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Current Reference Control for Shunt Active Power Filters Under Unbalanced and Distorted Supply Voltage Conditions

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ABSTRACT This paper proposes a current reference control method for shunt active power filter under unbalanced and distorted supply voltage conditions. The method uses the Kalman filter and the symmetrical component method to obtain the fundamental sequence component of the supply voltage. The Fryze-Buchholz-Dpenbrock method is used to decompose the load current under the reference of the fundamental positive-sequence voltage to obtain the reference value of the compensation current. The method is characterized without need of coordinate transformation, simple calculation, and clear physical meaning. The harmonic current, reactive current and negative sequence current can be compensated at the same time even under the condition of unbalanced supply voltage. The proposed method is compared with the traditional method under various experimental conditions to prove the validity and accuracy of the proposed method. The results show that the proposed method has wider applicability.

INDEX TERMS Fryze-Buchholz-Dpenbrock method, Kalman filter, shunt active power filter, symmetrical component method, unbalanced and distorted supply voltage.

I. INTRODUCTION

In recent years, with the widespread use of power electronic devices, non-linear and unbalanced loads, large quantities of harmonic current, reactive current and negative sequence current are injected into the power grid, which seriously threatens the safe operation of power grids and electrical equipment [1]. Shunt Active Power Filter (SAPF) can also be called switching compensator, which can dynamically suppress harmonics, compensate reactive power and negative sequence current. It is one of the most effective power quality adjustment methods at present [2].

Reference current control is the key to determining the performance of SAPF compensation. It can be divided into two parts: 1) detecting the reference value of SAPF injection current; 2) ensuring that the SAPF injection current accurately tracks the reference value. For the first part, the existing detection methods can be divided into frequency-domain detection mode, time-domain detection mode, and learning techniques. Frequency-domain detection method mainly includes discrete Fourier transform and fast Fourier transform [3], [4]. Time-domain detection method mainly includes Fryze-Buchholz-Dpenbrock (FBD) method and the p-q method based on instantaneous reactive power theory [5], [6]. Learning techniques include Genetic Algorithms (GA) and Artificial Neural Networks (ANN) [7], [8]. In the second part, the control methods that have been widely used in current tracking include hysteresis control, deadbeat control and proportional-integral regulator control, etc [9]–[12].

The main content discussed in this paper is the reference current detection link under unbalance and distorted supply voltage. In the reference current detection link, although the frequency-domain method has high detection accuracy, it has shortcomings such as a large amount of calculation and poor real-time performance; learning techniques also have problems such as making calculation complicated and difficult to realize [13]. The time-domain method has the advantages of simple calculation and clear physical meaning. The p-q method requires complex coordinate transformation, which not only increases the calculation amount but also limits its application range. In [14]–[16], the characteristics of p-q power theory and Fryze's power theory applied in the switching compensator control algorithm are analyzed. The Currents' Physical Components (CPC) power

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theory is the main theoretical tool for the presented analysis [17], [18]. In the case of distortion or asymmetry of the supply voltage, the p-q method cannot accurately extract the active component of the load current [19]. The compensation of the switching compensator based on the Fryze's power theory in real system is a recursive process. After the recursive process is completed, the supply current will converge to the active current defined according to the CPC power theory.

The presented compensation method is based on the FBD method, which follows the Fryze's power theory. The main principle of the FBD method is to equivalent the load in the actual circuit to the ideal conductance. It is considered that the power in the circuit is consumed on this equivalent conductance, and the current is decomposed according to the equivalent conductance. Since the calculation of the equivalent conductance is based on voltage, if the voltage contains harmonics or imbalance in the actual three-phase circuit, the final test result will be affected. In [20] it was used a voltage filter to extract the fundamental component of the grid voltage, which can accurately detect the reference value of the compensation current when the grid voltage is not sinusoidal. However, this method is not applicable in the case of unbalanced supply voltage. In [21] it was used the Fourier transform method to obtain the equilibrium component from the unbalanced voltage. This method requires a great deal of calculation and is not conducive to the rapid response of the system. In [22], [23], the compensation strategies of active power filter under distorted voltages have been discussed. Although good compensation results are obtained, the methods used are all complicated and not conducive to practical application. In [24], the Kalman filter (KF) is used to directly obtain the fundamental positive sequence component of the current, so it is not affected by the voltage, but the algorithm can only compensate the harmonic current but not the reactive current.

In this paper, the KF and the symmetrical component method are used to obtain the fundamental positive sequence component of distorted voltage, and then the current is decomposed by the FBD method under the fundamental positive sequence reference voltage to obtain the reference current. This method can simultaneously compensate harmonic current, negative sequence current and reactive current in three-phase system. Since the compensated supply current will no longer contain harmonic and negative sequence components, the active power originally generated by the harmonic and negative sequence components will be converted to the fundamental active current of the supply in the form of equal power.

