Novel ZVS Three-Phase PFC Converters and Zero-Voltage-Switching Space Vector Modulation (ZVS-SVM) Control

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Abstract – In three-phase PFC converter, there exist severe switch anti-parallel diode reverse recovery problems. The effective measures of Compound Active-clamping and Minimal Voltage Active-clamping techniques in single phase PFC are extended to three-phase PFC. A family of Active-clamping ZVS soft switching PFC converter is derived. They can effectively suppress the diode reverse recovery and realize ZVS for all the switches. In order to refuce the number of switching for the auxiliary switch. A ZVS space vector modulation (ZVS-SVM) is proposed. The switching frequency of the main switch and the auxiliary switch is fixed. In the proposed circuit only one auxiliary switch is needed, which can realize ZVS for all the switches. At the same time the input current waveform is improved. One DSP controlled 4kW ZVS Compound Active-clamping PFC converter prototype is implemented.

Keywords – Three-phase PDC, zero- voltage- switching, space vector modulation

I. Introduction

Six-switch three-phase boost rectifier is one of the preferred topology for implementing the active input-current shaping in three-phase AC-DC converter. It has several advantages such as lower current stree, high efficiency, and small input EMI filter. However, the anti-parallel diodes of all the switches in the rectifier experience reverse recovery problem which will cause severe switching loss, high di/dt and EMI problems. The anti-parallel diode reverse recovery loss is one of the main losses in the six-switch boost rectifier [1].

For passing years, many works about soft switching for three-phase rectifier or inverter have been undertaken to solve the diode reverse recovery problem. The DC-rail ZVT boost rectifier proposed in [2] adopts a DC-rail diode and a ZVT branch to suppress the diode reverse recovery and to realize the ZVS of the main switches. However the auxiliary switch is hard switching. The auxiliary resonant commutated pole (ARCP) converter put the soft-switching circuit at the ac side to reduce the auxiliary circuit conduction loss and facilitate bi-directional power flow. However it needs six extra auxiliary switches to realize the soft switching [3]. The resonant dc link (RDCL) proposed in [4][5] has the simplified topology. However the switches in RDCL converter suffer from high voltage stress (about 2.5 times the output voltage). The active clamped RDCL in [6] has a low voltage stress (about 1.3 ~ 1.4 times the output voltage). Instead of using PWM control, RDCL and ACRDCL converters have to use discrete pulse modulation (DPM), which normally causes undesirable sub-harmonics. DPM requires the dc-link resonating frequency to be several times higher than the switching frequency of the PWM converter for the same current spectral performance [1][6].

In this paper, the concept of Compound Active-clamping and Minimal-voltage Active-clamping [9][10] in single phase PFC is extended to three-phase PFC. A family of Active-clamping ZVS three-phase PFC is proposed. To suppress the diode reverse recovery of the three-phase switch, a novel zero voltage switching space vector modulation (ZVS-SVM) for the Active-clamping ZVS three-phase PFC is proposed. The switching frequency of both the main switches and the auxiliary switch is fixed. The switching frequency of the auxiliary switch is equal to that of the main switches. The diode reverse recovery of the switch anti-parallel diode is suppressed and all the switches can be turned on under zero voltage condition. The voltage stress on the switches is much lower than that on the RDCL and the ACRDCL converters.

A 4kW DSP (TMS320F2407A) controlled Compound Active-clamping ZVS Three-Phase PFC is built to verify the theory.

II. Novel ZVS Three-Phase PFC Converter Family

In single phase PFC converter, there also exists severe diode reverse recovery problem. In the passing years, there are many significant works to solve the diode reverse recovery problem [7]-[10]. Among them, the Compound Active-clamping (CAC) and Minimum-voltage Active-clamping (MVAC) techniques can effectively suppress the diode reverse recovery and create ZVS for both the main switch and the auxiliary switch. Fig.1 and Fig.2. show the CAC and MVAC PFC converters separately. The key ideas of these two Active-clamping soft-switching techniques are as follows:

1. An inductor is placed in series with the diode and the main switch. The inductor can suppress the diode reverse recovery and reduce the diode reverse recovery related loss.
2. A clamping branch composed of one clamping capacitor and one auxiliary switch is placed in parallel with the inductor, thus it can clamp the voltage stress of the inductor when the main switch turns off. The auxiliary circuit can also help to realize ZVS for the two switches.

