse recovery time of the main diode. This case can be defined as

$$\frac{V_o}{L_r} 3t_{rrn} \leq I_{i\max} \quad (29)$$

- 2) Snubber capacitor  $C_B$  is selected to charge up to approximately the output voltage, when the energy accumulated in the snubber inductor is transferred completely to it. For this stage, from (12) and (22)

$$\frac{1}{2} L_r (I_{i\max} + I_{rr\max})^2 + \frac{1}{2} C_r V_o^2 \cong \frac{1}{2} C_B V_o^2 \quad (30)$$

can be derived. Here,  $I_{rr\max}$  is the reverse recovery current of the main diode, for the values  $I_F = I_{i\max}$  and  $-di/dt = -V_o/L_r$ .

- 3) Additionally, the snubber inductor  $L_r$  and the snubber capacitor  $C_B$  are selected to allow the voltage rise time rates of the main and auxiliary transistors to be minimally their fall time ratings. In this case, from (21) and (27)

$$t_{45} = \frac{\pi}{2} \sqrt{L_r C_B} \geq t_{f2} \quad (31)$$

$$t_{67} = \frac{C_r + C_B}{I_{i\max}} V_o \geq t_{f1} \quad (32)$$

are obtained, respectively. In these equations,  $t_{f1}$  and  $t_{f2}$  are the fall time ratings of the main and auxiliary transistors respectively.

### IV. CONVERTER FEATURES

The features of the proposed new ZVT-PWM converter can be summarized as follows.

- 1) All of the semiconductor devices are both turned on and off under exact or near ZVS and/or ZCS. The main transistor  $T_1$  is turned on perfectly under ZVS provided with ZVT, and turned off with near ZVS. The main diode  $D_F$  is both turned on and off with ZVS. The auxiliary transistor  $T_2$  is turned on with near ZCS, and turned off with

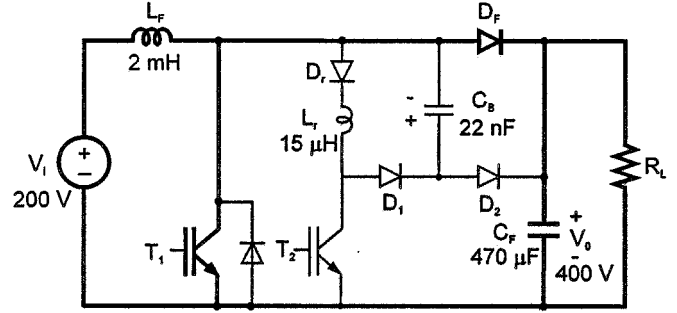


Fig. 4. Experimental circuit scheme of a 2 kW and 50 kHz IGBT-PWM boost converter.

TABLE I  
SOME SIGNIFICANT NOMINAL VALUES OF THE SEMICONDUCTOR DEVICES USED IN THE PRACTICAL CIRCUIT

| COMPONENT       | PART NUMBER   | V (V) | I (A) | $t_r$ (ns) | $t_f$ (ns) | $t_{rr}$ (ns) |
|-----------------|---------------|-------|-------|------------|------------|---------------|
| $T_1$           | IXSK35N120AU1 | 1200  | 35    | 150        | 700        | -             |
| $T_2$           | IXGH10N100A   | 1000  | 10    | 100        | 500        | -             |
| $D_F$           | MUR860        | 600   | 8     | -          | -          | 60            |
| $D_r, D_1, D_2$ | MUR860        | 600   | 8     | -          | -          | 60            |

TABLE II  
LOSSES OF THE SEMICONDUCTOR DEVICES AND TOTAL EFFICIENCIES OF THE CIRCUITS IN THE HARD SWITCHING AND THE PROPOSED SOFT SWITCHING CONVERTER

