Improved i_p-i_q Reactive Current Detection Method Without PLL

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ABSTRACT—As the traditional d-q transformation method is not sufficient in detecting the three-phase asymmetric components, a new detection method in which a single phase voltage is input to a differentiator to get an orthogonal differential is proposed. The synchronous rotary angle can be obtained by using the orthogonality relationship based on mathematical relationship. The new detection method is suitable for both asymmetric load and asymmetric supply voltage systems. The effect of time delay caused by phase-locked loop (PLL) is eliminated without using PLL circuit to obtain synchronous rotation angle in the detection process. The phase shifting deviation is solved without shifting the phase of three-phase current. The unbalance degree of input voltage in Static Synchronous Compensator (STATCOM) is effectively reduced by using this method. Simulation and experiment results show that the proposed method is valid and feasible.

1. INTRODUCTION

With the development of modern industrial technology, more and more power electronic device has been applied into the power grid, therefore a large number of harmonics and reactive current have been produced which have brought great hidden danger and harmonic pollutions to the normal operation of the power grid [1]. The reactive power and harmonics can be effectively reduced by active filter and reactive power compensation technology, as the safety and stability of the power grid operation can be improved. The key to active filter and reactive power compensation technology is that the harmonic and fundamental current can be detected quickly and accurately [2].

In recent years, a variety of detection methods have been put forward, such as the method based on instantaneous reactive power theory [3] [4]. In practice, the mainstream is still the detection method based on instantaneous reactive power theory [5] [6]. An improved design method based on the traditional i_p-i_q detection method is proposed, in which a function is constructed to replace the phase-locked loop (PLL). The design scheme has the advantages of simple structure, strong anti-interference, fast response and high precision. Simulation analysis based on MATLAB is in positive to the analysis showing the accuracy and the feasibility of the improved method [7].

2. TRADITIONAL I_p-I_q DETECTION METHOD

The methods of detecting reactive current are consist of p-q detection method and i_p-i_q detection method. Where, the p-q detection method is only suitable for power grid voltage with no distortion. The i_p-i_q detection method is suitable for both distorted power grid voltage and asymmetric power grid voltage.
The sine signal $\sin \omega t$ and cosine signal $\cos \omega t$ in phase with the a-phase power voltage fundamental component are used in traditional $i_p$-$i_q$ detection method which is obtained by a PLL and a signal producing circuit. The diagram of traditional $i_p$-$i_q$ detection method is shown in Fig. 1.

The detection principle is as follows:

The $i_p$ and $i_q$ can be calculated according to the transformation of $\alpha$-$\beta$ coordinate. The DC component $i_{am}$, $i_{bm}$ and $i_{cm}$ of detecting current can be calculated by $\overline{i_p}$ and $\overline{i_q}$. Harmonic component $i_{an}$, $i_{bn}$ and $i_{cn}$ are obtained by subtracting fundamental component $i_{am}$, $i_{bm}$ and $i_{cm}$ from detecting current $i_a$, $i_b$ and $i_c$.

$$\begin{align}
C = \begin{bmatrix}
\cos \omega t & \sin \omega t \\
\sin \omega t & -\cos \omega t
\end{bmatrix}
\end{align}$$

(2)

Where, $C$ is

As the Fig.1 shown, we can obtain:

$$\begin{align}
\begin{bmatrix}
i_{am} \\
i_{bm} \\
i_{cm}
\end{bmatrix} &= C_{32}^{-1} C
\begin{bmatrix}
i_p \\
i_q
\end{bmatrix}
\end{align}$$

(1)

The objects controlled by STATCOM are reactive current, harmonic current, negative sequence current and zero sequence current. Let be the $i_q = 0$, the active component $i_{am}$, $i_{bm}$ and $i_{cm}$ can be calculated. The harmonic and reactive current component can be obtained by subtracting the active component from the detection current.

Three-phase current to be detected is as follows:

$$\begin{align}
i_a &= \sum_{n=1}^{\infty} \sqrt{3} I_n \sin (n\omega t + \phi_n) \\
i_b &= \sum_{n=1}^{\infty} \sqrt{3} I_n \sin [n(\omega t - 2\pi/3) + \phi_n] \\
i_c &= \sum_{n=1}^{\infty} \sqrt{3} I_n \sin [n(\omega t + 2\pi/3) + \phi_n]
\end{align}$$

(3)