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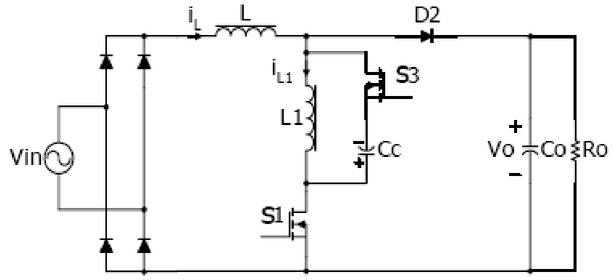


Fig.1: CAC PFC converter

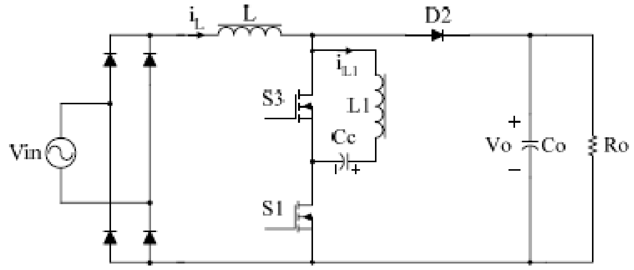


Fig. 2: MVAC PFC converter

In three-phase PFC, the diode reverse recovery problem in every phase is similar to that in single-phase PFC. Thus we extend the concept of Active-clamping techniques to three-phase PFC, and can get Compound Active-clamping three-phase PFC converters that are shown in Fig. 3 and Fig.4.

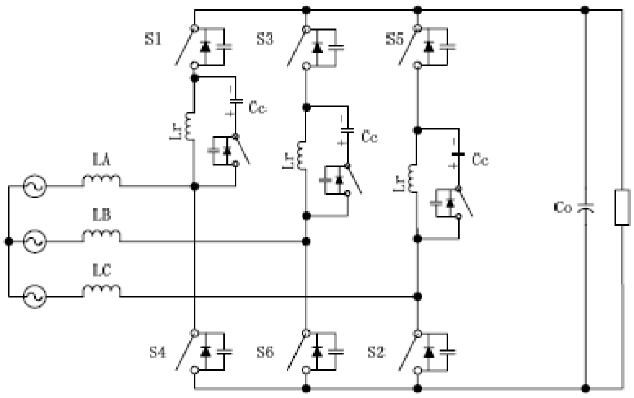


Fig. 3: CAC PFC converter (1)

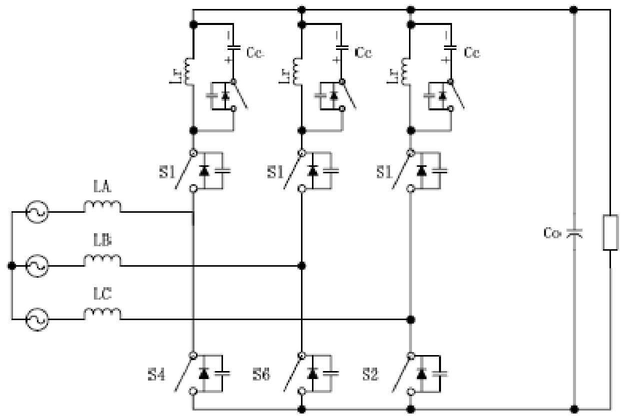
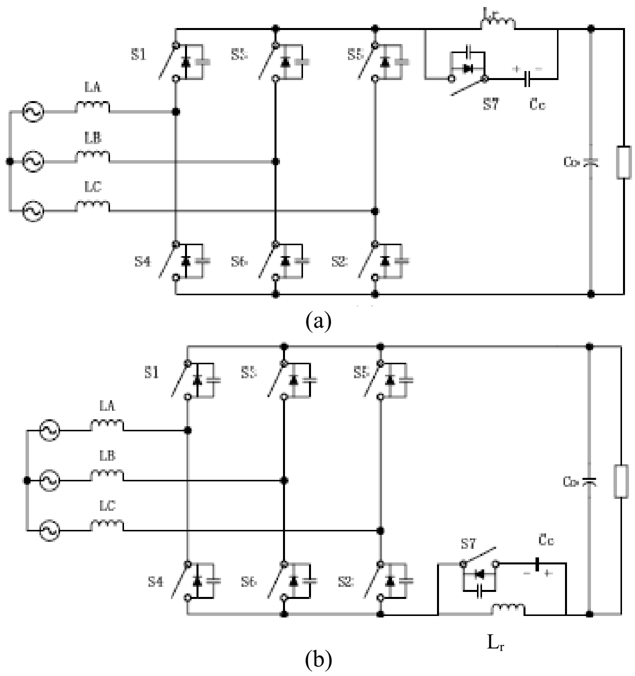


Fig. 4: CAC PFC converter (2)

These two kinds of ZVS three-Phase PFC can suppress the diode reverse recovery and realize ZVS for all the switches. However, the topology needs three extra switches.

Fig. 5 shows the CAC ZVS three-phase PFC converters, Fig. 6 shows the MVAC ZVS three-phase PFC converters.

