Design of A 2KW Soft-Switching ZVT Power Factor Correction Converter With Active Snubbers

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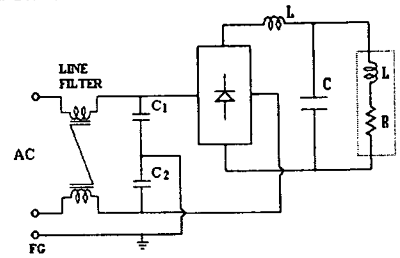
Abstract - In this paper a soft switching ZVT power factor converter using active snubbers is designed to improve efficiency and reduce voltage spike and parasitic ringing. The main switch achieves ZVT and the auxiliary switch performs with ZCS. A 2KW soft switching ZVT converter is designed with switching frequency 100kHz, output voltage 400VDC. Then the designed system is realized and experimental results show that the measured efficiency and power factor are over 97.45% and 0.997 respectively with an input current THD less than 3%.

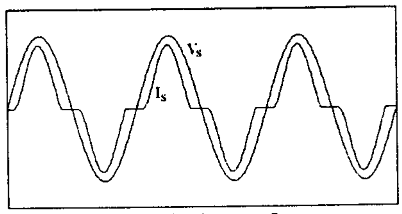
1.Introduction

In telecom applications, communication systems, and image and sound systems using a semiconductor device, power supplies that satisfy low voltage, high quality DC power are required. To satisfy these conditions, the common AC voltage is rectified to DC voltage. Fig. 1 shows that a simple circuit for rectifier load consists of line filter, diode rectifier, and L-C filter. This circuit has an advantage of low cost, but contains harmonics in input current. To meet the harmonic current limit, which is strengthening by the law, and to improve input power factor, power factor correction circuit is investigated and required. This circuit can obtain unity power factor and sinusoidal input current, but they have many problems, such as electromagnetic interference and switching losses caused by switching noise in main switch[1]. The trend in power converters is towards increasingly higher power densities. Usually, the method to achieve this is to increase the switching frequency, which allows a reduction in the filter component's size. Raising the switching frequency however, significantly increases the system switching losses which generally precludes operating at switching frequencies greater then 100kHz.

In order to increase the switching frequency while maintaining acceptable efficiency, several soft switching techniques have been developed. Zero voltage transition (ZVT) converters operate at a fixed frequency while achieving ZVS of the main switch and the auxiliary switch can achieve ZCS turn-off with small current stress. This is accomplished by employing resonant operation only during switch transitions. During the rest of the cycle, the resonant network is essentially removed from the circuit and converter operation is identical to its nonresonant counterpart. This technique allows an improvement in efficiency over the traditional boost converter, as well as operating the main switch with reduced stress.



(a) Rectifier circuit



(b) Typical waveforms

Fig. 1 Simple AC/DC rectifier circuit and its waveforms.

Every method has its own benefits and drawbacks from different points of views, such as efficiency, electrical stresses, EMI issues, cost, and degree of circuit complexity, depending on different practical application requirements. However, currently, the efficiency issue seems the main consideration of the present. Soft switching of the blocking diode also reduces EMI, an important system consideration.[2][3]

This paper shows an example of this technology combination. Based on the concepts of two existing ZVT soft switching technologies using a coupled inductor and snubber capacitor, respectively, this design of A 2KW Soft-Switching ZVT Power Factor Correction Converter with Active snubber achieves higher efficiency. Figure 2 shows the designed ZVT converter. The main switch has ZVT turn-on performance in converter.

This snubber capacitor C_f reduces the rate of voltage rise in both the main switch Q_1, and the auxiliary switch Q_2, during turn-off periods of each. In this designed converter, besides the advantages of ZVT turn-on for the main switch Q_1, and ZCS turn-off for the auxiliary switch Q_2, with small current stress, the capacitor C_f, acts as a turn-off snubber capacitor for both the main switch Q_1, and the auxiliary switch Q_2, during their turn-off transition period.

