

# A Single Phase ZVT-ZCT Power Factor Correction Boost Converter

Yakup Sahin, Naim Suleyman Ting, Ismail Aksoy

**Abstract**—In this paper, a single phase soft switched Zero Voltage Transition and Zero Current Transition (ZVT-ZCT) Power Factor Correction (PFC) boost converter is proposed. In the proposed PFC converter, the main switch turns on with ZVT and turns off with ZCT without any additional voltage or current stresses. Auxiliary switch turns on and off with zero current switching (ZCS). Also, the main diode turns on with zero voltage switching (ZVS) and turns off with ZCS. The proposed converter has features like low cost, simple control and structure. The output current and voltage are controlled by the proposed PFC converter in wide line and load range. The theoretical analysis of converter is clarified and the operating steps are given in detail. The simulation results of converter are obtained for 500 W and 100 kHz. It is observed that the semiconductor devices operate with soft switching (SS) perfectly. So, the switching power losses are minimum. Also, the proposed converter has 0.99 power factor with sinusoidal current shape.

**Keywords**—Power factor correction, zero-voltage transition, zero-current transition, soft switching.

## I. INTRODUCTION

POWER factor correction (PFC) basically means to be reduced to zero reactive power and harmonics. These harmonic currents cause some problems such as higher harmonic distortion, poor power factor at AC input voltage and current. The boost converters are usually used in AC-DC PFC converters due to simple construction, easy control and high power density. These PFC converters are operated in continuous conduction mode (CCM) at high power applications. In this case, the reverse recovery current of the main diode causes to turning off loss of the main diode, turning on loss of the main switch, electromagnetic interference (EMI) noises [1], [2].

To obtain lower harmonic current, faster dynamic response and higher power density, AC-DC converters should be operated at high frequency as possible. However, the high switching frequency leads to switching power losses and electromagnetic interference (EMI) noises [3]. This problem can be solved by using the soft switching (SS) techniques instead of hard switching (HS) techniques. SS techniques are Zero Voltage Switching (ZVS), Zero Current Switching (ZCS), Zero Voltage Transition (ZVT), and Zero Current Transition (ZCT) techniques [4]-[20].

In recent years, a lot of papers have been proposed to realize soft switching for the boost PFC converter. Some of

these proposed converters have major disadvantages. In [7], the main switch turns off with HS. In [8], the SS is not provided under 0.5 duty cycle and there is an additional current stress on the main switch. In [9], a magnetic coupled inductor is used in the ZVT-ZCT converter. So, parasitic oscillations occur due to the leakage inductance. In [10], there is additional current stress on the main switch. It means to be increased losses of converter increase.

A converter is proposed in order to overcome all of these problems. The proposed ZVT-ZCT PFC boost converter is shown in Fig. 1. In this converter, the main switch turns on with ZVT and turns off with ZCT. The main diode turns on with ZVS and turns off with ZCS. Also, there is no additional current or voltage stress on the main devices. The auxiliary switch and the auxiliary diode both turn on and turn off with ZCS. The proposed converter decreases EMI noise and operates even under a wide range of line and load voltages. Due to this features, the proposed converter has a high power factor and lower total harmonic distortion.

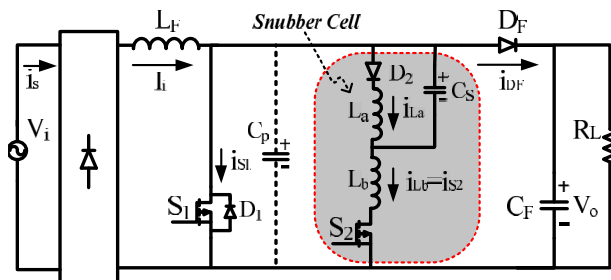


Fig. 1 The basic circuit scheme of the proposed signal phase ZVT-ZCT PFC boost converter

## II. OPERATING STEPS

The circuit scheme of the single phase soft switching PFC boost converter is given in Fig. 1. In this converter,  $V_i$  is rectified input dc voltage,  $V_o$  is output voltage,  $L_F$  is main inductance,  $C_F$  is output capacitor,  $R_L$  is output load,  $S_1$  is the main switch,  $S_2$  is the auxiliary switch, and  $D_F$  is the main diode.  $D_1$  is the body diode of the main switch.  $C_p$  is the sum of the parasitic capacitors of the main switch and the main diode.  $L_a$  and  $L_b$  are upper and lower snubber inductances,  $C_s$  is snubber capacitor, and  $D_2$  is the auxiliary diode. Also, in Fig. 1,  $i_s$  is input AC current,  $i_i$  is main inductance current,  $i_{S1}$  is current of the main switch,  $i_{S2}$  is current of the auxiliary switch,  $i_{L_a}$  is  $L_a$  inductance current,  $i_{L_b}$  is  $L_b$  inductance current,  $i_{DF}$  is main diode current.

