

An intelligent control for three-phase and four-wire active power filter

Junsheng Jiao

School of Electronic Engineering, Tongling University, Tongling City, Anhui Province, China, 244061
E-mail: jiaotlu@sina.com

Abstract. The paper presents a compensating system for the harmonics and the reactive power using active power filter in three-phase and four-wire systems. The conventional active power filters have been designed based on the $p-q$ theory. However, these types of the filter can only compensate for the reactive power for the load and the detection result is not accurate if the three-phase voltage is distorted. To overcome this deficiency, a novel i_p-i_q algorithm based on the $p-q$ theory is proposed for the control strategy of the active filter. The obtained simulation results show that by using the proposed control strategy, the total harmonics distortion in Matlab/Simulink can be minimized.

Keywords: Active power filter, Harmonics control, Instantaneous reactive power theory, Reactive power compensation, Three-phase and four-wire systems.

Intelligentni nadzor za tri-fazni, štiri-žični aktivni močnostni filter

V članku je predstavljen kompenzacijski sistem za višje harmonske komponente in jalovo energijo z uporabo aktivnega močnostnega filtra v tri-faznem in štiri-žičnem sistemu. Klasični aktivni močnostni filtri so zasnovani na osnovi teorije $p-q$. Takšna sita lahko kompenzirajo jalovo energijo le na bremenu in tudi kakovost kompenzacije je slabša v primeru popačenja zaradi višjeharmonskih komponent. V članku predlagamo algoritem i_p-i_q za nadzor aktivnega močnostnega filtra. Rezultati, dobljeni v simulacijskem okolju Matlab/Simulink, potrjujejo, da je s predlagano metodo nadzora možno zmanjšati popačenje zaradi višjeharmonskih komponent.

1 INTRODUCTION

The harmonic problem and power quality have become serious concerns due to the increasing of nonlinear loads in many power electronic equipments. The conventional approach for reactive and harmonic current compensation in power systems is to install shunt-connected switched capacitor banks. Passive LC branches tuned at harmonic frequencies can be added for additional harmonic compensation [1]. The problems associated with the application of switched capacitors are: they act slowly, taking many cycles to react; the mechanical action makes them prone to mechanical failure; and the switching action can cause over voltage transients in the system [2].

Using active power filter (APF) in place of the switched capacitors and LC filters can address these problems. APF is considered to be an effective and

practical solution. Its dynamical characteristics overcome the previous drawbacks of the passive filters. When being connected in parallel with a power system, APF acts as a controlled harmonic current source, injecting simultaneously suitable currents into the power system to eliminate the harmonic content caused by nonlinear loads and to obtain a unity input power factor.

Fig.1 depicts an active power filter that implements PWM voltage-source converter connected in parallel with three-phase and four-wire nonlinear loads using a control method that based on instantaneous representative active power equality [3]. This active power filter will inject undesired currents to make the source currents nearly sinusoidal [4]. Application of this active power filter in three-phase and four-wire system will reduce the neutral current.

Most of active power filters control methods are based on extraction of harmonic components by using the imaginary $p-q$ theory proposed by Akagi due to its advantages and superiority [5]. The $p-q$ theory has been used very successfully to design and control of the APF for three-phase systems. This theory was extended by Aredes [6], for applications in three-phase and four-wire systems. The $p-q$ theory was mostly applied to calculate the compensating currents assuming ideal mains voltages. However, the drawbacks of the theory are: It can not compensate the harmonic current component when the mains voltages are distorted [7-8]. In order to solve the problems of conventional $p-q$ theory, a new i_p-i_q (current of instantaneous real power and current of instantaneous imaginary power) algorithm is proposed for active power filter.