2. Operational principle of the designed ZVT converter

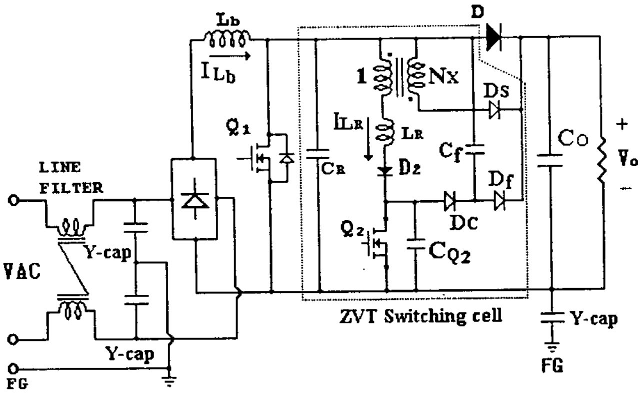


Fig. 2 Single-phase ZVT PFT converter with active snubber using a coupled inductor

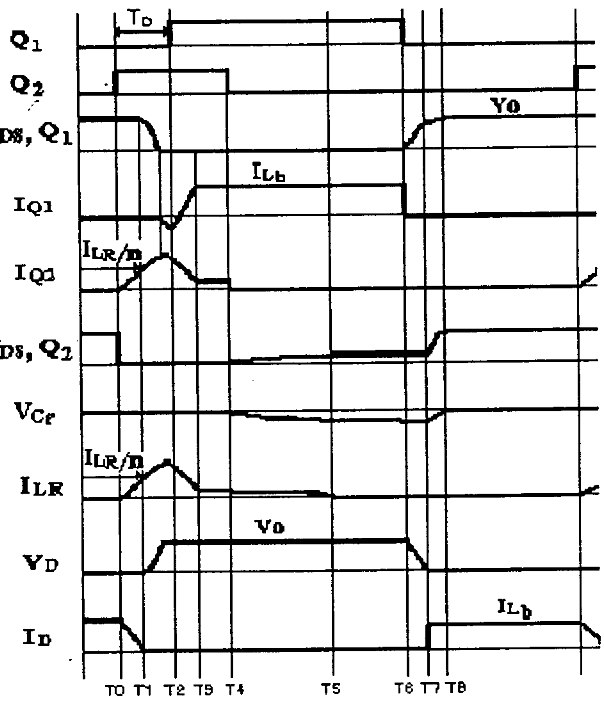


Fig. 3. Ideal waveforms of the designed converter.

Fig. 3 shows the ideal waveforms of the designed ZVT converter. Switching operations are divided into nine circuit modes. This is composed of a main switch Q_1, an auxiliary switch Q_2, a boost inductor L_b, a magnetic circuit(coupled inductor), a resonant capacitor C_R, a resonant inductor L_R, a blocking diode D, a snubber capacitor C_f and parallel capacitor of the auxiliary switch C_{Q2}. The following figures 4 show the detailed operation modes of the designed converter.

Circuit mode 1 : [Before T_0]

Mode 1(Before T_0), the main switch Q_1 and the auxiliary switch Q_2 are off, and the blocking diode D is conducting. The boost inductor current I_{Lb} is flowing to the load side through the path of the blocking diode D. Also, the snubber