The content structure of this paper is as follows: Section II introduces the basic structure and the existing reference current calculation method of the shunt active power filter. Section III refers to the proposed reference current calculation method. The experimental results in various cases are given in Section IV. Section V is the conclusion.

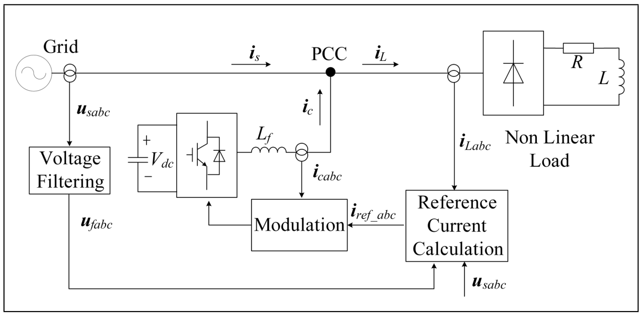

FIGURE 1. Shunt active power filter system structure.

II. RELATED WORK

A. SHUNT ACTIVE POWER FILTER

The structure of the three-phase shunt active power filter system is shown in Figure 1. The main circuit of SAPF consists of a DC capacitor and a voltage source inverter (VSI) which is connected to a point of common coupling (PCC) through a filter inductor and in parallel with a non-linear load. In this figure, the supply current is indicated by i_s, the compensation current is represented by i_c, the load current is represented by i_L, i_{ref} is the reference value of the compensation current, the supply voltage is represented by u_s, and u_f is the fundamental component of the supply voltage. The letters a, b and c in the variable subscript represent phases a, b and c, respectively.

The basic working principle of SAPF is to detect the voltage and current of the compensation object, obtain the reference value of the compensation current through the reference current calculation algorithm, and then control the pulse width modulation (PWM) converter output compensation current according to the reference signal. It can compensate the harmonic component of the load current and make the incoming current sinusoidal. Due to the characteristics of the DC side capacitor, SAPF can also output reactive power and increase the power factor of the system.

B. EXISTING CURRENT REFERENCE CONTROL METHOD

The block diagram of the existing current reference control method is given in Figure 2, which consists mainly of two parts. The first is voltage filtering. The second is reference current calculation.

1) VOLTAGE FILTERING

The voltage filtering is a series resonant analog filter whose differential equation can be written as

$$u(t) = i(t) \cdot R + L\frac{di(t)}{dt} + \frac{1}{C}\int_{-\infty}^{t} i(t)dt \tag{1}$$

Taking $\frac{du}{dt}$ as input and $\frac{di}{dt}$ as output, according to formula (1), the state equation of the system can

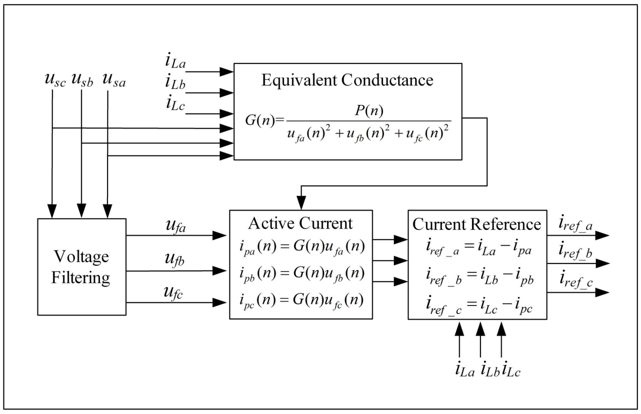

FIGURE 2. Structure of existing control method.

be obtained as

$$\begin{cases}\begin{bmatrix}\frac{di}{dt}\\ \frac{d^2i}{dt^2}\end{bmatrix}=\begin{bmatrix}0 & 1\\ -\omega_0^2 & -\frac{1}{L}\end{bmatrix}\begin{bmatrix}i\\ \frac{di}{dt}\end{bmatrix}+\begin{bmatrix}0\\ -\frac{1}{L}\end{bmatrix}\frac{du}{dt}\\ \frac{di}{dt}=\begin{bmatrix}0 & 1\end{bmatrix}\begin{bmatrix}i\\ \frac{di}{dt}\end{bmatrix}\end{cases} \tag{2}$$

Above $\frac{1}{LC}$ has been renamed as ω_0^2, and $R = 1$, In actual use, its output is the fundamental component of the supply voltage. After discretizing the above formula, the discrete transfer function of the voltage filter can be calculated as shown in equation (3). The specific calculation process and filter parameter design can be referred to [20].

$$\frac{y}{u}=\frac{\Gamma_{21}z^{-1}-(\Phi_{11}\Gamma_{21}-\Phi_{21}\Gamma_{11})z^{-2}}{1-(\Phi_{11}+\Phi_{22})z^{-1}+(\Phi_{11}\Phi_{22}-\Phi_{21}\Phi_{12})z^{-2}} \tag{3}$$

where u is the input and y is the output. Both $\mathbf{\Phi}$ and $\mathbf{\Gamma}$ are parameter matrices of discrete space state equations.

