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Carrier phase shifted SPWM based on current sourced multi-modular converter for active power filter

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Abstract: A novel current-source active power filter (APF) based on multi-modular converter with carrier phase-shifted SPWM (CPS-SPWM) technique is proposed. With this technique, the effect of equivalent high switching frequency converter is obtained with low switching frequency converter. It is very promising in current-source APF that adopt superconducting magnetic energy storage component.

Key words: Current sourced multi-modular converter, Carrier phase shifted SPWM, Active power filter

Document code: A **CLC number:** TM71,TM93

INTRODUCTION

Active power filter (APF) (Grady *et al.*, 1990) is a power conversion system for compensating the harmonic and reactive power from the nonlinear load. The block diagram of a general parallel APF is shown in Fig.1, where i_{sj} is the injected harmonic current, i_1 is fundamental current, i_L is load current, i_h is the harmonic current, which is drawn by the nonlinear load, and i_{out} is the resulting input current. Fig.1 shows that these currents' relations would be:

$$i_{out} = i_L + i_{sj} \tag{1}$$

$$i_L = i_1 + i_h \tag{2}$$

The basic idea of APF is to make the magnitude and phase of i_{sj} exactly the opposite of i_h, expressed below:

$$i_{sj} = -i_h \tag{3}$$

Combine Eqs.(1), (2) and (3) yields:

$$i_{out} = i_1 \tag{4}$$

The resulting i_{out} is sinusoidal and high quality. In this way, APF could provide the harmonic current, which is an essential requirement of the nonlinear load. APF can be divided into different types (Akagi, 1996) according to their system configurations. With the remarkable progress of self turn-off switching devices, attention has been focused on the active power using a current-source or voltage-source PWM converter (Kawahira, 1983; Akagi *et al.*, 1985). As shown in Fig.2 and Fig.3, respectively, the current-source APF has a dc inductor with a constant DC current, while the voltage-source APF has a capacitor on the DC side with a constant DC voltage. Although the voltage-source filters are better in regard to switching loss and the capacity to eliminate PWM carrier harmonics, the current-source filters which can directly output harmonic current, are better with regard to reliability and protection. Furthermore, considering the use of a super conducting magnet in the near future, the current-source filters may be a more practical solution, especially when the active filter is required to compensate not only the ordinary harmonics but also the sub-harmonics related to the variation of the APF (Ishikawa *et al.*, 1988).

In this paper, a novel current sourced multi-modular converter based carrier phase shifted SPWM (CPS-SPWM) for active power filters is presented. With this technique, the same harmonics elimination can be achieved at a lower switching frequency compared to SPWM. The CPS-SPWM principle was proposed in Zhang *et al.*(1993) for SVG and SMES. Analysis showed that this technique has several advantages:

(1) The semiconductor device can be used at a comparatively low switching frequency so that the switching loss could be reduced greatly.

(2) Since the converter system can directly output harmonic current at a low switching rate, with a reasonable bandwidth of the modulating signal, it is easy to apply different controls.

(3) With CPS-SPWM, the undesirable harmonics in the output are decreased considerably. In this way, the quality of the power system can be enhanced to a great extent.

All of the above good points discussed show that the new current-source APF, which combines CPS-SPWM and SMES technique, is promising. The simulated and experimental results confirmed the theoretical conclusion. This technique must have wide usage in high power converter systems in the near future.

