Simulation and reliability analysis of shunt active power filter based on instantaneous reactive power theory

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Abstract: This paper first discusses the operating principle of instantaneous reactive power theory. Then, the theory is introduced into shunt active power filter and its control scheme is studied. Finally, Matlab/Simulink power system toolbox is used to simulate the system. In the simulation model, as the most common harmonic source, 3-phase thyristor bridge rectifier circuit is constructed. The simulation results before and after the shunt active filter was switched to the system corresponding to different firing angles of the thyristors are presented and analyzed, which demonstrate the practicability and reliability of the proposed shunt active filter scheme.

INTRODUCTION

In recent years, the increasing harmonic contamination in power transmission/distribution system with the proliferation of power electronics equipment in industry has been paid great attention to. Many researchers have put forward approaches to solve the problem and many papers have been released.

The traditional approach of eliminating the harmonics is adopting LC passive filter, which exhibits impedance lower than the source impedance at a tuned harmonic frequency to reduce the harmonic currents flowing into the source. However, passive LC filters have inevitable disadvantages, such as large size, resonance, fixed compensation characteristics, and so on (Fujita and Akagi, 1991).

Shunt active filters proposed and studied for about 3 decades are connected in parallel to the power distribution. Since then, theories and applications of active power filters have become more and more popular and have attracted much attention, especially after instantaneous reactive power theory was pro-posed and used as the basis of the calculation of compensation current. Shunt active filter adopting such a configuration can enable power system with inductive load to be free from harmonic currents by injecting the compensating current into the power system to make the source current into sinusoid shape. In this case, the shunt active filter serves as a current source (Wang *et al.*, 2001).

Many researches conducted on shunt active filter have resulted in many achievements. Zhuo *et al.*(2000) successfully introduced the principle into three-phase four-wire system. Literature (Yang and Wang, 1995; Yang *et al.*, 1996; Hossein *et al.*, 2003; Kale and Özdemir, 2005) showed that shunt active filter is competent for non ideal operating conditions. However, in most of them, 3-phase diode rectifier circuit is made the harmonic source, which in fact is not advisable in industry application. This paper aims at making the 3-phase thyristor bridge rectifier, the most common harmonic source. As the firing angle can vary from 0° to 120°, the model in this paper selects 0°, 30°, 60° and 90° as the firing angle respectively,

then simulation results of the currents waveform before and after the shunt active filter was switched into the system are presented and analyzed. The reliability of the shunt active filter was verified.

INTRODUCTION OF INSTANTANEOUS REACTIVE POWER THEORY

p-q theory

In 3-phase circuits with balanced voltage, instantaneous currents and voltages are converted into instantaneous space vectors. The traditional definitions of the power components are all based on the direct quantities of 3-phase voltages and currents vectors: e_a, e_b, e_c and i_a, i_b, i_c. In instantaneous reactive power theory, the instantaneous 3-phase currents and voltages are expressed as the following equations. These space vectors are easily converted into α-β coordinates (Peng and Akagi, 1990; Peng and Lai, 1996.).

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = C_{32} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}, \qquad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = C_{32} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix}, \qquad (2)$$

where $C_{32} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix}$, α and β are

orthogonal coordinates. e_α and i_α are on α axis, e_β and i_β are on β axis.

When the source supplies nonlinear loads, the instantaneous power delivered to the loads includes both active and reactive components. So, the current vector i was divided into active current component and reactive current component, which are i_p and i_q respectively, as shown in Fig.1.

In the representation of electric quantities, instantaneous active and reactive powers are calculated as follows:

$$p=ei_p, \quad q=ei_q,$$

where, $i_p = i\cos\varphi$, $i_q = i\sin\varphi$ make up Eq.(3):

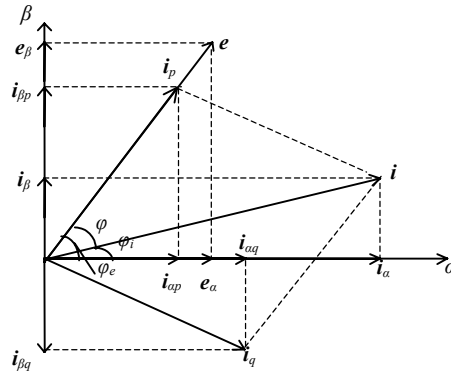**Fig.1 Vector diagram of voltages and currents**

