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A new control strategy of three-phase SAPF based on non-ideal mains voltages

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Abstract: **A new control strategy for three-phase shunt active power filter (SAPF) was raised to enhance its performance based on non-ideal mains voltages. The method was enlightened by our discovering that the typical instantaneous reactive power theory based algorithm was not satisfied on the part of isolating positive sequence fundamental active components precisely based on non-ideal mains voltages. Then, a modified reference current computational way was introduced. With application of the novel way, both the positive sequence and the fundamental active current components can be exactly separated from load current. The simulation results reveal that the suggested strategy is valid with preferable tracking capacity and reduce THD (total harmonic distortion).**

Keywords: Shunt active power filter; Non-ideal mains voltages; Deadbeat closed-loop control; Fundamental active current

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1. Introduction

Active power filter (APF) has aroused great interest owing to its high precision and quick dynamic response, because APF can generate real-time compensation current, and which is injected into power grid or micro grid to eliminate and compensate harmonics and reactive power [1]. Because of the active filter design, the instantaneous reactive power theory was often applied to calculatee the required amount of compensation current as the main paradigm [2]. This theory assumed that the mains voltage was an ideal source. For instance, the p-q algorithm based on the instantaneous reactive power theory can accurately detect the foundational positive sequence current only with balanced and undistorted mains voltage [3]. Several novel project ways have been raised to get over the shortcomings of traditional project ways under non-ideal mains voltages. A famous method is a modified version of p-q theory, called i_p - i_q method [4], which can isolate the fundamental positive sequence current from the load current in the condition of unbalanced and undistorted mains voltages.In Ref. [5], a control algorithm for APF to compensate harmonic and reactive power of three-phase thyristor bridge rectifier under non-ideal mains voltage scenarios was also introduced. Nevertheless, while mains voltages are both unbalanced and distorted, these i_p - i_q based ways can not accurately extract both fundamental and positive sequence active components of load currents.

In order to enhance the performance of SAPF based on unbalanced and distorted mains voltages, a new isolation way of reference current is raised in this work. Not only fundamental but also positive sequence active currents can be extracted from the load currents, and a deadbeat closed-loop control model based on predictive control way is established under the unbalanced and distorted mains voltages in order to remove both delay error and tracking error between reference voltages and compensation voltages.

2. Methods

2.1. Instantaneous Reactive Power Theory Based Algorithm

A three-phase three-leg SAPF system is described in Figure 1, the load currents include fundamental positive and negative sequence currents and harmonic currents. Likewise, mains voltages include fundamental positive, negative and even zero sequence voltages, as well as harmonic voltages.On the basis of the symmetrical component method, load currents and mains voltages can be represented as:

$$\begin{cases} i_{1a}=\sqrt{2}\sum_{n=1}^{\infty}\left[I_n^+\sin(n\omega t+\theta_{in}^+)+I_n^-\sin(n\omega t+\theta_{in}^-)\right] \\ i_{1b}=\sqrt{2}\sum_{n=1}^{\infty}\left[I_n^+\sin(n\omega t+\theta_{in}^+-2\pi/3)+I_n^-\sin(n\omega t+\theta_{in}^-+2\pi/3)\right] \\ i_{1c}=\sqrt{2}\sum_{n=1}^{\infty}\left[I_n^+\sin(n\omega t+\theta_{in}^+2\pi/3)+I_n^-\sin(n\omega t+\theta_{in}^--2\pi/3)\right] \end{cases} \quad (1)$$

$$\begin{cases} u_{sa}=\sqrt{2}\sum_{n=1}^{\infty}[U_n^+\sin(n\omega t+\theta_{un}^+)+U_n^0\sin(n\omega t+\theta_{in}^0)+ \\ \qquad U_n^-\sin(n\omega t+\theta_{un}^-)] \\ u_{sb}=\sqrt{2}\sum_{n=1}^{\infty}[U_n^+\sin(n\omega t+\theta_{un}^+-2\pi/3)+U_n^0\sin(n\omega t+\theta_{in}^0)+ \\ \qquad U_n^-\sin(n\omega t+\theta_{un}^-+2\pi/3)] \\ u_{sb}=\sqrt{2}\sum_{n=1}^{\infty}[U_n^+\sin(n\omega t+\theta_{un}^++2\pi/3)+U_n^0\sin(n\omega t+\theta_{in}^0)+ \\ \qquad U_n^-\sin(n\omega t+\theta_{un}^--2\pi/3)] \end{cases} \quad (2)$$