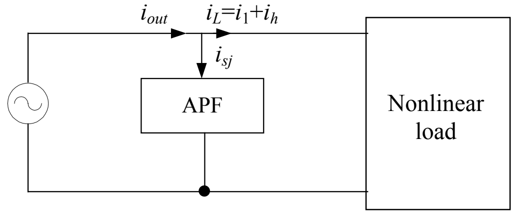

Fig.1 Block diagram of the general parallel APF

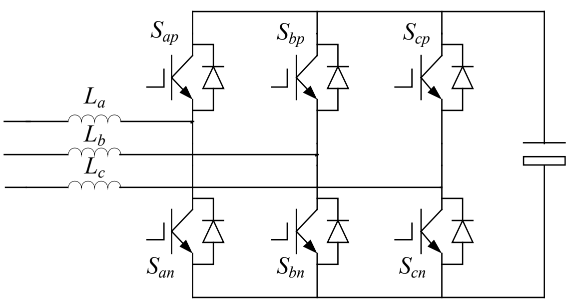

Fig.2 Voltage-source APF

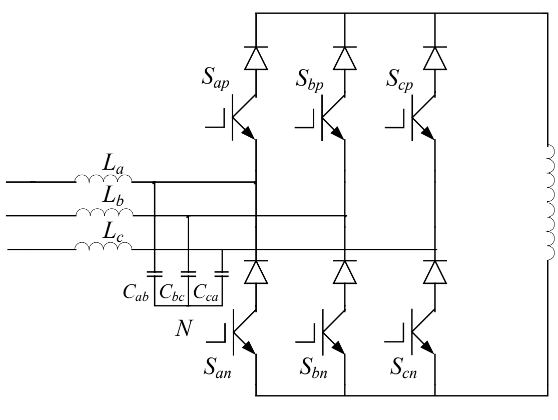

Fig.3 Current-source APF

PRINCIPLE OF CPS-SPWM

Bi-logic principle of CPS-SPWM

Fig.4 shows a single-phase voltage-source CPS-SPWM converter with N units. Based on the bi-logic PWM principle, the shifted-phase of the triangular carrier signal is $\Delta\theta$ ($\Delta\theta=\theta/N$). Fig.5b shows the individual outputs of N converters. All N outputs are added up to generate the output of the whole multi-modular converter, as shown in Fig.5c. The spectra of the multi-modular converters' output and of an individual converter's output, shown in Fig.5e and Fig.5d respectively, were calculated through FFT. The spectrum of the multi-modular converter's output has much lower harmonics than that of any converter unit.

Therefore, the bandwidth of multi-modular CPS-SPWM converters with switching frequency at ω_c is equivalent to that of a usual converter with switching frequency at $N\omega_c$. This technique can also be applied in the current-source APF of multi-modular converter (Ooi and Zhang, 1993). However, transforming from 2-level PWM to 3-level PWM would be necessary for the current sourced multi-modular converter.

Current sourced multi-modular converter based CPS-SPWM for APF

The topology of the three-phase current-source APF presented in this paper is shown in Fig.6. Although the harmonic component of nonlinear load current i_L is not negligible, if the APF current i_{sj} is made to follow the nonlinear load harmonic current, the source current i_{out} will consist of the fundamental component only of the load current i_L. The three-phase active power filter is composed of N current sourced converter units. Here, each current sourced converter unit is a three-phase six-switch current sourced converter. The N converters are connected in parallel on the AC side to build the current-source multi-modular converter. The switch is composed of such devices as GTO and IGBT in series of diodes. The 2-order low pass filter is composed of L and C to filter out switching frequency harmonics. R represents the parasitical resistance in the inductor L and the circuit, not the real resistance. As the CPS-SPWM is applied, the low switching frequency modulations of SPWM that occur in the N converters are characterized by the same frequency ratio "k", amplitude ratio "m" and input harmonic current signal "S_m" (S_{ma}, S_{mb}, S_{mc}).

Fig.7 shows the structure of a single unit of the current-source APF in Fig.6, the currents i_a, i_b, i_c and the corresponding switching state should follow the tri-logic SPWM principle in (Wang and Ooi, 1993). Fig.7 also includes the block diagram of the signal processing logic used to control these currents

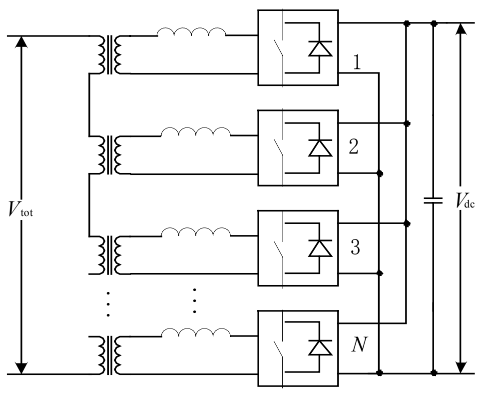

Fig.4 Topology schematic of single-phase voltage sourced multi-modular converters with CPS-SPWM