2) REFERENCE CURRENT CALCULATION

The FBD method is used to decompose the reference current. In [25], the active current of the single-phase system is defined as the minimum current required for active power transfer. According to this, the load current of a single-phase system can be decomposed into two parts as shown in equation (4).

$$i_L(t) = i_p(t) + i_q(t) \tag{4}$$

Above $i_p(t)$ is the active current, with the same waveform as the voltage waveform. And $i_q(t)$ is orthogonal to the voltage waveform, which is the current component to be compensated in a single-phase system, i.e. the current reference.

The active current in a three-phase system can be calculated by (5)

$$\mathbf{i}_p(t)=\begin{bmatrix}i_{pa}(t)\\ i_{pb}(t)\\ i_{pc}(t)\end{bmatrix}=\frac{P}{\|\mathbf{u}_s\|^2}\begin{bmatrix}u_{sa}(t)\\ u_{sb}(t)\\ u_{sc}(t)\end{bmatrix}=G\begin{bmatrix}u_{sa}(t)\\ u_{sb}(t)\\ u_{sc}(t)\end{bmatrix} \tag{5}$$

where P is active three-phase power, and $\|\mathbf{u}_s\|$ denotes the three-phase root mean square value of the voltage system, and G is equivalent conductance. The expressions of P and $\|\mathbf{u}_s\|$ are respectively:

$$P=\frac{1}{T}\int_0^T [u_{sa}(t)i_{La}+u_{sb}(t)i_{Lb}+u_{sc}(t)i_{Lc}] \tag{6}$$

$$\|\mathbf{u}_s\|=\sqrt{u_{sa}^2+u_{sb}^2+u_{sc}^2} \tag{7}$$

Therefore, according to equation (8), the active current $\mathbf{i}_p$ in phase with the voltage fundamental component can be obtained.

$$\mathbf{i}_p(t)=\begin{bmatrix}i_{pa}(t)\\ i_{pb}(t)\\ i_{pc}(t)\end{bmatrix}=\frac{P}{\|\mathbf{u}_f\|^2}\begin{bmatrix}u_{fa}(t)\\ u_{fb}(t)\\ u_{fc}(t)\end{bmatrix} \tag{8}$$

$\mathbf{u}_f$ is the fundamental component of the supply voltage.

In discrete-time, the active power P and the three-phase root mean square value of the fundamental component of the voltage $\|\mathbf{u}_f\|$ at an instant n can be calculated by (9) and (10), respectively.

$$P(n)=\frac{1}{NT_s}\sum_{m=n-N+1}^{n}\begin{bmatrix}u_{sa}(m)\\ u_{sb}(m)\\ u_{sc}(m)\end{bmatrix}^T\begin{bmatrix}i_{La}(m)\\ i_{Lb}(m)\\ i_{Lc}(m)\end{bmatrix} \tag{9}$$

$$\|\mathbf{u}_f(n)\|=\sqrt{u_{fa}(n)^2+u_{fb}(n)^2+u_{fc}(n)^2} \tag{10}$$

where N corresponds to the signal period and T_s is the sampling period.

Finally, the current reference at an instant n can be expressed as follows:

$$\begin{bmatrix}i_{ref\_a}(n)\\ i_{ref\_b}(n)\\ i_{ref\_c}(n)\end{bmatrix}=\begin{bmatrix}i_{La}(n)\\ i_{Lb}(n)\\ i_{Lc}(n)\end{bmatrix}-\frac{P(n)}{\|\mathbf{u}_f(n)\|^2}\begin{bmatrix}u_{fa}(n)\\ u_{fb}(n)\\ u_{fc}(n)\end{bmatrix} \tag{11}$$

The source current obtained by the above method is in phase with the fundamental component of the supply voltage, but when the supply voltage is unbalanced, the source current will also be unbalanced, so the method cannot be used in the case where the supply voltage is unbalanced.

III. PROPOSED CURRENT REFERENT CONTROL METHOD

In order to obtain the desired source current under the condition of unbalanced or non-sinusoidal voltage, the equivalent conductance must be calculated using the fundamental positive sequence component of the supply voltage as the reference voltage.The proposed reference current generation method is shown in Figure 3.

The proposed method differs from the existing method in that:

(1) Acquiring the fundamental sequence component of the supply voltage by KF and symmetrical component method.

