A SERIES ACTIVE POWER FILTER ADOPTING CONTROL APPROACH OF DETECTING LOAD VOLTAGE

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ABSTRACT — In this paper a new control approach of detecting load voltage is proposed. It can directly detect the ac side harmonic voltage of a voltage source load for the series APF to do dynamic compensation for harmonic voltages. In addition, the control methods of PWM inverter and its dc side voltage are discussed. According to these, a prototype of the series APF is manufactured and corresponding experiment studies are done.

1. INTRODUCTION

With the development of power electronic technology, the application of electronic appliances, such as a variety of power converters, switching model power supplies and UPS as well as electronic ballasts, is increasing day by day. The harmonic contamination they produce in power lines has given rise to widespread attention[1]. There is a large filter capacitor on the dc side of the rectifiers in these power electronic devices, so they intrinsically belong to voltage source loads (voltage type harmonic sources). Due to them, there is serious distortion in the input current waveshape on the ac side of the rectifiers, which makes a great number of harmonic currents pour into power lines, therefore serious harmonic pollution is brought in power lines. Because of this, there is need to study the approach to reduce the harmonic pollution produced by voltage source loads.

The harmonics generated by voltage source loads can effectively be suppressed by using series active power filters (APF)[1]. An series APF, whose power circuit is a three phase voltage source PWM inverter, is connected in series between ac source and a three phase diode bridge rectifier with a large filter capacitor (voltage source load) through three current transformers (CT), as shown in Fig. 1, so it is known as a series APF[2][3]. Its principle of operation is different from the shunt APF[4]. The series APF can be considered as a controlled voltage source. A compensating voltage can be produced by controlling it. The controlled voltage and the load or the source

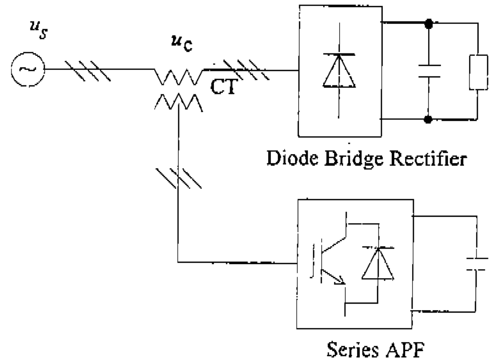


Fig. 1 System configuration of the series APF

harmonic voltage are equal in amplitude but opposite in phase, thereby cancels them and the input current of the load is changed into sinusoidal current or the input voltage of the load into sinusoidal voltage.

In this paper, a new control approach of detecting load voltage is proposed by analyzing the basic operation principle of a series APF. It can directly and instantaneously detect the ac side harmonic voltages of a voltage source load and thus doing dynamic compensation to the load. It is practically a development to the instantaneous reactive power theory. This paper simultaneously discusses the control methods of PWM inverter and its dc side voltage. On the basis of these, a prototype of a series active power filter is manufactured and corresponding experiment studies are done. The results demonstrate that when introducing the new control approach of detecting load voltage the stability and effectiveness of the series APF are good. The series APF presented can be used to suppress the harmonic voltage brought by the voltage source loads

2. CONTROL APPROACH OF DETECTING LOAD VOLTAGE

According to Fig. 1, the equivalent circuit of illustrating the basic operation principle of a series APF is shown in Fig. 2, where u_s denotes source voltage, i_s source current and Z_s source equivalence impedance, while u_{Lf} and u_{Lh} stand for the fundamental and the harmonic component of load voltage, and i_{sf} and i_{sh} represent the fundamental and the harmonic component of i_s. u_c the compensation voltage produced by the series APF. From Fig. 2, if

$$u_c = -u_{Lh} \tag{1}$$

then when there is no distortion in u_s, we have

$$\dot{I}_{sh} = \frac{-\dot{U}_c - \dot{U}_{Lh}}{Z_s} = 0 \tag{2}$$

Namely, there is no harmonic component in i_s. The ac side voltage u_l of the voltage source load is a sinusoidal wave. So, the aim of harmonic voltage compensation can be realized by the series APF.

