Research on APF Improved Control Strategy Under Three-phase Voltage Distortion

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Abstract. At present, the most commonly used harmonic current detection algorithms are the p-q algorithm and the i_p-i_q algorithm based on the instantaneous reactive power theory. The premise of using the above algorithms is that the three-phase voltage is the ideal sinusoidal voltage. However, harmonic pollution distorts the voltage of the power grid to different degrees, which will affect the detection accuracy and compensation effect of APF. This paper presents a current detection algorithm based on positive sequence fundamental wave extractor, which can avoid the detection of positive sequence fundamental wave voltage of power grid, and can effectively avoid the shortcomings of p-q algorithm and i_p-i_q algorithm without using PLL, complex coordinate transformation and low-pass filter. In the current control algorithm, according to the characteristic that the gain of the generalized integrator is infinite when resonance occurs, the sinusoidal and cosine instructions can be tracked without static difference, this paper which is based on the generalized integrator adaptively adjusts the coefficients of the generalized integrator to improve the robustness of the current controller. Finally, the simulation model is established by MATLAB, and the simulation results show that the improved harmonic current detection algorithm and control algorithm are advanced and effective.

1. Introduction
Electric energy is an indispensable energy for production and life, but harmonic sources such as non-linear loads, power electronic equipment, various AC/DC motors, and smelting furnaces all generate a certain amount of harmonics, causing distortion of the grid voltage and current. When harmonics enter the power system, it will have a great impact on the power quality of the power system. The electrical equipment connected to the power grid will not work properly. In severe cases,
it will cause damage to the equipment or irreversible failure. Therefore, research and Improving power quality is of great significance.

In China, the more common method of suppressing harmonics is to use active power filter. The active power filter is based on digital signal and power electronic control. It can detect the current of the power system and compensate the harmonics. The output characteristics of the active power filter are independent of the parameters of the power grid, and are not affected by environmental factors. It can suppress and compensate the harmonics of different frequencies in the system, and it will not generate resonance. It has become a hot spot in today's research, and it is also the development trend of filters. The active power filter is mainly composed of two parts: a harmonic current detecting circuit and a compensation current generating circuit. The function of the harmonic current detecting circuit is to detect the harmonic current component in the load current. The function of the compensation current generating circuit is to generate a corresponding compensation current according to the harmonic current component detected by the harmonic current detecting circuit, which is composed of the main circuit, the compensation current control circuit and the drive isolation circuit [1].

This paper first introduces the traditional harmonic current detection and control algorithms. According to the shortcomings of the traditional algorithms, the improved detection and control algorithms of active power filter are proposed. Finally, the simulation model is established by MATLAB, and the simulation results show that the improved harmonic current detection algorithm and control algorithm are advanced and effective.

2. Traditional current detection and control algorithm

2.1. Traditional current detection algorithm

The high accuracy and real-time harmonic detection algorithm is the premise of high performance compensation of APF. So far, many harmonic current detection algorithms have appeared in engineering applications. The most widely used ones are the $p$-$q$ algorithm and the $i_r$-$i_q$ algorithm based on the instantaneous reactive power theory [2, 3]. The basic principle of the $p$-$q$ algorithm is shown in figure 1.

![Figure 1. Basic block diagram of $p$-$q$ harmonic current detection algorithm](image)

The $p$-$q$ harmonic current detection algorithm converts the three-phase voltage and the three-phase current in the $abc$ stationary coordinate system into the $\alpha$-$\beta$ two-phase stationary coordinate system by coordinate transformation, and calculates the instantaneous active power $p$ and the instantaneous reactive power $q$. The $p$ and $q$ pass the low-pass filter (LPF) and the inverse coordinate transformation
obtaining the three-phase current fundamental component, and then the three-phase current fundamental component is subtracted from the grid current, and finally the harmonic current component to be detected is obtained. The $p$-$q$ detection algorithm has good real-time performance in the three-phase balance system, and can quickly detect harmonic current. However, when the grid voltage waveform is distorted, its detection error increases, resulting in weaker compensation capability.