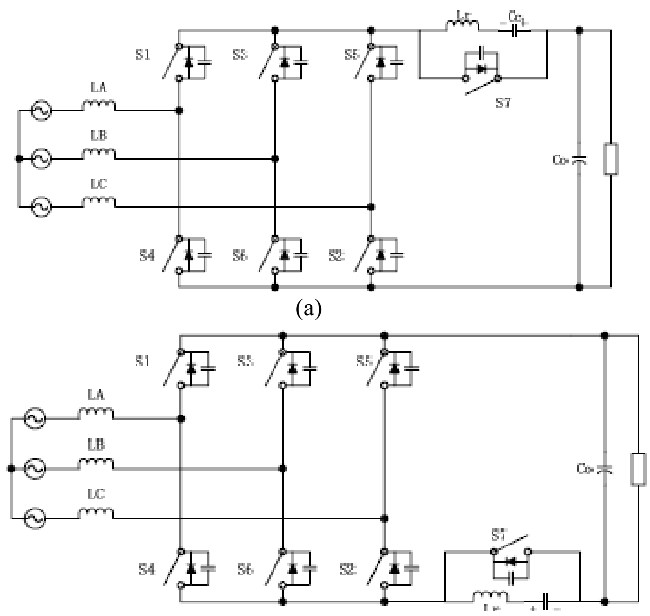
The ZVS PDC converters in Fig. 5 and Fig. 6 use only one auxiliary switch, one resonant inductor and one clamping capacitor. Since in most time of a switching cycle, the auxiliary switch is conducting, there is generally enough energy circulating in the auxiliary branch. When the auxiliary switch is turned off, the current in the resonant inductor will discharge the parallel capacitors of the main switches, then the main switches can be turned on under zero voltage condition. When the main switches are turned on, the resonant inductor can suppress the reverse recovery current of the anti-parallel diode of the opposite switch in the same pole.



(a)

(b)

Fig. 5: CAC ZVS three-Phase PFC converters



(a)

(b)

Fig. 6: CAC ZVS three-Phase PFC converters

Although the topology is the same as that of ACRDCL converter, the control pattern is quite different. To suppress the diode reverse recovery for the switches in three phase. Special control methods should be taken. In this paper, a novel Zero-Voltage-Switching Space Vector Modulation (ZVS-SVM) is proposed. Under the ZVS-

SVM control, all the diode reverse recovery of the switch anti-parallel diodes are suppressed and all the switches can be turned on under zero voltage condition. The switching frequency of both the main switches and the auxiliary switch are fixed. The switching frequency of the auxiliary switch is equal to that of the main switches.

Among the three-phase PFC converters, the VIENNA rectifier employs only three active switches and can achieve good current quality. However there also exists severe diode reverse recovery problem that limit the switching frequency of the VIENNA rectifier. In this paper, the concepts of Compound Active-clamping and Minimal-voltage Active-clamping are extended into the VIENNA rectifier and two kinds of ZVS VIENNA rectifies are got. Fig. 7 shows the CAC ZVS VIENNA rectifier and Fig. 8 shows the MVAC VIENNA rectifier.

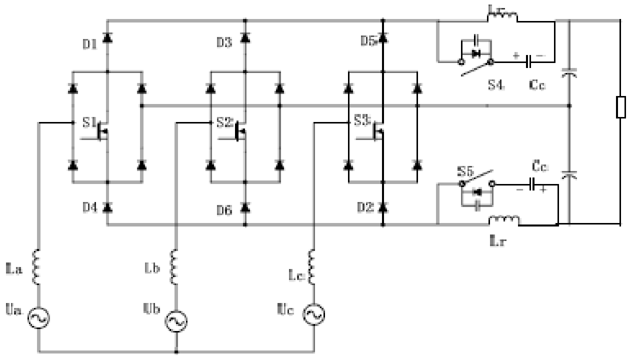


Fig. 7: CAC ZVS VIENNA rectifier

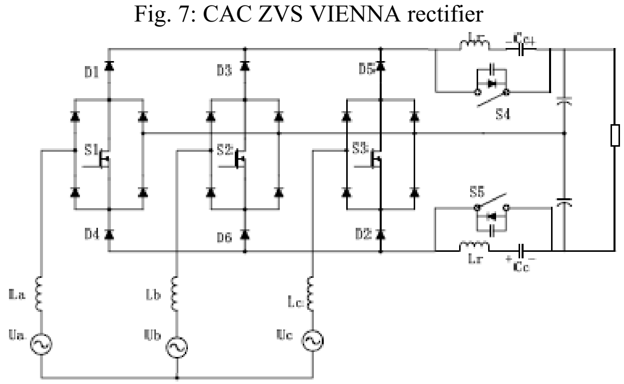


Fig. 8: MVAC ZVS VIENNA rectifier

III. Zero Voltage Switching Space Vector Modulation (ZVS-SVM)

In space vector modulation scheme, the phase voltage waveform and voltage space vector definition are shown in Fig. 9. V0 to V7 are the eight different switching states in the converter operation. In ZVS SVM, the whole utility cycle is divided into 12 sectors.