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The following assumptions are taken into consideration while making theoretical analysis of the proposed circuit.

- Output voltage  $V_o$  and input current  $I_i$  are constant for one switching cycle.
- All semiconductor devices and resonant circuits are ideal.
- The reverse recovery times of all diodes are not taken into account.

Twelve steps occur in the steady state operation of the converter in one switching cycle. The equivalent circuit schemes of the operation steps are shown in Fig. 2 (a)–(k).

#### A. Step 1 [ $t_0 < t < t_1$ : Fig. 2 (a)]

Before this step begins,  $S_1$  and  $S_2$  switches are in off state. The main inductance current  $I_i$  passes through the main diode  $D_F$ . At  $t = t_0$ ,  $i_{S1} = 0$ ,  $i_{DF} = I_i$ ,  $i_{S2} = i_{Lb} = 0$ ,  $i_{La} = 0$ ,  $v_{Cp} = V_o$  and  $v_{Cs} = -V_{C0}$  are valid. When a gate signal is applied to  $S_2$  switch, the current of  $D_F$  decreases while the current of  $S_2$  and the voltage of  $C_s$  increase. So,  $S_2$  switch turns on with ZCS because of  $L_b$  snubber inductance and the main diode  $D_F$  turns off with ZCS.

At the end of this step ( $t = t_1$ ), the current of  $D_F$  falls to zero when the current of  $L_b$  reaches to input current  $I_i$ . Also,  $C_s$  capacitor is charged until a voltage value ( $-V_{C1}$ ).

#### B. Step 2 [ $t_1 < t < t_2$ : Fig. 2 (b)]

At  $t = t_1$ ,  $i_{S1} = 0$ ,  $i_{DF} = 0$ ,  $i_{S2} = i_{Lb} = I_i$ ,  $i_{La} = 0$ ,  $v_{Cp} = V_o$  and  $v_{Cs} = -V_{C1}$  are valid. In this step, a resonance begins through  $C_p$ – $C_s$ – $L_b$ – $S_2$ . The energy of  $C_p$  is transferred to  $L_b$  and  $C_s$ . Therefore,  $v_{Cp}$  voltage decreases while  $i_{Lb}$  current and  $v_{Cs}$  voltage are increasing.

At the end of this step ( $t = t_2$ ), voltage of  $C_s$  falls to zero and current of  $L_b$  is maximum. Also, the voltage of  $C_s$  reaches to a valid ( $-V_{C2}$ ).

#### C. Step 3 [ $t_2 < t < t_3$ : Fig. 2 (c)]

At  $t = t_2$ ,  $i_{S1} = (I_i - I_{L2\_max})$ ,  $i_{DF} = 0$ ,  $i_{S2} = i_{Lb} = I_{L2\_max}$ ,  $i_{La} = 0$ ,  $v_{Cp} = 0$  and  $v_{Cs} = -V_{C2}$  are valid. At the beginning of this step,  $D_1$  diode turns on with ZVS and a new resonance starts through  $L_b$ – $L_a$ – $C_s$ . So, the energy of  $L_b$  is transferred to  $L_a$  and  $C_s$ . This step that  $D_1$  is at on state is called ZVT area. A gate signal is applied to  $S_1$  switch in the middle of this step. Therefore,  $S_1$  turns on with ZVT perfectly.

At  $t = t_3$ , the current of  $L_b$  falls to the input current value and  $D_1$  turns off with ZCS. Then, the current of  $S_1$  increases and the current of  $L_b$  goes on decreasing.

At the end of this step ( $t = t_4$ ), the current of  $L_b$  falls to zero when the current of  $S_1$  reaches to input current value.