The $i_p$-$i_q$ harmonic current detection algorithm is a simpler method based on the optimization of the $p$-$q$ algorithm. The basic principle is shown in figure 2.

![Figure 2. Basic block diagram of $i_p$-$i_q$ harmonic current detection algorithm](image)

It can be seen from the above analysis that the $p$-$q$ detection algorithm can accurately detect the harmonic current only when the three-phase voltage is symmetrical and without distortion, and the $i_p$-$i_q$ detection algorithm can detect the positive fundamental component of the current in the case of voltage asymmetry and distortion, but there is a certain error in the positive fundamental component of the current detected under asymmetric conditions. The above two current detection methods based on the instantaneous reactive power theory have their own shortcomings, which are only applicable to the grid operation mode under certain working conditions. For grid operating modes under other working...
conditions, the harmonic current cannot be detected very well. In turn, it affects the compensation effect of harmonic current.

2.2. Traditional current control algorithm

The APF uses the detected harmonic current as a command signal to generate a current opposite to the compensated harmonic current, thereby eliminating harmonic currents in the system. Since the waveform of the compensation current is opposite to the harmonic current, the control requirement of the compensation current is high, and the harmonic current must be accurately and real-timely tracked, so that the ideal compensation effect can be achieved. At present, there are several commonly used control algorithm: hysteresis current comparison control algorithm, deadbeat control algorithm, repetitive control algorithm, and sliding mode control algorithm. The hysteresis current comparison control algorithm has a large switching frequency range, a fast current change, and a poor real-time control of the controlled quantity. The deadbeat control algorithm has complicated calculation, large time cost and weak parameter adaptability. The repetitive control algorithm has a simple structure and is easy to implement. The control algorithm is currently widely used, but it also has problems. The repetitive control algorithm based on the internal model principle must meet the stability conditions of the internal model when designing, and any carelessness will cause the output to be in a divergent state that cannot converge. The shortcoming of sliding mode control algorithm is that the compensation accuracy is low, and the discontinuous switching characteristics of the sliding mode control are easy to cause the control system to vibrate, which may activate the high frequency signal in the control system and may even make the system unstable [4-8].

3. Traditional current detection and control algorithm

3.1. Current detection algorithm based on positive sequence fundamental wave extractor

Aiming at the shortcomings of traditional harmonic current detection algorithm, an improved harmonic current detection algorithm based on positive sequence fundamental wave extractor is proposed [9,10]. This algorithm can effectively avoid the detection of the positive sequence fundamental voltage of the grid, and does not use voltage phase-locked loops, complex coordinate transformations and low-pass filters.

3.1.1. Implementation of positive sequence fundamental wave extractor. For the sinusoidal signal $e(t) = A \sin(\omega t + \phi)$, the amplitude-integrated signal is similar to the DC signal, and is $y(t) = A \sin(\omega t + \phi) t$. When $e(t)$ is delayed by $90^\circ$, it becomes the signal $x(t) = A \cos(\omega t + \phi)$. By performing a Laplace transform on the three signals, you can obtain:

$$E(s) = \frac{A_0 \omega \cos \phi}{s^2 + \omega_1^2} + \frac{A \sin \phi}{s^2}$$  \hspace{1cm} (1)

$$X(s) = -\frac{A_0 \sin \phi}{s^2 + \omega_1^2} + \frac{A \cos \phi}{s^2 + \omega_1^2}$$  \hspace{1cm} (2)
\[ Y(s) = \left( \frac{A_0 \cos \phi}{s^2 + \omega_0^2} + \frac{A \sin \phi}{s^2 + \omega_0^2} \right) \times \frac{s}{s^2 + \omega_0^2} + \left( -\frac{A_0 \sin \phi}{s^2 + \omega_0^2} + \frac{A \cos \phi}{s^2 + \omega_0^2} \right) \times \frac{\omega_0^2}{s^2 + \omega_0^2} \]  

(3)

This can be obtained:

\[ Y(s) = \frac{s}{s^2 + \omega_0^2} E(s) + \frac{\omega_0^2}{s^2 + \omega_0^2} X(s) \]  

(4)

The basic principle of the positive sequence fundamental wave extractor is to convert the input signal source into the expression (4) by Laplace transform. When the input signal source contains other harmonic components in addition to the fundamental component, the amplitude-integrated signal of the fundamental frequency sinusoidal signal can be obtained by the operation of the expression (4), so the operation of this expression has frequency selectivity [11].