In three-phase PFC, since there are three legs in the main bridge, the auxiliary switch must be activated three times per switching cycle if the switches in the three legs are modulated asynchronously. Actually in one sector the switch states of the phase with the highest current is fixed, only other two phases need to be considered about the diode reverse recovery suppressing and ZVS condition. If the switches in the other two phases are so controlled that the turn on time of the other two phase switches is synchronized, the diode reverse recoveries of them can be coped with at the same time. Thus the auxiliary switch need only to operate once in one switching cycle to resonant the DC bus to zero and create ZVS condition for the two phase switches and suppress the diode recoveries of both phases. Thus the auxiliary switch can work at the same frequency with the main switches.

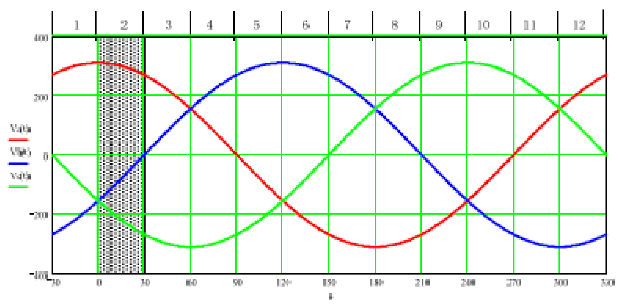
Since the operation of the converter is symmetrical in every 30°, to understand the operation of the circuit, we assume that the converter is operating in sector 2 as an instance where input current Ia>0, Ic<0 and Ib<0. There are three switch states in one switching cycle, as shown in Fig. 10. The three switch states are state 100, state 111 and state 110. The equivalent circuits of these three states are shown in Fig. 11. In this sector, phase A has the highest input voltage and the highest input current. Switch S1 is always on while switch S4 is always off in sector 2. The switches in the other two phases are controlled in the PWM manner. According to the proposed ZVS-SVM scheme, the switch S3 and S5 are to be turned on simultaneously when switching state 100 changes to state 111.

In state 100, although the driving singles of S1, S6 and S2 are effective, it is the anti-parallel diodes of S1, S6 and S2 being conducting. If the rectifier state is changing from 100 to 111, switch S3 and S5 will starts to conduct while the anti-parallel diodes of S6 and S2 will turn off. During the commutation from the lower-leg diodes to the upper-leg diodes to the upper-leg switches there exist diode reverse recovery problems. In state 100, switch S7 is conducting and the current in the resonant inductor Lr is increasing. The energy stored in the resonant inductor can help to realize ZVS for both switch S3 and S5 in the transition from state 100 to 111.

In state 111, the energy in the input inductor is increasing while the current in the resonant inductor Lr is charging the clamping capacitor Cc. Later the current in Lr changes its direction.

In he state transition from 111 to 110, switch S5 is turned off, the current in input inductor Lc will charge S5's paralleled capacitor and discharge S2's paralleled capacitor. Thus S5 is ZVS turned off. Once the voltage on S5 decrease to zero, S2's anti-parallel diode starts to conduct. Therefore the current naturally transfers from S5 to S2's anti-parallel diode.

In the state transition from 110 to 100, S3 is turned off, the current in input inductor Lb will charge S3's paralleled capacitor and discharge S6's paralleled capacitor. Thus S3 is ZVS turned off. Once the voltage on S3 decrease to zero, S6's anti-parallel diode starts to conduct. Therefore the current naturally transfers from S3 to S6's anti-parallel diode.



