An Improved Harmonic Current Detection Method Based on Parallel Active Power Filter

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Abstract. Harmonic detection technology plays an important role in the applications of active power filter. The accuracy and real-time performance of harmonic detection are the precondition to ensure the compensation performance of Active Power Filter (APF). This paper proposed an improved instantaneous reactive power harmonic current detection algorithm. The algorithm uses an improved $i_p-i_q$ algorithm which is combined with the moving average value filter. The proposed $i_p-i_q$ algorithm can remove the $\alpha\beta$ and $dq$ coordinate transformation, decreasing the cost of calculation, simplifying the extraction process of fundamental components of load currents, and improving the detection speed. The traditional low-pass filter is replaced by the moving average filter, detecting the harmonic currents more precisely and quickly. Compared with the traditional algorithm, the THD (Total Harmonic Distortion) of the grid currents is reduced from 4.41% to 3.89% for the simulations and from 8.50% to 4.37% for the experiments after the improvement. The results show the proposed algorithm is more accurate and efficient.

1. Introduction
With the rapid development of power electronics, a large number of nonlinear electric power equipment is continuously connected to the power grid [1-2]. The problems of harmonic pollution are more and more serious, affecting the normal operation of the power grid severely. Active power filter (APF) can detect and suppress harmonics in real time and precisely [3]. Its working principle is to detect the harmonics in the power grid, producing and injecting the corresponding compensation signal into the grid in the same time according to the results of the detection, to improve the power quality. The harmonic detection technology is the key technology to ensure the effective operation of APF, the accuracy and rapidity of the detection results determine if the APF can generate the compensation signals in real time and precisely to improve the power quality [4-5]. This paper proposed an improved harmonic current algorithm, using an improved $i_p-i_q$ algorithm, which removes the $\alpha\beta$ and $dq$ coordinate transformation, decreasing the cost of calculation, improving the detection speed [6-8], and combining with the moving average value filter, which is used to replace the traditional low-pass filter, detecting the harmonic currents more precisely [9-12].

2. The principle of $i_p-i_q$ detection algorithm
The principle of $i_p$-$i_q$ algorithm is from the instantaneous reactive power theory of three-phase circuit, which proposes Phase locked loop (PLL) to extract the phase of the A phase grid voltage $e_a$, whose sine and cosine values are calculated. By using the obtained sine and cosine value, the signal of load current is transformed into instantaneous active current $i_p$ and reactive current $i_q$ by $a\beta$ coordinate and $dq$ coordinate transformation. $\overline{I}_p$ and $\overline{I}_q$, the DC components are extracted from the DC component extraction. The calculation formulas of $i_p$ and $i_q$ are as follows:

$$
\begin{bmatrix}
i_p \\
i_q
\end{bmatrix} = C_{pq} C_{32} \begin{bmatrix}
i_a \\
i_c
\end{bmatrix}
$$

(1)

where, $C_{pq} = \begin{bmatrix} \sin \omega t & -\cos \omega t \\ -\cos \omega t & -\sin \omega t \end{bmatrix}$, $C_{32} = \sqrt{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}$.

Three-phase fundamental currents are obtained by coordinate inverse transformation to the $\overline{I}_p$ and $\overline{I}_q$. Here, $\overline{I}_p$ and $\overline{I}_q$ are produced by $i_{a0}$, $i_{b0}$, $i_{c0}$, therefore, $i_{a0}$, $i_{b0}$, $i_{c0}$ can be calculated by $\overline{I}_p$ and $\overline{I}_q$.

Where, $C_{23}$ is the inverse matrix of $C_{32}$. The differences between the load currents and three-phase fundamental currents are the harmonic compensating command currents. As shown in Figure 1 is the algorithm block diagram of $i_p$-$i_q$ detection algorithm.

![Algorithm block diagram of $i_p$-$i_q$ detection algorithm](image)

3. Improved $i_p$-$i_q$ detection algorithm

As above, the instantaneous value of three-phase currents $i_a$, $i_b$, $i_c$ should be input in the process of $i_p$-$i_q$ detection at the same time. At this time, the algorithm can only be applied to three-phase three-wire circuit. On the other hand, only the fundamental phase information is extracted from the voltage signal in the $i_p$-$i_q$ algorithm, are the amplitude and phase ignored. Therefore, the $i_p$-$i_q$ method is meaningless in the calculation of instantaneous active and reactive power. It also doesn't need $a\beta$ coordinate transformation and its inverse transformation.