From its operation principle, for the series APF to rapidly and accurately detect the harmonic voltages in the voltage source load and to get the reference voltage u_c^* is important to ensure good harmonic compensation effectiveness. The detecting approaches of harmonic voltage available now are mainly filtration method by the fixed filter (such as high-pass filter) and sampling digital calculation method on the basis of FFT[5][6]. However, there are some problems when using them. The former is difficult to select the circuit parameters because of the requirements of selectivity and phase, and exists in time lag and frequency drift, and its detecting precision is not high. The latter needs high precision analog to digital converters and its detecting velocity is slow, therefore its real-time specialties often can not meet the requirements of the series APF very well. Is there a better detecting approach for the harmonic voltage? It is one of the major work expounded in this paper.

A. Calculation of the Reference Voltage

Three phase load instantaneous voltages u_{Lu}, u_{Lv}, u_{Lw} and instantaneous currents i_{Lu}, i_{Lv}, i_{Lw} according to the instantaneous reactive power theory[1][2][7], can be transformed into two phase instantaneous voltages u_α, u_β and instantaneous currents i_α, i_β in the α-β orthogonal coordinates by 3-2 transformation, i. e. ,

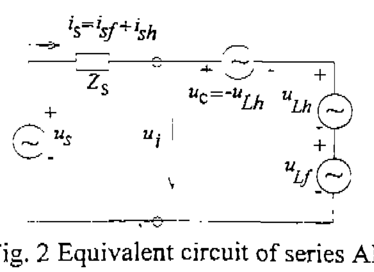


Fig. 2 Equivalent circuit of series APF

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_{Lu} \\ u_{Lv} \\ u_{Lwc} \end{bmatrix} = C_{32} \begin{bmatrix} u_{Lu} \\ u_{Lv} \\ u_{Lwc} \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} = C_{32} \begin{bmatrix} i_{Lu} \\ i_{Lv} \\ i_{Lw} \end{bmatrix} \tag{4}$$

where C_{32} is a coordinate transformation matrix from three-phase to two-phase. On the α-β plane, $\vec{u}$ can be considered to be composed of $\vec{u}_\alpha$ and $\vec{u}_\beta$, and $\vec{i}$ of $\vec{i}_\alpha$ and $\vec{i}_\beta$, *i. e.*,

$$\vec{u} = \vec{u}_\alpha + \vec{u}_\beta \qquad \vec{i} = \vec{i}_\alpha + \vec{i}_\beta \tag{5}$$

The instantaneous active and reactive power are

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} iu\cos\theta \\ iu\sin\theta \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \tag{6}$$

where i and u are the norm of vectors $\vec{i}$ and $\vec{u}$, respectively, and θ the angle between $\vec{i}$ and $\vec{u}$.

In terms of the instantaneous reactive power theory, when three phase voltages and currents are sinusoidal and symmetrical, p and q are exactly equal to the active and reactive power of three phase circuit in conventional power theory, respectively; when three phase voltages are sinusoidal and symmetrical but three currents asymmetrical or distorted, the dc components in p and q are corresponding to the positive sequence fundamental active and reactive components in three phase currents, while the ac components in p and q are corresponding to the harmonic or asymmetrical components in three phase currents. From this, it is deduced that when three phase currents are sinusoidal and symmetrical, but three voltages are asymmetrical or distorted, the dc components in p and q are corresponding to the positive sequence fundamental active and reactive components in three phase voltages, while the ac components in them are corresponding to the harmonic or asymmetrical components. An instantaneous detection approach of detecting load voltage can be inferred in the light of this thought.

Assume that u_p is a projection of $\vec{u}$ in the direction of $\vec{i}$ and u_q a projection of $\vec{u}$ in the vertical direction of $\vec{i}$. Equation (6) can again be represented as

$$\begin{bmatrix} p \\ q \end{bmatrix} = i \begin{bmatrix} u_p \\ u_q \end{bmatrix} = \begin{bmatrix} i_\alpha & i_\beta \\ -i_\beta & i_\alpha \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \tag{7}$$

Suppose three phase currents are symmetrical sinusoidal currents, then their expression formulas are

$$\begin{cases} i_{Lu} = I_m \sin\omega t \\ i_{Lv} = I_m \sin(\omega t - \frac{2\pi}{3}) \\ i_{Lw} = I_m \sin(\omega t + \frac{2\pi}{3}) \end{cases} \tag{8}$$