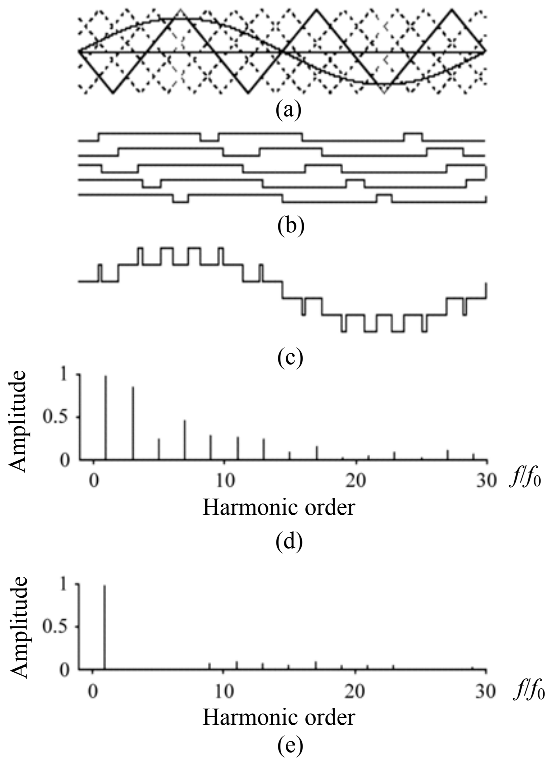

Fig.5 Modulated principle of CPS-SPWM

(a) Modulated wave and carrier waves; (b) individual outputs of N converters; (c) total output of the whole converters; (d) output spectrum of one of the N converters; (e) spectrum of total output

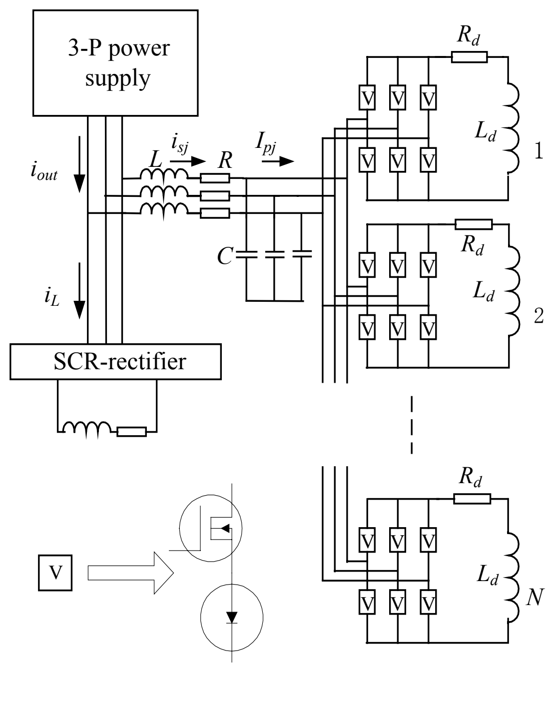

Fig.6 Main circuit structure of proposed APF

with the input signals S_{ma}, S_{mb} and S_{mc}. As illustrated in Fig.7, this is achieved by the SPWM using triangular carrier signals Sc. The bi-logic PWM signals X_1, X_2 and X_3 are then translated into tri-logic PWM signals Y_a, Y_b and Y_c. The transform block is easily implemented by summers and proportional amplifiers. The tri-logic PWM signals are finally fed to the gating logic block to switch the valve. The formula for transforming the biologic PWM variables X_1, X_2, X_3 (which have values +1 or −1) to the tri-logic PWM variables Y_a, Y_b, Y_c is based on the linear mapping (Ooi and Zhang, 1993):

$$\begin{bmatrix} Y_a \\ Y_b \\ Y_c \end{bmatrix} = \frac{1}{2}[C]\begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \tag{5}$$

where,

$$[C] = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \tag{6}$$

CONTROL CIRCUIT DESIGN

State feedback of AC side

Fig.8 is a simplified version of Fig.6. The L, R and C in both figures are identical. The current source CPS-SPWM multi-modular converter is drawn as the current-source i_{pj}.

The voltage source V_{sj} represents the 3-phase power system. Additional resistances in series with the inductors can damp these oscillations. However, this solution will lead to considerable energy consumption, which is not acceptable in large power systems. State feedback based on pole-placement control is introduced in Fig.9. Poles of the original system are placed to increase damping. Fig.10 is the Bode scheme of the system in Fig.8, with the controlled current i_{pj} as input. In general, the transient response has been improved within the distance from poles to original.

