Improving the Power Density of the ZVS-SVM Controlled Three-Phase Boost PFC Converter

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Abstract- **The compound active clamping three-phase boost rectifier proposed by authors has a clamp branch composed of an active switch, a resonant inductor and a clamping capacitor. With a novel zero voltage switching space vector modulation (ZVS-SVM) method, the rectifier can realize ZVS operation for all switching devices and effectively suppress the reverse recovery process of the bridge leg switch anti-parallel diode. In addition, both the main switches and the auxiliary switch have the same and fixed switching frequency. In this paper, the soft switching condition of the ZVS-SVM controlled three-phase boost PFC is analyzed. The relationship between the switching loss of the converter and the circuit resonant parameters is studied. The EMI noise between hard switching and soft switching converter is also investigated. The results are verified by a 20kW prototype.**

Index Terms- **Three phase PFC, ZVS, SVM, Power density**

I. INTRODUCTION

The six-switch three-phase boost rectifier has several advantages such as lower current stress, high efficiency, and small input filter. So it is a preferred topology in higher power application. However the anti-parallel diodes of the bridge leg switches in the rectifier experience reverse recovery process which will cause severe switching loss, high di/dt problems. The diode reverse recovery related loss is one of the main losses in the six-switch boost rectifier. The high dv/dt and di/dt due to the fast switching process could bring serious EMI issues.

In the past years, many works have been undertaken to solve the diode reverse recovery problem and improve the efficiency and power density of the three-phase rectifiers or inverters. The ZCS rectifier proposed in [1] adopts zero current switching technique in the three-phase single-switch PFC to realize the ZCS of the main switch, but the auxiliary switch is still in hard switching condition. In similarly, the DC-rail ZVT boost rectifier proposed in [2] can only realize the zero voltage switching of the main switches, not of the auxiliary switch. Although the auxiliary resonant commutated pole (ARCP) [3] converter can reduce the conduction loss of the auxiliary circuit, it needs six extra auxiliary switches. The resonant dc link (RDCL) converter proposed in [4, 5] has a simplified topology，but the voltage stress in the switches is high. Compared with RDCL converter, the active clamped RDCL (ACDCL) converter [5, 6] has lower voltage stress. However, both RDCL and ACRDCL converters need discrete pulse modulation (DPM) which requires the dc-link resonating frequency to be several times higher than the switching frequency of the PWM converter for similar current spectral performance [7].

The ZVS-SVM controlled three-phase boost rectifier [9-11] proposed by authors can realize zero voltage switching operation for all switching devices and effectively suppress the reverse recovery process of the bridge switch anti-parallel diode. Due to the switching loss can be reduced in this soft-switching ZVS three-phase boost rectifier, a higher switching frequency can be used to realize higher power density. Moreover, both the main switches and the auxiliary switch have the same and fixed switching frequency. The voltage stress in both main and auxiliary switches is only a little higher than DC bus voltage.

In this paper, the soft switching condition of the ZVS-SVM controlled three-phase boost PFC converter is analyzed. The efficiency of the converter in different input voltage and different output load is measured. The EMI noise compare between hard switching and soft switching conditions is also investigated. A three phase ZVS-SVM boost rectifier prototype is built to verify the theory.

II. OPERATION PRINCIPLE OF THE ZVS-SVM CONTROLLED BOOST RECTIFIER

A. Converter topology and Modulation scheme

The circuit of the ZVS-SVM controlled three-phase boost PFC is shown in Fig.1. This topology consists of a standard three phase boost rectifier and a clamp branch. The clamp branch consists of an active switch S7, a resonant inductor Lr and a clamping capacitor Cr. During most time of the operation, the auxiliary switch is conducting, and there is 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 switch, then the main switch can be turned on under zero voltage condition. When the main switch is turned on, the resonant inductor can suppress the reverse recovery current of the opposite switch's anti-parallel diode.