#### D. Step 4 [ $t_4 < t < t_5$ : Fig. 2 (d)]

At  $t = t_4$ ,  $i_{S1} = I_i$ ,  $i_{DF} = 0$ ,  $i_{S2} = i_{Lb} = 0$ ,  $i_{La} = I_{L4}$ ,  $v_{Cp} = 0$  and  $v_{Cs} = V_{C4}$  are valid. At the beginning of this step,  $S_2$  switch turns off with ZCS since the current of  $S_2$  is equal to zero at that moment. Additionally, the energy of  $L_a$  inductance is transferred to  $C_s$  with  $L_a$ – $D_2$ – $C_s$  resonance.

At the end of this step ( $t = t_5$ ), the voltage of  $C_s$  is equal to maximum value ( $-V_{C5}$ ) in reverse direction and the current of  $L_a$  is equal to zero.

#### E. Step 5 [ $t_5 < t < t_6$ : Fig. 2 (e)]

During this step, the main switch  $S_1$  conducts the input current  $I_i$ . The duration of this step is a large part of the on state duration of the conventional PWM boost converter and is determined by the PWM control to provide PFC.

#### F. Step 6 [ $t_6 < t < t_8$ : Fig. 2 (f)]

At  $t = t_6$ ,  $i_{S1} = I_i$ ,  $i_{DF} = 0$ ,  $i_{S2} = i_{Lb} = 0$ ,  $i_{La} = 0$ ,  $v_{Cp} = 0$  and  $v_{Cs} = -V_{C5}$  are valid. At the beginning of this step, a gate signal is applied to  $S_2$  and it turns on with ZCS due to  $L_b$  inductance. A resonance begins through  $C_s$ – $L_b$ – $S_2$ – $D_1$ . Then, the current of  $S_1$  switch decreases while the current of  $L_b$  is increasing.

At  $t = t_7$ , the current of  $S_1$  is equal to zero when the current of  $L_b$  is equal to the input current value. Then,  $D_1$  conducts the excess of input current. This step that  $D_1$  is at on state is called ZCT area. The control signal of  $S_1$  is removed in the middle of this step. For this reason,  $S_1$  switch turns off with ZCT perfectly.

At the end of this step ( $t = t_8$ ), the current of  $L_b$  reaches to maximum value ( $I_{L8\_max}$ ) when the voltage of  $C_s$  is equal to zero.

#### G. Step 7 [ $t_8 < t < t_9$ : Fig. 2 (g)]

At  $t = t_8$ ,  $i_{S1} = (I_i - I_{L8\_max})$ ,  $i_{DF} = 0$ ,  $i_{S2} = i_{Lb} = I_{L8\_max}$ ,  $i_{La} = 0$ ,  $v_{Cp} = 0$  and  $v_{Cs} = 0$  are valid. In this step, a new resonance begins through  $L_b$ – $L_a$ – $C_s$ . The energy of  $L_b$  is transferred to  $L_a$  and  $C_s$ . Then, the voltage of  $C_s$  begins to become positive and the current of  $L_a$  begins to increase. At  $t = t_9$ ,  $D_1$  turns off when the current of  $L_b$  falls to the input current value.

#### H. Step 8 [ $t_9 < t < t_{10}$ : Fig. 2 (h)]

At  $t = t_9$ ,  $i_{S1} = 0$ ,  $i_{DF} = 0$ ,  $i_{S2} = i_{Lb} = i_{La} = I_i$ ,  $v_{Cp} = 0$  and  $v_{Cs} = V_{C9}$  are valid. In this step, a resonance occurs through  $C_p$ – $L_a$ – $L_b$ – $C_s$ . During this step, the current of  $L_a$  and the voltage of  $C_s$  increase while the current of  $L_b$  inductance decreases.

At the end of this step ( $t = t_{10}$ ), the current of  $L_b$  falls to zero and the control signal of  $S_2$  is removed. So,  $S_2$  turns off with ZCS.

#### I. Step 9 [ $t_{10} < t < t_{11}$ : Fig. 2 (i)]

At  $t = t_{10}$ ,  $i_{S1} = 0$ ,  $i_{DF} = 0$ ,  $i_{S2} = i_{Lb} = 0$ ,  $i_{La} = I_{L10}$ ,  $v_{Cp} = V_a$  and  $v_{Cs} = V_{C10}$  are valid. In this step, both the parasitic capacitor  $C_p$  is charged under the constant input current and the energy of  $L_a$  is transferred to the  $C_s$  through  $L_a$ – $D_2$ – $C_s$  resonance.