Suppose the sine signal and cosine signal are $\sin(\omega t + \theta)$ and $\cos(\omega t + \theta)$, where $\omega_1$ is inconsistent with the current frequency $\omega$ and phase angle $\theta$ is an arbitrary value. After the transformation of $\alpha$-$\beta$, we can obtain:

$$\begin{align}
\begin{bmatrix}
i_p \\
i_q
\end{bmatrix} &= \sqrt{3} \begin{bmatrix}
\sum_{n=1}^{\infty} \pm I_n \cos([\omega t + n\pi/3] + \theta + \phi_n) \\
\sum_{n=1}^{\infty} \pm I_n \sin([\omega t + n\pi/3] + \theta + \phi_n)
\end{bmatrix}
\end{align}$$

(4)

Low pass filtering is used to $i_p$ and $i_q$, the low-frequency component $\overline{i_p}$ and $\overline{i_q}$ are given by
Where, DC component can be obtained when \( \omega_1 \) is equal to \( \omega \). In practice, the frequency of the power grid voltage is 50±0.2 Hz, and its maximum can be 50±0.5 Hz with a certain amount of AC, and at this time, \( \omega_1 \) is not equal to \( \omega \). Thus, it is necessary to ensure the pass-band higher than \[ \omega_1-\omega \], and the stop-band frequency must be lower than the minimum of \( \omega_1+\omega \) and \( \omega_1-2\omega \). The obtained low frequency component \( \tilde{i}_p \) and \( \tilde{i}_q \) are transformed inversely and fundamental component of the three-phase current can be obtained:

\[
\begin{bmatrix}
\tilde{i}_{3p} \\
\tilde{i}_{3q} \\
\tilde{i}_{3n}
\end{bmatrix} = C_{23} \begin{bmatrix}
\sin(\omega t + \theta) & \cos(\omega t + \theta) \\
\cos(\omega t + \theta) & -\sin(\omega t + \theta)
\end{bmatrix} \times \sqrt{3} \begin{bmatrix}
I_p \cos(\omega t - \omega t + \theta - \phi_p) \\
I_q \cos(\omega t - \omega t + \theta - \phi_q)
\end{bmatrix} = \begin{bmatrix}
\sqrt{2}I_1 \sin(\omega t + \phi) \\
\sqrt{2}I_1 \sin(\omega t - 2\pi/3 + \phi) \\
\sqrt{2}I_1 \sin(\omega t + 2\pi/3 + \phi)
\end{bmatrix}
\]

Where, \( C_{23} \) is

\[
C_{23} = C_{32}^{-1} = \begin{bmatrix}
1 & 0 \\
-\frac{1}{2} & \frac{\sqrt{3}}{2} \\
-\frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\]

From the consequence we can find that although the sine signal and cosine signal are different from each other, the relationship between a and \( \varphi \) needs to be devoiced, as the power grid voltage and current phase angle \( \varphi \) can be obtained. The relationship between angle \( \varphi \) and power grid voltage is not tight. Thus, the power grid voltage

3. IMPROVED I_p-I_q DETECTION METHOD WITHOUT PLL

From the research of the traditional detection \( i_p-i_q \) method, it can be seen that sampling power grid voltage is actually to find the relationship among power grid voltage, current frequency and phase. Although the fundamental frequency and initial phase angle of three-phase current can be obtained by using PLL, it is often affected by the signal. Moreover, the area of the circuit board will be increased with PLL circuit, its designing and debugging is complicated. Whether the function of PLL can be replaced by mathematical calculations is a question. The improved diagram is shown in Fig.2. The feasibility will be proved as following:

![Improved i_p-i_q detection method diagram](image)

The three-phase unbalanced a-phase voltage can be expressed by:

\[
u_a = A \sin \omega t
\]

In order to obtain \( \cos \omega t \) in \( i_p-i_q \) algorithm, taking the partial derivative on \( u_a \), we can obtain:

\[
\frac{du_a}{dt} = \omega A \cos \omega t
\]

From the defined analysis, it can be seen that we just need to know the direction of the current needs to be devoiced, as the power grid voltage and current phase angle \( \varphi \) can be obtained. The relationship between angle \( \varphi \) and power grid voltage is not tight. Thus, the power grid voltage
distortion has no effect on the $i_p$-$i_q$ detection method. Supposing $\omega=2\pi f=2\pi \times 50=314$, then the following can be obtained:

$$\frac{u_a}{314} = B \cos \omega t$$

(10)

Where $B \approx A$. Then the formula (11) is obtained:

$$\begin{bmatrix} u_a \\ u_\beta \end{bmatrix} = \begin{bmatrix} u_a / 314 \\ u_\beta \end{bmatrix} = \begin{bmatrix} B \cos \omega t \\ A \sin \omega t \end{bmatrix}$$