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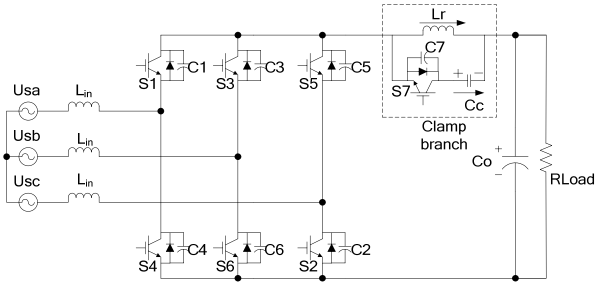
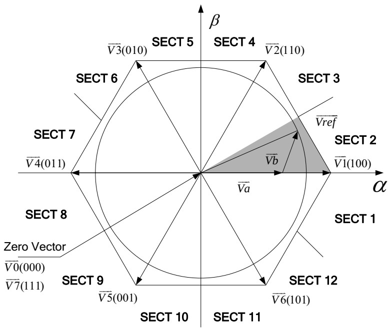
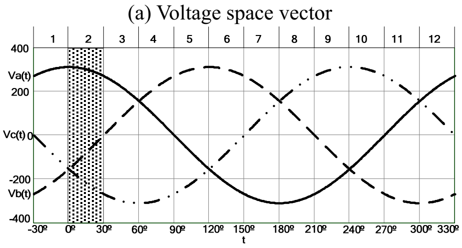


Fig.1. ZVS-SVM controlled active-clamp three-phase boost rectifier



(a) Voltage space vector



(b) Three-phase voltages

Fig.2. Three-phase voltages and voltage space vectors

To suppress the diode reverse recovery process of the switch in three bridge legs, a zero voltage switching space vector modulation (ZVS-SVM) control method is used. Since there are three bridge legs in the main circuit, the auxiliary switch must be activated three times per cycle if the switch in the three legs is modulated asynchronously. If the switch which conducts the highest phase current is continuously on, there would be no transition in this phase, then there are only two other phases transitions which need to suppress the diode reverse recovery and create ZVS condition. The switches in the other two phases are controlled in the PWM manner, and the turn on time of the other two bridge leg switches is synchronized. So the diode reverse recoveries of these two phases happen at the same time. Thus the auxiliary switch need only to act once in one switching cycle to resonant the DC bus to zero and create ZVS condition for two phases switch and suppress the diode reverse recoveries of both phases. The auxiliary switch can work at the same frequency with the main switch. And the main switch can be turned on and off at the exact time decided by SVM control.

In the ZVS-SVM control, the phase voltages' waveforms and voltage vectors' definitions are shown in Fig. 2. The whole utility cycle is divided into 12 sectors. Since the operation of the converter is symmetrical in every 30^o, we assume that the converter is operating in the sector 2 where Ia>0 and Ic<Ib<0. In this sector, phase A has the highest input voltage and current. The switch S1 is always conducting, while the switches in the other two phases are controlled in the PWM manner. There are three switch states in one switching cycle in sector 2, as shown in Fig.3.

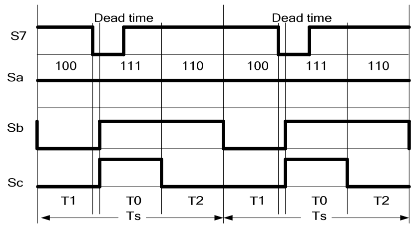


Fig.3. Switching sequence in sector 2: 100-111-110-100

B. Zero voltage switching of the switches

According to the ZVS- SVM scheme, the switch S3 and S5 are to be turned on simultaneously. That is just the instant when switching state 100 changes to state 111.

In state 100, although the driving signals of S1, S6 and S2 are high, it is the anti-parallel diodes of S1, S6 and S2 that are conducting. When the state change to state 111, S3 and S5 will starts to conduct and the anti-parallel diode of S6 and S2 will stop to conducts. During the transition there will be diode reverse recovery.

In state 100, S7 are conducting and the current in the resonant inductor Lr is increasing. The energy stored in the resonant inductor can help to realize ZVS for S3 and S5 in the transition from state 100 to 111.

Before the turn on of the two switches, the auxiliary switch S7 is turned off first. Thus the energy in the resonant inductor Lr will discharge the parallel capacitor of the switch S3, S4, and S5, resonant the bridge voltage to zero. The switch S3 and S5 can be turned on under ZVS condition.