(2) In the reference current calculation, the fundamental positive sequence component of the supply voltage is used as the reference voltage.

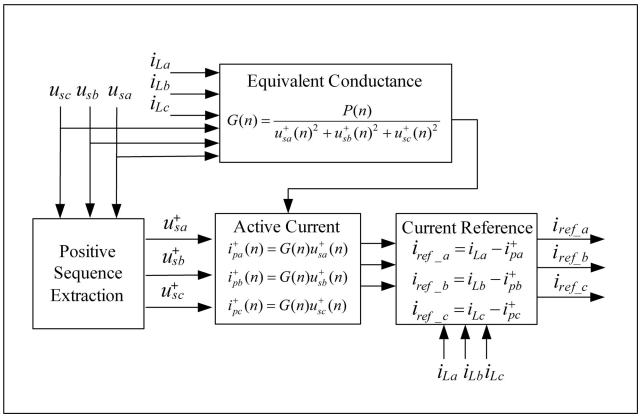

FIGURE 3. Structure of proposed control method.

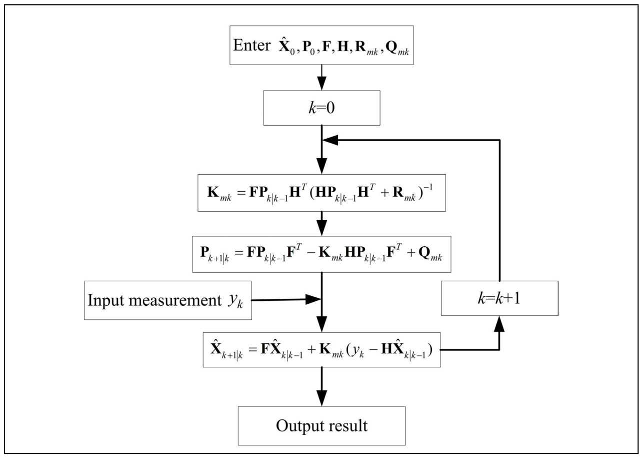

FIGURE 4. Working flow chart of KF.

A. POSITIVE SEQUENCE EXTRACTION

To separate the fundamental component of the voltage, resonant or low pass filters, analog or digital, are commonly used. However, these methods need to perform phase shift calculation when acquiring the in-quadrature component of the voltage fundamental, which will undoubtedly increase the amount of calculations performed by the algorithm. In [24] it was indicated that KF is the optimal estimation for linear systems. Through KF algorithm, both in-phase and in-quadrature components are directly estimated and thus have a faster calculation speed.

Using the KF algorithm to estimate the in-phase and in-quadrature components of the fundamental voltage, the 5 in-phase and quadrature components of the voltage fundamental wave are taken as state variables.

The state space equation of the system is expressed as follows:

$$\mathbf{X}_{k+1} = \mathbf{F}\mathbf{X}_k + \mathbf{W}_{mk} \tag{12}$$

$$y_k = \mathbf{H}\mathbf{X}_k + \mathbf{V}_{mk} \tag{13}$$

In the formula, $\mathbf{X}_k$is the state vector, $\mathbf{W}_{mk}$ and $\mathbf{V}_{mk}$ are the process and measurement noises,respectively. The state transition matrix $\mathbf{F}$ and the observed value $\mathbf{H}$ are given below:

$$\mathbf{F} = \begin{bmatrix} \cos(\omega_1 T_s) & \sin(\omega_1 T_s) \\ -\sin(\omega_1 T_s) & \cos(\omega_1 T_s) \end{bmatrix} \tag{14}$$

$$\mathbf{H} = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{15}$$

where ω_1 is the fundamental angular frequency, and T_s is the sampling period. Representing the estimate of $\mathbf{X}_{k+1}$ as $\hat{\mathbf{X}}_{k+1|k}$, the recursive estimation expression used to calculate the state variable is given by the following:

$$\hat{\mathbf{X}}_{k+1|k} = \mathbf{F}\hat{\mathbf{X}}_{k|k-1} + \mathbf{K}_{mk}(y_k - \mathbf{H}\hat{\mathbf{X}}_{k|k-1}) \tag{16}$$

where $\mathbf{K}_{mk}$ is the Kalman gain and is represented as follows:

$$\mathbf{K}_{mk} = \mathbf{F}\mathbf{P}_{k|k-1}\mathbf{H}^T(\mathbf{H}\mathbf{P}_{k|k-1}\mathbf{H}^T + \mathbf{R}_{mk})^{-1} \tag{17}$$

