Design and Performance of a Shunt Active Power Filter for Three-phase Four-wire System

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Abstract –Active power filter is an advanced power electronic device, which can be used for integrated compensating harmonics and improving power quality. A shunt active power filter using for three-phase four-wire system is introduced in this paper. The basic operation principles and structure are analyzed. This paper proposes the design of a shunt active power filter, which can be used under the condition of unbalanced and nonlinear loads. The main circuit is given and the control method is discussed. A 3 KW experimental prototype is built and the experiment results indicate that the active power filter has good performances.

Keywords - Active power filter, three-phase four-wire system, harmonic suppression, instantaneous reactive power theory

I. INTRODUCTION

As the development of modern power electronics technology and the wider application of various nonlinear devices, the current distortion makes increasingly serious pollution to the grid. Therefore, harmonic current compensation has been drawn great attention.

Active power filter is a new type of power electronic device using for dynamic suppressing harmonics and compensating reactive power. It can compensate harmonics with varying amplitude and frequency, and can overcome the shortage of passive filter effectively. It is a harmonics suppression device with prospect [1].

In 1980's, with the self turn-off power semiconductor appeared, PWM control technology and the instantaneous reactive power theory for three-phase system put into use, study on active power filter become fast.

Because of extensive use for three-phase four-wire in power system, such as industry, official and business, many people pay more attention to the trouble which is caused by harmonics and unbalance of three-phase. Therefore, it is important to compensate harmonics and reactive power in three-phase four-wire system [2].

This paper introduces a shunt active power filter for three-phase four-wire system. It presents the principles and structure. And the design and performance of a 3KW experimental prototype is proposed.

II. PRINCIPLE AND STRUCTURE

The structure of a shunt active power filter used for three-phase four-wire is shown in Fig. 1. In this system, the load may product harmonics and unbalance current in three-phase, and current is flown in neutral wire.

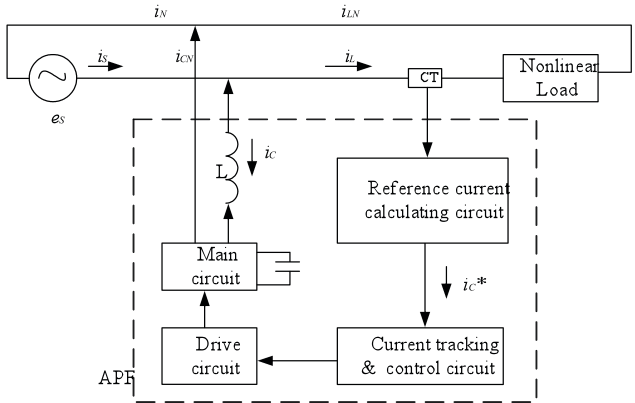

Fig. 1: The structure of active power filter for three-phase four-wire system

The shunt active power filter is a voltage source inverter controlled as a current source by means of pulse width modulation signals. As it can be seen in Fig. 1, the filter is connected in paralleled with the nonlinear load. Harmonic current compensation is achieved by injecting equal but opposite harmonic current components at the point of connection, therefore canceling the original distortion and improving the power quality [3]. In most cases, the load also needs reactive power, which can also be generated by the same current source. In three-phase unbalanced and nonlinear loads, it is also possible to redistribute power and to keep the system balance. The active power filter is composed of the reference current calculating circuit, current tracking circuit, driving circuit and the main circuit. While, the generation circuit of compensating current is composed of the last three parts [4].

Three-phase four-wire system is different from three-phase three-wire system because of the neutral wire. Thus, handling zero-sequence components of three-phase current is the key point. Reference current calculating circuit should product the reference current correctly and fast in three-phase four-wire system. That means it should detect the harmonics, fundamental negative-sequence current components and zero-sequence current components of the compensating [5]. The generation circuit of compensating current should product compensating current correctly according to the reference current signals.