When S3 and S5 is conducting, S7 is still off, thus the resonant inductor Lr can suppress the reverse recovery current of switch S4 and S5's anti-parallel diodes.

The reverse recovery energy can help to discharge the parallel capacitor of S7, then S7's anti-parallel diode starts to conduct, and S7 can be turned on under ZVS condition.

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

In the state transition from 111 to 110, S5 is turned off, the current in input inductor Lc will charge S5's parallel capacitor and discharge S2's parallel capacitor. Thus S5 is turned off under ZVS condition. Then S2's anti-parallel diode starts to conducts and S2 is turned on under ZVS condition.

In the state transition from 110 to 100, S3 is turned off, the current in input inductor Lb will charge S3's parallel capacitor and discharge S6's parallel capacitor. Thus S3 is ZVS turned off. Then S6's anti-parallel diode starts to conducts and S2 is turned on under ZVS condition.

Thus with the ZVS-SVM control, the ZVS

active-clamping three-phase rectifier can realize ZVS condition for all the switch and suppress all the diode reverse recovery. The switching frequency of the auxiliary switch is equal to that of the main switch. Thus the ZVS three-phase rectifier can work with higher frequency.

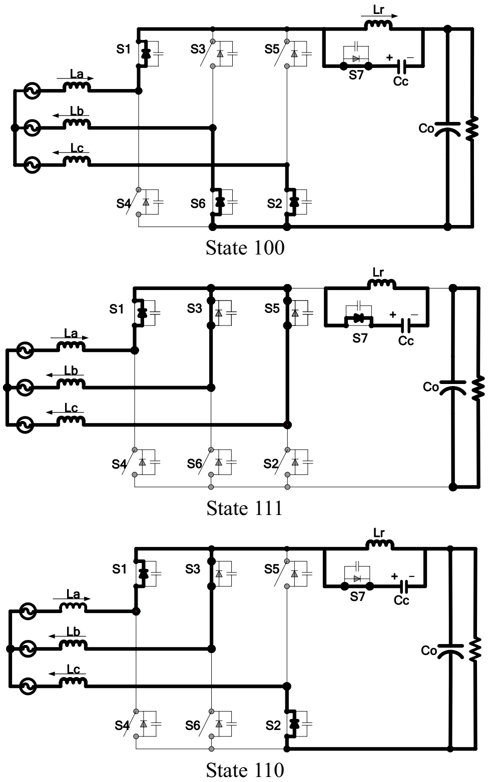


Fig. 4 Three switching states in sector 2

III. EMI COMPARISON OF THE SVM CONTROLLED BOOST RECTIFIER

In the hard switching PFC converter, the high dv/dt and di/dt due to the fast switching of IGBT could bring serious EMI problems. With the ZVS-SVM control strategy, all the switches work in the ZVS condition, smaller dv/dt brings lower EMI noise. The conducted EMI noise spectrum of the three-phase PFC converter prototype is measured to compare the EMI noise under hard switching and soft switching conditions. The circuit connection of the measurement is shown in Fig. 5.

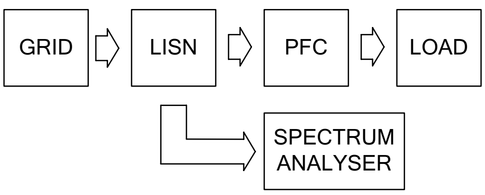


Fig.5 Circuit connection of the conducted emission measurement

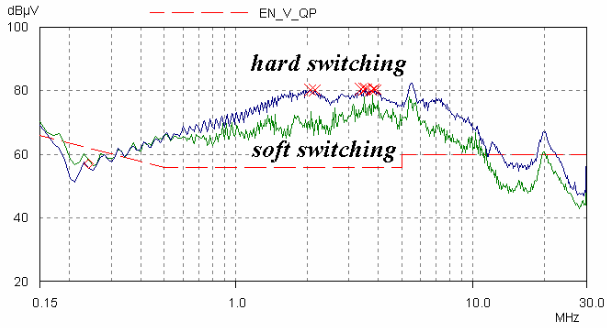


Fig.6. Comparison of conducted EMI in hard switching and soft switching conditions

Fig.6 shows the comparison of the input conducted EMI noise spectrum both in hard switching and in soft switching conditions. It is obtained with the following setting, the input and output voltages of the converter are 220V AC and 750V DC, the output power is 10kW, the switching frequency is 50 kHz. The upper curve is the conducted EMI noise in hard switching condition, and the lower curve is obtained in soft switching condition. It can be seen from the figure that the EMI noise of the converter in soft switching condition is about 3 to 10 dB smaller than that in hard switching condition when the noise frequency is higher than 0.5MHz. Therefore the soft switching PFC converter needs only a smaller EMI filter than the hard switching converter to satisfy the EMC guideline.