At the end of this step ( $t = t_{11}$ ), the main diode  $D_F$  turns on with ZVS when the voltage of  $C_p$  reaches to output voltage.

#### J. Step 10 [ $t_{11} < t < t_{12}$ : Fig. 2 (j)]

At  $t = t_{11}$ ,  $i_{S1} = 0$ ,  $i_{DF} = I_i$ ,  $i_{S2} = i_{Lb} = 0$ ,  $i_{La} = I_{L11}$ ,  $v_{Cp} = V_o$  and  $v_{Cs} = -V_{C11}$  are valid. In this step, all of the energy of  $L_a$  is transferred to  $C_s$ .

At the end of this step ( $t = t_{12}$ ), the current of  $L_a$  falls to zero and  $v_{Cs}$  reaches to  $-V_{C0}$  value.

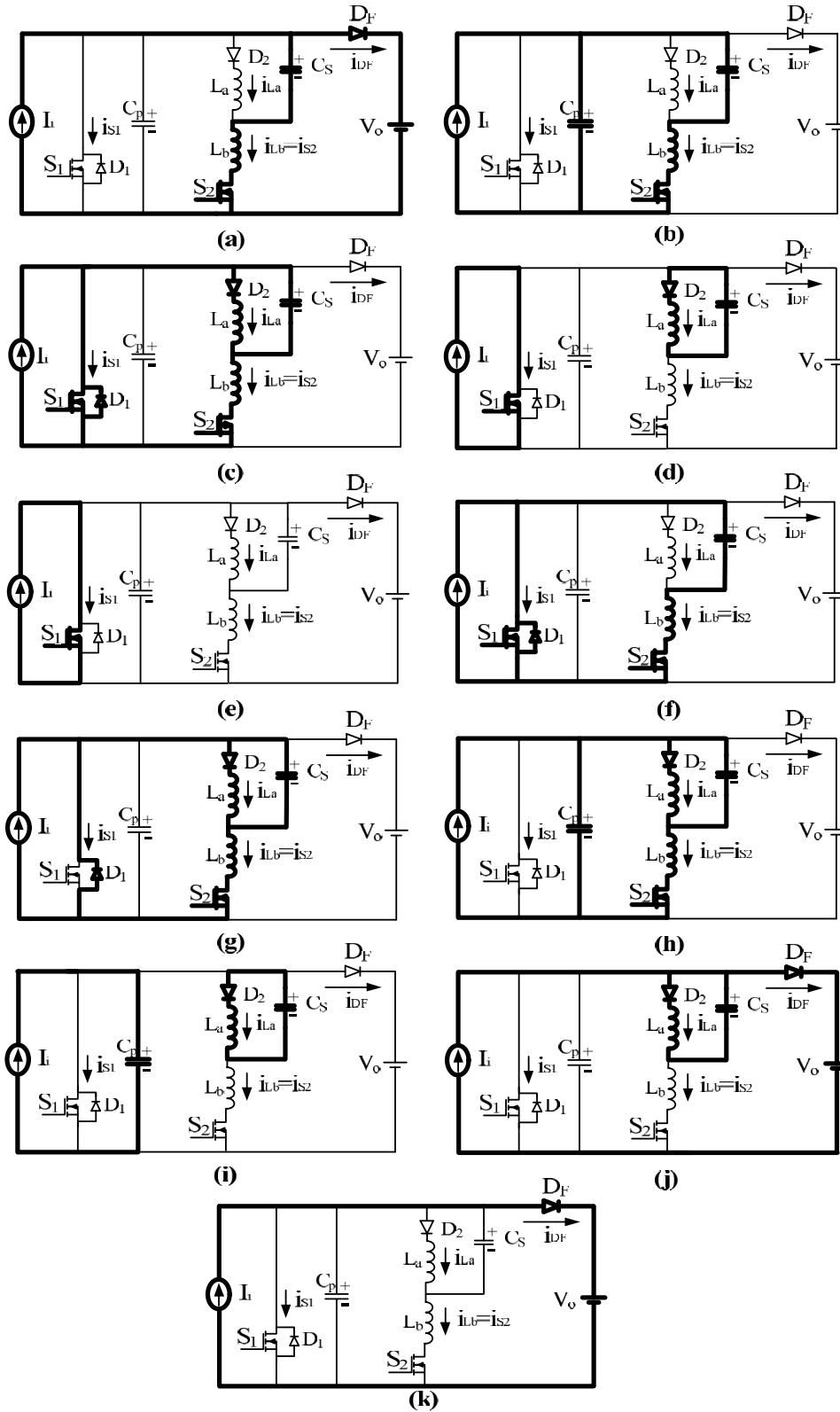


Fig. 2 Equivalent circuit of the operating steps in proposed single phase ZVT-ZCT PFC converter. (a) Step 1, (b) Step 2, (c) Step 3, (d) Step 4, (e) Step 5, (f) Step 6, (g) Step 7, (h) Step 8, (i) Step 9, (j) Step 10, (k) Step 11

*K. Step 11 [ $t_{12} < t < t_{13}$ : Fig. 2 (k)]*

During this step, the main diode  $D_F$  conducts input current  $I_i$  and the snubber circuit is not active. This time period is determined by the PWM control and large part of the off state of the converter.

At  $t = t_{13}$ , the operation steps are finished and it is returned to initial conditions. The steps expressed are repeated in the next switching cycle.

III. SIMULATION RESULTS

It is realized a prototype of the proposed single ZVT-ZCT PFC boost converter for 500 W and 100 kHz in PSIM program. The simulation parameters and the value of the devices are given in Table I.

TABLE I  
THE SIMULATION PARAMETERS AND THE VALUE OF THE DEVICE OF PROPOSED CONVERTER

Output Power ( $P_o$ )	500 W	Upper Snubber Inductance ( $L_a$ )	4 $\mu$ H
Switching Frequency ( $f$ )	100 kHz	Lower Snubber Inductance ( $L_b$ )	2 $\mu$ H
AC Input Voltage ( $V_i$ )	200 V	Snubber Capacitor ( $C_s$ )	15 nF
DC Output Voltage ( $V_o$ )	400 V	Parasitic Capacitor ( $C_p$ )	6 nF
Main Inductance ( $L_r$ )	500 $\mu$ H	Output Capacitor ( $C_F$ )	470 $\mu$ F

The simulation circuit scheme of the proposed converter is given in Fig. 3. The control signals of the switches are obtained with PFC average current mode controller. The block scheme is given Fig. 4. The simulation results of the converter are shown in between Figs. 5-7.