Because the sum of three-phase current is not zero in three-phase four-wire system, the detection method based on instantaneous reactive power theory should be modified. The way is to calculate the zero-sequence current components, then subtract them from three-phase current. Finally three-phase current without zero-sequence components can be detected by the method based on instantaneous reactive power theory.

The compensating current signals of the neutral wire can be also calculated by turning the polarity of the neutral wire current over [6]. The principle of reference current calculating circuit is shown in Fig. 2. In which, i_a, i_b, i_c are load currents. The zero-sequence component of three-phase current i_n is calculated as:

$$i_n = \frac{1}{3}(i_a + i_b + i_c) \quad (1)$$

Then zero-sequence components can be subtracted from three-phase current:

$$\begin{aligned} i_a' &= i_a - i_n \\ i_b' &= i_b - i_n \\ i_c' &= i_c - i_n \end{aligned} \quad (2)$$

Eventually the three-phase currents without zero-sequence component i_a', i_b', i_c' will comply with:

$$i_a' + i_b' + i_c' = 0 \quad (3)$$

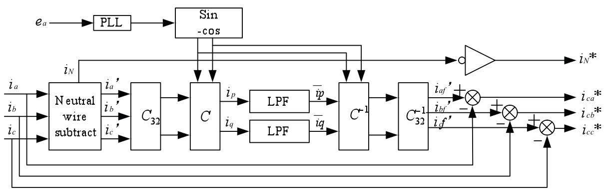

Fig. 2: The principle diagram of reference current calculating circuit

Afterward, as shown in Fig. 2, the three-phase currents without zero-sequence components i_a', i_b', i_c' are coordinately transformed and achieve corresponding active power current component i_p and reactive power current component i_q, then it can acquire dc component $\overline{i_p}, \overline{i_q}$ through the low pass filters. Fundamental positive-sequence components $i_{af}', i_{bf}', i_{cf}'$ can be calculated by inverse coordinate transformation. When the positive-sequence components are subtracted from load current i_a, i_b, i_c, there will be reference current $i_{ca}^*, i_{cb}^*, i_{cc}^*$. After the compensating currents generated by the reference signals offset the harmonics, the currents flowing into source which are equal to fundamental positive-sequence components are sinusoid and balanced [7].

III. DESIGN OF SHUNT ACTIVE POWER FILTER

Active power filter is an advanced power electronic device, which can be used for integrated compensating harmonics, reactive currents and negative-sequence currents. Because of the characteristics of real time and accurate compensation, it is possible to take full advantage of digital signal processing and many other technologies. If so, the performance of active power filters can be improved significantly.

A. Control circuit

The control circuit consists of current control and voltage control. The principle is shown in Fig. 3. The current controller uses the current error between reference current i_c^* and compensating current i_c filtered by a proportional-integral regulator as the modulating signal. The current control circuit uses a tracking PWM current control and timing comparing. The comparator is judged at each clock-cycle, so the PWM control signals change once at least one clock cycle. The clock-cycle limits the highest frequency of switching devices in the main circuit, thus damages to the devices due to over-high switching frequency may be avoided. The shortcoming of this control method is that the tracking error of compensating current is unfixed [8].

For voltage control, it mainly means controlling of DC-link voltage. There are two control techniques: PI control and fuzzy control. PI control is similar to the current control, but there is some difference. When the supply voltage is unbalanced or distorted, the input of the voltage controller is not the actual supply voltage but a unitary sinusoidal waveform in phase with the supply voltage [9]. Therefore, the active power filter will have good performance even under the condition of unbalanced or distorted source voltage. In other words, PI control uses the voltage error between DC-link voltage and its reference filtered by a proportional-integral regulator multiplied by the unitary sinusoidal waveform in phase with the supply voltage to obtain the reference current.