IV . LOSS ANALYSIS OF THE ZVS-SVM CONTROLLED BOOST RECTIFIER

The switching loss of the converter composed of the turn-on loss and turn-off loss of IGBT. With the ZVS-SVM control, the reverse recovery process of the switch anti-parallel diodes is suppressed well and all the switches can be turned on under zero voltage condition, then the diode reverse recovery related loss can be neglected. But the turn-off loss of the IGBT can not be neglected because of its tail current.

The tail current of the IGBT occurs in the switch commutation from the IGBT to the diode, as shown in Fig.4， from state 110 to the state 100. In this state transition, S3 is turned off, the current in the input inductor Lb charges S3's parallel capacitor and discharges S6's parallel capacitor. The voltage on S3 starts to increase and the voltage on S6 starts to decrease. Due to the IGBT tail current, S3 can not be turned off immediately, so the turn off loss is produced. Obviously, with larger paralleled capacitor, the turn-off loss of IGBT would be smaller. That is because if the paralleled capacitor is larger, the CE (collector-emitter) voltage across S3 will increase slower when it is turned off. The overlay between the tail current and IGBT CE voltage is smaller, so the turn-off loss is smaller. However, a larger resonant capacitor will cause larger duty ratio loss, higher switch voltage stress and larger resonant circulation current, expressly at higher switching frequency.

Therefore, the resonant capacitor needs to be selected properly in order to reduce the turn-off loss and increase the efficiency with some tradeoffs.

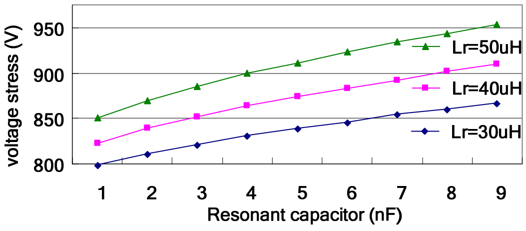


Fig.7 Voltage stress vs. resonant parameter（simulation result）

The curve of IGBT voltage stress vs. resonant parameter is shown in Fig.7. It is obtained with the following setting, the input and output voltages of the converter are 220V AC and 750V DC, the output power is 20kW, the switching frequency is 50 kHz. It can be found that when a larger paralleled capacitor is used, the voltage stress of the IGBT will be higher. In similarly, the larger the resonant inductor is designed, the higher the switch voltage stress is produced.

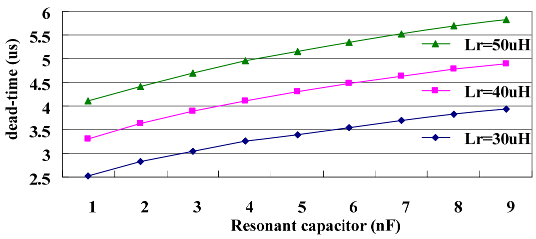


Fig.8 switching dead-time vs. resonant parameter（simulation results）

The curve of IGBT switching dead-time vs. resonant parameter is shown in Fig.8. It can be seen from the Fig.8 that the larger the paralleled capacitor is designed, the longer the switching dead-time is needed. The larger the resonant inductor is designed, the longer the switching dead-time is needed. The switching dead-time will bring duty ratio loss. Considering it, the switching dead-time should not be too long and the IGBT resonant parameter should not be too large, especially when the switching frequency is high.