$V_i = 200 \text{ V}, V_o = 400 \text{ V}$  and  $f_p = 50 \text{ kHz}$

| $I_o$ (A) | Hard or Soft | POWER LOSSES (W) |       |       |                   |      |      | $P_i$ (W) | $P_o$ (W) | $\eta$ (%) |
|-----------|--------------|------------------|-------|-------|-------------------|------|------|-----------|-----------|------------|
|           |              | $T_1$ (+DT1)     | $T_2$ | $D_F$ | $D_r + D_1 + D_2$ | ADD. | TOT. |           |           |            |
| 1.0       | H            | 30               | -     | 4     | -                 | 9    | 43   | 443       | 400       | 90,3       |
|           | S            | 13               | 6     | 2     | 3                 | 4    | 28   | 428       | 400       | 93,4       |
| 2.0       | H            | 61               | -     | 8     | -                 | 14   | 83   | 883       | 800       | 90,6       |
|           | S            | 20               | 9     | 3     | 3                 | 4    | 39   | 839       | 800       | 95,3       |
| 3.0       | H            | 89               | -     | 12    | -                 | 21   | 122  | 1322      | 1200      | 90,8       |
|           | S            | 28               | 12    | 4     | 3                 | 5    | 52   | 1252      | 1200      | 95,8       |
| 4.0       | H            | 119              | -     | 15    | -                 | 27   | 161  | 1761      | 1600      | 90,9       |
|           | S            | 34               | 15    | 5     | 3                 | 6    | 63   | 1663      | 1600      | 96,2       |
| 5.0       | H            | 149              | -     | 18    | -                 | 31   | 198  | 2198      | 2000      | 91,0       |
|           | S            | 40               | 17    | 6     | 3                 | 6    | 72   | 2072      | 2000      | 96,5       |

near ZVS. Moreover, the auxiliary diodes  $D_r, D_1$  and  $D_2$  operate with soft switching.

- 2) The converter has a simple structure and low cost. Whereas the proposed converter is about as simple and cheap as the normal ZVT-PWM converter [2], it overcomes most of the drawbacks of the normal ZVT-PWM converter.
- 3) The converter has ease of control. For the control of this new converter, a normal PWM control signal is applied to the gate of the auxiliary transistor  $T_2$  by the time  $T_1$  voltage drops to zero, and after this time it is applied to the gate of the main transistor  $T_1$ . Furthermore, the emitter terminals of  $T_1$  and  $T_2$  are connected to the same point, and this feature makes control easy.
- 4) The circulating energy is minimal. In the ZVT-PWM converters presented before [2], [7]–[9], [12], there is the snubber capacitor  $C_r$  in parallel with the main switch, and this capacitor increases the circulating energy signi-