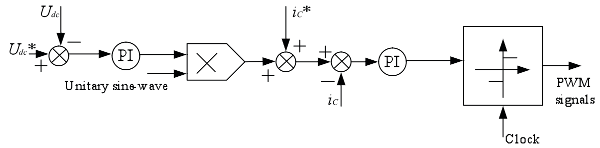

Fig. 3: The principle diagram of control circuit

Fuzzy control can be also applied to DC-link voltage control. The input of the controller is the error voltage and its incremental variation. And the output is the incremental variation of the amplitude of the active current injected into active power filter. Compared with PI control, fuzzy control has better dynamic response and can keep the DC-link voltage stability well. However, fuzzy control makes the controller complicated. This paper adopts PI control as control method.

B. Main circuit

In three-phase four-wire system, active power filter not only compensates the harmonics of three-phase current, but also suppresses the current of neutral wire to get rid of the neutral wire current of the source. There are many methods to suppress the neutral current. Generally, four-leg converter and three-leg converter are commonly used [10]. The structures of their main circuit are shown respectively in Fig. 4 and Fig. 5.

For four-leg structure, to compensate the neutral current is provided through the forth leg which products the compensating current of the neutral wire, which offset the neutral current of the source side. The compensating principle of this method is easy, but it makes the circuit more complicated and the cost is high. In this paper, the main circuit uses three-leg converter. Through reference current calculating circuit, it can acquire reference current signals of compensating three-phase currents and the neutral current. The compensating current of three-phase currents is equal to the sum of harmonics, fundamental negative-sequence and zero-sequence components in load current which offsets the load current. So the supply current flowing into the source which is equal to the fundamental positive-sequence components becomes sinusoidal and balanced. For three-leg structure, to keep the DC-link voltage balance is to control the neutral current to be zero [11]. From the point of active power filter, the sum of harmonics and fundamental negative-sequence components of three-phase current without zero-sequence components is aero. The sum of zero-sequence components of three-phase current is equal to the compensating neutral current which is regulated through DC-link control.

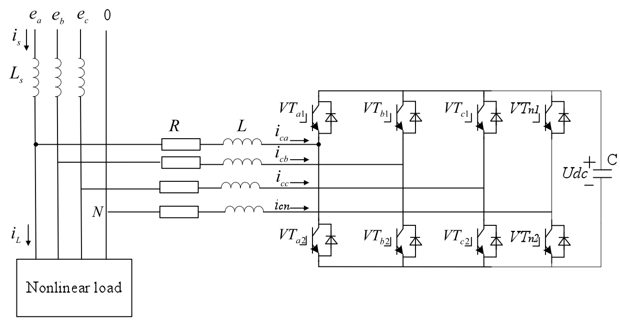

Fig. 4: The four-leg structure of main circuit

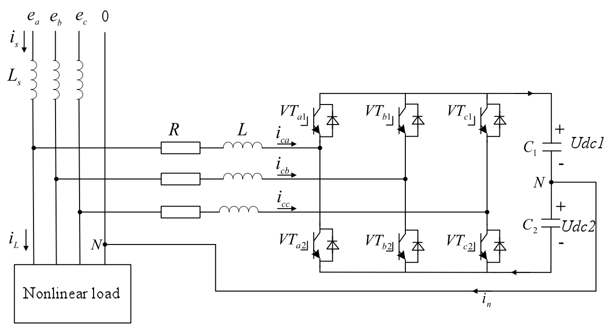

Fig. 5: The three-leg structure of main circuit

After compensation of active power filter, the three-phase supply current will be sinusoidal and balanced, the neutral current of the source will be zero.

A 3kW shunt three-phase four-wire active power filter experimental prototype is constructed. Firstly, the minimum DC-link voltage U_c should be greater than the value three times of AC phase peak voltage E_m. If DC-link voltage is too small, compensation current can not track instruction current as requests, and the compensation effect will be unsatisfied. On this basis, the greater Uc is, the faster i_c changes, the higher voltage the devices should endure [12]. Secondly, the smaller inductance L is, the faster i_c changes. Thirdly, the longer current controlling cycle t_c is, the greater ripple current tracking error has. The value of t_c also determines the highest time of harmonic which the active power filter can compensate and the frequency demands for switching devices.