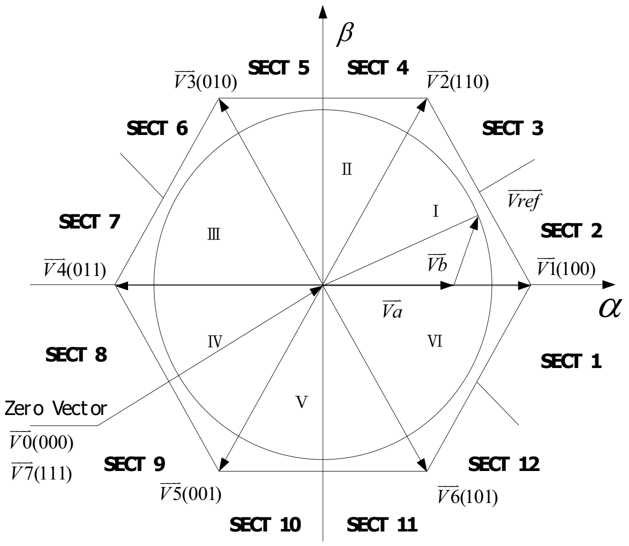


Fig. 9: Three-phase voltages and voltage space vectors

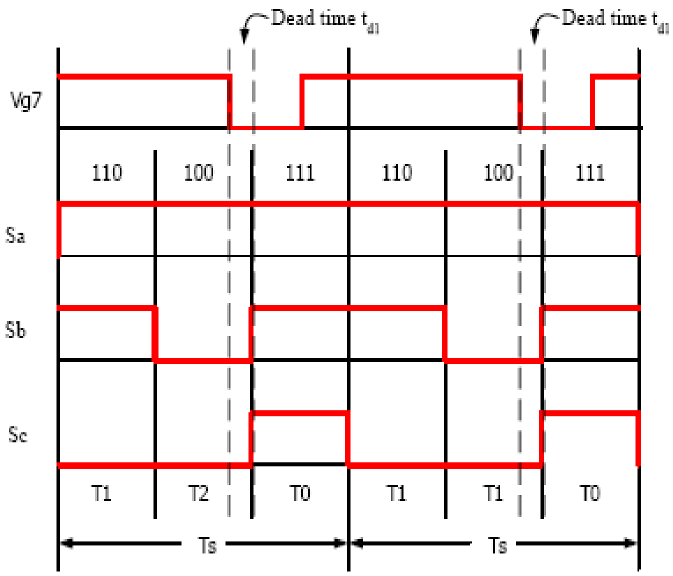
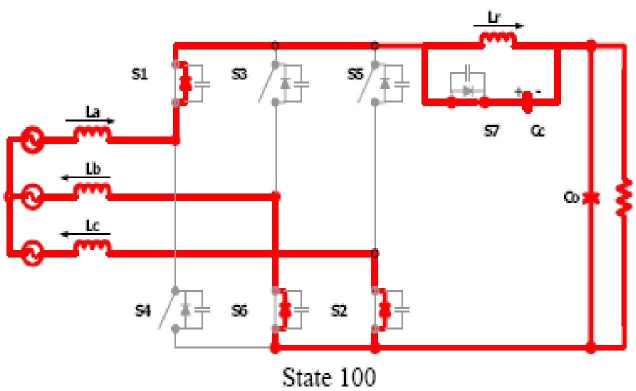
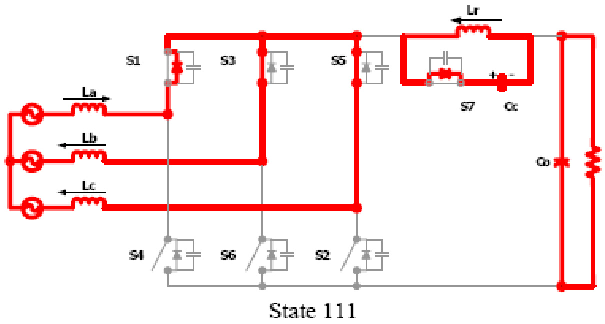


Fig. 10: switching sequence in sector 2: 100-111-110-100

Thus with the ZVS-SVM control the ZVS Active-clamping three-phase PFC can realize ZVS for all the switches and suppress all the diode reverse recovery. The switching frequency of the auxiliary switch is equal to that of the main switch.





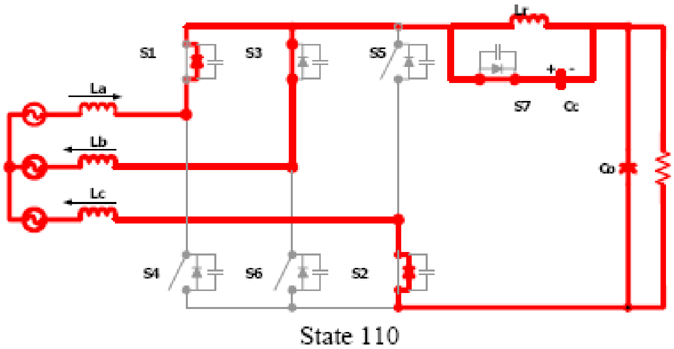


Fig. 11: operation stages of three switching states

IV. Theoretical Analysis of CAC ZVS Three-Phase PFC Converter

In this paper, we take the Compound active-clamping thre-phase PFC converter as an example to do the theoretical analysis. Since in the ZVS-SVM control the operation of the converter is symmetrical in every 30°, we still take sector 2 as an example to analyze.

The following assumptions are made to simplify the analysis of the proposed CAC PFC converer:

- The capacitances C1 to C6 paralleled with main switches S1 to S6 respectively include parasitic capacitance and external capacitance. The capacitance C7 paralleled with the auxiliary switch S7also includes parasitic capacitance and external capacitance.
- The input filter inductors L1, L2, L3 are so large that their currents can be considered as constant current source in one switching cycle.
- The output filter capacitor C_o is represented by a constant voltage source.
- The value C_c is large enough so that the voltage can be seen as a constant.
- The resonant frequency of C_c and L_r is much lower than the operation frequency of the converter.

The steady-stage and key waveforms of the CAC ZVS three-phase PFC are shown in Fig. 12 and Fig. 13 respectively. The switching cycle can be divided into 8 stages.

