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A High Performance Three-Phase Active Power Filter

Maoh-Chin Jiang[1*], Shyh-Shing Perng[1],
Ter-Feng Wu[1], Bing-Jyun Shih[1], and Tai-Chun Liu[1]

[1] Department of Electrical Engineering, National Ilan University
Yilan 260, Taiwan, ROC
mcjiang@niu.edu.tw

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Abstract. A high performance three-phase active power filter is proposed in this paper. A novel circuit for detecting the amplitude of the active part of the fundamental load current is also proposed. The detection time of the current is not more than 1/4 cycle. Its transient response is superior to the other conventional techniques. Moreover, the proposed algorithm avoids the use of mains voltage signal in the calculation of reference compensation current. Therefore, the mains current after compensation still has a purely sinusoidal waveform even when the mains voltage is distorted. In addition, a simple control scheme, based on the energy balance concept, is proposed to control the voltage of an energy-storage capacitor. Because the energy change in the energy-storage capacitor can be fast compensated, a small energy-storage capacitor is required. The advantages of the proposed active power filter are low cost, small size and fast transient response. Finally, some simulation results are presented for verification.

Keywords: active power filter, energy balance, energy-storage capacitor

1 Introduction

Harmonic pollution has become an important issue in recent years because more and more power electronic devices have been adopted into people's lives and industry. Injecting harmonic currents into a utility grid may cause some problems such as distorted voltage waveform, generating intermittent electrical noise from connections loosened by thermal cycling, causing nuisance tripping of circuit breakers and so on. Therefore, how to eliminate the harmonic pollution is a closely related research topic.

Conventionally, LC filters have been used to eliminate line current harmonics and to improve the load power factor. However, passive filters exhibit several disadvantages. First, the source impedance strongly affects the filtering characteristics. Secondly, the compensation effect is dependent on the condition of the system such as harmonics frequency variation. Thirdly, the parallel and series resonance between the power system and the passive filter may produce excessive harmonic currents flowing into both the source side and the filter at specific frequency [1].

Recently, active power filters have been used to eliminate the harmonics and improve the power factor of a power system. Fig. 1 shows the typical configuration of a three- phase active power filter which has been studied in many researches. Besides, many algorithms have been developed to calculate the reference compensation current such as, the full-cycle integration algorithm [2], the half-cycle integration algorithm [2], the current-sampling detection algorithm [3] and the synchronous detection algorithm [4-10]. However, all of these algorithms need to use the main voltage signal in the calculation of the reference compensation current. Therefore, the performance of these algorithms would be degraded when mains voltage is distorted.

A novel algorithm for a three-phase active power filter is proposed to improve compensation accuracy under distorted mains voltage. Some simulation results are provided to demonstrate the theoretical analysis and system performance.

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* Corresponding Author

2 Proposed Three-Phase Active Power Filter

2.1 Basic Theory

The purpose of the proposed APF is to inject the compensation current to eliminate the harmonics of a nonlinear load. Assuming the mains voltage $v_s\,(t)$ is a pure sine wave that can be expressed as

$$v_S(t) = \sqrt{2}V_1 \sin(\omega t) \tag{1}$$

The nonlinear load current $i_L(t)$ can be written as

$$i_L(t) = \sum_{n=1}^{\infty} \sqrt{2} I_n \sin(n\omega t + \theta_n) \tag{2}$$

The nonlinear load current can be divided into fundamental and harmonic components as

$$i_L(t) = i_{L1}(t) + i_{Ln}(t) = \sqrt{2} I_1 \sin(\omega t + \theta_1) + \sum_{n=2}^{\infty} \sqrt{2} I_n \sin(n\omega t + \theta_n) \tag{3}$$

The fundamental current component $i_{L1}\,(t)$ can be subdivided into the real power current component $i_{L1P}\,(t)$ and the reactive power current component $i_{L1Q}\,(t)$, and the fundamental component current $i_{L1}\,(t)$ can be expressed as

$$i_{L1}(t) = i_{L1P}(t) + i_{L1Q}(t) = \sqrt{2} I_1 \cos\theta_1 \sin(\omega t) + \sqrt{2} I_1 \sin\theta_1 \cos(\omega t) \tag{4}$$