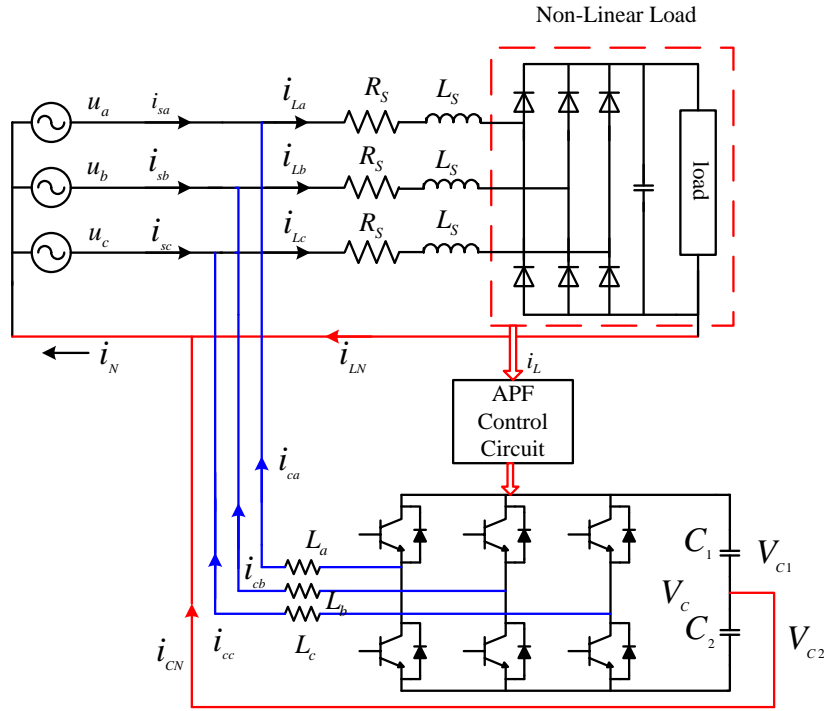


Figure 1. The basic compensation principle of the APF

This paper is organized as follows. Section 2 introduces the instantaneous reactive power theory. Section 3 presents i_p - i_q algorithm. Section 4 demonstrates and discusses the results, and Section 5 draws conclusions.

2 CONVENTIONAL p - q THEORY

In Fig.2, the p - q theory is based on the α - β transformation, also is called Concord transformation, where three-phase mains voltages and load currents can be transformed into two-axis representations as below: It consists in a real matrix, to the α - β stationary reference frame measuring three-phase power supply voltage (u_{sa}, u_{sb}, u_{sc}) and load current (i_{La}, i_{Lb}, i_{Lc}). It can be shown in Eq.1 and Eq.2 [9].

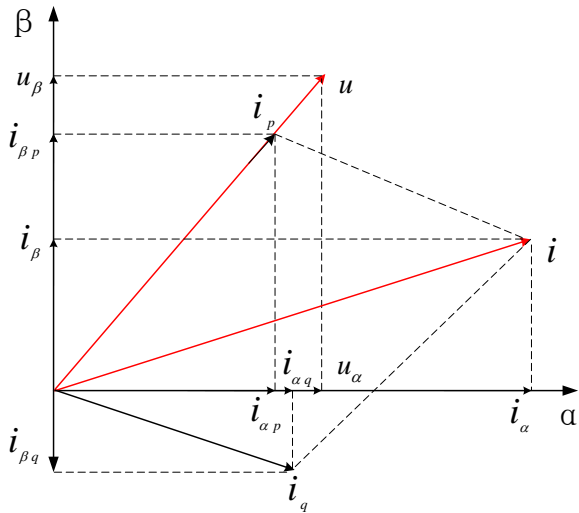


Figure 2. α - β Coordinates vector

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (2)$$

In the p - q theory, instantaneous real power (p) and instantaneous imaginary power (q) are illustrated as [10]:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta \\ -u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

The method based on control algorithm with load current measurement both p and q contain a DC term and an AC term [11]. They can be calculated as:

$$p = \bar{p} + \tilde{p} \quad (4)$$

$$q = \bar{q} + \tilde{q} \quad (5)$$

The single DC component of the real and imaginary power is therefore selected as compensation power reference for harmonic and reactive power compensation. The compensation current references in α - β coordinates are calculated by Eq.6.