The experimental curve of the efficiency vs. the output power respectively obtained in hard switching and soft switching conditions with different resonant component parameters is shown in Fig.9. It can be seen from the curves that with SVM soft switching, the conversion efficiency at the rating operating point with full load is about 95.4%, while the conversion efficiency is about 92.5% in hard switching condition. When the paralleled resonant capacitor is designed larger, the turn off loss is reduced and the efficiency is higher actually. But the paralleled capacitor could not be designed too large without limit, which will bring bad effects to the work of the circuit. The reason has been explained above.

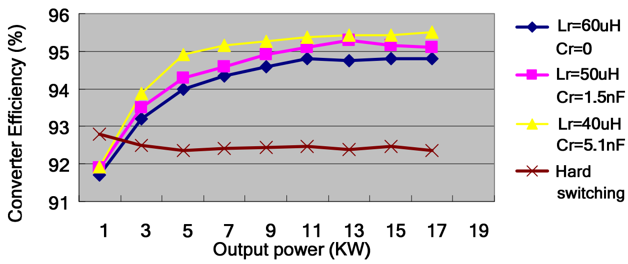


Fig.9 Efficiency vs. Po with different resonant components parameters (fs=50kHz) (experimental results)

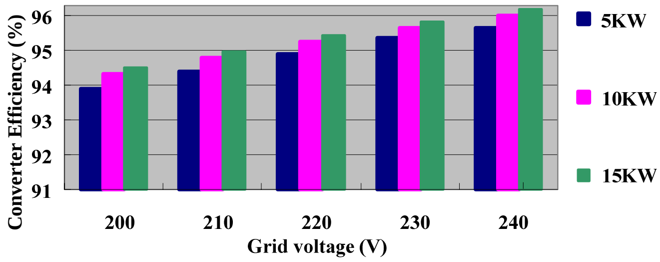


Fig.10 Efficiency vs. Uin with different output load (fs=50kHz) (experimental results)

The experimental curve of the efficiency vs. the input grid voltage is shown in Fig.10, where Cr=5.1nF, Lr=40μH.

V .EXPERIMENTAL RESULTS

A prototype of the ZVS-SVM controlled three-phase rectifier, as shown in Fig.1, is built to verify the theoretical analysis. DSP (TMS320F2407A) is used for control. The input and output voltages are 220V AC and 750V DC, the main switches and the auxiliary switch, S1~S7: SKM100GB128 DN, IGBT module. The input filter inductor and the output filter capacitor are: L_{in}=3.8*mH*, C_O=3300*uF*. The switching frequency f=50 kHz.

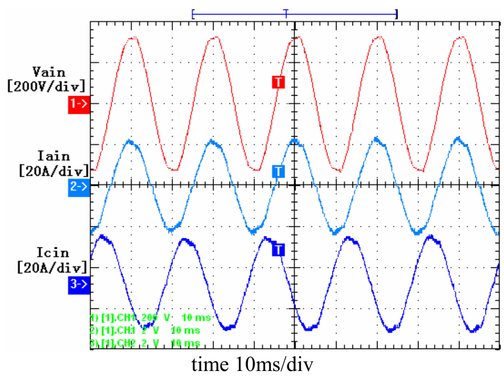


Fig. 11 Input voltage and current

Fig.11 shows the input voltage and the input current. The harmonic spectrum of the input current is shown in Fig. 12. The measured power factor is 0.993 and the THD is 3.582%. The waveform of the CE voltages and the driving signals of the main switch S3 and the auxiliary switch S7 in the sector 2 is shown in Fig. 13 and Fig.14

respectively.

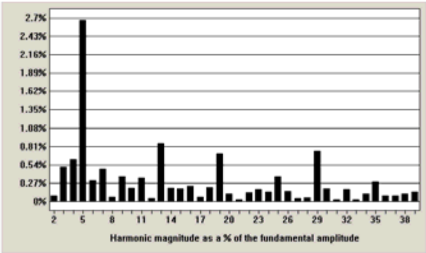
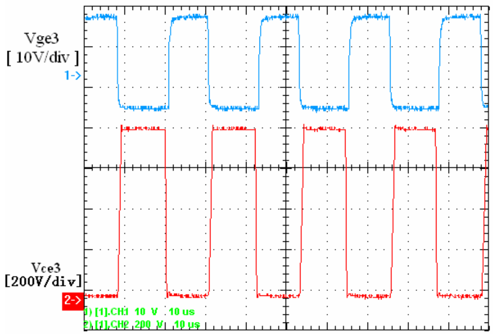
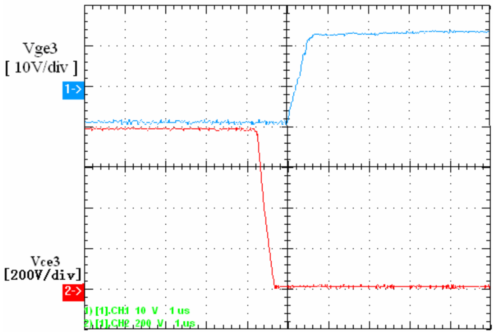