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \overline{p} + \tilde{p} \\ \overline{q} + \tilde{q} \end{bmatrix} = C_{pq} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}. \qquad (3)$$

Here, $C_{pq} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}$, "–" and "~" stand for

dc and ac components, respectively. $\overline{p}$ and $\overline{q}$ are the instantaneous active and reactive power (dc value) originating from the symmetrical fundamental (positive-sequence) component of the load current, $\tilde{p}$ and $\tilde{q}$ are the instantaneous active and reactive power (ac value) originating from harmonic and the asymmetrical fundamental (negative-sequence) component of the load current. These power quantities given above for an electrical system are represented in *a-b-c* coordinates and have the following physical meaning (Kale and Özdemir, 2005):

$\overline{p}$, the mean value of the instantaneous active power—corresponds to the energy per time unit transferred from the power supply to the load, through *a-b-c* coordinates, in a balanced way. $\tilde{p}$, alternated value of the instantaneous active power—it is the energy per time unit that is exchanged between the power supply and the load through *a-b-c* coordinates. $\overline{q}$, instantaneous reactive power—corresponds to the power that is exchanged between the phases of the load. This component does not imply any exchange of energy between the power supply and the load, but is responsible for the existence of undesirable currents, which circulate between the system phases. $\tilde{q}$, the mean value of the instantaneous reactive power that is equal to the conventional reactive power.

From Eq.(3), in order to measure the harmonic currents and reactive current component, fundamental active current corresponding to reactive power on α-β

coordinates should be first calculated by Eq.(4):

$$\begin{bmatrix} i_{\alpha f} \\ i_{\beta f} \end{bmatrix} = C_{pq}^{-1} \begin{bmatrix} \overline{p} \\ 0 \end{bmatrix}. \tag{4}$$

The fundamental active currents in α-β reference frame are then transformed into a-b-c reference frame and they are:

$$\begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_{\alpha f} \\ i_{\beta f} \end{bmatrix}. \tag{5}$$

Finally, the reference compensation currents are obtained by Eq.(6):

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix}. \tag{6}$$

i_p-i_q theory

It is supported that when the supply voltages are distorted, the p-q theory does not hold (Yang and Wang, 1995). This paper adopts an improved harmonic current detecting method based on instantaneous reactive power theory called i_p-i_q theory. The block diagram for calculating the reference current in this paper is shown in Fig.2.
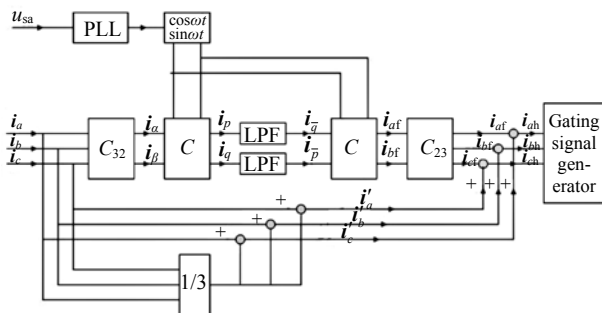

Fig.2 Block diagram of calculation for the reference current

Yang and Wang (1995) and Chang and Shee (2002) suggest that the accuracy is not affected no matter whether the source voltage is balanced or not if i_p-i_q theory is adopted. The main difference between i_p-i_q theory and p-q theory lies in that i_p-i_q theory does

not use source voltage directly, and C_{pq} in p-q theory is replaced by C here:

$$C = \begin{bmatrix} \sin\omega t & \cos\omega t \\ -\cos\omega t & \sin\omega t \end{bmatrix},$$

where ω corresponds to the fundamental frequency of the source voltage.

