Phase delay solution based on instantaneous reactive power theory

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Abstract. According to the theoretical detection method of instantaneous reactive power, the paper proposes a harmonic current detection method based on the combination of synchronous rotating coordinate system and PI control. This method adds PI adjustment after the filtering link to accurately track the current amplitude, realizes zero error control, and performs phase compensation on the rotating coordinate system to compensate the fixed phase delay time of the filter, so as to achieve the accuracy of the harmonic detection link. The analysis of the experimental results shows that the improved harmonic detection method is equally effective under the three-phase symmetrical load and three-phase asymmetrical load. Under three-phase symmetrical load conditions, the improved harmonic detection method reduces the THD of the grid current by 0.72% compared with the original method. Under three-phase asymmetrical load conditions, the improved method reduces the THD of the grid current by 0.11% compared to the original method.

1. Introduction

With the development of industrial technology, the nonlinear load in the power system has increased greatly, causing serious pollution to the grid, resulting in harmonic and reactive power problems, which not only reduces the quality of customers’ electricity consumption, but also affects the stability of the system.

Parallel active power filter (APF) is a power electronic device that compensates for power system harmonics and reactive power. Its core is to compensate for harmonics in real time. The key factor that determines the filtering performance is the detection and control method of harmonic currents. But the delay in the actual digital control system is unavoidable, and the active filter still has a certain response time when the current changes suddenly, so the active filter cannot achieve real-time non-deviation compensation in the true sense. The existence of time delay may even amplify the pollution of harmonics and seriously affect the harmonic compensation performance of the active filter. Therefore, the realization of parallel APF for real-time and accurate compensation of rapidly changing harmonic currents is conducive to improving the stability and dynamic performance of the system, and is helpful to the subsequent corresponding research of the system.

In the research on the reference current method, Literature [1] aiming at the special working conditions of system interharmonics, an improved sliding window discrete Fourier transform (DFT) harmonic current detection method is proposed here, which reduces the calculation amount of the digital processor and the space used by registers, has a higher detection accuracy. Literature [2] proposes a full-current harmonic detection method based on a sinusoidal amplitude integrator (SAI),
which uses the positive sequence fundamental wave extraction structure of SAI to replace the LPF in the original detection method to extract the positive sequence fundamental. The wave current is calculated to obtain the harmonic command current to compensate the power grid. Literature [3] proposed an improved adaptive harmonic detection algorithm based on the load current characteristics combined with the least squared mean error algorithm (LMS) to ensure that the APF has a better steady-state accuracy in the steady state, and a faster response speed in the event of a sudden change. Literature [4] centralized current loop is optimized with amplitude and phase correction based on comprehensive analysis of the single PI current loop and selective harmonic detection under multiple rotating reference frame. In order to ensure the accuracy of the harmonic current injected into the power capacitor, Literature [5] proposes a harmonic current frequency division detection method, which applies the harmonic current detection method based on instantaneous reactive power theory and d-q transformation to a single-phase harmonic current injection system. This method can accurately track the current amplitude and calculate the compensation angle of the system. The above research content only covers the results of 2015-2020, and mainly focuses on the research of harmonic detection methods. However, during the experiment, only the three-phase symmetrical load condition was analyzed, and the robustness of the algorithm under unbalanced power supply voltage was not proposed. And the explanation of the problems under different conditions and scenarios is not detailed enough.

Harmonic detection is an important part of the entire system. An accurate reference current is the prerequisite for achieving APF accurate compensation. According to the theory of instantaneous reactive power detection method, the paper proposes a harmonic current detection method based on the combination of synchronous rotating coordinate system and PI control. Through the phase compensation of the synchronous rotating coordinate system and the PI control of the filtered current, this method reduces the dependence of the measurement accuracy of the filter link on the parameters, compensates the fixed phase delay time of the filter, and realizes the accuracy of the harmonic detection link. In addition, the paper conducts experimental analysis under the conditions of three-phase symmetrical load and three-phase asymmetrical load.

2. System structure and mathematical model

The main circuit structure of the three-level APF applied to the three-phase three-wire system is shown in Figure 1. The three-phase grid voltage is represented by $e_a$, $e_b$, and $e_c$, and the three-phase compensation current output by the APF is represented by $i_a$, $i_b$, and $i_c$. The output voltage of each relative N point is represented by $u_{aN}$, $u_{bN}$, and $u_{cN}$, the DC side capacitance is represented by $C_1$, $C_2$, the DC side voltage is represented by $V_{dc}$, the two DC side capacitor currents are $i_{dc1}$, $i_{dc2}$, and the DC side midpoint current, expressed by $i_o$. L and R is output filter inductance and equivalent resistance respectively [6].