$$\begin{bmatrix} i_{F\alpha}^* \\ i_{F\beta}^* \end{bmatrix} = \frac{1}{u_\alpha^2 + u_\beta^2} \begin{bmatrix} u_\alpha & -u_\beta \\ u_\beta & u_\alpha \end{bmatrix} \begin{bmatrix} \bar{p} \\ \bar{q} \end{bmatrix} \quad (6)$$

The compensation current references in the α - β coordinates are then transformed back into the a-b-c coordinates through the inverse simplified Clarke Transformation.

$$\begin{bmatrix} i_{Fa}^* \\ i_{Fb}^* \\ i_{Fc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{F\alpha}^* \\ i_{F\beta}^* \end{bmatrix} \quad (7)$$

3 i_p - i_q ALGORITHM

When the three-phase voltage is distorted, according to p - q method, the detection result is not accurate. Because the measures of the p - q must satisfy that u_a , u_b , u_c participate harmonic current detection operation, the desired u_a , u_b , u_c voltage which it should be no distortion of the sine wave, which will bring the error detection for the harmonic distortion of the current waveform. The compensated phase current value must contain harmonic voltage distortion components.

In the detection circuit of three-phase harmonic current, assuming instantaneous current of each phase:

$$i_{an}(t) = \sqrt{2}I_{+n} \sin(n\omega t + \phi_{+n}) + \sqrt{2}I_{-n} \sin(n\omega t + \phi_{-n}) \quad (8)$$

$$i_{bn}(t) = \sqrt{2}I_{+n} \sin[n\omega t + \phi_{+n} - (2\pi/3)] + \sqrt{2}I_{-n} \sin[n\omega t + \phi_{-n} + (2\pi/3)] \quad (9)$$

$$i_{cn}(t) = \sqrt{2}I_{+n} \sin[n\omega t + \phi_{+n} + (2\pi/3)] + \sqrt{2}I_{-n} \sin[n\omega t + \phi_{-n} - (2\pi/3)] \quad (10)$$

where n indicates the harmonic order; I_{+n} is the virtual value of positive-sequence; I_{-n} is the virtual value negative sequence.

Applying the Clarke transformation yields the following currents:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{3} \begin{bmatrix} I_{+n} \sin(n\omega t + \phi_{+n}) + I_{-n} \sin(n\omega t + \phi_{-n}) \\ -I_{+n} \cos(n\omega t + \phi_{+n}) + I_{-n} \cos(n\omega t + \phi_{-n}) \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} i_p \\ i_q \end{bmatrix} = C_\omega \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{3} \begin{bmatrix} I_{+n} \cos[(n-1)\omega t + \phi_{+n}] - I_{-n} \cos[(n-1)\omega t + \phi_{-n}] \\ -I_{+n} \sin[(n-1)\omega t + \phi_{+n}] - I_{-n} \sin[(n-1)\omega t + \phi_{-n}] \end{bmatrix} \quad (12)$$