When mains current $i_s\,(t)$ is equal to the real power current component $i_{L1P}\,(t)$ as

$$i_S(t) = \sqrt{2} I_1 \cos\theta_1 \sin(\omega t) \tag{5}$$

Obviously, both mains voltage $v_s\,(t)$ and current $i_s\,(t)$ are pure sine waves, and in phase with each other; therefore, the desired compensation current can be obtained by subtracting equation (2) from equation (5) as

$$i_{cr}(t) = i_L(t) - i_S(t) \tag{6}$$

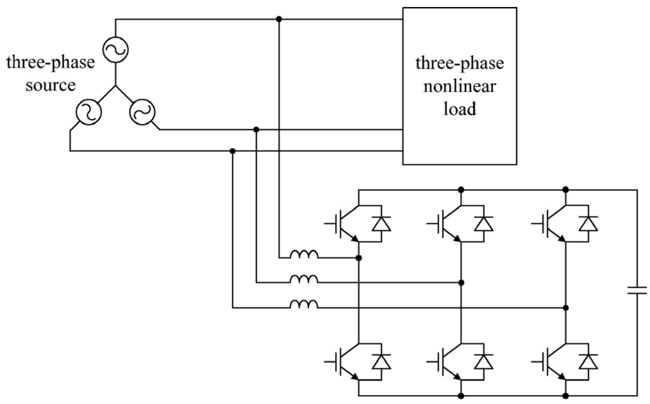


Fig. 1. The typical configuration of a three-phase active power filter

2.2 Operation Principle

The controlled method of each phase is the same in the proposed active power filter. Fig. 2 shows the control block diagram of the proposed APF. It mainly consists of a compensation current calculation circuit, and a dc voltage control circuit. The compensation current calculation circuit is to obtain the amplitude of real power component of each phase load current, then multiplying a unit sine wave signal which is in phase with the source voltage of each phase to produce the current reference signal $i_{sc}\,(t)$. Subtracting the current reference signal $i_L(t)$ and the load current $i_{sc}\,(t)$ of each phase would have the desired compensation current $i_{cr}(t)$. As a result, the real power current component can be obtained from the ac source to the nonlinear load; on the other hand, the reactive power current component and harmonic current component can be supplied by the active power filter. Hence, the proposed APF can compensate the current harmonics and improve the power factor.

The mains voltage $v_{sa}(t)$ is added to the control circuit that is used to generate the phase reference signal. In other words, the calculation accuracy would not be influenced even if the source voltage is distorted.

In general, one can use the error between the capacitor voltage feedback signal $v_o(t)$ and the capacitor voltage reference signal $v_o^*(t)$ through a PI controller to maintain constant the dc voltage and to supply the switching losses of the converter. On the other hand, an energy balanced circuit is adding to further improve the transient response.

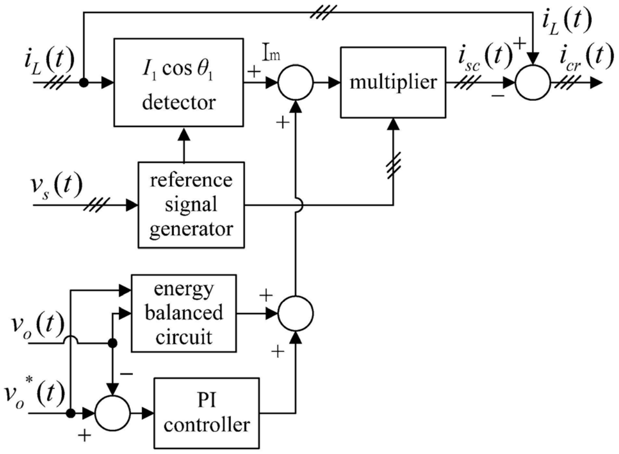


Fig. 2. The control block diagram of the proposed APF

3 The Proposed $I_1\cos\theta_1$ Detector

The $I_1\cos\theta_1$ detecting technique adopted in this paper will be analyzed in this section. Fig. 3 shows the block diagram of the proposed $I_1\cos\theta_1$ detector. At first, the mains voltage $v_s(t)$ is fed to the reference signal generator to produce a reference voltage signal $v_r(t)$. The peak value of the reference signal $v_r(t)$ is unity; beside, it is in phase with the mains voltage, hence the signal $v_r(t)$ can be represented as