The work process of active power filter is also the process of capacitor charging and discharging. The fluctuation of DC-link voltage can be explained by the changes of the stored charges volume, and the volume can be obtained from the integral of current to time. According to the parameters design method for capacitance in [13] and [14], the capacitor C under ideal condition can be calculated by equation (4)), where C is capacitor value; Q is the electric charges stored on capacitor; u is reference capacitor voltage; Q_1 is the maximal charge, $\Delta u \backslash u$ is the maximal voltage fluctuation; i_a^* is compensating current of phase a; i is fundamental active current; I_d is load current.

$$\begin{cases} C = \dfrac{Q}{u} \\ Q = Q_1 * \dfrac{u}{\Delta u} \\ Q_1 = \dfrac{1}{\omega} \displaystyle\int_{\pi/3}^{2\pi/3} i_a^* d\omega t \\ i = \dfrac{3\sqrt{6}}{\pi^2} i_d \\ i_a^* = i_d - \sqrt{2} * i \sin(\omega t + \pi/6) \end{cases} \qquad (4)$$

C. Driving circuit

IGBT is used as switching device in this system. The IGBT driving circuit uses the driving block M57962L produced by MITSUBISHI company in Japan. This drive block is a mix integrated circuit. Because of gathering the drive and over-current protecting circuit, it can satisfy the needs perfectly.

IV. EXPERIMENT RESULTS

According to the design described above, a 3 KW experimental prototype of shunt active power filter for three-phase four-wire system is developed. The experiment results are given in Fig. 6 and Fig. 7. The nonlinear load is composed of the inductance three-phase transistor rectifier bridge. Fig. 6 is the waveform of the supply current before using the active power filter. It is three-phase unbalanced and distorted current source. Fig. 7 is the waveform of the supply current after compensation, and it is three-phase balanced and sinusoidal current. This indicates that the proposed active power filter has a good performance and the design method is basically correct.

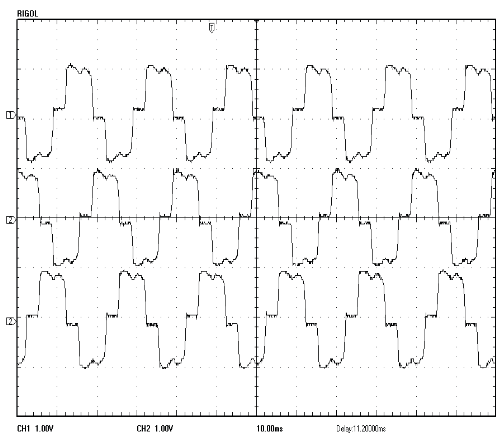

Fig. 6: Three-phase currents before compensation

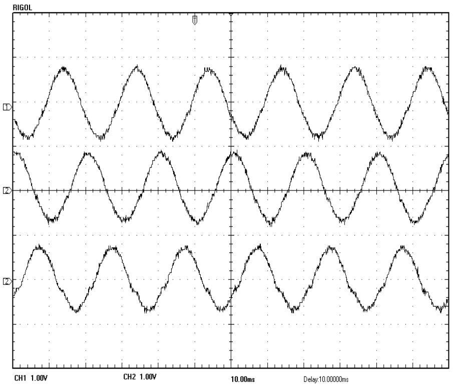

Fig. 7: Three-phase currents after compensation

V. CONCLUSION

This paper introduces a shunt active power filter using for three-phase four-wire system. It provides a real-time detection method of separating the neutral wire current. It presents the principles and structure of the filter. The design methods are given and a 3 KW shunt active power filter prototype is achieved. The experiment results are given to prove that the design method is correct and acquire excellent performances.

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