(11)

According to the expression of synchronous rotation angle voltage $u_a$, we have:

$$\cos \varphi = \frac{u_a}{\sqrt{u_a^2 + u_\beta^2}}$$

(12)

$$\sin \varphi = \frac{u_\beta}{\sqrt{u_a^2 + u_\beta^2}}$$

(13)

Substitute (10) into (12) and (13), we can obtain:

$$\cos \varphi = B \cos \omega t \sqrt{(A \sin \omega t)^2 + (B \cos \omega t)^2}$$

(14)

$$\sin \varphi = A \sin \omega t \sqrt{(A \sin \omega t)^2 + (B \cos \omega t)^2}$$

(15)

Thus, the fundamental component of the output current can be expressed by:

$$\begin{bmatrix} i_{com} \\ i_{im} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix} \times \begin{bmatrix} u_a/\sqrt{u_a^2 + u_\beta^2} \\ u_\beta/\sqrt{u_a^2 + u_\beta^2} \\ u_a/\sqrt{u_a^2 + u_\beta^2} \\ -u_\beta/\sqrt{u_a^2 + u_\beta^2} \end{bmatrix} \begin{bmatrix} T_p \\ T_q \end{bmatrix} = C_{32}^{-1} C \begin{bmatrix} T_p \\ T_q \end{bmatrix}$$

(16)

Where, $C$ is

$$C = \begin{bmatrix} u_a/\sqrt{u_a^2 + u_\beta^2} & u_\beta/\sqrt{u_a^2 + u_\beta^2} \\ u_\beta/\sqrt{u_a^2 + u_\beta^2} & -u_a/\sqrt{u_a^2 + u_\beta^2} \end{bmatrix}$$

(17)

And $C_{32}^{-1}$ is

$$C_{32}^{-1} = \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ -1/2 & -\sqrt{3}/2 \end{bmatrix}$$

(18)

The influence of PLL traditional detection method is overcome and the computational complexity of synchronous rotary angle is decreased by the method of single-phase power voltage.

4. SIMULATION ANALYSIS

To verify the feasibility of the proposed method, it is simulated on MATLAB.

Overall block diagram of the simulation on MATLAB is shown in Fig.3. The simulation model has 3 parts: the source and load module, the reactive extraction module and the PWM generator module.
The Improved \( i_p-i_q \) detection method module which is shown in Fig.4 is built. The main parameters are as follows: the power line voltage is 380V, the switching frequency is 10 KHz, the grid frequency is 50 Hz, the load inductance is 0.025H and the load resistance is 5Ω.

**Fig.3** Overall block diagram of the simulation on MATLAB

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**Fig.4** Improved \( i_p-i_q \) detection method module

### 4.1. Symmetrical Three-Phase Voltage With no Higher Harmonics

For a symmetrical three-phase voltage is shown in Fig.5, the reactive current waveform of the improved \( i_p-i_q \) detection method is shown in Fig.6.
The improved \( i_p-i_q \) detection method is accurate of a-phase reactive current and traditional method with no higher harmonics.

4.2. Distorted Three-phase Voltage

System voltage distortion occurs at 0.1 s. is shown in Fig.7 Reactive current of a-phase detected by improved \( i_p-i_q \) detection method is shown in Fig.8.

By comparing the figure in Fig.6 and Fig.8, it can be seen that the improved \( i_p-i_q \) detection method can always detect the reactive current accurately whether the three-phase voltage distorted or not. The advantages of the improved \( i_p-i_q \) detection method on speed and complexity degree are in positive to the feasibility of the design.

4.3. Three-phase Asymmetric Load

Supposing the other simulation conditions maintain the original value, the load of a-phase is 5Ω, b-phase is 10Ω, c-phase is 15Ω, and put it into the STATCOM device at the time of 0.1s. The wave of the current is shown in Fig.9.

From Fig.9, it can be seen that three-phase current is symmetric after putting into STATCOM device for one cycle and it has a good effect on compensating for three-phase asymmetric. It is in positive to the effectiveness and rapidity of the SATACOM device using the proposed detection method.
5. CONCLUSION
Traditional synchronous detection method is proposed based on three symmetric systems, in practice, the three-phase asymmetry occurs frequently. Thus, the synchronous rotation angle is constructed by using a single-phase voltage in the new detection method. The influence of PLL in traditional synchronous detection method has been overcome, and the complexity of compute synchronous rotation angle is also reduced. Simulation result shows that the proposed detection method has a high precision and fast response characteristic when detecting reactive current. The desired effect can also received by applying the method to STATCOM device.

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