$$v_r(t) = \sin(\omega t) \tag{7}$$

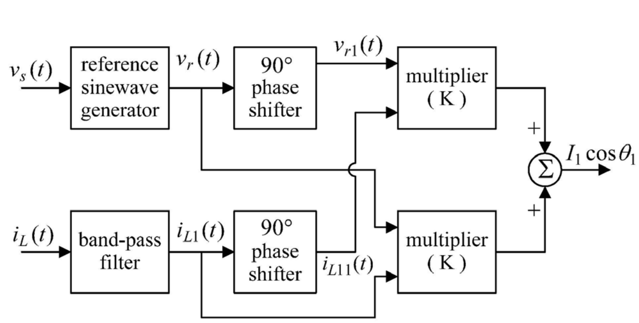


Fig. 3. The block diagram of the proposed $I_1\cos\theta_1$ detector

If $v_r(t)$ is sent to a 90° shift circuit, then

$$v_{r1}(t) = \cos(\omega t) \tag{8}$$

On the other hand, a band-pass filter is used to eliminate the harmonic components of the nonlinear load current $i_L(t)$. Thus, the fundamental current component can be represented as

$$i_{L1}(t) = \sqrt{2} I_1 \sin(\omega t + \theta_1) \tag{9}$$

Similarly, $i_{L1}(t)$ is sent to a 90° shift circuit, then

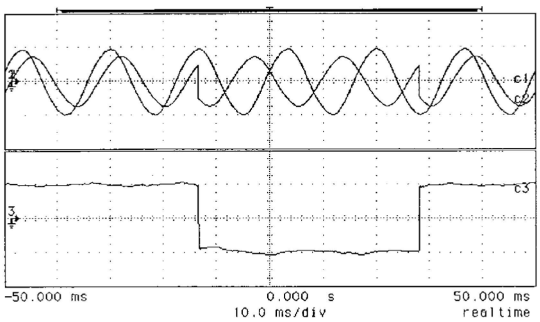
$$i_{L11}(t) = \sqrt{2} I_1 \cos(\omega t + \theta_1) \tag{10}$$

Summing up the product of multiply $v_{r1}(t)$ by $i_{L11}(t)$ and $v_r(t)$ by $i_{L1}(t)$, then the summation can be given as

$$v_o(t) = v_{r1}(t) i_{L11}(t) + v_r(t) i_{L1}(t) = \sqrt{2} K I_1 \cos\theta_1 \tag{11}$$

where K is the scaling factor of the multiplier.

According to equation (11), the output voltage $v_o(t)$ is the amplitude of the real power component of the load current by adjusting the scaling factor K of the multiplier. Fig. 4 shows transient response for different step phase angle changes, namely $45^{\circ} \rightarrow 135^{\circ} \rightarrow 45^{\circ}$. It can be seen that the transient response time of the proposed detector is less than one-fourth cycle.



(v_S:10V/div; i_L:10A/div; v_o:7.5V/div; time:10ms/div)

Fig. 4. The transient response of the proposed $I_1 \cos\theta_1$ detector

4 Simulation Results

To verify the feasibility and performance of the proposed three-phase active power filter, some simulation results are provided for verification. The system parameters of the proposed APF are shown in Table 1.

Table 1. System parameters

System Parameters	Inductor	$L = 7$ mH
	Capacitor	$C = 2200$ μF
	Power Switch Model	GT50J101
	Power Diode Model	F10A60
	Output Power	500 W

Fig. 5 shows the mains voltage v_a and line current i_a for a three-phase full-wave rectifier bridge, while Fig. 5 shows the spectrum of the line current i_a. The total harmonic distortion (THD) of the line current is 54.11% before compensation. Fig. 6 shows the mains voltage v_a and line current i_a after compensation, and Fig. 6 shows the spectrum of the line current i_a. It is obvious from Fig. 6 that the line current is sinusoidal and is in phase with mains voltage. Further to analysis the harmonics component and total harmonics distortion (THD) of different frequency; Table 2 shows the normalized harmonics component of line current. As can be seen, the harmonics component of each frequency is quite low. Besides, the dominant harmonics are lower than the fundamental harmonic about 2.68%; while the THD of line current is significantly suppressed from THD=54.11% to THD=3.549%. Fig. 7 shows the transient responses of the mains voltage v_a, the line current i_a, the load current i_{la}, the compensation current i_{fa}, and the dc capacitor voltage v_o under a step load change from 60 W to 310 W. It can be seen that the proposed APF has a good dynamic performance.