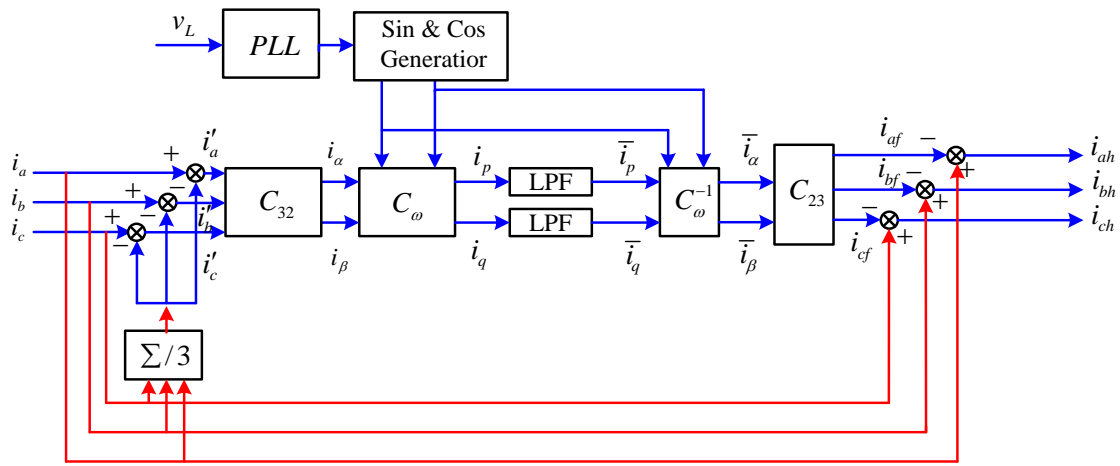
$$\text{where } C_\omega = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix}$$

The DC component of instantaneous reactive and active current can be obtained through a low pass filter (LPF).

$$\begin{bmatrix} \bar{i}_p \\ \bar{i}_q \end{bmatrix} = \sqrt{3}I_{+1} \begin{bmatrix} \cos\phi_{+1} \\ \sin\phi_{+1} \end{bmatrix} \quad (13)$$

I_{+1} is the virtual value of fundamental wave current. \bar{i}_p and \bar{i}_q is fundamental positive sequence component of i_a , i_b , i_c . So, it can get three-phase current fundamental positive sequence component.

$$\begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix} = C_{23} C_\omega \begin{bmatrix} \bar{i}_p \\ \bar{i}_q \end{bmatrix} = \sqrt{2}I_{+1} \begin{bmatrix} \sin(\omega t + \phi_{+1}) \\ \sin(\omega t + \phi_{+1} - 2\pi/3) \\ \sin(\omega t + \phi_{+1} + 2\pi/3) \end{bmatrix} \quad (14)$$

Figure 3. Control circuit using p - q theory

where

$$C_{23} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}$$

The three-phase current signals minus fundamental positive sequence current component. We can get the harmonics and negative sequence current signal of i_{ah} , i_{bh} , i_{ch} . In three-phase four-wire circuit, i_a , i_b and i_c contain zero-sequence component and they contain zero sequence component is equal value.

$$i_0 = \frac{i_a + i_b + i_c}{3} \quad (15)$$

Current signal (i'_a , i'_b , i'_c) which contains only positive and negative sequence components will be achieved if zero-sequence component in each phase current can be removed. It can still be applied i_p - i_q method for testing three-phase and four-wire circuit.

$$i'_a = i_a - i_0 \quad (16)$$

$$i'_b = i_b - i_0 \quad (17)$$

$$i'_c = i_c - i_0 \quad (18)$$

Fig.3 shows a block diagram of the proposed control circuit capable of improving the system stability. The control circuit extracts the fundamental components from detected supply currents by using the p - q method and inverse transformations as follows. The DC components of i_p and i_q , are extracted from i_p and i_q by two first-order and low-pass filters (LPF).

The phase-locked-loop (PLL) circuit generates together with the “sin and cos generator” two signals equal to $\sin(\omega t)$ and $\cos(\omega t)$, where ω is the line angular

frequency and Φ is a generic phase angle guaranteeing that the generated $\sin(\omega t + \Phi)$ is in phase with the a phase voltage.

4 SIMULATION RESULTS

To verify the analysis, Simulation is conducted using Matlab/Simulink to evaluate the load harmonic cancellation performance of the proposed active power filter based on Fig.1 and Fig.3. The simulations use main currents which contain distortion to show the capability of the i_p - i_q based the control method in doing compensation. Parameters used in the simulation are shown in Table 1.