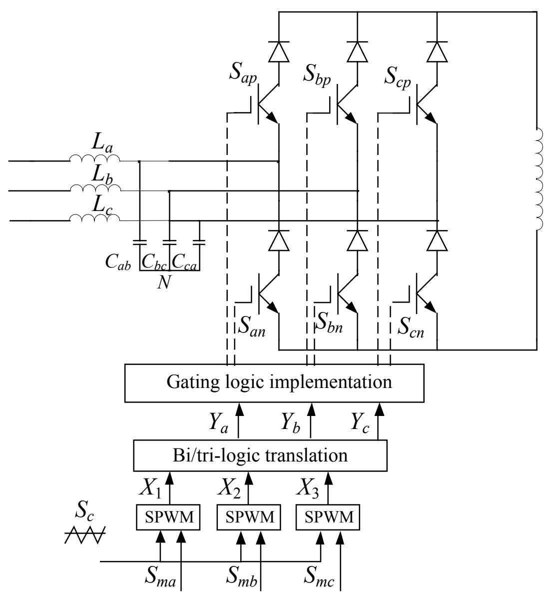

Fig.7 Current sourced converter with tri-logic PWM

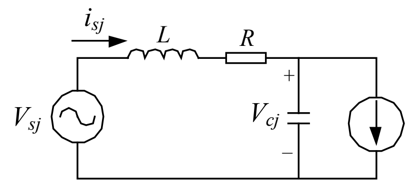

Fig.8 Equivalent circuit of current-source APF

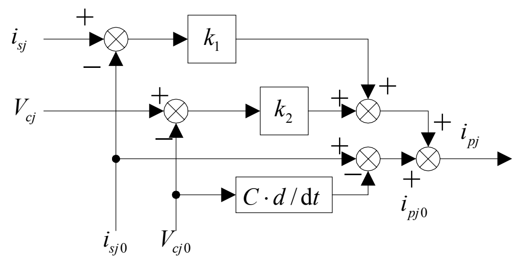

Fig.9 Control scheme on AC side of APF (V_{cj0}, i_{sj0}, i_{pj0} are steady values of APF, k_1, k_2 are PI coefficients)

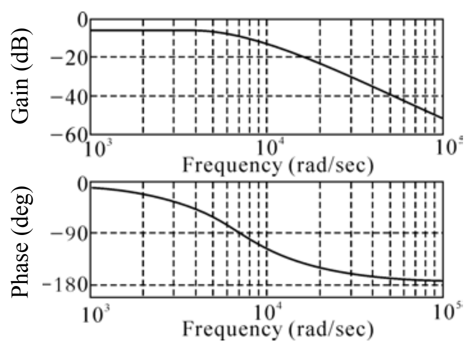

Fig.10 Closed-loop frequency response of system

PI feedback of DC side

In order to compensate for the converter loss, the PI feedback is implemented at the DC side. Additionally, the feedback at the DC side is also necessary for the multi-modular CPS-SPWM converter and is used to achieve dynamical current equilibrium.

RESULT

Simulation results

In order to simulate the system shown in Fig.6, we built the whole control system of APF with four-modular current sourced multi-modular converters. Some typical waveforms are shown in Fig.11 under the following conditions: C=48 μF, L=0.8 mH, f_0=812 Hz, R=1 Ω, Ld=160 mH. Satisfactory compensation was obtained under relatively low frequency (900 Hz).

Experimentation verification

The validity of the proposed control system was proved by the simulation result. Additionally, a 5-kVA experimental setup (Fig.6) with the same component parameter as in simulation completed, in which DSP (TMS320C203) was adopted to implement the control system. Experimental waveform and the spectrum of the compensated current are shown in Fig.12 and Fig.13 respectively, under the same setup as that for the simulation above.

CONCLUSIONS

Current sourced multi-modular converters based on CPS-SPWM for APF with satisfactory performance are presented in this paper. They could reduce harmonic and reactive power components of the load current resulting in sinusoidal and unity power factor source currents under transient and steady state conditions. It was also observed that:

1. They reduce the single converter's switching frequency and switching loss, cancel the undesirable switching harmonics, improve the output wave;