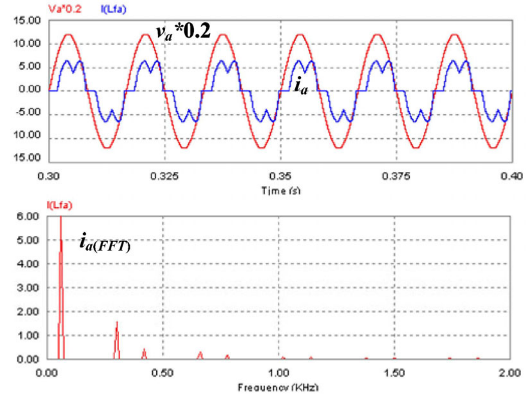


Fig. 5. A-phase phase-to-neutral voltage v_a and line current i_a of full-wave rectifier bridge before compensation, and spectrum of line current i_a

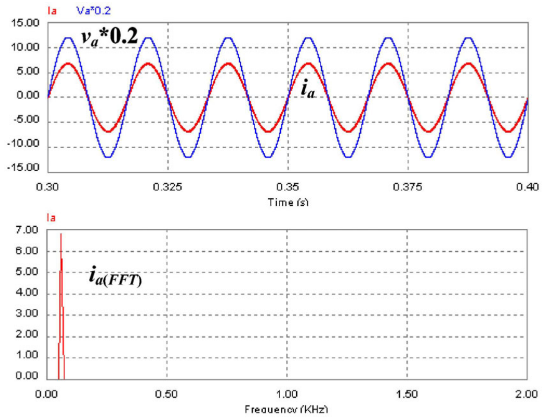


Fig. 6. A-phase phase-to-neutral voltage v_a and line current i_a after compensation, and spectrum of line current i_a

Table 2. The harmonics component of line current

Harmonics Order	Frequency (Hz)	Percentage (%)
1st	60	100
2nd	120	0.51
3th	180	2.68
4th	240	0.14
5th	300	1.11
6th	360	0.16
7th	420	0.73
8th	480	0.08
9th	540	1.07
10th	600	0.15
11th	660	1.17
12th	720	0.05
13th	780	0.43
14th	840	0.09
15th	900	0.49
16th	960	0.06
17th	1.02k	0.40
18th	1.08k	0.08
19th	1.14k	0.28

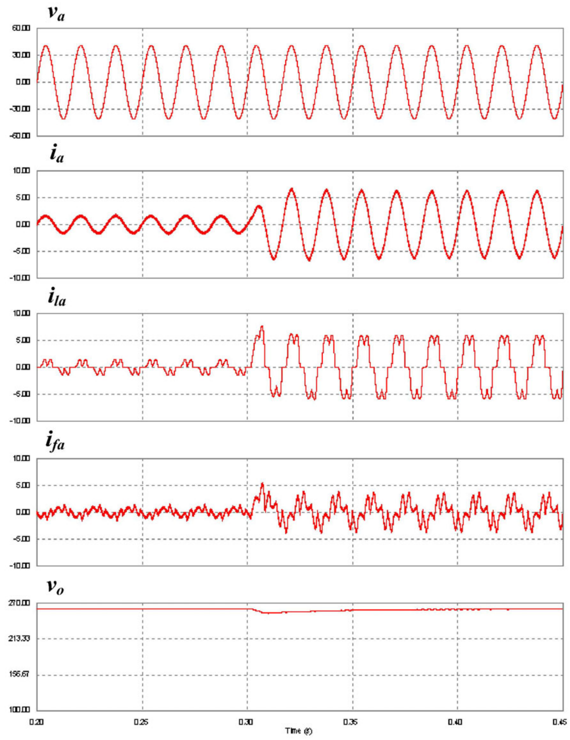


Fig. 7. A-phase phase-to-neutral voltage v_a, line current i_a, the load current i_{la}, the compensation current i_{fa}, and the dc capacitor voltage v_o under a step load change from 60 W to 310 W

5 Conclusion

This paper presents a novel algorithm for a three-phase active power filter. In the proposed algorithm, the mains voltage would not be used in the calculation of the reference compensation current. Therefore, the line current is sinusoidal and in phase with the mains voltage after compensation even if the mains voltage is distorted. Furthermore, a fast response the amplitude of the real power current component detector has been presented in this paper to improve the performance of the proposed APF. On the other hand, an energy balanced circuit is adding to further strengthen the transient response of the system. Finally, some simulation results show that the proposed three-phase active power filter has good performance under steady-state and transient operation.

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