$\mathbf{P}_{k|k-1}$ is the error covariance matrix, where k in the subscript indicates the value of the current sampling period, and $k-1$ in the subscript indicates that it is related to the value of the previous sampling period. The recursive relationship of the error covariance matrix is:

$$\mathbf{P}_{k+1|k} = \mathbf{F}\mathbf{P}_{k|k-1}\mathbf{F}^T - \mathbf{K}_{mk}\mathbf{H}\mathbf{P}_{k|k-1}\mathbf{F}^T + \mathbf{Q}_{mk} \tag{18}$$

$\mathbf{R}_{mk}$ and $\mathbf{Q}_{mk}$ are the measurement and process error covariance matrices, respectively.

$$\mathbf{P}_{k+1|k} = E\{(\mathbf{X}_{k+1} - \hat{\mathbf{X}}_{k+1|k})(\mathbf{X}_{k+1} - \hat{\mathbf{X}}_{k+1|k})^T\} \tag{19}$$

$$\mathbf{Q}_{mk} = E\{\mathbf{W}_{mk}\mathbf{W}_{mk}^T\} \tag{20}$$

$$\mathbf{R}_{mk} = E\{\mathbf{V}_{mk}\mathbf{V}_{mk}^T\} \tag{21}$$

where $E\{\cdot\}$ denotes the expectation operator. Figure 4 is the working flow chart of KF.

The positive sequence voltage can be calculated by the following formula:

$$\begin{bmatrix} U_{sa}^+ \\ U_{sb}^+ \\ U_{sc}^+ \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & \alpha & \alpha^2 \\ \alpha^2 & 1 & \alpha \\ \alpha & \alpha^2 & 1 \end{bmatrix}\begin{bmatrix} U_{fa} \\ U_{fb} \\ U_{fc} \end{bmatrix} \tag{22}$$

where $(U_{sa}^+, U_{sb}^+, U_{sc}^+)$ are the positive sequence voltage and $\alpha = e^{j120^\circ}$. Considering 120 degrees phase shift operator can be expressed as follows:

$$\alpha = e^{j120^\circ} = -\frac{1}{2} + \frac{\sqrt{3}}{2}e^{j90^\circ} \tag{23}$$

Bring equation (23) into equation (22):

$$\begin{cases} U_{sa}^+ = \frac{1}{3}U_{fa} - \frac{1}{6}(U_{fb} + U_{fc}) + \frac{\sqrt{3}}{6}(qU_{fc} - qU_{fb}) \\ U_{sb}^+ = \frac{1}{3}U_{fb} - \frac{1}{6}(U_{fc} + U_{fa}) + \frac{\sqrt{3}}{6}(qU_{fa} - qU_{fc}) \\ U_{sc}^+ = \frac{1}{3}U_{fc} - \frac{1}{6}(U_{fa} + U_{fb}) + \frac{\sqrt{3}}{6}(qU_{fb} - qU_{fa}) \end{cases} \tag{24}$$

In the above formula, $q = e^{j90^\circ}$. U_{fa}, U_{fb}, U_{fc}, qU_{fa}, qU_{fb} and qU_{fc} are the estimated values returned by the KF.

B. NEW REFERENCE CURRENT CALCULATION

The proposed fundamental positive sequence active current $\mathbf{i}_p^+(t)$ and equivalent conductance G can be expressed as follows:

$$\mathbf{i}_p^+(t) = \begin{bmatrix} i_{pa}^+(t) \\ i_{pb}^+(t) \\ i_{pc}^+(t) \end{bmatrix} = \frac{P}{\|\mathbf{u}_s^+\|^2} \begin{bmatrix} u_{sa}^+(t) \\ u_{sb}^+(t) \\ u_{sc}^+(t) \end{bmatrix} = G \begin{bmatrix} u_{sa}^+(t) \\ u_{sb}^+(t) \\ u_{sc}^+(t) \end{bmatrix} \tag{25}$$

In discrete-time, the active power P and the three-phase root mean square value of the fundamental positive sequence component of the voltage $\|\mathbf{u}_s^+\|$ at an instant n can be calculated by (26) and (27), respectively.

$$P(n) = \frac{1}{NT_s} \sum_{m=n-N+1}^{n} \begin{bmatrix} u_{sa}(m) \\ u_{sb}(m) \\ u_{sc}(m) \end{bmatrix}^T \begin{bmatrix} i_{La}(m) \\ i_{Lb}(m) \\ i_{Lc}(m) \end{bmatrix} \tag{26}$$

$$\|\mathbf{u}_s^+(n)\| = \sqrt{u_{sa}^+(n)^2 + u_{sb}^+(n)^2 + u_{sc}^+(n)^2} \tag{27}$$

where, $u_{sa}^+(n), u_{sb}^+(n), u_{sc}^+(n)$ are the fundamental positive sequence component of the voltage in the instant n and can be calculated by (24).