where i_{1a}, i_{1b}, i_{1c} denote three-phase load currents,

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and u_{sa}, u_{sb}, u_{sc} denote mains voltages. Subscript character n represents the harmonic order. Subscript characters +, − and 0 denote separately positive sequence, negative sequence and zero sequence components of load currents or mains voltages. For instance, θ_{in}^{+} denotes the phase angle of the positive sequence current component of the n order harmonic current.

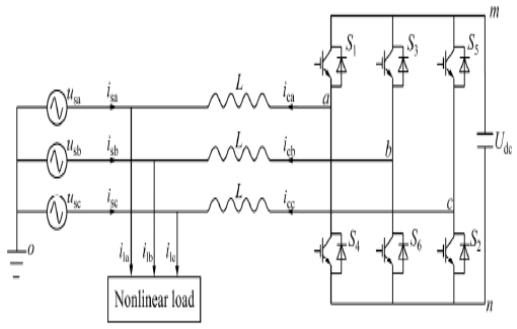

Figure 1. Structure of three-phase three-leg SAPF.

Shown in Figure 1, L represents the equivalent inductance of the converter, $s_i (i = 1,2,\cdots,6)$ are the IGBT power semiconductors, and u_{dc} is the dc-link voltage value. The SAPF implements the function to generate compensation currents $(i_{cx} (x = a,b,c))$ as a current source,by which the reference currents (i_{cx}^{+}) are expected to be tracked.The compensation currents consist of harmonic and reactive power current isolated from load currents (i_{1x}), but with reverse polarity.The source currents (i_{sx}) will be sinusoidal and in phase with the fundamental positive sequence mains voltages (u_{fx}) by injecting the compensation currents into power feeder,

As taking the i_p - i_q algorithm based on the instantaneous reactive power theory to detect the foundational positive sequence current an example, the principle diagram is shown in Figure 2.

Where i_{af}, i_{bf}, i_{cf} are the three-phase foundational positive currents,and i_{ah}, i_{bh}, i_{ch} are the differences between the three-phase load currents and foundational positive currents, which consist of harmonic and foundational positive currents; PLL (Phase Lock-Loop) is the phase lock-loop circuit, which is used to obtain the sinusoidal and cosine signals with the same frequency and phase as the main voltage of Phase A. The matrices $C_{2/3}$ and $C_{3/2}$ are stacked and given by

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

$$C_{3/2} = C_{2/3}^{T} \tag{4}$$

Assuming that the phase angle of the mains voltage of Phase A gauged by PLL is $\omega t + \gamma (\gamma \in [0, 2\pi])$, C and C^{-} can be calculated as follows:

$$C^{-} = C = \begin{bmatrix} \sin(\omega t + \gamma) & -\cos(\omega t + \gamma) \\ -\cos(\omega t + \gamma) & -\sin(\omega t + \gamma) \end{bmatrix} \tag{5}$$

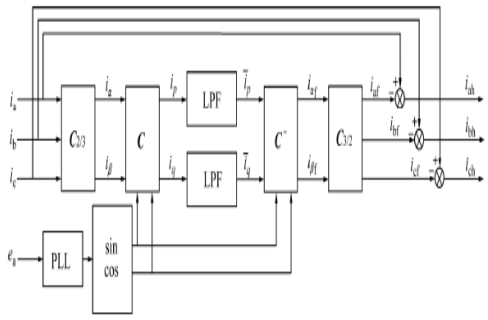

Figure 2. Principle diagram of detection method.