A neutral line exists in 3-phase 4-wire power system. The current i_a, i_b, i_c is composed of positive, negative and zero components. So, the theory above is not suitable for such power system. Zhuo et al.(2000) presents a simple resolution. In 3-phase 4-wire power system, the zero components in i_a, i_b and i_c are equal to each other:

$$i_0 = (i_a + i_b + i_c)/3.$$

Subtract i_0 from i_a, i_b, i_c, to get following expressions:

$$i_a' = i_a - i_0, \tag{7a}$$
$$i_b' = i_b - i_0, \tag{7b}$$
$$i_c' = i_c - i_0. \tag{7c}$$

The current quantity i_a', i_b', i_c' is composed of positive and negative components. Draw the fundamental positive components of the currents i_a, i_b, i_c. Finally the composition of harmonics, fundamental negative and zero components are obtained by subtracting the currents i_a, i_b, i_c and their fundamental positive components.

CONTROL SCHEME

Fig.3 shows the topology of the main circuit of the active power filter proposed in this paper. It adopts 3-phase PWM voltage-source inverter, mostly making IGBT as their switches, connected parallel to the harmonic loads. The active power filter deals with the compensating operation by controlling the 3-phase PWM inverter to inject appropriate current waveform into the power system. The PWM signals are generated by the reference current.

The actual active power filter compensating currents are monitored instantaneously, and then compared to the reference currents generated by the
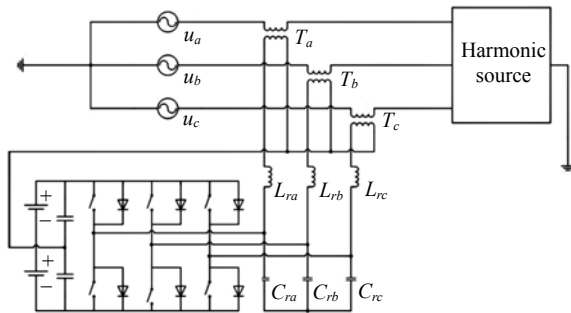
Fig.3 The topology of the main circuit of the active filter

control algorithm. In order to get precise instantaneous current control, the current control method must supply rapid current controllability and respond rapidly. There are various current control methods proposed for such active filter configurations, but in terms of rapid current controllability and easy implementation, hysteresis band current control method has the highest rate among the current control methods.

The hysteresis band current control scheme is shown in Fig.4. The reference harmonic current of the active power filter is i_c^* and the actual compensating current of the active power filter is i_c. After comparison between i_c^* and i_c the difference was used to serve as the input of the hysteresis band current controller. The hysteresis band current controller generates the PWM signals which are driven to control the inverter's switches to enable the actual compensating current i_c to follow the reference current i_c^*.
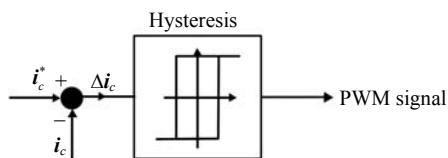

Fig.4 Hysteresis band current controller

The main drawback of hysteresis band current control is that the hysteresis band width may cause high switching frequency.

SIMULATION RESULTS

The presented simulation results were obtained by using Matlab/Simulink, for a 3-phase 3-wire

power system with a shunt active power. In the model, 3-phase thyristor bridge rectifier circuit was used as the main harmonic source. The model has been simulated under four scenarios, including the firing angles of the thyristors being 0°, 30°, 60° and 90° respectively. The simulation results are discussed below. Because the waveforms of the three phases were the same, A phase was selected as their representation. In consideration of the delay introduced by the computing of the LPF (Wang *et al.*, 1999) and the time of the circuit come to stability area, the start time of frequency analysis was fixed at 0.02 s, the number of cycles was made 3.

Firing angle is 0°

In fact, this is the same as the situation when the 3-phase diode rectifier is the harmonic source. Fig.5 shows the results before and after compensation, and frequency analysis was conducted.

In this case, with the compensation of the active filter, the current THD level decreased from 28.54% to 5.68%.

Firing angle is 30°

In this case, the firing angle was fixed at 30°, the current THD level was 33.20% and higher than the equivalent when the firing angle was 0° before the active filter was connected to the circuit. With the operating of the active filter, the THD also decreased to 7.94% effectively (Fig.6).