Stage 1 (t0-t1): In this stage, S1, S2, S6 and the auxiliary switch S7 is on. The energy in input inductor is sending to the output. The current in resonant inductor Lr increases at the rate of

$$\frac{di_{Lr}}{dt} = \frac{V_{Cc}}{Lr} \qquad (1)$$

Stage 2(t1-t2): In t1, S7 is turned off, the resonant inductor Lr will discharge the main switch S3, S5, S4's paralleling capacitors C3, C4, C5. At time t2, the voltages on these capacitors decrease to zero and the anti-parallel diode of these main switches start to conduct. Then S3 and S5 can be turn on with zero voltage switching. At time t2 the voltage on S7 reaches $V_O + V_{Cc}$.

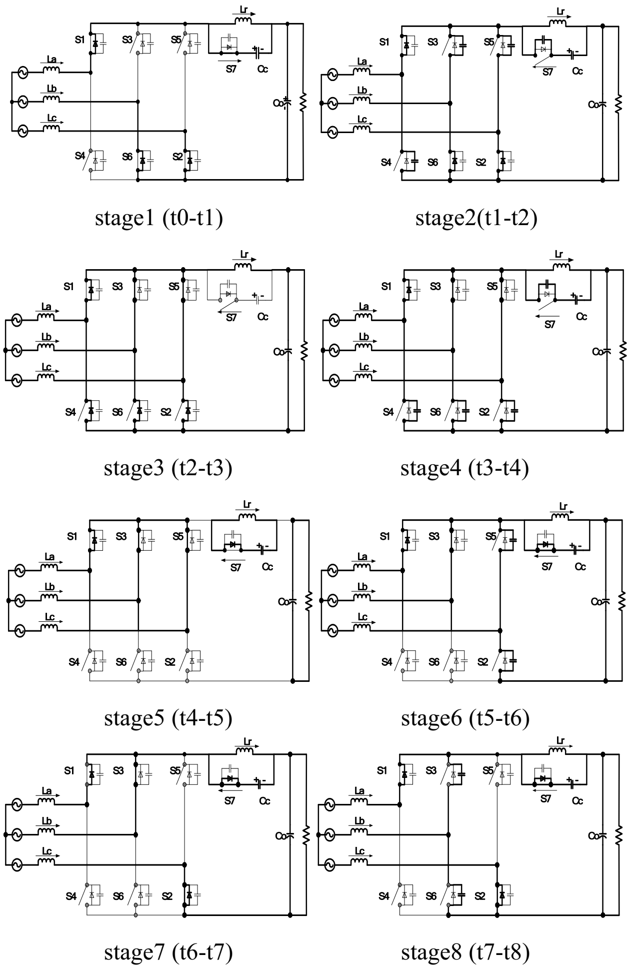


Fig. 12: operation stages of CAC ZVS PFC

Stage 3 (t2-t3): From this stage, the anti-parallel diode of S6 and S2 experience diode reverse recovery. Due to the existence of the resonant inductor Lr, the diode reverse recovery is suppressed. At time t3, the current of the anti-paralleled diodes of both switch S6 and S2 drop to zero.

Stage 4 (t3-t4): At t3, the voltage on S6 and S2 start to rise. Lr, C2, C6 and C7 start to resonance. The voltage on S7 starts to decrease. At t4, the voltage on S7 decrease to zero, and the anti-parallel diode of S7 start to conduct. S7 can be ZVS turn on.

Stage 5 (t4-t5): At t4, the diode reverse recovery process completes. The circuit enters the state 111. The main switch S1, S3, S5 and the auxiliary switch S7 are on. The resonant inductor is charging the clamping capacitor Cc.

Stage 6 (t5-t6): At t5, the main switch S5 is turned off. Since the existence of C5 and C2, it is ZVS turn off. The input inductor Lc will charge C5 and discharge C2.

Stage 7 (t6-t7): At t6, the voltage on S2 decrease to zero, the anti-parallel diode starts to conduct. S2 can be ZVS turn on. The circuit enters state 110. The lasting time is decided by the SVM control.

Stage 8 (t7-t8): At t7, the main switch S3 is turned off, since the existence of C3 and C6, it is ZVS turn off. The input inductor Lb will charge C3 and discharge C6. At t8, the voltage on S6 decrease to zero, the anti-parallel diode starts to conduct. S6 can be ZVS turn on. The circuit enters state 100. After t8, the next switching cycle starts again.