Table 1. Main parameters of the simulation system

| | |
|--------|--------------------------|
| source | voltage=220V |
| | $R_s=0.08\Omega$ |
| | $L_s=0.2\text{mH}$ |
| APF | $L_a=L_b=L_c=5\text{mH}$ |
| | $f=10\text{kHz}$ |
| load | $R=0.06\Omega$ |
| | $L=0.3\text{mH}$ |

Simulation of without compensation and with compensation under proposed control topologies are carried out. As an example of current for phase ‘a’, Fig.4 to Fig.5, represent simulation results of currents without APF.

Fig.4 shows that the waveform is observed to be non-sinusoidal. It represents the behavior of the three-phase and four-wire system source currents, which are highly distorted. Fig.5 shows the harmonic order of current for Phase ‘a’ and the THD (total harmonic distortion) is observed to be equal to 37.26 %.

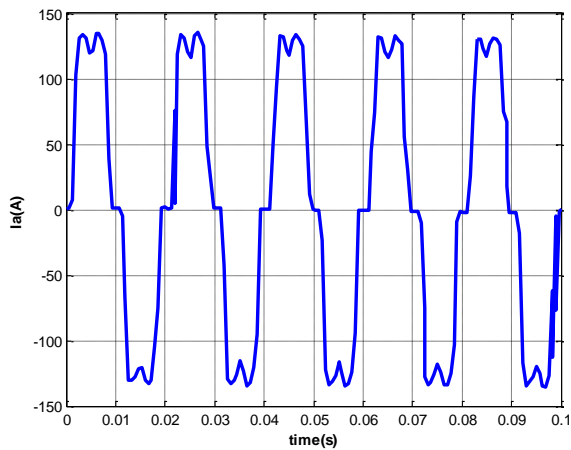


Figure 4. Current before the active power filter

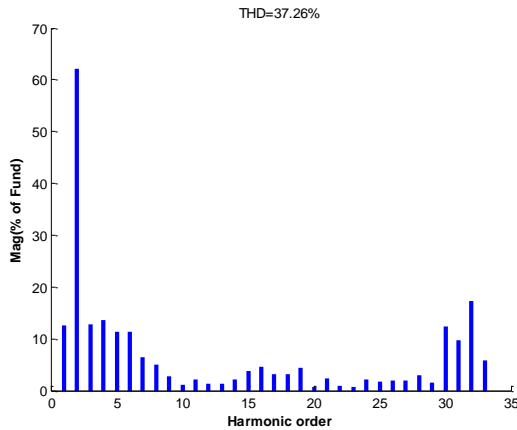


Figure 5. Harmonic spectrum before the active power filter

In Fig.6 and Fig.7, it is observed that the current are very close to sinusoidal as compared to the results obtained before the active power filter. THD decreases from 37.26% to 4.12%. It is proved to be less than the IEEE-519 standards, which also shows that the i_p-i_q control technique is successfully compensated.