![Figure 1. Main circuit structure of three-level parallel APF.](image)
The working principle of the parallel active power filter is: the voltage and current of the compensation object are detected by the voltage and current transformers, and the command current signal is obtained by the command current calculation circuit, and then the compensation current is generated by the compensation current generation circuit and injected into the grid to eliminate harmonics on the grid side. Theoretically, when the actual compensation current and the harmonics and reactive components in the load current are equal in magnitude and opposite in direction, they can be completely offset, so that the grid current reaches an ideal sinusoidal state [6].

According to the main circuit structure of APF shown in Figure 1, and ignoring the branch resistance and inductance, the mathematical model of the system in the abc coordinate system can be deduced as:

\[
\begin{align*}
\dot{u}_{AN} &= e_a + R_1 i_a + L_1 \frac{di_a}{dt} \\
\dot{u}_{BN} &= e_b + R_1 i_b + L_1 \frac{di_b}{dt} \\
\dot{u}_{CN} &= e_c + R_1 i_c + L_1 \frac{di_c}{dt}
\end{align*}
\]

(1)

In order to perform digital control, the continuous differential equation shown in equation (1) is discretized to obtain the discrete mathematical model of APF:

\[
\begin{align*}
\dot{u}_{AN}(k) &= e_a(k) + R_1 i_a(k) + \frac{L_1}{T_s} [i_{ca}(k+1) - i_{ca}(k)] \\
\dot{u}_{BN}(k) &= e_b(k) + R_1 i_b(k) + \frac{L_1}{T_s} [i_{cb}(k+1) - i_{cb}(k)] \\
\dot{u}_{CN}(k) &= e_c(k) + R_1 i_c(k) + \frac{L_1}{T_s} [i_{cc}(k+1) - i_{ca}(k)]
\end{align*}
\]

(2)

Where: \(T_s\) is the sampling period of the discrete system (also the control period of APF); \(k\) and \((k+1)\) represent the current beat and the next beat; \(i_a(k), i_b(k), i_c(k)\) are APF output current values of the current beat, \(i_a(k+1), i_b(k+1), i_c(k+1)\) are the APF output current values of the next shot, which can be replaced by expected values. Since the power supply voltages \(e_a(k), e_b(k), e_c(k)\) are measured values, the inverter output reference voltage can be calculated as long as the APF output current reference value can be obtained. The calculation formula of the reference voltage is shown in equation (3):

\[
\begin{align*}
\dot{u}_{AN}(k) &= e_a(k) + R_1 i_a(k) + \frac{L_1}{T_s} [i_{ca}^*(k+1) - i_{ca}(k)] \\
\dot{u}_{BN}(k) &= e_b(k) + R_1 i_b(k) + \frac{L_1}{T_s} [i_{cb}^*(k+1) - i_{cb}(k)] \\
\dot{u}_{CN}(k) &= e_c(k) + R_1 i_c(k) + \frac{L_1}{T_s} [i_{cc}^*(k+1) - i_{ca}(k)]
\end{align*}
\]

(3)

3. Research and analysis of harmonic detection methods

3.1. Detection method based on instantaneous reactive power theory

The harmonic current command detection algorithm is based on instantaneous reactive power theory which mainly includes p-q method and ip-iq method. The p-q method is to sample the current on the non-linear load side or the grid-side current and the grid-side three-phase voltage, and transform the sampled three-phase current and voltage signals to the \(\alpha\beta\) coordinate system, and multiply the two to obtain the active power p and reactive power q. At this time, the coordinates of p and q are transformed to the rotating coordinate system, and the fundamental active power and fundamental reactive power can be obtained through the low-pass filter (LPF). Then the system fundamental wave current is obtained by transforming the rotating coordinate system to the three-phase static coordinate system, and finally the harmonic current command can be obtained by subtracting the fundamental wave current of the system from the harmonic source current signal obtained by sampling [8]. The principle diagram of the p-q method is shown in Figure 2:
The p-q method greatly improves the shortcomings of the previous methods with poor real-time performance, and at the same time ensure high detection accuracy. The disadvantage is that this method is less effective in the face of asymmetric grid voltage. The ip-iq method is an improvement of the p-q method. It can still guarantee its high precision and good real-time characteristics in the case of asymmetrical grid voltage, and it can work normally even in the case of grid voltage distortion. The schematic diagram of ip-iq is shown in Figure 3:

3.2. Improved ip-iq harmonic current detection method

In the instantaneous reactive power theoretical detection method, what kind of filtering method the low-pass filter adopts, and the selection of the cut-off frequency will affect the detection accuracy and the speed of convergence; in addition, the signal passes through the filter with a fixed phase delay time. To solve the above problems, make the following adjustments:

1. Add PI regulator after low-pass filter

Assuming that the low-pass filter has been selected, there are two better ways to improve the accuracy of the detection method on this basis: one is to make the simulation of the coefficient of the device as accurate as possible. This method has higher requirements for components, so it is accompanied by a substantial increase in price and poor cost performance; the second is to improve the method to reduce the dependence of measurement accuracy on parameters. Therefore, based on the traditional detection method, the detection current first undergoes coordinate transformation, and then filtered through a low-pass filter to obtain a DC signal, which is then sent to the PI regulator for proportional integral calculation and then sent to the inverse transformation part. In this way, the sensitivity requirements for the parameters of the previous link of the PI regulator are reduced, and the impact of disturbances on the stability of the system is reduced. The sensitivity of the main parameters of the system to the filtering detection accuracy is significantly reduced, reducing the dependence of measurement accuracy on parameters, and improving the detection accuracy of wave and reactive current [9]. The principle block diagram after adding PI adjustment after low-pass filter is shown in Figure 4:
(2) Phase compensation based on synchronous rotating coordinate system

The core idea of the delay compensation method based on the SRF phase shift control is to obtain the phase compensation of the rotation vector on the SRF through the phase control of the SRF [10]. The specific principle is shown in Figure 5:

Suppose the synchronous rotating harmonic current phasor $I_n$ on the SRF is

$$I_n = I_n \angle \varphi_n$$

In the formula, $I_n$ and $\varphi_n$ are the amplitude and initial phase of the nth harmonic current respectively (the fundamental wave current is regarded as the harmonic component of order 1), as shown in Figure 5(a).

When the phase of the control SRF moves forward by a phase angle $\Delta \theta$ in the rotation direction, as shown in Figure 5(b), the phase of the phasor $I_n$ relative to the stationary coordinate system also moves forward by $\Delta \theta$, leading the phase can realize the phase compensation for the current control delay. The specific implementation process is as follows:

The arbitrary load current of the three-phase three-wire system is expressed as

$$\begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} = \begin{bmatrix} I_n \sin (nwt + \varphi_n) \\ I_n \sin (nwt + \varphi_n - \frac{2\pi}{3}) \\ I_n \sin (nwt + \varphi_n + \frac{2\pi}{3}) \end{bmatrix}$$

Among them, $n$ is the harmonic order ($n \geq 1$, the fundamental wave current is regarded as the harmonic component of order 1), $I_n$, $\varphi_n$ are the amplitude and initial phase of the nth harmonic current respectively.

In the harmonic detection link, a low-pass filter is used to filter out the AC component on the d-q axis, and then the DC components $I_d$ and $I_q$ of the fundamental wave can be detected. Advance the phase shift of the SRF, the phase shift angle is $\Delta \theta$, and the transformation formula of the nth ($n \geq 1$) SRF to the abc coordinate system after the phase shift is defined as
Use \( C_{dqn-abc} \) to transform \( I_d \) and \( I_q \) into a three-phase stationary coordinate system, and get

\[
\begin{align*}
C_{dqn-abc} &= \begin{bmatrix}
\sin(n\omega t + \Delta \theta) - \cos(n\omega t + \Delta \theta) \\
\sin(n\omega t - \frac{2}{3}\pi + \Delta \theta) - \cos(n\omega t - \frac{2}{3}\pi + \Delta \theta) \\
\sin(n\omega t + \frac{2}{3}\pi + \Delta \theta) - \cos(n\omega t + \frac{2}{3}\pi + \Delta \theta)
\end{bmatrix} \\
I_n &= \begin{bmatrix}
I_{an} \\
I_{bn} \\
I_{cn}
\end{bmatrix}
\end{align*}
\]

Use \( C_{dqn-abc} \) to transform \( I_d \) and \( I_q \) into a three-phase stationary coordinate system, and get

\[
I_n = \begin{bmatrix}
I_n \sin(m\omega t + \varphi_n + \Delta \theta) \\
I_n \sin(m\omega t + \varphi_n + \Delta \theta - \frac{2}{3}\pi) \\
I_n \sin(m\omega t + \varphi_n + \Delta \theta + \frac{2}{3}\pi)
\end{bmatrix}
\]

Compared with equation (5), the three-phase n-th harmonic current in equation (7) leads the phase angle \( \Delta \theta \), that the phase is compensated. There is a relationship \( \Delta \theta = n\omega \cdot \Delta T \), where \( \Delta T \) corresponds to the delay time, and \( n \) is the harmonic order \( (n \geq 1) \).