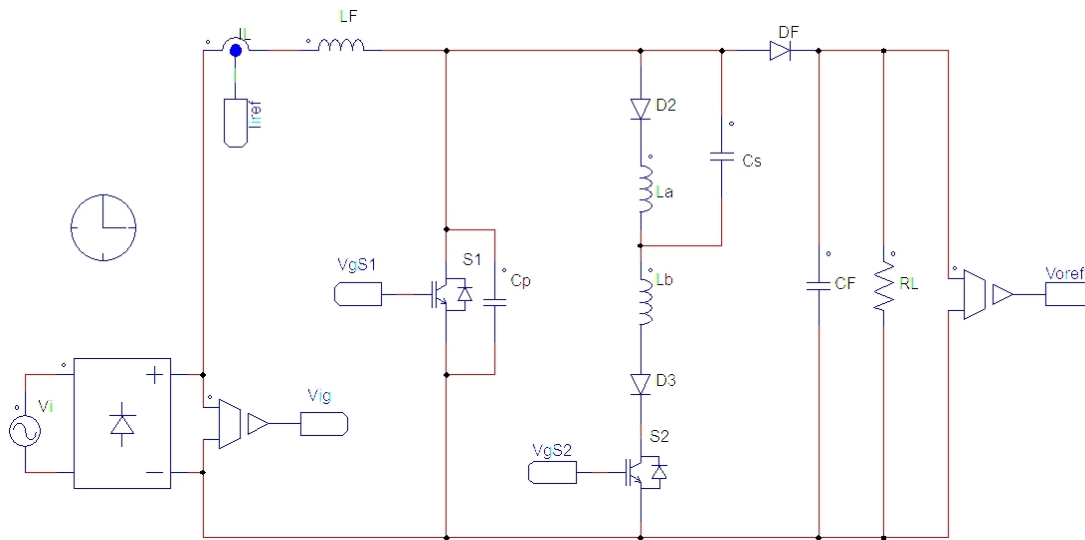


Fig. 3 The simulation circuit scheme of the proposed PFC converter

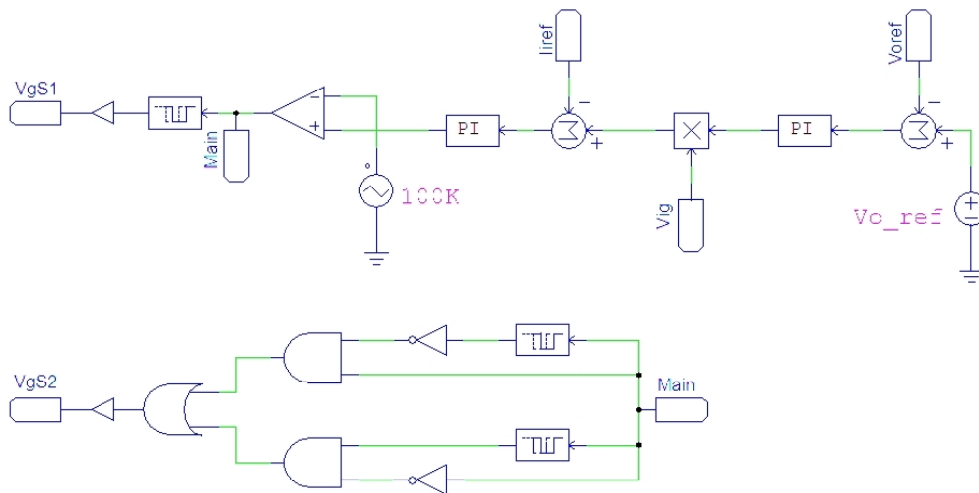


Fig. 4 The average current control block scheme for PWM control signals

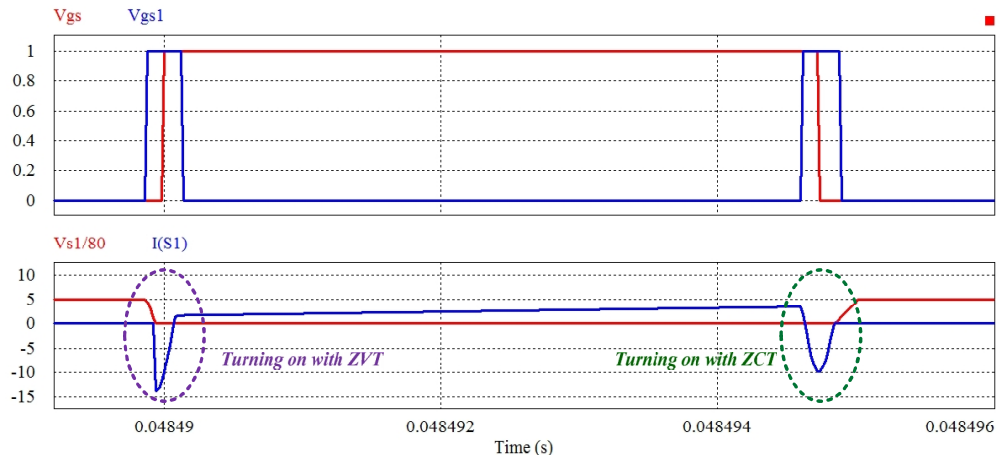