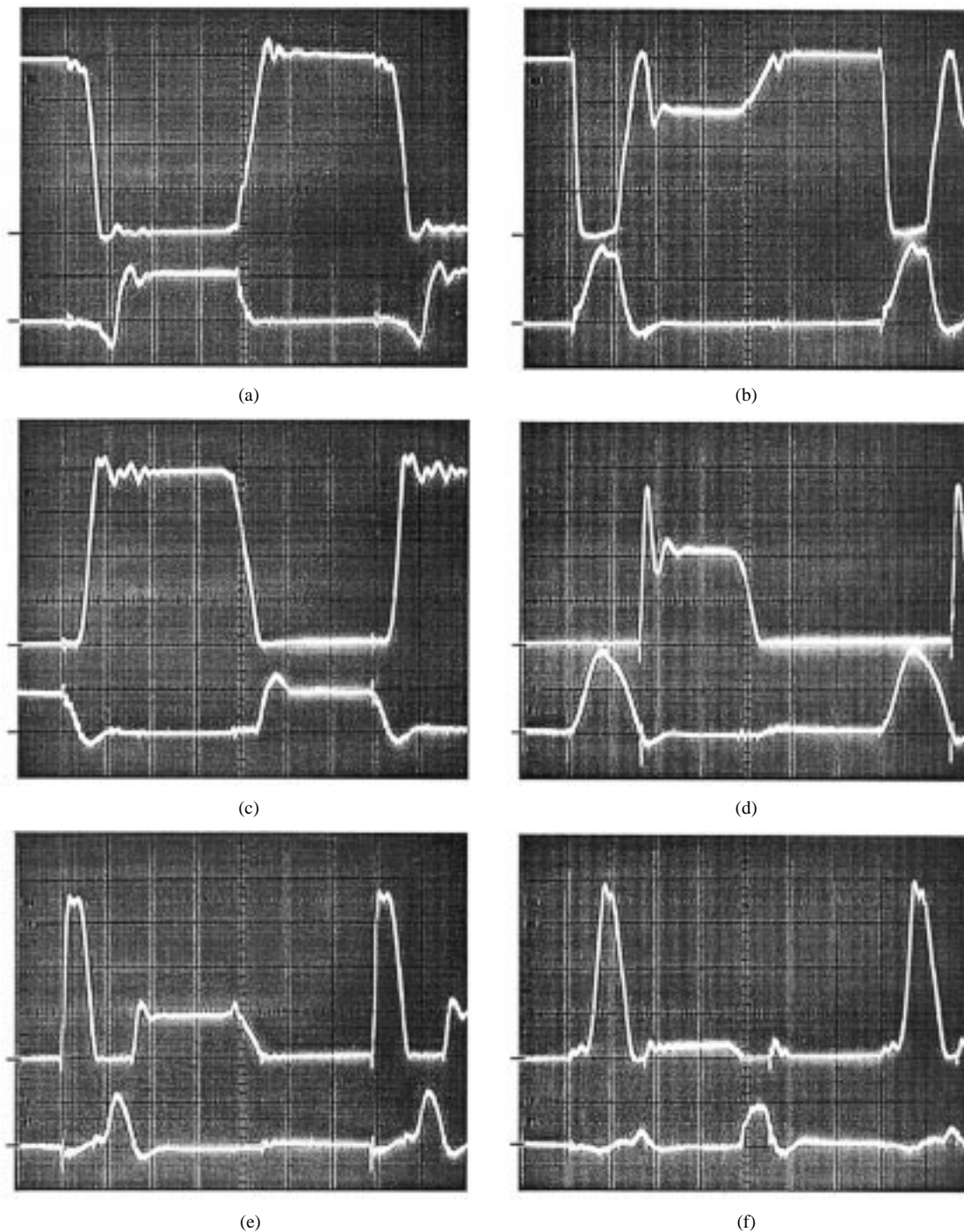


Fig. 5. Oscillograms of (a) the main transistor  $T_1$ , (b) the auxiliary transistor  $T_2$ , (c) the main diode  $D_F$ , (d) the auxiliary diode  $D_r$ , (e) the auxiliary diode  $D_1$ , and (f) the auxiliary diode  $D_2$ , with 100 V/div, 10 A/div and 2  $\mu$ s/div scales, in the practical soft switching converter.

ficiently. In the proposed new converter, whereas there is no  $C_r$ , there is the capacitor  $C_B$ , which is located in a different place and is larger than  $C_r$ . While the capacitor  $C_B$  performs the duties of  $C_r$  more perfectly, it does not increase the circulating energy. Moreover,  $C_B$  provides both the turn off of the auxiliary switch with soft switching and the transfer of the snubber energy to the load. As a result, the circulating energy and additional losses are minimal in the proposed converter.

5) No additional voltage and current stresses on the main transistor  $T_1$  and the main diode  $D_F$  occur. Also, the

voltage and current stresses on the auxiliary transistor  $T_2$  and the auxiliary diodes  $D_r$ ,  $D_1$  and  $D_2$  stay at allowable levels.

- 6) The converter acts as a conventional PWM converter during most of the time, because the time periods on which the snubber cell is active are very short.
- 7) The converter can operate at wide line and load ranges. The operation of ZVT-PWM converters is generally dependent strongly on the load current values, and so the line and load ranges are not wide. However, in the proposed new converter, when the load current decreases,

the time periods  $t_{01}$  and  $t_{12}$  fall proportionally, the period  $t_{23}$  rises very lightly, the periods  $t_{34}$ ,  $t_{45}$  and  $t_{67}$  do not vary. Therefore, as long as the active snubber cell is designed for the maximum load condition, the proposed new converter can operate over wide line and load ranges.