By 3-2 transformations,

$$i_\alpha = \sqrt{\frac{3}{2}} I_m \sin\omega t \qquad i_\beta = -\sqrt{\frac{3}{2}} I_m \cos\omega t \tag{9}$$

Equation (9) is substituted into (6), and (3) is simultaneously considered, then

$$\begin{aligned} i\begin{bmatrix} u_p \\ u_q \end{bmatrix} &= \sqrt{\frac{3}{2}} I_m \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} \\ &= \sqrt{\frac{3}{2}} I_m C_{pq} \begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \sqrt{\frac{3}{2}} I_m C_{pq} C_{32} \begin{bmatrix} u_{Lu} \\ u_{Lv} \\ u_{Lw} \end{bmatrix} \end{aligned} \tag{10}$$

It can be known that $i = \sqrt{\frac{3}{2}} I_m$ through (9), therefore

$$\begin{aligned} \begin{bmatrix} u_p \\ u_q \end{bmatrix} &= \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \\ &\times \begin{bmatrix} u_{Lu} \\ u_{Lv} \\ u_{Lw} \end{bmatrix} = C_{pq} C_{32} \begin{bmatrix} u_{Lu} \\ u_{Lv} \\ u_{Lw} \end{bmatrix} \end{aligned} \tag{11}$$

Granted that there is distortion in the load voltages. They can be spread out by using ***Fouries*** series, *i. e.*,

$$\begin{cases} u_{Lu} = \sum_{k=1}^{\infty} U_{km} \sin(k\omega t - \theta_k) \\ u_{Lv} = \sum_{k=1}^{\infty} U_{km} \sin[k(\omega t - \frac{2\pi}{3}) - \theta_k] \\ u_{Lw} = \sum_{k=1}^{\infty} U_{km} \sin[k(\omega t + \frac{2\pi}{3}) - \theta_k] \end{cases} \tag{12}$$

Substitution of (12) into (11) gives

$$\begin{bmatrix} u_p \\ u_q \end{bmatrix} = \sqrt{\frac{3}{2}} \sum_{k}^{\infty} U_{km} \begin{bmatrix} \pm\cos[(k \mp 1)\omega t - \theta_k] \\ \sin[(k \mp 1)\omega t - \theta_k] \end{bmatrix} \tag{13}$$

where the upper signs are used for the positive sequence components and the lower ones for the negative sequence components. Apparently, u_p and u_q in (12) contain both the dc and the ac components. If $\bar{u}_p$ and $\bar{u}_q$ express the dc components, respectively, then.

$$\begin{bmatrix} \bar{u}_p \\ \bar{u}_q \end{bmatrix} = \sqrt{\frac{3}{2}} U_{1m} \begin{bmatrix} \cos\theta_1 \\ -\sin\theta_1 \end{bmatrix} \tag{14}$$

They can easily be attained by low-pass filters. Now, substitute (14) into (11), and at the same time carry out the inverse transformations, then

$$\begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ \cos\omega t & \sin\omega t \end{bmatrix} \begin{bmatrix} \bar{u}_p \\ \bar{u}_q \end{bmatrix} = C_{pq}^{-1} \begin{bmatrix} \bar{u}_p \\ \bar{u}_q \end{bmatrix} \tag{15}$$

After undergo 2-3 transformations, we have

$$\begin{bmatrix} u_{Luf} \\ u_{Lvf} \\ u_{Lwf} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} = C_{23} \begin{bmatrix} u_{\alpha f} \\ u_{\beta f} \end{bmatrix} \tag{16}$$

where C_{23} is a coordinate transformation matrix from two-phase to three-phase. Substitute (15) and then (14) into (16), we finally obtain,

$$\begin{cases} u_{Luf} = U_{1m} \sin(\omega t - \theta_1) \\ u_{Lvf} = U_{1m} \sin(\omega t - \frac{2\pi}{3} - \theta_1) \\ u_{Lcf} = U_{1m} \sin(\omega t + \frac{2\pi}{3} - \theta_1) \end{cases} \tag{17}$$