Fig. 5 Respectively; the control signals of main switch and auxiliary switch, the voltage of main switch and the current of main switch

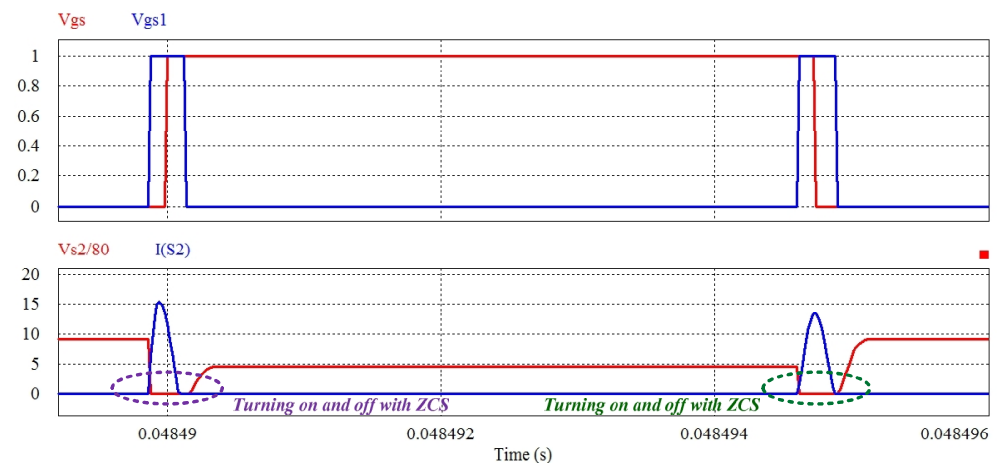


Fig. 6 Respectively; the control signals of main switch and auxiliary switch, the current and voltage of auxiliary switch