The current reference at an instant n can be expressed as follows:

$$\begin{bmatrix} i_{ref\_a}(n) \\ i_{ref\_b}(n) \\ i_{ref\_c}(n) \end{bmatrix} = \begin{bmatrix} i_{La}(n) \\ i_{Lb}(n) \\ i_{Lc}(n) \end{bmatrix} - \frac{P(n)}{\|\mathbf{u}_s^+\|^2} \begin{bmatrix} u_{sa}^+(n) \\ u_{sb}^+(n) \\ u_{sc}^+(n) \end{bmatrix} \tag{28}$$

IV. EXPERIMENTAL VALIDATION

A. EXPERIMENT SETUP

The experimental device is shown in Figure 5. The proposed reference current algorithm is implemented by DSPF28335. The grid voltage is provided by a three-phase programmable AC power supply. The SAPF DC side voltage is provided by a rectifier circuit. The non-linear load is an uncontrollable rectifier circuit with RL load. System parameters are shown in Table 1.

In order to verify the method proposed in this paper, four test cases were set to compare the method of this paper with the method of [20].

B. TEST CASE 1: SINUSOIDAL AND BALANCED VOLTAGE

Figure 6 shows the experimental waveforms of the existing method and the proposed method when the supply voltage is sinusoidal and balanced. Where u_s is the supply voltage, i_L, i_s and i_c are the load current, the source current and the compensation current, respectively.

It can be seen from the waveform of the load current that its harmonic content is high. After compensation, the waveform of the source current is approximately sinusoidal and in phase with the supply voltage. The compensation current is the output current of SAPF, and its value is approximately the sum of harmonic current and reactive current in the load current. At this time, the THD value of the load current is 29.54%. The THD value of the source current compensated by the existing method is 3.94%, and the THD value of the source current compensated by the proposed method is 3.92%. It can also be seen from the waveforms of the supply voltage and the source current that both methods can achieve a unity power factor.

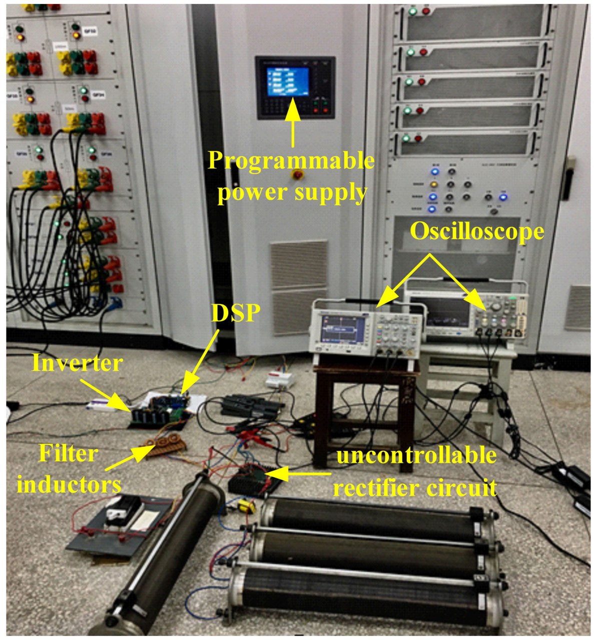

FIGURE 5. Experimental setup.

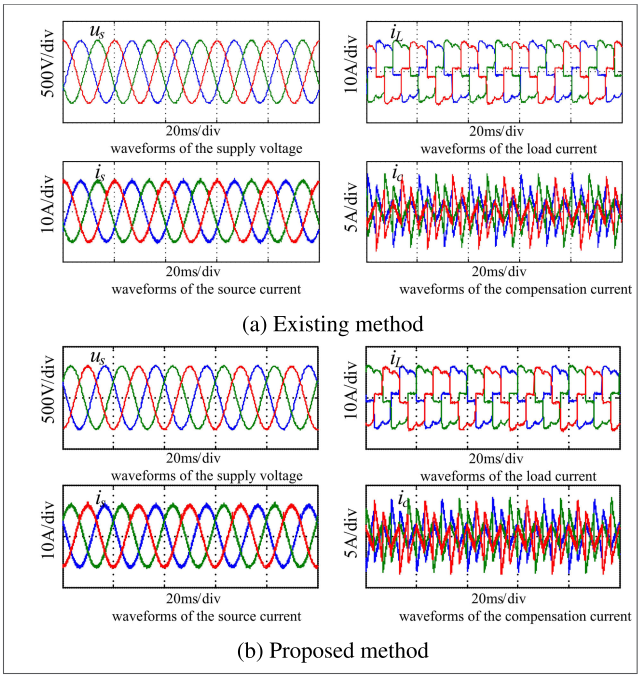

FIGURE 6. Test case 1: experimental waveform with voltage sinusoidal and balanced.