Firing angle is 60°

With the firing angle was increased to 60°, the current THD level reached 56.79%. In such situation, the active filter was able to play its role in decreasing the current THD level to 12.10% (Fig.7).

Firing angle is 90°

The simulation results and frequency analysis are shown in Fig.8 obviously indicating that the current harmonic pollution was most serious in the four scenarios and that the THD level here reached to 125.16%.

The simulation results showed that the harmonic pollution became more and more serious when the firing angle varied from 0° to 90° in 3-phase thyristor bridge rectifier circuit and that the current THD level reached maximum finally. Also by comparison be-
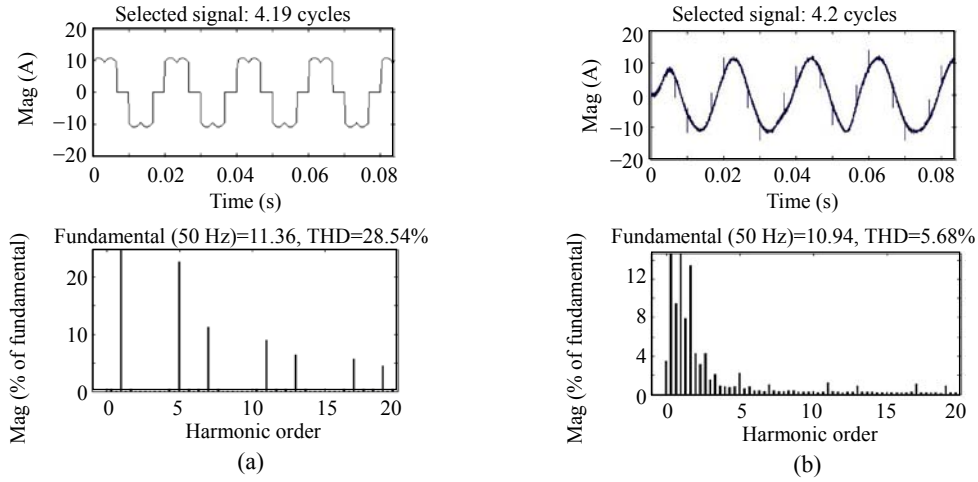
Fig.5 Simulation results and frequency analysis of the scenarios if the fire angle is 0° before (a) and after (b) compensation
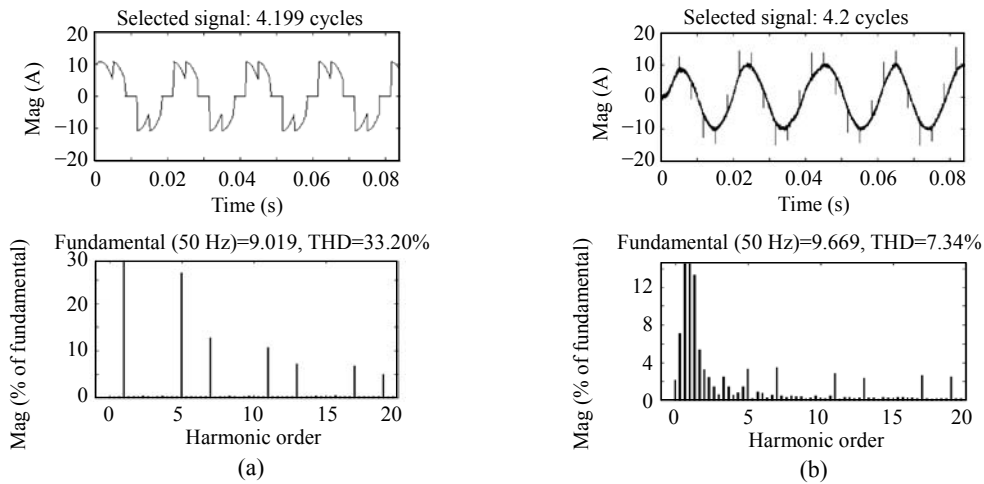