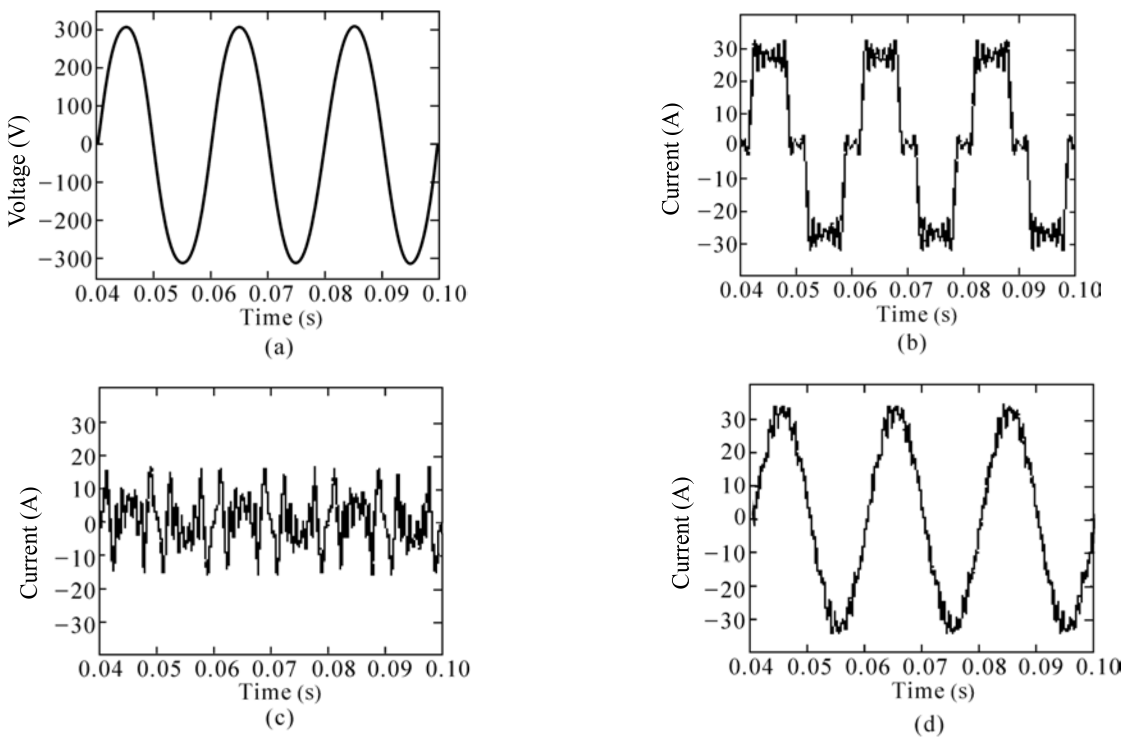

Fig.11 Working waveforms of APF (switching frequency: 900 Hz)
(a) waveforms of power network (phase A); (b) waveforms of load current; (c) output waveforms of APF; (d) waveforms of compensated current

2. The CPS-SPWM technique can be easily implemented in large power applications, such as APF.

3. The technique is based on SPWM, so the existing control strategy used in general SPWM can be introduced.

4. The transmitting bandwidth is much wide, which is more promising to APF.

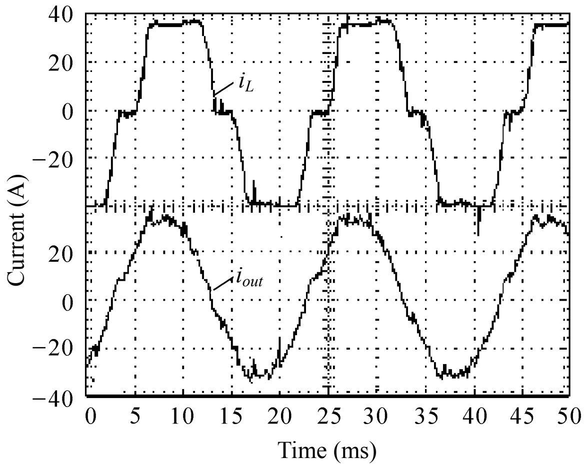

Fig.12 Experimental waveforms of APF (i_L: load current, i_{out}: compensated current)

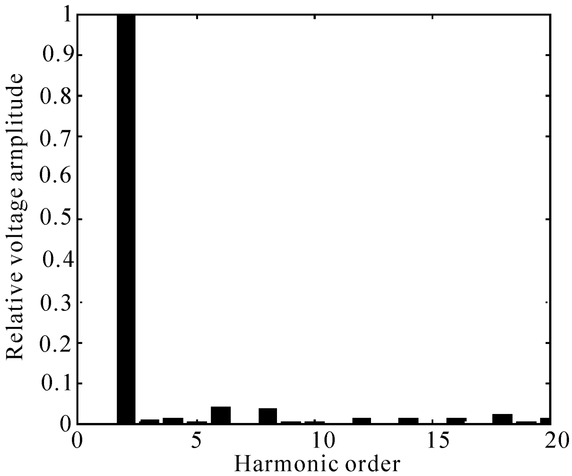

Fig.13 Spectrum of compensated current (i_{out})

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