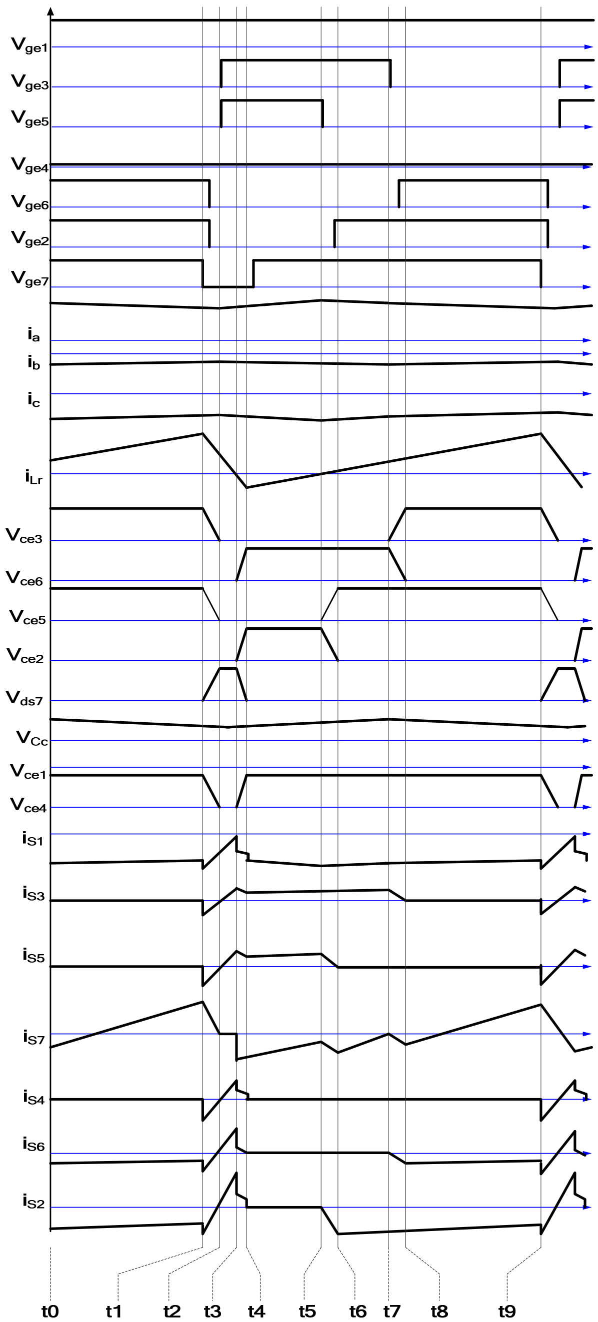


Fig. 13: Steady-state waveforms of the proposed converter

V. Theoretical Analysis of CAC ZVS Three-Phase PFC Converter

In every switching cycle there are three switching states, if we still take sector 2 as an example, the three states are 100-111-110. The duration of the three states can be expressed as T1, T0, and T2, where T is the operation period.

$$T_1 = \sqrt{3}\frac{|U_{rf}|}{E_{dc}} T \sin(\frac{\pi}{3} - \theta_r) \quad (2)$$

$$T_2 = \sqrt{3}\frac{|U_{rf}|}{E_{dc}} T \sin\theta_r \quad (3)$$

$$T_0 = T - T_1 - T_2 \quad (4)$$

A. Voltage stress on the switches

The maximum voltage stresses on the switches is

$$V_{max} = V_o + V_{Cc}$$

$$= V_o + \frac{L_r\left(I_a T_1 + |I_c| T_2 + V_o\sqrt{\frac{3C + C_7}{L_r}}\right)}{T} \quad (5)$$

In sector 2, the voltage stresses on the switches vs. the output voltage are shown in Fig.. The switch voltage stresses are only a little higher than the output voltage.

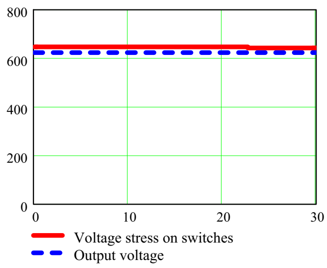


Fig.14: Voltages stress on switches vs. output voltage

B. Soft switching condition

The auxiliary switch is always zero-voltage turn–on condition. However the main switches satisfy zero-voltage turn-on condition when there is enough energy stored in resonant inductor to discharge the paralleling capacitor of the main switches. The zero-voltage switching condition for the main switch is:

$$2I_a\frac{T_1}{T} + 2|I_c|\frac{T_2}{T} - I_a - \frac{K \cdot V_{CE(on)}}{L_r} \cdot T > 0 \quad (6)$$

$$(0 < k < 1)$$

Where Vce(on) is the conduction voltage drop of the auxiliary switch. It is easy to achieve soft switching in the ZVS-SVM scheme.

VI. Experimental Results

A 4 kW prototype of the ZVS-SVM controlled CAC PFC converter, as shown in Fig.5 (a), is built to verify the theory, which is controlled by DSP (TMS320F2407A). The parameters of the circuit are: phase voltage Vin=220Vac, output voltage Vo=620Vdc, L=12mH, Lr=80μH, Cc=45μF. The parallel capacitors of the switches are C1=C2=…=C7=2nF. The operation frequency f=12.8kHz. The main switches, S1~S6: IRGPH50K. The auxiliary switch S7: CT60AM-20F.

Fig. shows the input voltage and the input current. The harmonic spectrum of the input current is shown in Fig..

The measured Power factor is 0.998 and the THD is 3.295%.