- 8) The proposed converter does not require any additional passive snubber cells.
- 9) The proposed active snubber cell can be easily applied to the other basic PWM dc–dc converters and to all switching converters.
- 10) The presented new converter has many more advantages than the other ZVT-PWM converters. In this converter, most of the drawbacks of the normal ZVT-PWM converter [2] are overcome both perfectly and easily.

## V. EXPERIMENTAL RESULTS

To verify the predicted operation principles and theoretical analysis of the proposed new ZVT-PWM converter, a prototype of a 2 kW and 50 kHz IGBT-PWM boost converter given in Fig. 4 has been realized.

Some nominal values of the semiconductor devices used in the practical circuit are listed in Table I with reference to the handbooks of the manufacturers.

In the hard switching and the proposed soft switching converters, the losses of the semiconductor devices and the total efficiencies of the circuits are summarized for various load current values in Table II.

The experimental results are determined by measuring the temperature rise rates of the switch and diode heatsinks, and the voltage and current values of the input and the output. Moreover, in the hard switching converter, the measurements are done with the circuit operated at low frequency values to estimate the experimental results.

The oscillograms of the main transistor  $T_1$ , the auxiliary transistor  $T_2$ , the main diode  $D_F$ , and the auxiliary diodes  $D_r$ ,  $D_1$  and  $D_2$  are given in Fig. 5(a)–(f) respectively.

In Fig. 6, the efficiency curves of the hard and proposed soft switching converters are shown comparatively. Oscillograms concerning the hard switching converter are not given in this study because they are given in most of the similar studies presented before.

From the oscillograms given in Fig. 5, it can be seen that  $T_1$  is turned on perfectly with ZVS and turned off under near ZVS.  $T_2$  is turned on under near ZCS and turned off under near ZVS. Also, the devices  $D_F$ ,  $D_r$ ,  $D_1$  and  $D_2$  operate with soft switching. Moreover, additional voltage and current stresses on the main devices  $T_1$  and  $D_F$  do not take place, and the auxiliary devices  $T_2$ ,  $D_r$ ,  $D_1$  and  $D_2$  are subjected to allowable voltage and current values. It is also observed that the proposed new converter operates at light load conditions without any problems.

In connection with Table II and Fig. 6, it can be seen that the efficiency of the proposed soft switching converter is larger than that of the hard switching one, especially at high output power levels. At full output power in the proposed soft switching con-

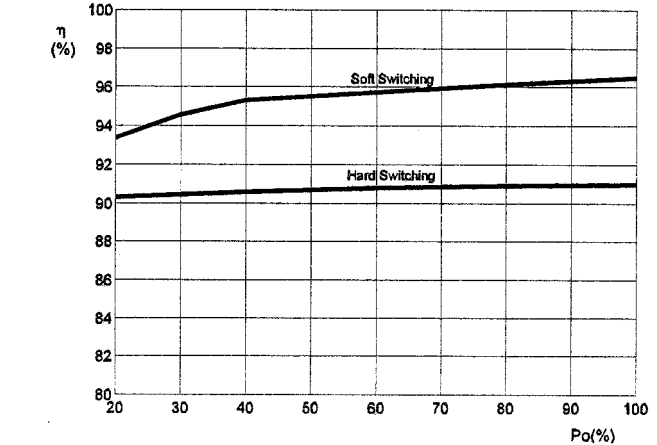


Fig. 6. Overall efficiency curves of the hard switching and the proposed soft switching converters comparatively.

verter, the main switch loss is about 27% and the total circuit loss is about 36% of that in its counterpart hard switching converter, and so the overall efficiency, which is about 91% in the hard switching case, increases to about 97%.

As a result, it can be clearly seen that the predicted operation principles and analysis of the proposed converter are verified with all of the experimental results. In the proposed converter, most of the drawbacks of the normal ZVT-PWM converter are overcome both perfectly and easily. All of the semiconductor devices in this converter are both turned on and off under exact or near ZVS and/or ZCS. Any additional voltage and current stresses on the main devices do not occur, and the auxiliary devices are subjected to allowable voltage and current values.