TABLE 1. System parameters.

Parameters	Values	explanation
U_s /V	220	Supply voltage RMS
f_s/Hz	50	Supply frequency
V_{dc}/V	750	DC-link voltage
L_f/mH	20	Filter inductor
L/mH	1.5	Load inductor
R/Ω	100	Load Resistance
f_{pwm}/ kHz	10	Switching frequency
f_c/ kHz	25	Sampling frequency

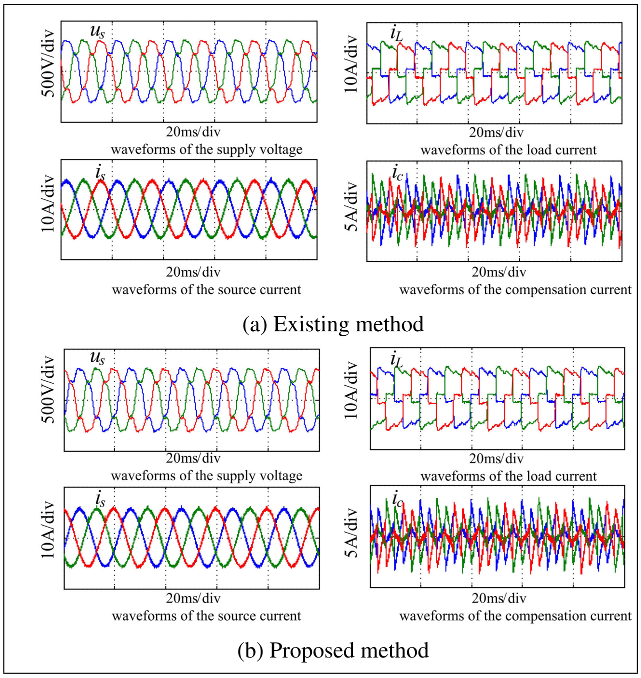

FIGURE 7. Test case 2: experimental waveform with voltage non-sinusoidal and balanced.

C. TEST CASE 2: NON-SINUSOIDAL AND BALANCED VOLTAGE

Figure 7 shows the experimental waveforms when the supply voltage is balanced but not sinusoidal. The supply voltage contains 5% of the 3rd harmonic, 10%of the 5th harmonic and 8% of the 7th harmonic. As can be seen from the figure, the harmonic content of the load current is high. After compensation, the waveform of the source current is approximately sinusoidal. The value of the compensation current is approximately the sum of the harmonic current and the reactive current in the load current. At this time, the THD value of the load current is 29.82%. The THD value of the source current compensated by the existing method is 4.42%. And the THD value of the source current compensated by the proposed method is 4.33%. The source current is in phase with the fundamental component of the supply voltage.

D. TEST CASE 3: SINUSOIDAL AND UNBALANCED VOLTAGE

Figure 8 shows the experimental waveforms when the supply voltage is sinusoidal but unbalanced. The RMS values of each phase of the supply voltage are 240V, 220V

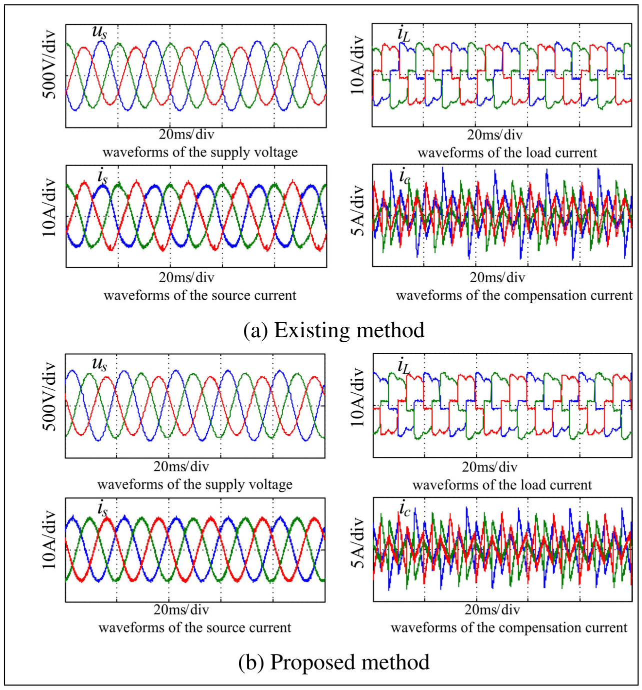

FIGURE 8. Test case3: experimental waveform with voltage sinusoidal and unbalanced.

and 200V respectively. In the case of supply voltage unbalanced, the waveform of the load current contains not only more harmonics but also unbalanced. At this time, the THD value of the load current is 32.08%. It can be seen that the source current compensated by the existing method is unbalanced and the harmonic content is high. This shows that the existing method cannot accurately extract the active component of the load current under the condition of unbalanced supply voltage. The source current compensated by the proposed method is sinusoidal and balanced, and its THD value is 3.97%, and the source current is in phase with the fundamental positive sequence component of the supply voltage. The compensation current obtained by the proposed method is approximately the sum of harmonic current, reactive current and negative sequence current in the load current.