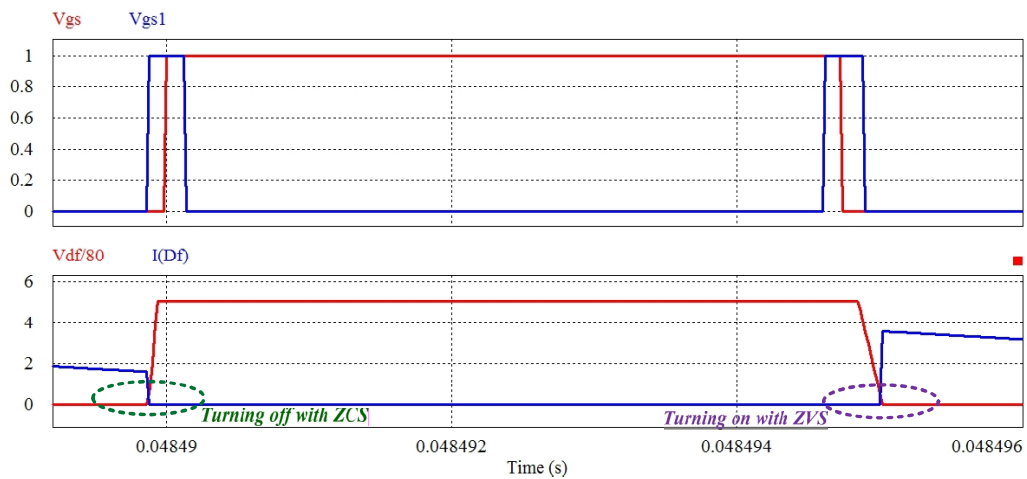


Fig. 7 Respectively; the gate signals of the switches, the current and voltage of the main diode