Figure 12. Input current harmonic spectrum

In the sector 2, the switch S1 is always conducting, while the switches in the other two phases are controlled in the PWM manner. Before S3 is turned on, S7 has been turned off. Lr discharges the paralleled capacitors C3, C4, and C5 of the main switches S3, S5, and S4. When the voltages on those capacitors drop to zero, S3 and S5 can be turned on under the condition of zero voltage switching. It can be seen from Fig.16that the CE voltage of S3 drops to zero before the driving signal turns high. Thus S3 is turned on under ZVS condition. From the states 100 to 111, Lr, C2, C6 and C7 resonate to make the voltage on S7 decrease to zero. After that, S7 can be turned on under the condition of zero voltage switching, as shown in Fig. 14.



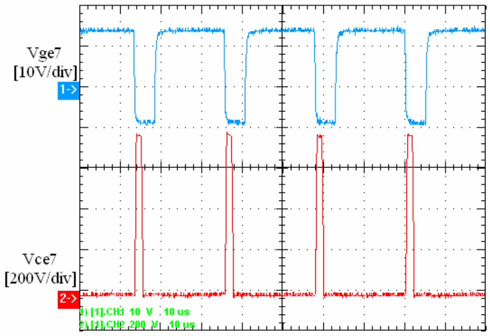
(a) time 10us/div



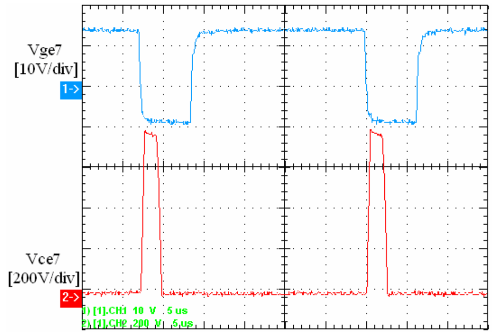
(b) time 1us/div

Fig. 13 CE voltage and driving signal of the main switch S3

The clamping capacitor voltage and the resonant inductor current are shown in Fig.15.Due to V_{Cc} is less than 100V, the voltage stress of the switches in the proposed rectifier is only about 850V (V_O+V_{Cc}). It can be concluded that the additional voltage stress of the main switches is low.

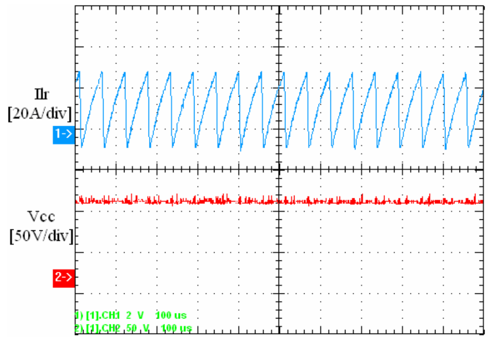


(a) time 10us/div



(b) time 5us/div

Fig.14 CE voltage and driving signal of the auxiliary switch S7



Time 100us/div

Fig. 15 Current of Lr and voltage on clamping capacitor

VI. Conclusion

The soft switching condition of the ZVS-SVM controlled three-phase boost PFC is analyzed. The EMI noise of the converter in soft switching condition is smaller than in hard switching condition. The switching loss of the IGBT can be reduced with a properly selected resonant capacitor. With the soft switching feature, the proposed ZVS-SVM controlled three-phase boost PFC converter is suitable for high density and high switching frequency rectifier application.

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