If (17) is compared with (12), then it is made clear that u_{Luf}, u_{Lvf} and u_{Lwf} are exactly the fundamental voltages of u_{Lu}, u_{Lv} and u_{Lw}, respectively. The load harmonic voltage components are therefore obtained by

$$\begin{cases} u_{Luh} = u_{Lu} - u_{Luf} \\ u_{Lvh} = u_{Lv} - u_{Lvf} \\ u_{Lwh} = u_{Lw} - u_{Lwf} \end{cases} \tag{18}$$

By the above deduction the reference voltage u_c^* of the series APF can be got. Its principle block diagram is shown in Fig. 3, where LPF a low-pass filter, which can consist of second-order ***Bessel*** low-pass filter. By it the dc component $\bar{u}_p$ or $\bar{u}_q$ can be obtained. PLL is a phase lock-in loop, which can generates the standard sine and cosine signals that are synchronous with the source voltage u_s.

B. Control of PWM Inverter dc Side Voltage

When working, there is energy loss in APF to bring about the reduction in its dc side (capacitance) voltage U_d. U_d must keep constant to guarantee the normal work state of PWM inverter, so a feedback control link of U_d is introduced. If on the basis of the above control approach of detecting load voltage and a simple circuit is attached, shown in Fig. 3, then the control method of PWM inverter dc side voltage is obtained. In Fig. 3, the error ΔU_d got after the given value U_d^* is compared with the feedback value U_d first passes a PI regulator and then subtracted from $\bar{u}_p$. Thus, extra fundamental components Δu_{Luf}, Δu_{Lvf} and Δu_{Lwf} are added to the load harmonic voltages u_{Luh}, u_{Lvh} and u_{Lwh}. At the same time they are contained in the

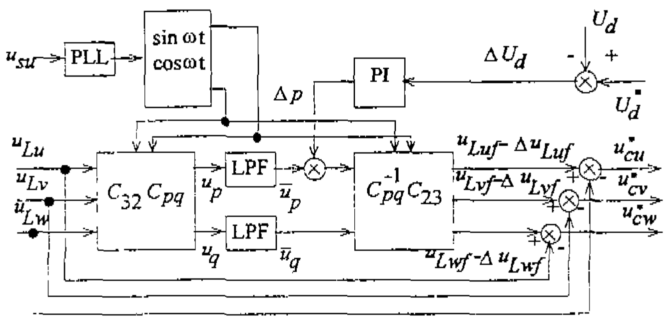


Fig. 3 Calculation circuit of reference harmonic voltages

reference voltage u_c^*. Finally, while PWM inverter is forming the demand harmonic voltage, the fundamental voltage is provided. The fundamental voltages interact on each other with the fundamental currents of source, then controlling the energy flow of PWM inverter to maintain the constant of the dc side voltage U_d.

C. Control of PWM Inverter

The voltage following PWM control method of time comparison is adopted in the series APF developed in this paper, to control PWM inverter to produce the required compensation voltage u_c. The control operation principle is shown in Fig. 4. When the series APF works, the reference voltage u_c^* is sent into a comparator and compared with u_c, then the output of the comparator controls the on-off of PWM inverter main circuit elements, and the purpose of real time tracking u_c^* is reached. In the method of the time comparison, the PWM signals do not change a time till surpassing a clock signal period or more. So the clock signal frequency restricts the highest frequency of elements operation. Thereby the circumstances that elements are damaged because of too high switching frequency can be avoided. Each phase in the control method only requires a comparator and a D flip-flop. The hardware circuits are very simple and easy to realization.

3. EXPERIMENTAL STUDIES

In this paper, adopting the control approach of detecting load voltage and the main circuit configuration of the series APF discussed above, we manufacture a prototype of three phase series APF. By it the experimental studies on compensating the three phase bridge rectifier there being a large filter capacitor on its dc side for harmonics are done. When the series APF operates, the clock frequency is selected as 20kHz. Thus, the highest frequency of elements will not exceed 10kHz.

