A Fast Instantaneous Power Calculation Algorithm for Single-phase Rectifiers Based on Arbitrary Phase-delay Method

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***Abstract*—The instantaneous power for three-phase rectifier can be calculated directly in the orthogonal coordinate system via coordinate transformation. However, it is difficult to calculate the instantaneous power directly for single-phase rectifier due to the lack of another phase, an orthogonal signal generator (OSG) is therefore required to create an orthogonal coordinate system. Currently, conventional OSG algorithms suffer from long response time, to remedy this problem, an arbitrary phase-delay OSG algorithm based on the monophase complex vector theory is developed in this paper. The developed algorithm can quickly calculate the instantaneous active power and reactive power. Through the analysis of its principle, it can be known that the developed algorithm brings faster response speed, easy implementation and less computational burden Compared with other common OSG algorithm. Finally, the proposed OSG algorithm is applied to the direct power control system in single phase rectifier and compared with other traditional OSG algorithms. The validity and advancement of the proposed algorithm are verified by simulations and hardware-in-loop experimental tests.**

Keywords—Instantaneous Power Calculation; single-phase rectifier; orthogonal signal generator; Arbitrary Phase-delay; direct power control.

I. Introduction

Single phase pulse rectifier has been widely used in electric locomotives and high speed EMUs because of its advantages such as low harmonic content of input current, high power factor on the grid side, and bi-directional energy flow [1]. With the rapid development of high-speed railway, increasingly requirements are put forward for its control, and various approaches have been proposed in succession. e.g., Indirect current control [2], hysteresis current control [3], transient current control [4], predictive current control [5], D-Q current decoupling control [6]. These approaches have different characteristics, though all of them are based on the current regulation to achieve the unit power operation of the rectifier. Compared with the current control, the direct power control (DPC), which is characterized by simple algorithm and fast dynamic response, can realize unit power factor by means of direct control of active power and reactive power based on the instantaneous power theory. Hence, it has been widely studied and applied in three-phase system [7-8].

To implement DPC in rectifier, it is necessary to calculate the instantaneous active power and instantaneous reactive power. For three-phase system, it is very easy to calculate the instantaneous power in the orthogonal coordinate system via Park/Clark transform. However, due to the lack of another phase in single phase system, and therefore it can't constitute orthogonal coordinate system to calculate instantaneous power. Therefore, it is necessary to create a set of orthogonal signals according to the original signal.

Orthogonal signal generators (OSG) mainly generate the corresponding orthogonal signal x_β according to the detected single-phase signal x_α, and thus establish the single-phase orthogonal coordinate system for power calculation. The key issue of OSG is to generate the orthogonal signal x_β fast and accurately. The common methods of generating orthogonal signals include quarter-cycle delay method [9], first-order differentiating [10], filters method [11], second-order generalized Integrator (SOGI) [12] and so on. Among them, quarter-cycle delay still needs response time of 0.25 grid cycles, the first order differentiating operator generates a quadrature signal with fast response, but the random noise is significantly enlarged with high sampling frequency. If the sampling frequency is reduced, the orthogonal signal generated by this method will exist a large approximation error. In [11], x_β is chosen as zero to abandon the OSG, but after the coordinate transformation, there exist harmonic with twice grid frequency in *d-q* frame. Usually a band-pass filter (BPF) or low pass filter is used to filter out the harmonics, but this will lead to a reduction in the bandwidth of the loop, and increase the response time. In recent years, OSG based on SOGI has attracted much attention due to its frequency-adaptive performance and harmonic/noise immunity. However, it suffers from long response time, although the research has focused on how to optimize the response speed [13]. That makes it limited in fast detection and control in single-phase system.

Considering the requirements of simple digital implementation, low computation burden and fast response

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speed, the quarter-cycle delay method and the first-order differentiating method are still the main choice for generating orthogonal signals. In order to overcome the defects of the two algorithms in response speed, precision and noise immunity. Therefore, an OSG algorithm with arbitrary phase delay is proposed in this paper to establish the orthogonal coordinate system and calculate the instantaneous power for single phase rectifier. The proposed OSG algorithm is applied to the DPC system in single phase rectifier and compared with other traditional OSG algorithms. The validity and advancement of the proposed algorithm are verified by simulations and hardware-in-loop experimental tests.

The rest of this paper is structured as follows. Section II describes the instantaneous power theory based on complex vector and a common predictive DPC algorithm. Section III explains the principles of the arbitrary phase-delay OSG method. In section IV, a comparison of the proposed methods and traditional OSG methods is carried out through simulation and experimental tests. Section V concludes the paper.