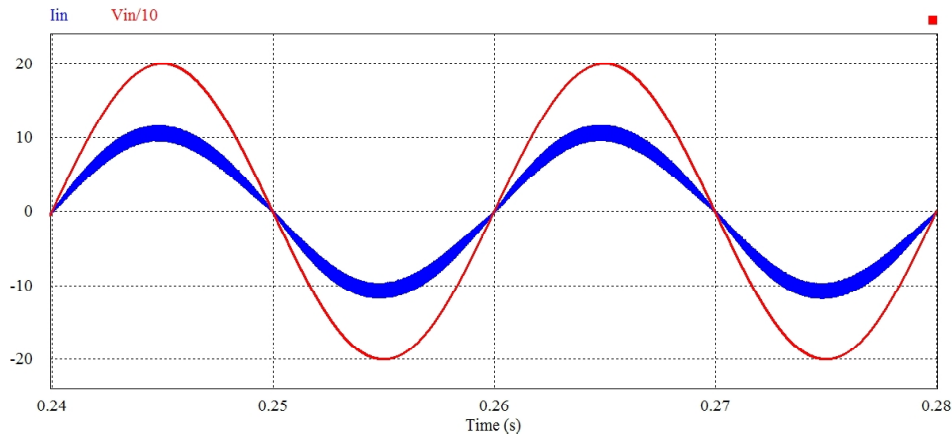


Fig. 8 The input voltage and current waveforms of proposed PFC converter

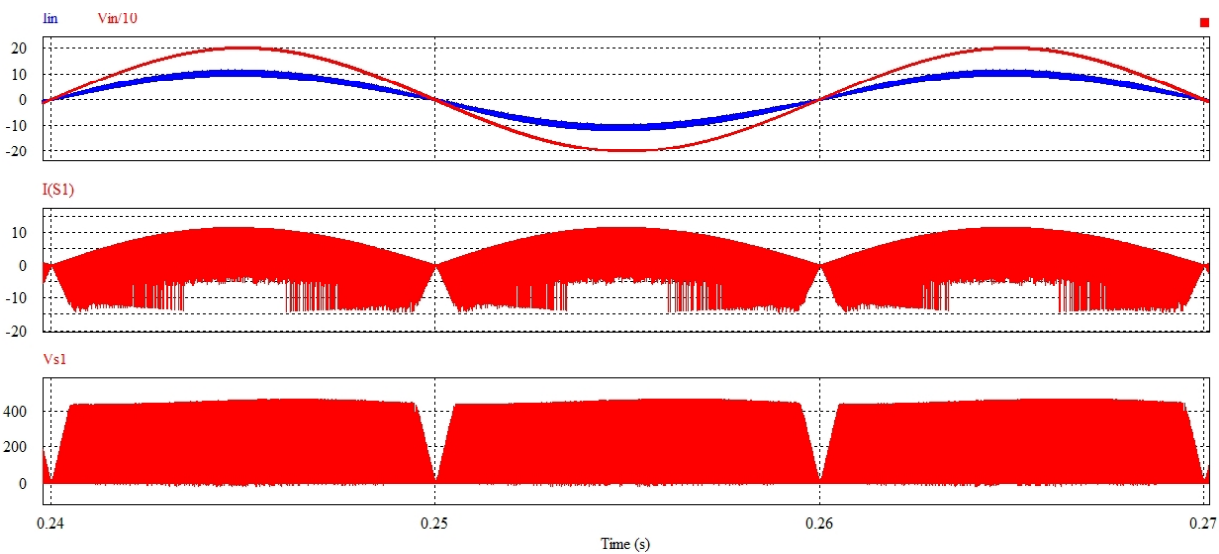


Fig. 9 Respectively; the input voltage and current waveforms of proposed PFC converter, the current waveform and the voltage waveform of the main switch

The gate signal and current–voltage waveforms of the main switch  $S_1$  are given in Fig. 5. As shown in the figure, the voltage of main switch is fallen to zero with the aid of the snubber cell before the main switch is turned on. Then, the main switch turns on with ZVT while the body diode of main switch is on state. For turning off, the current of main switch is fallen to zero with the aid of the snubber cell. Then, the main switch turns off under ZCT while the body diode of main switch is on state. Moreover, there is no additional voltage or current stress on the main switch during this process.

The gate signal and current–voltage waveforms of the main switch  $S_2$  are given in Fig. 6. As shown in the figure, the auxiliary switch turns on and off with ZCS. However, there is additional voltage stress on the auxiliary switch and its value is equal to almost  $2V_o$ .

The gate signal of the switches and current–voltage waveforms of the main diode  $D_F$  are given in Fig. 7. As shown in the figure, the main diode turns on with ZVS and turns off

with ZCS. Also, it is clear that there is not any voltage and current stress on the main diode.

The input voltage and current waveforms are given in Fig. 8. The power factor of the proposed converter is near unity with 0.99. Also, it is seen that the proposed PFC converter operates in CCM. The proposed converter is tested at universal input line voltage and very wide load ranges. It is observed that it keeps operating under soft switching conditions successfully for the whole line and load ranges. Also, the input voltage and current waveforms are given together with the voltage and current waveforms of the main switch in Fig. 9. The input voltage value is scaled 1/10 ratio in Figs. 8 and 9. The voltage value of the main switch is scaled 1/80 ratio in Fig. 9.

#### IV. CONCLUSIONS

In this paper, a ZVT-ZCT PFC boost converter with active snubber cell is proposed. The snubber cell provides to ZVT turning on and ZCT turning off for the main switch. It

operates in a little part of the switching period. Also, it provides ZVS turning on and ZCS turning off for the main diode. For this reason, it minimizes the reverse recovery losses of the main diode. The proposed converter does not compose any extra voltage or current stress on the main devices.

The auxiliary switch turns on and turns off under ZCS. However, extra voltage stress occurs on the auxiliary switch. The extra current or voltage stress does not occur on the other auxiliary elements and all of them operate under soft switching.

The proposed converter solves many drawbacks of the PFC converters presented earlier. All semiconductor devices in the circuit are switched with soft switching. A detailed steady-state analysis of the proposed converter is presented. The theoretical analysis of the proposed converter is exactly verified by 500 W and 100 kHz prototype. The average current mode control method is used in the proposed converter. The power factor of the proposed converter is measured nearly 0.99.

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