The source current flowing in power lines and its spectrum before the series APF carries out harmonics compensation, obtained by a TDS340 storage oscilloscope, are shown in Fig. 5. After the series APF is used, the source current and its spectrum are shown in Fig. 6(a) and (b), respectively. It can be seen from Fig. 6 that the source current waveform got after the harmonic voltage is compensated approximates a sinusoidal wave, and its harmonic content decreases greatly. Through comparison, the main harmonic content before and after the series APF is used is given in Tab. 1. From it, total harmonic distortion (THD) and power factor (PF) before compensation are 70% and 0.821, respectively, while after compensation, THD and PF are changed into 3.9% and 0.999, respectively. Therefore, it can be known that the compensation performance is good when the series APF

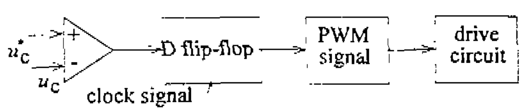
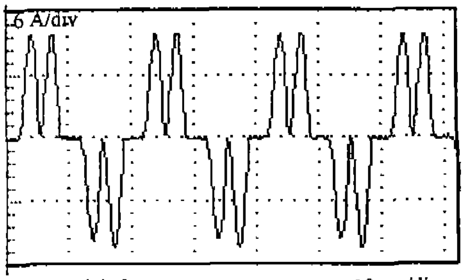
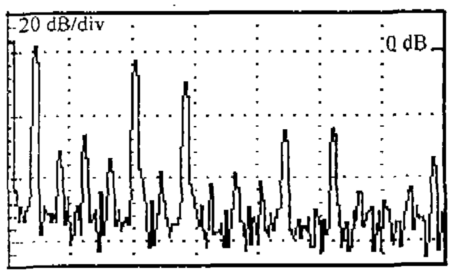


Fig. 4 Principle of generating PWM signal

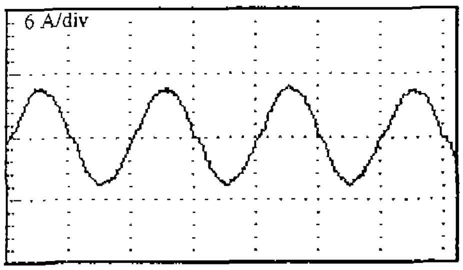


(a) Source current 10 ms/div

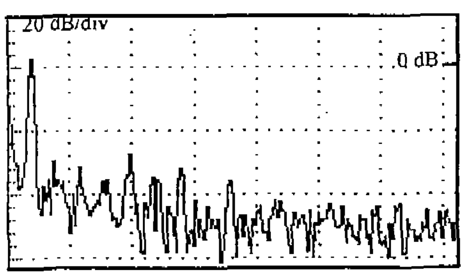


(b) Its spectrum 125 Hz/div

Fig. 5 Source current and its spectrum before compensation



(a) Source current 10 ms/div



(b) Its spectrum 125 Hz/div

Fig. 6 Source current and its spectrum after compensation

Tab. 1 Main harmonic content in source current before and after the series APF is used.

Order	1	2	3	4	5	6	7	8	11	13	16	17
(a)	1	0.018	0.037	0.015	0.632	0.013	0.288	0.018	0.042	0.057	0.020	0.022
(b)	1	0.020	0.012	0.000	0.028	0.000	0.015	0.000	0.000	0.000	0.000	0.000

(a) Before compensation. (b) After compensation.

developed in this paper is utilized.

4. CONCLUSIONS

There are various different properties of loads (harmonic sources) in power lines. Therefore, different active power filters of possessing different harmonic suppressive mechanism and configuration should be investigated. The series APF is suitable for compensating the harmonics produced by voltage source loads. In this paper, through analyzing the operation principle of the series APF, a new control approach of detecting load voltage is proposed and its circuit realization configuration is given. The new control approach extends the instantaneous reactive power theory and can instantaneously detect out the load harmonic voltage. It is simple and straightforward, and easy to realize. In addition, the control methods of PWM inverter and its dc side voltage are discussed in this paper. On the basis of these, a prototype of three phase series APF is manufactured by six MOSFETs and other elements. Corresponding experimental studies are done. The results show that the series APF adopting the control approach of detecting load voltage, when compensating voltage source loads, its stability is high and its harmonics compensation performance is good.

5. ACKNOWLEDGMENTS

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