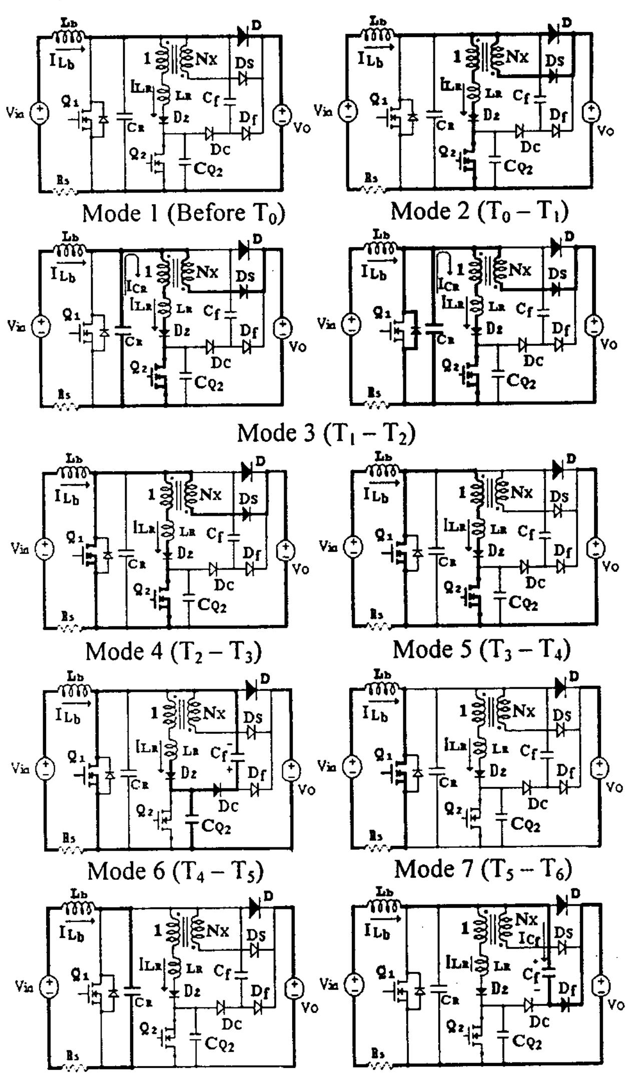


Fig. 4. Operation modes of the designed converter.

capacitor C_f has been already discharged to zero, the resonant capacitor C_R is charged with output voltage V_O. Furthermore, all of the magnetizing energy has been discharged to the load side.

Circuit mode 2 : [T_0 -T_1]

The auxiliary switch Q_2 is turned on by ZCS before the main power switch Q_1 is turned on. The auxiliary current linearly ramps up until it reaches I_{Lb}/n. The resonant inductor current I_{LR} is reflected into primary side until the current reaches to I_{Lb}/n. Meanwhile, the coupled current from the secondary side flows through the diode D_S, to the load side. Therefore, the auxiliary switch carries less current then the resonant current. At this time, since the current of the blocking diode D is decreased and becomes zero. At the end of this mode, the diode D also achieves soft switching.

Circuit mode 3 : [T_1 -T_2]

In this mode, when current of the auxiliary circuit reaches to I_{Lb}/N_x, and diode D is turned off. As a result, L_L

and C_R start to resonate. Resonant period is maintained until voltage on C_R becomes zero. Current flowing through L_L is continuously increased while C_R discharges. The required time that the drain voltage of the main switch Q_1 reaches to zero voltage is 1/2 of the resonant period. The body diode of the main switch is turned on at the end of this period. During this period, the current amount through the primary side and the secondary side of the coupled inductor is greater then the boost inductor current.

Circuit mode 4 : $[T_2 - T_3]$

In this mode, the drain voltage of the main switch Q_1 becomes zero and resonant current becomes to freewheel through $C_R \rightarrow L_L \rightarrow$ body diode of Q_1. Thus, the body diode is turned on. At the same time, main switch Q_1 is turned on at ZVS. The switching loss can be considerably reduced. The current through the main switch is then increasing.

Circuit mode 5 : $[T_3 - T_4]$

In this mode 5, both the main switch, and the auxiliary switch are still being turned on. Therefore, the current of the auxiliary switch decreases linearly, and the magnetizing current I_{Lm} of the coupled inductor is flowing to the input voltage source V_{in}. Meanwhile, the boost inductor L_b begins to be charged by the input voltage source though the path of the main switch and the boost inductor.

Circuit mode 6 : $[T_4 - T_5]$

After the auxiliary switch is turned-off by ZCS, the magnetizing current of the coupled inductor is charging to the snubber capacitor C_f until the residual energy of the coupled inductor and resonant inductor is completely transferred to the snubber capacitor and parallel capacitor of the auxiliary switch. Then the voltage polarity of the snubber capacitor is reversed to negative. In this period, the snubber capacitor is acting as the turn-off snubber of the auxiliary switch to reduce voltage spike and parasitic ringing. The stored energy in the snubber capacitor will be recycled and used to suppress the turn-off voltage spike of the main switch.