When detecting the single phase current, it’s similar to the $i_p$-$i_q$ algorithm, the voltage signals are converted into a sine wave whose amplitude is a unit length, such as: $e = \sin \omega t$. Detecting the value of the phase current (Taking A phase as an example), as shown in equation (2).

$$
i = \sum_{k=1}^{\infty} \sqrt{2} I_k \sin(kt + \phi_k)
$$

(2)

According to the definition, $i_p$ is the product of unit instantaneous voltage and instantaneous current, $i_q$ is the product of unit instantaneous voltage with $\pi/2$ phase delay and instantaneous current, as shown in equation (3).

$$
\begin{align*}
i_p &= i \cdot \cos \omega t = \sum_{k=1}^{\infty} \sqrt{2} I_k \left\{ \cos[(k + 1)\omega t + \phi_k] + \cos[(k - 1)\omega t + \phi_k] \right\} \\
i_q &= i \cdot \sin \omega t = \sum_{k=1}^{\infty} \sqrt{2} I_k \left\{ \sin[(k + 1)\omega t + \phi_k] - \sin[(k - 1)\omega t + \phi_k] \right\}
\end{align*}
$$

(3)

Let $C_i = \begin{bmatrix} \cos \omega t & \sin \omega t \end{bmatrix}$, then equation (3) is rewritten as the matrix form, shown as: $\begin{bmatrix} i_p \\
i_q
\end{bmatrix} = C_i i$. 

2
As seen in the equation (3), the physical meaning of calculation process to the instantaneous active current $i_p$ and the instantaneous reactive current of $i_q$ is the same as the definition of instantaneous active power and instantaneous reactive power.

The DC components $\overline{i_p}$ and $\overline{i_q}$ can be obtained after DC component extraction. Where,

$$\begin{bmatrix} \overline{i_p} \\ \overline{i_q} \end{bmatrix} = \begin{bmatrix} \sqrt{2} \overline{I_p} \cos \varphi_p \\ \sqrt{2} \overline{I_q} \sin \varphi_q \end{bmatrix}$$ \hspace{1cm} (4)

As shown in equation (4), under the condition of unit single-phase sinusoidal voltage, $\overline{i_p}$ is equal to the fundamental active power, $\overline{i_q}$ is equal to the fundamental reactive power. Therefore, the active power can be controlled accurately by controlling $\overline{i_p}$, and the reactive power can be controlled accurately by controlling $\overline{i_q}$. What’s more, there is not any other harmonic information in $\overline{i_p}$ and $\overline{i_q}$. So it is very easy to obtain the instantaneous fundamental currents.

From equation (2), the instantaneous value of the fundamental current is,

$$i_i = \sqrt{2} \overline{I_i} \cos (wt + \varphi_i) = 2 \left( \frac{\sqrt{2}}{2} \overline{I_p} \cos \varphi_p \cos wt - \frac{\sqrt{2}}{2} \overline{I_q} \sin \varphi_q \sin wt \right) = 2 \left( \overline{I_p} \cos wt - \overline{I_q} \sin wt \right)$$ \hspace{1cm} (5)

Let $C_2 = [2\cos(wt) - 2\sin(wt)]$, and from equation (5), we can get the equation: $i_i = C_2 \begin{bmatrix} \overline{i_p} \\ \overline{i_q} \end{bmatrix}$.

From equation (5), $i_i$ is the instantaneous fundamental current of each phase, being subtracted by the instantaneous fundamental current is the instantaneous harmonic current. The above process is the derivation of the improved $i_p$-$i_q$ detection algorithm. Figure 2 is the principle block diagram.

![Figure 2. The principle block diagram of improved $i_p$-$i_q$ detection algorithm](image)

Single phase instantaneous currents are converted to $i_p$ and $i_q$ by the $C_2$ coordinate transformation, eliminating the three-phase to two-phase coordinate transformation relative to $i_p$-$i_q$ method, and it can detect any phase currents. The inverse transformation process is only by the $C_2$ coordinate transformation, reducing the amount of calculation greatly.

4. Optimal Design of Instantaneous Current DC Components Extraction

In all harmonic current detection methods, the DC current components should be extracted from the instantaneous currents. It is obvious that the performance of instantaneous current DC components extraction determines the accuracy of the detection method and the dynamic tracking speed directly, and affects the compensation performance of APF ultimately. Therefore, the design of this link is very important one.

In the traditional harmonic detection method, the sampling and calculation process of the low pass filter for extracting the DC components will cause the hysteresis error, that would affect the accuracy of the harmonic detection. To improve the detection accuracy and improve the dynamic response performance, the moving average method is used to replace the traditional low-pass filter.