E. TEST CASE 4: NON-SINUSOIDAL AND UNBALANCED VOLTAGE

Figure 9 shows the experimental waveforms when the supply voltage is not sinusoidal and unbalanced. The voltage harmonic content was the same as in Test Case 2, and the imbalance was the same as Test Case 3.At this time, the THD value of the load current is 32.35%, and the source current is also unbalanced and the harmonic content is high compensated by the existing method. It is again stated that the existing method cannot accurately extract the active component of the load current under the condition of unbalanced supply voltage. The proposed method can still make the source current sinusoidal and balanced, and its THD value is 4.48%, and the source current is in phase with the fundamental positive sequence component of the supply voltage. The compensation current obtained by the proposed method is

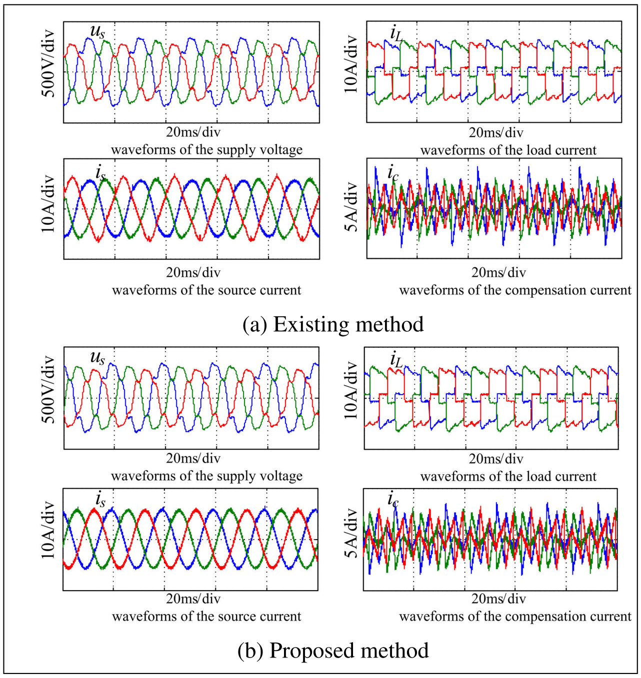

FIGURE 9. Test case 4: experimental waveform with voltage non-sinusoidal and unbalanced.

TABLE 2. THD% of Phase-A source current.

Test Case	Before Compensation	After Compensation	
		Proposed Method	Existing Method
Test Case 1	29.54%	3.92%	3.94%
Test Case 2	29.82%	4.33%	4.42%
Test Case 3	32.08%	3.97%	6.68%
Test Case 4	32.35%	4.48%	7.30%

approximately the sum of harmonic current, reactive current and negative sequence current in the load current.

F. EXPERIMENT SUMMARY

From the comparison of the experimental waveforms in the four cases in Figure 6–9, it can be seen that both methods can meet the requirements of current compensation in the case of supply voltage balance. When the supply voltage is unbalanced, the harmonics of the source current compensated by the existing method are high and unbalanced. But the proposed method can still meet the compensation requirements, which illustrates the effectiveness of the proposed method.

Table 2 shows the THD values before and after source current compensation in various test cases. Both methods meet the requirements of IEEE-519 [26] in each case. However, in the case of unbalanced voltage, the THD value using the conventional method is much higher than that of the proposed method. This also shows that the proposed method has better compensation effect than the existing method under the condition of unbalanced voltage.

V. CONCLUSION

In this paper, a reference current control method for the active power filter under unbalanced grid voltage is proposed. A fundamental positive sequence component extraction strategy based on the KF algorithm and symmetrical component method is constructed, which can effectively obtain the fundamental positive sequence component of voltage under the condition of unbalanced supply voltage. Combined with the FBD method, the reference value of compensation current can be accurately obtained without coordinate transformation by taking the positive sequence component of fundamental wave of the voltage as reference. The results of multiple sets of comparative experiments show that the method can compensate the load harmonic current, reactive current and negative sequence current simultaneously under the unbalanced grid voltage, which has wider applicability than the existing methods.

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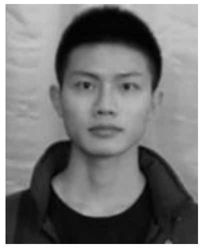

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