Circuit mode 7 : $[T_5 - T_6]$

During this time period, the main switch Q_1 continues to be turned on and the auxiliary switch Q_2 is off. The boost inductor L_b is charged by the input voltage source V_{in}. At that time, the output capacitor discharges to the output load.

Circuit mode 8 : $[T_6 - T_7]$

This mode starts when the main switch Q_1 is turned off by ZVS at t6. The voltage on the main switch is gradually increased since current flowing into the switch Q_1 is transferred to the current of the resonant capacitor C_R. Also dv/dt of the drain voltage is controlled by C_R. This is the reason why it can reduce turn-off switching loss. In this mode, the voltage on blocking diode D is gradually decreased.

Circuit mode 9 : $[T_7 - T_8]$

In this mode, the resonant capacitor C_R is charged with output voltage V_O, when the increasing voltage across C_R is greater then (V_O+V_{Cf}), the snubber capacitor C_f begins to discharge through the path of the D_f, the output capacitor C_O, and the resonant capacitor C_R of the main switch. This discharge of C_f can slow down the rising voltage slope of the rising voltage across the main switch. Therefore, the C_f is performing as a turn-off snubber for the main switch to suppress the turn-off voltage spike and the turn-off voltage slope of the main switch. Simultaneously, the blocking diode D turns on at zero voltage and the boost inductor current I_b flows into the output load. This means that the blocking diode D is turned on in ZVS. Therefore, voltage stress can be reduced. During this mode, the main switch Q_1 and the auxiliary switch Q_2 are in turn-off state.

3. System Configuration

2000W, 100kHz, high efficiency soft switching ZVT converter is implemented. The peak to peak ripple current of the boost inductor L_b is designed with 15% of the boost inductor current. Boost inductor L_b is 350uH, and MPP55254 core of Magnetics Inc. is used to reduce switching loss. Resonant capacitor is the sum of MOSFET capacitor and external node capacitor and it also needs a low ESR and ESL in the case of high frequency. When the switching current flows into capacitor, it needs a specific characteristic that can charge a large capacity to reduce a turn-off loss. Since resonant capacitor C_R has to be determined with consideration of parasitic inductor and capacitor, a low loss ceramic capacitor with dissipation factor 0.2% is adopted. The specifications of this MOSFET Q_1 are 500V, 30A, $R_{DS}(on)=0.18\,\Omega$ (25℃), and C_{oss}=600pF. The specifications of this auxiliary MOSFET Q_2 are 500V, 18.5A, $R_{DS}(on)=0.24\,\Omega$ (25 ℃), and C_{oss}=470pF. The reverse recovery time T_{rr} of blocking diode is 50ns. The control circuit of the designed high efficiency soft switching ZVT converter consists of a voltage compensator, a multiplier, a current compensator and a triangle wave generator. In this system, an integrated circuit UC3854BN is used to control power factor over 0.999 and to limit input current harmonic distortion under 3%.

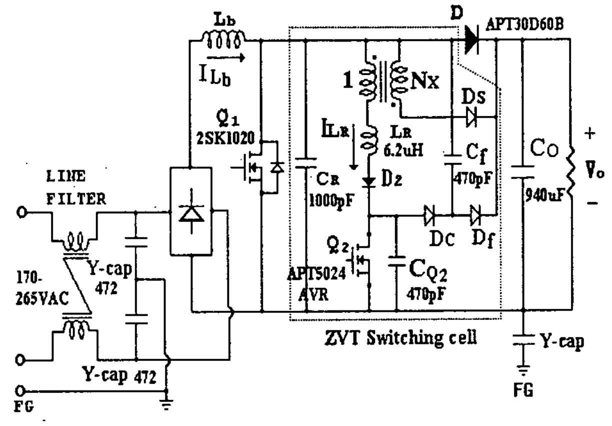


Fig. 5. The designed converter circuit.