By expression (4), we can get a brief block diagram of the \( \alpha-\beta \) coordinate system, and it is shown in figure 3.

![Figure 3](image-url)  
Figure 3. Block diagram of the \( \alpha-\beta \) coordinate system

Since for the positive sequence, the \( \alpha \)-axis leads the \( \beta \)-axis by 90°, the block diagram of the positive-sequence system can be obtained in figure 4.

![Figure 4](image-url)  
Figure 4. Block diagram of the positive sequence system

The block diagram of the positive sequence fundamental wave extractor can be obtained in figure 5, and in the figure, \( K \) is the proportional coefficient.
Since the positive-sequence fundamental wave extractor is insensitive to the frequency deviation of the system, the positive-sequence fundamental signal can be extracted efficiently. According to the principle and applicability of the positive-sequence fundamental wave extractor, this paper applies it to the current detection of APF, which can improve the harmonic current compensation effect under voltage distortion conditions.

3.1.2. Harmonic current detection based on positive sequence fundamental wave extractor. The positive sequence fundamental wave extractor can avoid the influence of grid voltage distortion, accurately extract the positive sequence fundamental current component of the system, and does not need to perform multiple coordinate transformations. It is fast, accurate and has high real-time performance, and has great application prospects. The specific process of the method is as follows: Firstly, the sampled three-phase current signal is subjected to $abc \rightarrow \alpha \beta$ coordinate transformation, and the two-phase current signal obtained by the transformation is used as an input signal of the positive-sequence fundamental wave extractor, and the output signal is an ideal two-phase positive-sequence fundamental current signal. Then the two-phase positive-sequence fundamental current signal is inversely transformed, and the reference value of the positive-sequence fundamental current in the three-phase coordinate system can be obtained. Finally, the positive-sequence fundamental reference current is subtracted from the original three-phase current to obtain the desired harmonic current reference value. As shown in figure 6:

![Block diagram of the positive sequence fundamental wave extractor](image1)

**Figure 5.** Block diagram of the positive sequence fundamental wave extractor

**Figure 6.** Improved harmonic current detection algorithm schematic
3.2 Current Control Algorithm Based on Generalized Integral

The principle of generalized integral control is that the gain is infinite when resonance occurs, and the sinusoidal and cosine command can be tracked without static difference. Based on the generalized integrator, the coefficients of the generalized integrator are adaptively adjusted, thereby improving the robustness of the current controller [12,13]. Under normal circumstances, in order to achieve the tracking of the current reference signal without static difference, multiple integrators of different frequencies are required to be connected in parallel. Considering the actual situation, the APF only needs to compensate for the finite harmonics. For example, a three-phase rectifier bridge generates only \( 6n \pm 1 \) harmonics. When the filter compensates for the 5th, 7th, 11th, 13th, 17th and 19th harmonics, the current of the system is close to a sinusoidal waveform, so only 6 integrals are needed. The integrals are connected in parallel and then connected to the proportional controller for good current tracking control. The transfer function of the generalized integrator can be designed as follows:

\[
u_c(s) = i_{ih}(s)(K_p + \sum_{h=5,7,11,13,17,19} \frac{K_{i,h}s}{s^2 + (h\omega_0)^2})
\]

(5)

Its control block diagram is expressed in figure 7:

![Control block diagram of generalized integrator](image)

**Figure 7.** Control block diagram of generalized integrator

The proportional link is used to amplify the system deviation \( a \). When the deviation of the system is large, the proportional increase of the proportional coefficient can obtain a relatively fast response speed. When the system deviation is small, the proportional coefficient can be appropriately reduced, which can effectively prevent system oscillation caused by overshoot.