Before the DC components extraction link, the DC value of the $d$ axis signal corresponds to the load’s fundamental active power, and the DC value of the $q$ axis signal corresponds to the load’s fundamental reactive power. For the AC components of the $dq$ axis, within a base cycle, the sum of all the sampling points is 0. For the DC components, accumulating all the sampling points in a base cycle, and after dividing by the sampling points, the result is still the DC signal.
According to the above properties, sample \( N \) points of one base cycle, add the value of the sampling points, calculate the average value, then we can get the DC components. But in APF, calculating the average value in one base cycle cannot reflect the change of signal in real time. So in the proposed algorithm, when sampling point \( K \), the moving average method uses the latest sampling information \( i_d(k) \) instead of the oldest information \( i_d(k-N) \) of the \( N \) sampling points in the last period. We can get,

\[
\sum_{k=(l-N)}^{k} i_d(l) = \sum_{k-N}^{k} i_d(l) + i_d(k) - i_d(k-N)
\]

(6)

Where, \( i_d(k) \) is the latest data of the current moment, \( i_d(k-N) \) is the oldest data of the \( N \) sampling points in the last period. Once the data is sampled, the DC components are recalculated, and the moving average value is changed with it. Thus, we only need a new data of a sample point to calculate the new DC components of the input signal, in theory only a sampling period need to delay, so as to maintain the DC components according to the actual situation of real change, reflecting the rapid and real-time data updating. In theory, only one sampling period is delayed, so as to keep the DC components changing according to the actual situation in real time. It reflects the fast and real-time update of data.

5. Simulations and Experimental Verifications
To verify the feasibility and superiority of the proposed algorithm, simulations and experiments are carried out to the traditional instantaneous reactive power algorithm and the proposed one respectively under the same system hardware parameters. The system parameters are shown in table 1.

| Name of parameter          | Parameter values |
|----------------------------|------------------|
| Grid voltage               | 220V             |
| Grid frequency             | 50Hz             |
| Switching frequency        | 9.6kHz           |
| DC-link voltage            | 700V             |
| DC-link capacitor          | 10000μF          |
| Inverter side inductance   | 260μH/0.025Ω     |
| Grid side inductance       | 160μH/0.025Ω     |
| Three-phase rectifier with | 12Ω              |
| a resistive load           |                  |

Figure 3 is the simulation waveforms of system load current, output compensation command current, output compensating current and compensated current of the grid under the traditional instantaneous reactive power algorithm and the proposed one respectively.

![Figure 3. Current Simulation Waveforms of Two Algorithms](image-url)
Fundamental (50 Hz) = 58.1, THD = 4.41%

Figure 4. Harmonic Analysis to The Supply Current of Two Algorithms

Figure 4 is the harmonic analysis to the source current of two algorithms after compensation. The results show that the THD value of the source currents is reduced from 24.24% to 3.89%, which is better than 4.41% of the traditional algorithm. Using the proposed algorithm, the APF can detect the harmonic of the system more accurately and real-time, and the source current spikes at the commutations are smaller. The proposed algorithm has better compensation performance.

To verify the dynamic response performance of the proposed harmonic algorithm, a resistor with the value of $R=12\Omega$ is in parallel to the load in 0.6 seconds. The simulation results are shown in Figure 5.

Figure 5. Current Waveforms of Two Algorithms When the Load Changes

It can be seen that the harmonic command currents gotten by traditional instantaneous reactive power algorithm need 2 cycles to reach the new steady state, but the proposed one can reach a new steady state only after 1 cycle. The results show that the harmonic current can be detected by the proposed algorithm more accurately and in real time, which has better dynamic response performance.

Figure 6 show the current experimental waveforms of the system using the two harmonic detection algorithms. After comparing the currents of load, the compensating currents and the compensated currents respectively with each other of the two algorithms, the results show that the harmonic currents of load have been compensated effectively using the proposed algorithm, the THD of the source current is 4.37%, which meets the standards and is better than 8.50% in traditional algorithm.

Figure 6. Experimental Waveforms of Two Algorithms
6. Conclusions
This paper has proposed a harmonic current detection algorithm based on the combination of improved $i_p-i_q$ detection and the moving average filter. The coordinate transformation of the traditional $i_p-i_q$ detection algorithm is simplified, and the moving average filter improves the detection speed and accuracy. Compared with the traditional algorithm, the proposed algorithm is faster and more effective.

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