## VI. CONCLUSION

In this study, a new active snubber cell is presented to contrive a new family of ZVT-PWM converters. The drawbacks of the conventional ZVT-PWM converter are overcome in the converter with the proposed active snubber cell. The proposed converter operates at light load conditions without any problems. All of the semiconductor devices in this converter are turned on and off under exact or near ZVS and/or ZCS. Any additional voltage and current stresses on the main devices do not take place, and the auxiliary devices are subjected to allowable voltage and current values. Moreover, the converter has a simple structure, low cost and ease of control.

A ZVT-PWM boost converter implemented with the proposed new active snubber cell has been analyzed in detail. The predicted operation principles and theoretical analysis of the proposed converter have been completely verified with a prototype of a 2 kW and 50 kHz IGBT-PWM boost converter. It has been observed that the proposed converter has operated at light load conditions without any problems and all of the semiconductor devices have operated with soft switching.

Additionally, at full output power in the proposed soft switching converter, the main switch loss is about 27% and the total circuit loss is about 36% of that in its counterpart hard switching converter, and so the overall efficiency, which is about 91% in the hard switching case, increases to about 97%.

## REFERENCES

- [1] A. Ferraro, "An overview of low-loss snubber technology for transistor converters," in *Proc. IEEE Power Electron. Spec. Conf.*, 1982, pp. 466–477.
- [2] G. Hua, C. S. Leu, Y. Jiang, and F. C. Y. Lee, "Novel zero-voltage-transition PWM converters," *IEEE Trans. Power Electron.*, vol. 9, pp. 213–219, Mar. 1994.
- [3] G. Hua, E. X. Yang, Y. Jiang, and F. C. Lee, "Novel zero-current-transition PWM converters," *IEEE Trans. Power Electron.*, vol. 9, pp. 601–606, Nov. 1994.
- [4] A. Elasser and D. A. Torrey, "Soft switching active snubbers for dc/dc converters," *IEEE Trans. Power Electron.*, vol. 11, pp. 710–722, Sept. 1996.
- [5] H. Mao, F. C. Lee, X. Zhou, H. Dai, M. Cosan, and D. Boroyevich, "Improved zero-current-transition converters for high-power applications," *IEEE Trans. Ind. Applicat.*, vol. 33, pp. 1220–1232, Sept./Oct. 1997.
- [6] C. J. Tseng and C. L. Chen, "A passive snubber cell for nonisolated PWM dc/dc converters," *IEEE Trans. Ind. Electron.*, vol. 45, pp. 593–601, Aug. 1998.
- [7] —, "Novel ZVT-PWM converters with active snubbers," *IEEE Trans. Power Electron.*, vol. 13, pp. 861–869, Sept. 1998.
- [8] V. Grigore and J. Kyyra, "A new zero-voltage-transition PWM buck converter," in *Proc. 9th Mediterranean Electrotech. Conf. (MELECON'98)*, vol. 2, 1998, pp. 1241–1245.
- [9] J. M. P. Menegaz, M. A. Co., D. S. L. Simonetti, and L. F. Vieira, "Improving the operation of ZVT dc-dc converters," in *Proc. 30th Power Electron. Spec. Conf. (PESC'99)*, vol. 1, 1999, pp. 293–297.
- [10] K. M. Smith and K. M. Smedley, "Properties and synthesis of passive lossless soft-switching PWM converters," *IEEE Trans. Power Electron.*, vol. 14, pp. 890–899, Sept. 1999.
- [11] H. Bodur, M. H. Sarul, and A. F. Bakan, "A passive lossless snubber cell design for an ohmic loaded PWM IGBT chopper fed by a diode bridge from AC mains," in *Proc. Int. Conf. Elect. Electron. Eng. (ELECO'99)*, Bursa, Turkey, Dec. 1–5, 1999, pp. 440–444.
- [12] T. W. Kim, H. S. Kim, and H. W. Ahn, "An improved ZVT PWM boost converter," in *Proc. 31st Power Electron. Spec. Conf. (PESC'00)*, vol. 2, 2000, pp. 615–619.



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