Through low pass filtering (LPF), the direct components of load currents $\bar{i}_p$ and $\bar{i}_q$ can be achieved as follows:

$$\begin{bmatrix} \bar{i}_p \\ \bar{i}_q \end{bmatrix} = \begin{bmatrix} \sqrt{3} I_1^{+} \cos(\theta_{i1}^{+} - \gamma) \\ -\sqrt{3} I_{i1}^{+} \sin(\theta_{i1}^{+} - \gamma) \end{bmatrix} \tag{6}$$

After that, the three-phase foundational positive currents i_{af}, i_{bf} and i_{cf} can be gained by inverse transformation on the basis of the i_p - i_q algorithm as

$$\begin{bmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{bmatrix} = C_{3/2} C^{-1} \begin{bmatrix} \bar{i}_p \\ \bar{i}_q \end{bmatrix} = \begin{bmatrix} \sqrt{2} I_1^{+} \sin(\omega t + \theta_{i1}^{+}) \\ \sqrt{2} I_1^{+} \sin(\omega t + \theta_{i1}^{+} - 2\pi/3) \\ \sqrt{2} I_1^{+} \sin(\omega t + \theta_{i1}^{+} - 2\pi/3) \end{bmatrix} \tag{7}$$

At last, the references current i_{xh} can be acquired by the equation $i_{xh} = i_{xf} - i_{xl}$, where x=a,b, c.

Nnevertheless, we cannot acquire the foundational positive active currents and the foundational positive reactive currents precisely. While we cut off the $\bar{i}_q$ channel for acquiring the foundational positive active currents i'_{af}, i'_{bf} and i'_{cf}, Eq. (7) can be rewritten as

$$\begin{bmatrix} i'_{af} \\ i'_{bf} \\ i'_{cf} \end{bmatrix} = C_{3/2} C^{-1} \begin{bmatrix} \bar{i}_p \\ 0 \end{bmatrix} = \tag{8}$$

$$\begin{bmatrix} \sqrt{2} I_1^{+} \sin(\omega t + \gamma) \cos(\theta_{i1}^{+} - \gamma) \\ \sqrt{2} I_1^{+} \sin(\omega t + \gamma - 2\pi/3) \cos(\theta_{i1}^{+} - \gamma) \\ \sqrt{2} I_1^{+} \sin(\omega t + \gamma - 2\pi/3) \cos(\theta_{i1}^{+} - \gamma) \end{bmatrix}$$

Where the initial phase angles of i'_{af}, i'_{bf} and i'_{cf} are not equal to those of the foundational positive components of mains voltages anyway. Because the phase angle $\omega t + \gamma$ of the mains voltage of Phase A detected by PLL is the combination result of harmonic components with the positive and negative sequence

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components of the mains voltage of Phase A, other than the phase angles of the fundamental positive sequence components of the mains voltage of Phase A.Therefore, i'_{af}, i'_{bf} and i'_{cf} cannot represent the fundamental positive sequence active components of load currents. The question still exists while we attempt to acquire the fundamental positive sequence active components of load currents through cutting off $\bar{i}_p$ channel in Figure 2. So, the traditional i_p - i_q algorithm may not be fit for reactive power compensation applications under non-ideal mains voltages.

2.2. Reference Current Calculation and Voltage Prediction Under Non-ideal Mains Voltages Instantaneous Reactive Power Theory Based on Algorithm

Phase information of the fundamental positive sequence components of mains voltages is definitely needed in order to accurately isolate the fundamental positive sequence active current from load current.The principle diagram of the presented reference current calculation way is shown in Figure 3.

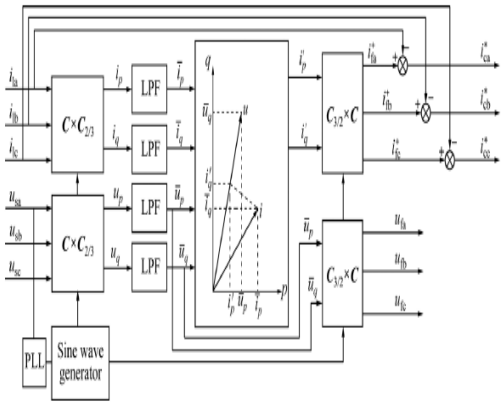

Figure 3. Principle diagram of proposed current reference isolation method.