■ Specifications

- Input voltage range : 170-265VAC

- Output voltage, Current : 400VDC, 5A
- Power : 20W-2000W
- Switching frequency : 100KHz
- Snubber capacitor C_f : 470pF
- Resonant capacitor C_R : 1000pF
- Resonant inductor L_R : 6.2uH
- Input boost inductor L_b : 350uH
- Output capacitor Co : 940uF

4. Simulation and Experimental Results

Fig. 6 shows simulation results obtained by a Pspice program. Operating characteristics of the high efficiency soft switching ZVT converter designed in this paper are confirmed by the experiment. Fig. 7 shows the waveforms obtained from the experiment under the condition of input voltage 220V, output voltage 400VDC, switching frequency 100kHz, 1.5kW. The power factor obtained was 0.997. Fig. 8 shows the analysis of the input current harmonics. The THD of the designed converter current is smaller than that of the hard switching converter current as shown in Table 1.

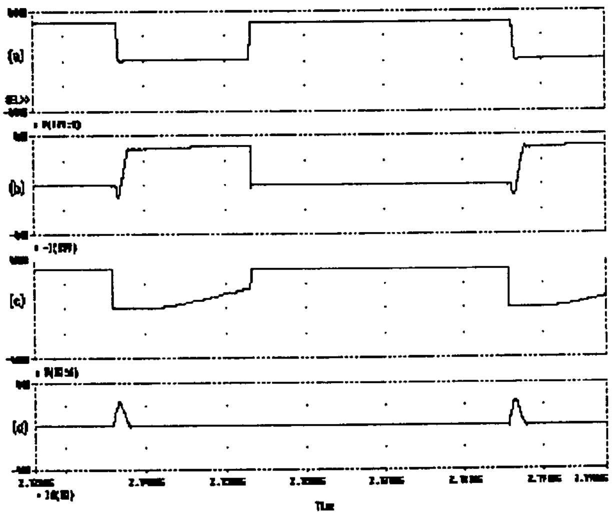


Fig. 6. Simulation results using a Pspice program.
(a) Main switch voltage (b) Main switch current
(c) Auxiliary switch voltage (d) Resonant inductor current

Fig. 9 (a) shows the voltage waveform V_{DQ1} and the current waveform I_{Q1} of the main switch. It is clear that the main switch Q_1 is working at ZVS soft switching condition. Fig. 9(b) shows the voltage waveform V_{DQ2} of the auxiliary switch and the resonant current of the auxiliary switch Q_2 is about 10[A]. The maximum efficiency obtained was 97.45 % with 1000[W] load as shown in fig. 10

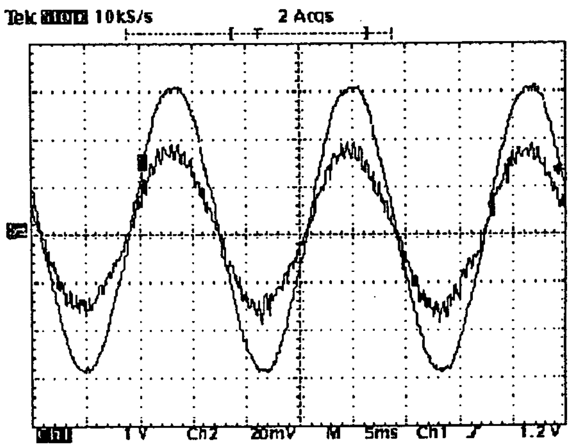
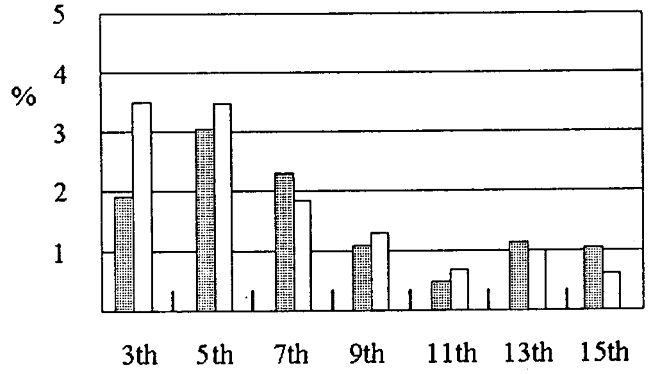