II. Instantaneous Power Theory And DPC Algorithm

A. Instantaneous Power Theory Based on Complex Vector

DPC of three-phase rectifier is based on instantaneous power theory, which was developed by Akagi in orthogonal coordinates. This paper explains the instantaneous power calculation by means of space complex vector. It can be seen from the following that this way to express power calculation has many advantages.

In the stationary α-β coordinate system, complex vectors $\boldsymbol{V}_s$ and $\boldsymbol{I}_s$ for sinusoidal voltage and current quantity are defined as follows:

$$\begin{cases} \boldsymbol{V}_s = u_m e^{j\omega t} = u_\alpha + \mathrm{j}u_\beta \\ \quad = u_m \cos\omega t + \mathrm{j}u_m \sin\omega t \\ \boldsymbol{I}_s = i_m e^{j\omega t+\varphi} = i_\alpha + \mathrm{j}i_\beta \\ \quad = i_m \cos(\omega t+\varphi) + \mathrm{j}i_m \sin(\omega t+\varphi) \end{cases} \tag{1}$$

Where ω refers to the fundamental angular frequency, u_α and u_β refer to the α axis component and the β axis component of the voltage complex vector respectively, i_α and i_β refer to the α axis component and the β axis component of the current complex vector, respectively. u_m and i_m are the amplitudes of the fundamental component in the voltage and current. φ is the phase-lagging angle of the fundamental component in current and voltage. It is noted that voltage complex vector coincides with α axis at the initial time.

Then, complex power S can be expressed as

$$S = \frac{1}{2}\boldsymbol{V}_s\boldsymbol{I}_s{*} = P + \mathrm{j}Q \tag{2}$$

Where the asterisk * denotes the complex conjugate value. P and Q refer to the Instantaneous active power and instantaneous reactive power corresponding the real and imaginary parts of instantaneous complex power respectively.

Substituting (1) into(2), it follows that

$$\begin{cases} P = \frac{1}{2}\left(u_\alpha i_\alpha + u_\beta i_\beta\right) \\ Q = \frac{1}{2}\left(i_\alpha u_\beta - i_\beta u_\alpha\right) \end{cases} \tag{3}$$

It is noted that the two components of the grid voltage vector are not equal to 0 in the stationary α-β coordinate system, the relationship between the active/reactive power and the current vector is relatively complex.

Similarly, complex vectors $\boldsymbol{V}_r$ and $\boldsymbol{I}_r$ for sinusoidal voltage and current quantity in the *d*-*q* coordinate system are defined as follows.

$$\begin{cases} \boldsymbol{V}_r = u_d + ju_q \\ \boldsymbol{I}_r = i_d + ji_q \end{cases} \tag{4}$$

Where u_d and u_q refer to the *d* axis component and the *q* axis component of the voltage complex vector respectively, i_d and i_q refer to the *d* axis component and the *q* axis component of the current complex vector, respectively.

The *d*-*q* coordinate system Rotates synchronously with angular velocity ω, so that *d* axis coincides with the Voltage complex vector all the time. Thus the coordinate transformation relation between complex in stationary reference frame and rotating reference frame can be deduced as

$$\begin{cases} \boldsymbol{V}_s = \boldsymbol{V}_r e^{\mathrm{j}\omega t} \\ \boldsymbol{I}_s = \boldsymbol{I}_r e^{\mathrm{j}\omega t} \end{cases} \tag{5}$$

Substituting (5) into(2), it can be derived that

$$S = \frac{1}{2}\boldsymbol{V}_r\boldsymbol{I}_r{*} = P + \mathrm{j}Q \tag{6}$$

Substituting (4) into (6) yields

$$\begin{cases} P = \frac{1}{2}\left(u_d i_d + u_q i_q\right) \\ Q = \frac{1}{2}\left(i_d u_q - i_q u_d\right) \end{cases} \tag{7}$$

Combining(1), (4) and(5), it follows that

$$\begin{cases} u_d = u_m \\ u_q = 0 \end{cases} \tag{8}$$

That is, in the *d*-*q* coordinate system, when *d* axis is completely coincident with the grid voltage, u_q=0. According to(8), the formula (7) can be further simplified to

$$\begin{cases} P = \frac{1}{2}u_m i_d \\ Q = -\frac{1}{2}u_m i_q \end{cases} \tag{9}$$

It can be seen that in this case, the active/reactive power is proportional to the active/reactive current i_d /i_q. Compared with stationary reference frame, the relationship between