Fig.6 Simulation results and frequency analysis of the scenarios if the fire angle is 30° before (a) and after (b) compensation
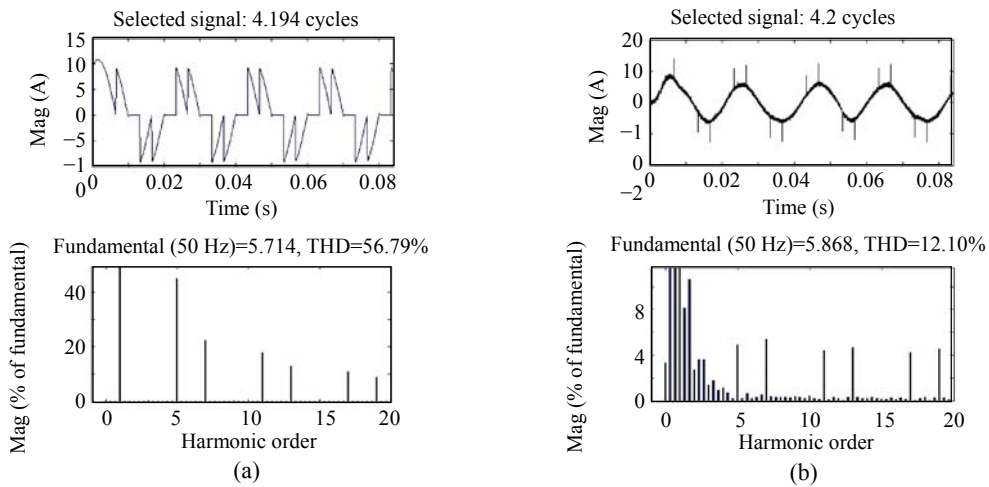

Fig.7 Simulation results and frequency analysis of the scenarios if the fire angle is 60° before (a) and after (b) compensation
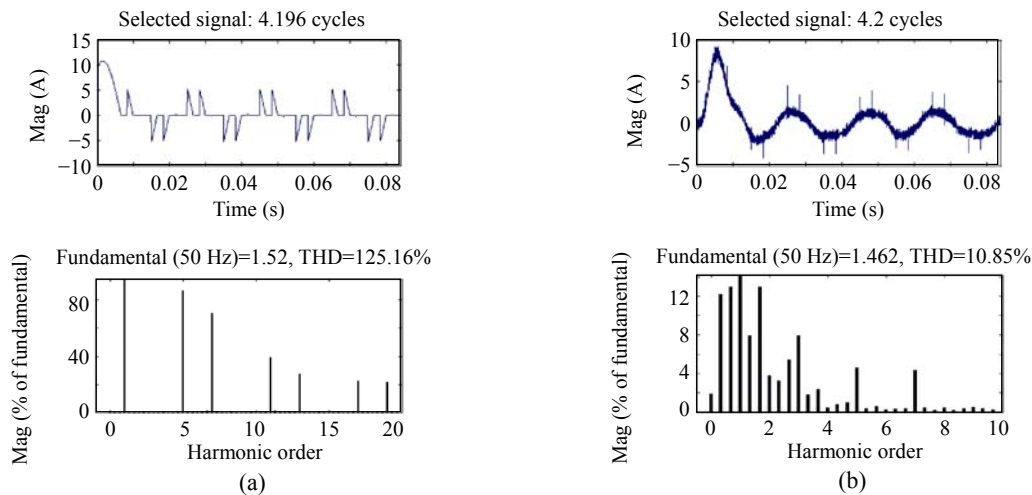
Fig.8 Simulation results and frequency analysis of the scenarios if the fire angle is 90° before (a) and after (b) compensation

tween the waveform before and after the active filter was switched into the circuit and the frequency analysis, it is easy to find that shunt active filter decreases the current THD level effectively.

CONCLUSION

In this work, the operating principle of the shunt active filter was studied and the simulation model was built. The simulation results and the frequency analysis led to the following conclusions:

(1) With the increasing fire angle, the harmonic current in 3-phase thyristor bridge rectifier circuit becomes more and more serious.

(2) Under various conditions, no matter which was the firing angle of the 3-phase thyristor bridge rectifier circuit, shunt active filters in this paper could enable give reliable operations.

Shunt active filter is expected to be installed in more industrial power systems.

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