The improved harmonic detection link is shown in Figure 6:

![Figure 6. Improved harmonic detection block diagram.](image)

4. Simulation results and analysis

In order to verify the correctness of the proposed detection method, Matlab/Simulink is used to simulate the system. The grid-side phase voltage adopts 220V sine wave, adopts a diode rectifier bridge circuit, and uses resistance series inductance as a nonlinear load to generate harmonics and reactive currents, and adopts SVPWM to track the reference current. The simulation is analyzed under the conditions of three-phase symmetrical load and three-phase asymmetrical load respectively.

(1) Simulation analysis under three-phase symmetrical load

The A-phase load current waveform and frequency spectrum analysis are shown in Figure 7. It can be seen from Figure 7 that after the grid is connected to a non-linear load, the current waveform is distorted. Through the analysis of the current waveform, in Figure 8, the total distortion rate of current harmonics is 12.91%, and 5, 7, 11, 13, 17, and 19 harmonics are more significant.

![Figure 7. The A-phase load current waveform and spectrum analysis.](image)

After connecting the APF to the system in parallel, the results of the traditional harmonic detection method and the improved harmonic detection method used in the system are simulated and analyzed respectively, and the FFT analysis diagram of the grid current is obtained. Figure 8 is the traditional
harmonic detection method. experimental results, Figure 9 is the experimental results of the improved harmonic detection method:

![Figure 8. Experimental results of traditional detection methods.](image1)

![Figure 9. Experimental results of improved detection methods.](image2)

Comparing Figure 7 to Figure 9, it can be found that both detection methods effectively reduce the harmonic content of the grid current. Among them, the traditional harmonic detection method reduces the THD of the grid current from 12.91% to 1.13%. The improved harmonic detection method reduces the THD of the grid current from 12.91% to 0.41%, which reduces the THD by 0.72% compared with the traditional method, and significantly improves the compensation accuracy of the harmonic current.

The tracking effect of the system is shown in Figure 10:

![Figure 10. System tracking effect.](image3)

It can be seen from Figure 10 that APF can accurately output according to the reference current to achieve real-time tracking control.

After the APF is connected to the grid in parallel, the grid current waveform is shown in Figure 11: the grid current is sine wave, and the improved harmonic detection method in this article is very effective.

![Figure 11. Grid current after parallel APF.](image4)

(2) Simulation analysis under three-phase asymmetrical load

Asymmetric loads often exist in the power grid. The three-phase asymmetric nonlinear load in the simulation is a single-phase diode rectifier circuit connected between the A phase and the B phase, and the resistance and inductance of the load are the same as the three-phase rectifier. The simulation results of load current and C-phase spectrum analysis are shown in Figure 12:
Through the FFT spectrum analysis of the C-phase current, it can be seen that the harmonic distortion rate of the current before compensation is 9.70%, which seriously exceeds the allowed harmonic standard in my country.

After connecting the APF to the system in parallel, the results of the traditional harmonic detection method and the improved harmonic detection method used in the system are simulated and analyzed respectively, and the FFT analysis diagram of the C-phase grid current is obtained. Figure 13 is the traditional harmonic detection method experimental results, Figure 14 is the experimental results of the improved harmonic detection method:

Comparing Figure 12 to Figure 14, it can be found that both detection methods effectively reduce the harmonic content of the grid current. Among them, the traditional harmonic detection method reduces the THD of the grid current from 9.70% to 0.96%. The improved harmonic detection method reduces the THD of the grid current from 9.70% to 0.85%, which reduces the THD by 0.11% compared with the traditional method. It can be seen that the improved detection method is also suitable for three-phase asymmetric load conditions.

5. Conclusions

Experimental analysis shows that, on the basis of the original ip-iq harmonic current detection method, adding PI adjustment after the filtering link and phase compensation to the rotating coordinate system can significantly improve the compensation accuracy of harmonic currents and inhibit the flow of harmonic currents into the grid. In the case of a three-phase symmetrical load, the improved method reduces the THD of the grid current by 0.72% compared with the original method. In the case of a three-phase asymmetric load, the improved method reduces the THD of the grid current compared to the original method 0.11%.
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