Where i^*_{fx} denotes the positive sequence fundamental active current component which is isolated from three-phase load currents, i^*_{rx} denotes the reference current, u_{fx} is one of three-phase fundamental positive sequence voltages, and x=a, b, c. The expressions of i_{1x} and u_{sx} are the same as Eq.(1) and Eq.(2), the values of $\bar{i}_p$ and $\bar{i}_q$ are the same as Eq.(6), and the values of $\bar{u}_p, \bar{u}_q$ are given as follows:

$$\begin{bmatrix} \bar{u}_p \\ \bar{u}_q \end{bmatrix} = \begin{bmatrix} \sqrt{3}u_1^+ \cos(\theta_{u1}^+ - \gamma) \\ -\sqrt{3}u_{i1}^+ \sin(\theta_{u1}^+ - \gamma) \end{bmatrix} \quad (9)$$

On the basis of Eq.(9),the three-phase fundamental positive sequence components of mains voltages can be acquired on the basis of Figure 3 as follows:

$$\begin{bmatrix} u_{fa} \\ u_{fb} \\ u_{fc} \end{bmatrix} = C_{3/2}C^{-1}\begin{bmatrix} \bar{u}_p \\ \bar{u}_q \end{bmatrix} = \begin{bmatrix} \sqrt{2}U_1^+ \sin(\omega t + \theta_{u1}^+) \\ \sqrt{2}U_1^+ \sin(\omega t + \theta_{u1}^+ - 2\pi/3) \\ \sqrt{2}U_1^+ \sin(\omega t + \theta_{u1}^+ - 2\pi/3) \end{bmatrix} \quad (10)$$

Where u_{fx} represents the three-phase fundamental positive sequence mains voltage, and x=a,b,c.

Shown in Figure 4, a *p-q* rectangular coordinate is introduced to illustrate the presented method.

Where $\bar{i}_p$ and $\bar{i}_q$ (or $\bar{u}_p$ and $\bar{u}_q$) are the coordinate values of vector I (or U).

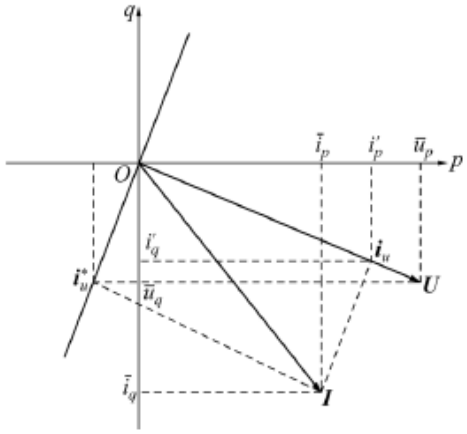

Figure 4. p-q rectangular coordinate.

Definition 1: In the *p-q* rectangular coordinate system, the instantaneous positive sequence active current vector i_u is the projection of vector I on vector U. The instantaneous positive sequence reactive current vector i^*_u is the projection of vector I on the normal line of vector U. The coordinate values of vector I and U can be acquired from three-phase currents and voltages by *p-q* transformation defined as follows:

$$\begin{bmatrix} i_p(u_p) \\ i_q(u_q) \end{bmatrix} = CC_{2/3}\begin{bmatrix} i_a(e_a) \\ i_b(e_b) \\ i_c(e_c) \end{bmatrix} \quad (11)$$

The reverse *p-q* transformation from p-q rectangular coordinate values to three-phase currents and voltages is

$$\begin{bmatrix} i_a(e_a) \\ i_b(e_b) \\ i_c(e_c) \end{bmatrix} = C_{3/2}C^{-}\begin{bmatrix} i_p(u_p) \\ i_q(e_q) \end{bmatrix} \quad (12)$$

We can know from Eq.(5) and Eq.(6) that $\bar{i}_p, \bar{i}_q$ and $\bar{u}_p$, $\bar{u}_q$ are only composed of fundamental components, then the positive sequence active current vector i_u only includes fundamental components.On the basis of Definition 1, the *p* and *q* coordinate values (i'_p, i'_q) of vector i_u can be acquired as follows:

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$$\begin{bmatrix} i'_p \\ i'_q \end{bmatrix} = \begin{bmatrix} \sqrt{3}I_1^+ \cos(\theta_{u1}^+ - \theta_{i1}^+)\cos(\theta_{u1}^+ - \gamma) \\ -\sqrt{3}I_{i1}^+ \cos(\theta_{u1}^+ - \theta_{i1}^+)\sin(\theta_{u1}^+ - \gamma) \end{bmatrix} \quad (13)$$

On the basis of Eq.(13),the fundamental positive sequence active currents are isolated from the load currents.As a result of performing reverse *p-q* transformation on i'_p, i'_q, i_{fx}^+ can be got as follows:

$$\begin{bmatrix} i_{fa}^+ \\ i_{fb}^+ \\ i_{fc}^+ \end{bmatrix} = C_{3/2}C^{-1}\begin{bmatrix} i'_p \\ i'_q \end{bmatrix} = \begin{bmatrix} \sqrt{2}I_1^+ \cos(\theta_{u1}^+ - \theta_{i1}^+)\sin(\omega t + \theta_{u1}^+) \\ \sqrt{2}I_1^+ \cos(\theta_{u1}^+ - \theta_{i1}^+)\sin(\omega t + \theta_{u1}^+ - 2\pi/3) \\ \sqrt{2}I_1^+ \cos(\theta_{u1}^+ - \theta_{i1}^+)\sin(\omega t + \theta_{u1}^+ - 2\pi/3) \end{bmatrix} \quad (14)$$

Comparing Eq.(14) with Eq.(1), we can give the three-phase reference currents i_{cx}^* (x=a, b, c) as follows:

$$i_{cx}^* = i_{fx}^+ - i_{1x} \quad (15)$$

From above, we know the PLL in Figure 3 could be employed to measure the angular frequency of mains voltages, which has nothing to do with the phase angle. Thus, the PLL can be eliminated if the angular frequency has been known as a constant.

3. Results and Discussion

The presented control strategy is simulated under unbalanced and distorted mains voltages, and an experimental prototype based on a DSP controller is implemented for the objective of testing of our strategy. The simulation model is established to compensate the source currents into the fundamental positive sequence active currents applying the presented control strategy. The mains voltages contain 3rd, 5th and 7th order harmonics with the ratios of 9.1%, 4.5% and 2.3%, separately. The initial phase angles of three-phase mains voltages are 25°, −125° and 120°. This implies that the mains voltages are unbalanced. A three-phase thyristor rectifier is taken as representative nonlinear load. Sampling rate is set to be 10 kHz. Simulation results are listed in Table 1. From Table 1, we can see that the THD of source current is reduced from 11%−16% to 3%−4% after the SAPF being connected.

Table 1 Experimental data

Phase	Source current/A					Mains voltage of Phase A/kV
	Before compensation			After compensation		
	A	B	C	A	B	
RMS of fundamental frequency	105.2	102.4	103.6	99.5	103.8	6.07
2nd order	1.14	0.96	1.12	0.46	0.48	0.20
3rd order	0.59	1.03	1.47	0.64	0.69	0.53
4th order	0.69	0.60	1.01	0.25	0.29	0.33
5th order	8.40	8.76	8.51	0.84	1.17	0.52
6th order	0.72	0.65	0.75	0.57	0.52	0.33
7th order	2.73	2.36	2.66	0.57	0.52	0.41
8th order	0.50	0.47	0.48	0.34	0.28	0.36
9th order	0.55	0.52	0.54	0.55	0.47	0.30
10th order	0.12	0.22	0.20	0.37	0.24	0.27
11th order	6.10	6.26	6.12	0.74	0.69	0.38
12th order	0.32	0.30	0.35	0.27	0.38	0.25
13th order	1.96	2.04	2.13	0.50	0.56	0.48
THD	11.05	11.32	11.07	3.24	3.46	1.31

4. Conclusion

The presented reference current calculation way can isolate both fundamental and positive sequence active current components of the load currents with unbalanced and distorted mains voltages.

2) The source current is sinusoidal and in phase with the positive sequence fundamental voltages after compensation.This implies that the SAPF is able to perform harmonic cancellation and reactive power compensation with non-ideal mains voltages.

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