The main purpose of the integral link is to eliminate the steady-state static difference of the power system. First, the generated harmonic deviation signal is integrated, so that there will be a certain hysteresis for the control system. If the integral coefficient is too large, the overshoot of the system will increase, which will cause the system to oscillate. Therefore, it is necessary to limit amplitude of the integral coefficient. The setting rule of the proportional integral control coefficient can be expressed by the following formula:

\[
K_p = \begin{cases} 
\alpha K_p & |e| > e_{\text{max}}, \alpha > 1 \\
\beta K_p & |e| < e_{\text{min}}, 0 < \beta < 1 
\end{cases}
\]

(6)

\[
K_{i,h} = \begin{cases} 
\gamma K_{i,h} & |y| > y_{\text{min}}, \gamma > 0, \gamma < 1 \\
\beta K_{i,h} & |y_h| < y_{h \text{ min}} 
\end{cases}
\]

(7)
4. Simulation analysis
In this paper, MATLAB is used for modeling and simulation to verify the reliability of the improved algorithm. According to the voltage distortion limit specified in GB/T14549-93 Power Quality Utility Grid Harmonics, the power harmonics in the model are designed, and the simulation models of traditional algorithm and improved algorithm are established, and the simulation analysis is carried out under the conditions of voltage distortion and voltage mutation.

(1) Voltage distortion rate exceeds 6%
   The grid voltage waveform is shown in figure 8. The voltage before 0.1s is the ideal voltage. The harmonic is added at 0.1s, and the voltage distortion rate is 6.8%. Under the action of nonlinear load, the current on the load side is shown in figure 9.

   ![Figure 8. System voltage waveform](image1)
   ![Figure 9. Load current waveform](image2)

   The current waveform after compensation by the traditional algorithm and FFT analysis are shown in figures 10 and 11. The current waveform after compensation by the improved algorithm and FFT analysis are shown in figures 12 and 13.

   ![Figure 10. Current waveform after compensation by traditional algorithm](image3)
   ![Figure 11. Current FFT Analysis Chart after Compensation by traditional algorithm](image4)
   ![Figure 12. Current waveform after compensation by improved algorithm](image5)
   ![Figure 13. Current FFT Analysis Chart after Compensation by improved algorithm](image6)
(2) Voltage mutation
The voltage waveform of the grid is shown in figure 14. The voltage before 0.1s is the ideal voltage, and the voltage mutation is added at 0.1s. Under the nonlinear load, the current on the load side is shown in figure 15.

Figure 14. System voltage waveform
Figure 15. Load current waveform

The current waveform after compensation by the traditional algorithm and FFT analysis are shown in figures 16 and 17. The current waveform after compensation by the improved algorithm and FFT analysis are shown in figures 18 and 19.

Figure 16. Current waveform after compensation by traditional algorithm
Figure 17. Current FFT Analysis Chart after Compensation by traditional algorithm
Figure 18. Current waveform after compensation by improved algorithm
Figure 19. Current FFT Analysis Chart after Compensation by improved algorithm

It can be seen from the above simulation waveform that the conventional algorithm cannot effectively compensate the harmonic current to improve the power quality of the power system regardless of voltage distortion or voltage mutation, and the effect of filtering the harmonic current is not achieved. In the case of voltage distortion, the distortion rate after current compensation is 0.9%. Under the condition of voltage mutation, the distortion rate after current compensation is 1.26%, and
the compensation effect is remarkable. It shows that the improved control algorithm has a very good compensation effect on the grid whose voltage changes.

5. Conclusions
Aiming at the shortcomings of $p-q$ algorithm and $i_p-i_q$ algorithm based on instantaneous reactive power theory and the problems of traditional harmonic current control algorithm, the current detection algorithm based on positive sequence fundamental wave extractor and current control algorithm based on generalized integral are proposed. The improved APF algorithm mentioned above can improve the detection accuracy and compensation effect of APF by avoiding the detection of positive sequence fundamental wave voltage and tracking the sinusoidal and cosine instructions without static difference in the case of voltage distortion or abrupt change of power grid. Finally, the simulation model is established by MATLAB, and the simulation results are compared and analyzed. The results show that the improved harmonic current detection algorithm and control algorithm are advanced and effective.

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