Fig. 7. Input voltage and current waveforms (100V/div, 5A/div, 5ms/div)

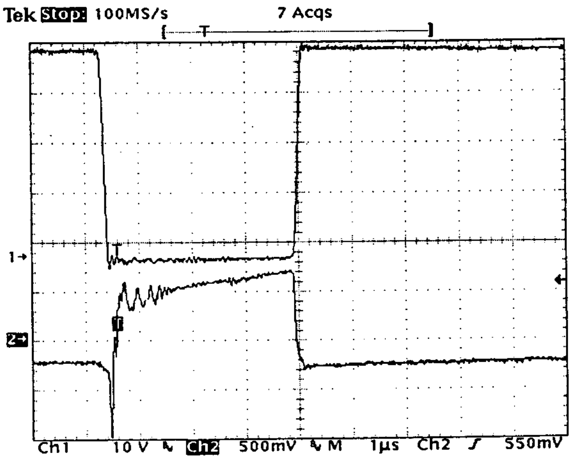


Hamonics (: Vin=170V, : Vin=265V)

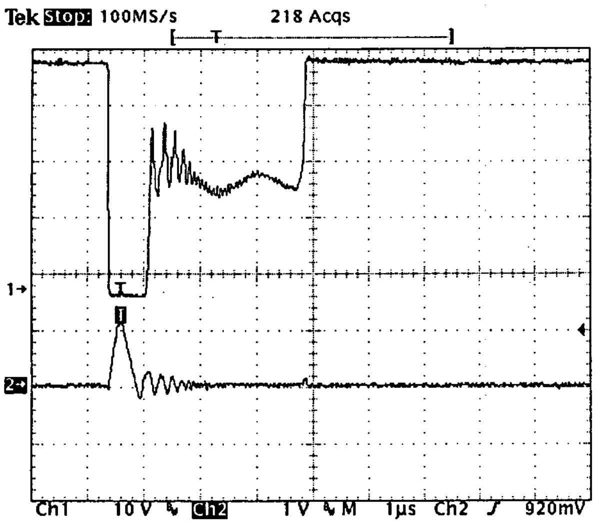
Fig. 8. Harmonic analysis of the input current. (P_o =2000W)

Table 1. THD of converter input currents

Converter	THD
Hard switching converter	0.0782
Designed soft switching converter	0.0295



(a) Main switch voltage and current waveforms
(b) (100V/div, 10A/div, 1us/div)



(c) Auxiliary switch voltage and current waveforms (100V/div, 10A/div, 1us/div)

Fig. 9. Experimental results

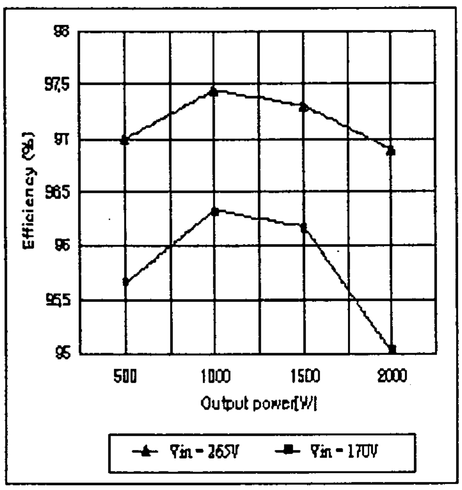


Fig.10. Efficiency curve of the designed converter.

3. Conclusion

In this paper a soft switching ZVT power factor converter using active snubbers is designed to improve efficiency and reduce voltage spike and parasitic ringing. The main switch achieves ZVT and the auxiliary switch performs with ZCS. A 2KW soft switching ZVT converter is designed with switching frequency 100kHz, output voltage 400VDC. Then the designed system is realized and experimental results show that the measured efficiency and power factor are over 97.45% and 0.997 respectively with an input current THD less than 3%.

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