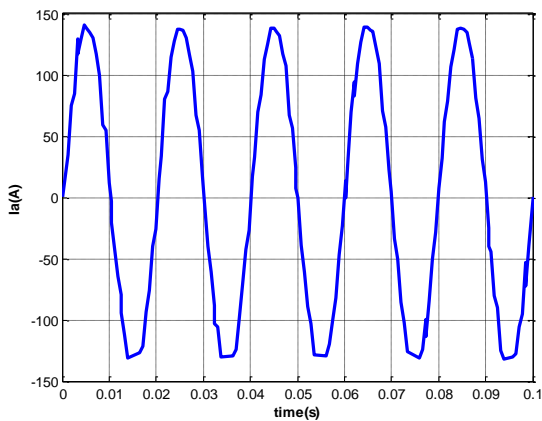


Figure 6. Current after the active power filter

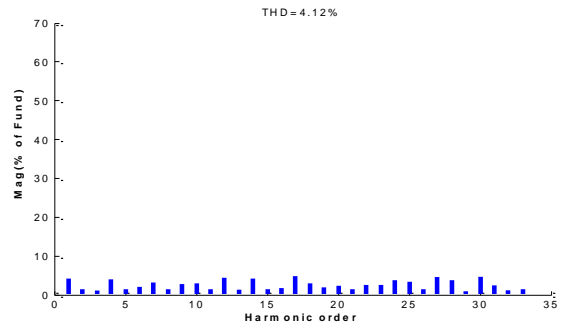


Figure 7. Harmonic spectrum after the active power filter

5 CONCLUSION

The performance of a control strategy based on the i_p-i_q theory has been studied and this control method be implemented in three-phase and four-wire system. It is capable to operate under non-ideal main voltages with keeping force the source phase currents be sinusoidal without using source voltage sensing. It is clear from the simulation results that the compensation process for the control strategy has a better transient response.

ACKNOWLEDGEMENTS

The work is supported by State Key Lab. of Advanced Metallurgy in China (No. GZYKF201306).

REFERENCES

- [1] Chu. R. F, Wang. J and Chiang. H, "Strategic Planning of LC Compensators in Nonsinusoidal Distribution Systems", *IEEE Transactions on Power Delivery*, 9(3), pp. 1558-1563, 1994.
- [2] Kolcio. N, Halladas. J. A, Allen. G. D and Fromholts. E. N, "Transient Overvoltages and Overcurrents on 12.47 kV Distribution Lines: Field Test Results", *IEEE Transactions on Power Delivery*, 7(3), pp. 1359-1370, 1992.
- [3] Odavic. M, Biagini. V, Zanchetta. P and Sumner. M, "One-sample-period-ahead Predictive Current Control for High-performance Active Shunt Power Filters", *IET Power Electronics*, 4(4), pp. 414-423, 2011.
- [4] Abdalla. I. I, Rao. K. S. R and Perumal. N, "Three-phase Four-Leg Shunt Active Power Filter to Compensate Harmonics and Reactive Power", *Proc. IEEE Symposium on Computers & Informatics*, pp. 495-500, 2011.
- [5] Akagi. H, Kanazawa and Y, Nabae. A, "Instantaneous reactive power compensators comprising switching devices without energy storage elements", *IEEE transactions on industry applications*, pp. 625-630. 20(3), pp. 625-630, 1984.
- [6] Aredes. M, Hafner. J and Heumann. K, "Three-phase four-wire Shunt Active Filter Control Strategies", *IEEE Transactions on Power Electronics*, 12(2), pp. 311-318, 1997.
- [7] Komatsu. Y, Kawabata. T, "A Control Method for the Active Power Filter in Unsymmetrical Voltage Systems", *International Journal of Electronics*, 86(10), pp. 1249-1260, 1999.
- [8] Huang. S. J, "A Study of Three-phase Active Power Filters under Nonideal Mains Voltages", *Electric Power Systems Research*, 49(2), pp. 129-137, 1999.

- [9] Kim. H, Blaabjerg. F, Bak-Jensen. B and Choi. J, “Instantaneous Power Compensation in Three-phase Systems by using p–q–r Theory”, *IEEE Transactions on Power Electronics*, 17(5), pp. 701-710, 2002.
- [10] Afonso. J, Couto. C and Martins. J, “Active Filters with Control based on the p–q Theory”, *IEEE Industrial Electronics Society Newsletter*, 47(3), pp. 5-10, 2000.
- [11] Lin. B. R, Lee. Y. C, “Three-phase Power Quality Compensator under the Unbalanced Sources and Nonlinear Loads”, *IEEE Transactions on Industrial Electronics*, 51(5), pp. 1009-1017, 2004.

Junsheng Jiao received his B.Sc. in Electrical Engineering and Automation from Anhui University of Science and Technology in China. He received his M.Sc. from Jiangsu University in China. He has teaching experience of eight years. His research interest fields include power electronics, renewable energy and simulation.