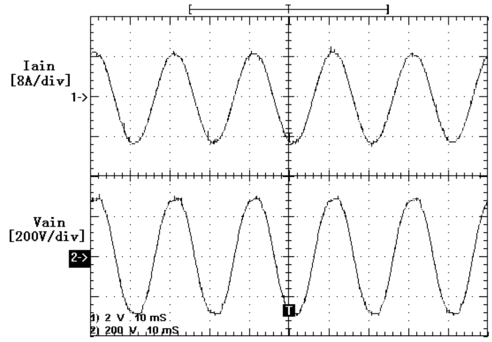


Fig.15: Input voltage and current

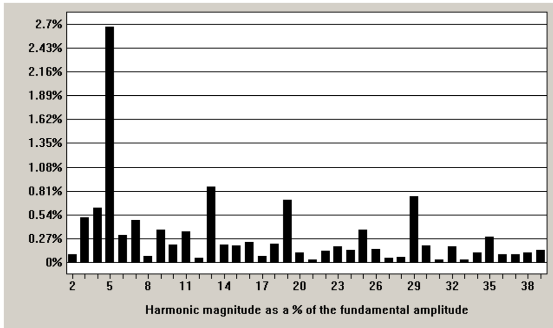
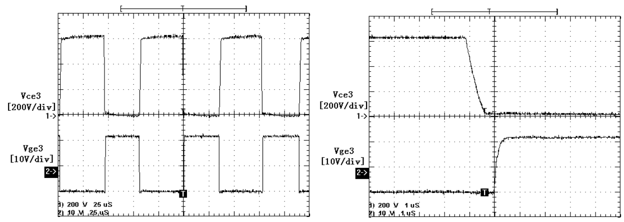


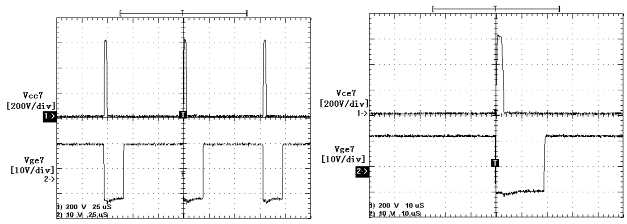
Fig.16: Input voltage and current

The CE voltage and the driving signal of the main switch and the auxiliary switch are shown in Fig. 17 and Fig. 18 respectively. As can be seen that the CE voltage drop to zero before the driving signal turn high. Thus both the main switch and auxiliary switch is ZVS turn on.



(a) time 25μs/div (b) time 1μs/div

Fig. 17: CE voltage and driving signal on main switch S3



(a) time 25μs/div (b) time 1μs/div

Fig18: CE voltage and driving signal on auxiliary switch S7

The clamping voltage on the clamping capacitor is less than 40V, as shown in Fig.. Thus the voltage stress of the switches in the proposed rectifier is only about 660V (V_O+V_{Cc}). So the voltage stress is lower.

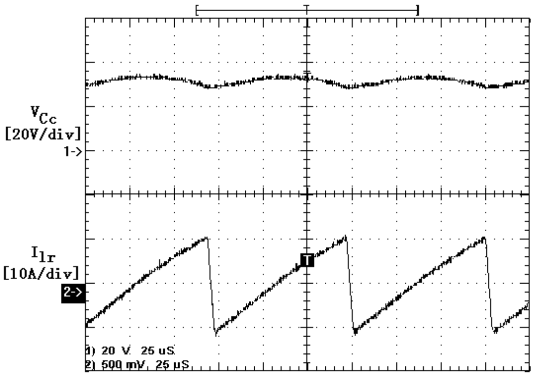


Fig. 19: Current of Lr and voltage on clamping capacitor

The efficiency of the ZVS PFC rectifier is shown in Fig. 20. The efficiency of a hard switching counterpart is also shown in Fig. 20.

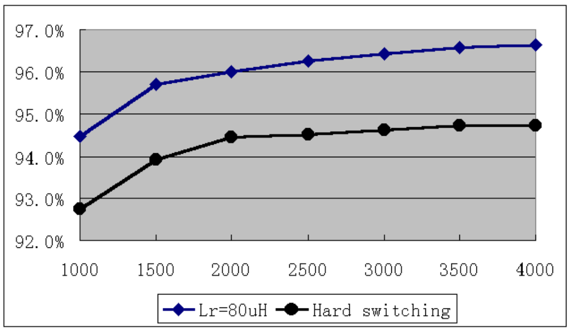


Fig. 20: Current of Lr and voltage on clamping capacitor

VII. CONCLUSION

A family of Active-Clamping ZVS Three-Phase PFC is proposed. A specially designed ZVS-SVM for the soft switching PFC converter is proposed too. It can suppress all the diode reverse recovery, meanwhile creating soft-switching condition for both the main switches and the auxiliary switch. The switching frequency is fixed, and the auxiliary switch works at the same frequency with other switches, thus the rectifier can work at higher frequency. The voltage stress in the Active-clamping ZVS Three-Phase PFC is lower. It is suitable for high-density rectifier application.

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