A Harmonic Current Detection Method for APF Under Unbalanced Voltage Condition Using Complex LMS Estimation

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Abstract. The unbalanced voltage conditions deteriorate the performance of the harmonic detection of active power filter (APF). To address this problem, a complex LMS based method is proposed in this paper. A complex Least Mean Squares (LMS) is designed for phase-tracking. DSPOC principle is utilized to adjust the estimate of synchronous frequency. Then, the proposed method is employed to improve the harmonic detection of APF. The effectiveness of the method is confirmed through simulation results.

Introduction

The effective measurement of harmonic current is crucial for active power filter [1] to deliver reliable power compensation. Many factors, such as the mismatched frequency between microgrid and main electrical grid, single-phase fault [2], will cause unbalance of voltage and perturbation of voltage frequency within a power grid [3]. All these deteriorates the harmonic current detection performance.

To improve the compensation accuracy of APF under voltage-unbalanced conditions, positive-sequence component filter was presented in [4]. This method shows an unsatisfied performance under an unbalanced-voltage condition. Also, through using multiple frequency rotation coordinates, the frequency perturbation is reliably overcome [5]. However, this technique falls short in the case of unbalanced voltage since it does not account for negative sequence [5]. A FBD-based method to extracting positive sequence component was introduced [6] and applied to effectively diagnose harmonic in a complicated electrical power system. A strategy was used to address the difficulty caused by unbalanced voltage to APF harmonic compensation. Have to mention that the shift of voltage frequency was not taken into account in these two methods [6][7]. Through modifying PLL technique to extract positive-sequence component[8], the harmonic compensation under an unbalanced voltage condition was improved. However, this method display the slow response and is over-sensitive to the variability of frequency as well. In addition, the analysis of the impact of the error of phase estimation on harmonic detection leaded to the design of a soft phase-locked loop [9]. However, an additional wave-filtering module in this method causes the slowdown of dynamic response. Furthermore, many advanced techniques have been adopted to deal with the aforementioned issues without a satisfactory performance.

In this paper, we propose a complex least mean square (LMS) algorithm under a (ip-id) based framework to detect harmonic current for an APF. A complex LMS based phase-measuring algorithm is detailed, and is integrated into APF. The effectiveness is confirmed through simulation results.

Frequency Estimation of Unbalanced Three-Phase Power System

An unbalanced three-phase line voltage \{Ea, Eb, Ec\} can be represented by the orthogonal sum of a positive and a negative sequence (eq. 1).

\[
E_{dq}(t_i) = e^{j\omega t_i} E_{dq}^p(t_i) + e^{-j\omega t_i} E_{dq}^n(t_i)
\]

(eq. 1)
here $\omega = 2\pi \times 50$[rad/s]. The subscripts s and e denote the quantities in the stationary coordinate and in the synchronous rotation coordinate with the phase $\omega$, respectively. Also, the superscripts p and n are the quantities of positive and negative sequence components, respectively. In addition, we have (2) (3) (4). After multiplying eq. 4 by $e^{-j\omega t_i}$, the phase angle of three-phase voltage is measured as

$$\varphi(t_i) = \angle(e^{-j\omega t_i} E_{dq(e)}(t_i)) = \angle(E_{dq(e)}^p(t_i) + e^{-j\omega t_i} E_{dq(e)}^n(t_i)) = \phi(t_i) + \tilde{\phi}(t_i)$$

where $\phi(t_i) = \angle E_{dq(e)}^p(t_i)$ is the phase angle of the positive sequence component in the synchronous rotation coordinate. $\tilde{\phi}(t_i)$ is the measurement error caused by the negative sequence, which contains AC ripple of $2\omega$. Under balanced voltage conditions, $\varphi(t_i)$ contains only DC component since negative sequence component is zero. When an unbalance voltage power system (say the one having the frequency in 50Hz) is applied, the 100Hz oscillating error $\varphi(t_i)$ is caused. The offsets of the estimate of phase will cause large detection error of current harmonics, fundamental component and reactive component [8].

### Complex-LMS Based Harmonic Detection for APF

To address the above problems caused by voltage unbalance, we developed a complex-LMS based harmonic detection modules for an APF, which is detailed in this section.

#### Complex Model of Unbalanced Three-Phase Voltage System

Eq. 1 can be rewritten in a format of matrix as

$$E_{dq(e)}(t_i) = \begin{bmatrix} E_{dq(e)}^p(t_i) & E_{dq(e)}^n(t_i) \end{bmatrix} \begin{bmatrix} e^{j\omega t_i} \\ e^{-j\omega t_i} \end{bmatrix}$$

(6)

$$y(t_i) = E_{dq(e)}(t_i) = E_{ds}(t_i) + jE_{qs}(t_i) = y_R(t_i) + jy_I(t_i)$$

(7)

$$\hat{w}^H(t_i) = \begin{bmatrix} E_{dq(e)}^p(t_i) & E_{dq(e)}^n(t_i) \end{bmatrix} = \begin{bmatrix} E_{ds}(t_i) + jE_{qs}(t_i) & E_{ds}(t_i) + jE_{qs}(t_i) \end{bmatrix}$$

(8)

$$u(t_i) = \begin{bmatrix} e^{j\omega t_i} \\ e^{-j\omega t_i} \end{bmatrix} = \begin{bmatrix} \cos \omega t_i + j \sin \omega t_i \\ \cos \omega t_i - j \sin \omega t_i \end{bmatrix} = u_R(t_i) + ju_I(t_i)$$

(9)

$$y(t_i) = \hat{w}^H(t_i)u(t_i)$$

(10)

where $R$ and $I$ are the real and imaginary part of a vector, eq. (6) is transformed as (10). Also, eq. 8 can be remodeled in a form of

$$\hat{w}(t_i) = \begin{bmatrix} E_{ds}(t_i) - jE_{qs}(t_i) \\ E_{ds}(t_i) - jE_{qs}(t_i) \end{bmatrix} = \hat{w}_R(t_i) + j\hat{w}_I(t_i)$$

(11)

### Complex-LMS-Based Algorithm for Phase Measurement

With the complex model introduced in the last section, we proposed a complex LMS algorithm for phase detection. A traditional LMS algorithm is shown in Fig.1 [10].
After parallelizing the complex model introduced in section 4.1 and the LMS algorithm, we can regard eq. 9 as the input of the transversal filter. Also, eq. 11 can be considered as the tap weight vector of and the output of adaptive weight-adjustment algorithm as well. Similarly, eq. 7 is the output of the transversal filter, which is used as the estimate of the expected response. After writing the estimation error $e(t_i)$ and the expected response $d(t_i)$ in a format of complex model, we have

$$e(t_i) = e_R(t_i) + je_j(t_i)$$  \hspace{1cm} (12)

$$d(t_i) = d_R(t_i) + jd_j(t_i)$$  \hspace{1cm} (13)

As to the complex model in section 4.1, the real and imaginary part of $d(t_i)$ correspond to $E_{ds}(t_i)$ and $E_{qs}(t_i)$, the result of transforming a given three-phase voltages through the 3-2 model. After applying the LMS algorithm to the real and imaginary part of eq. (7)(19)(11), we have

$$y_R(t_i) = \hat{w}_R^T(t_i)u_R(t_i) - \hat{w}_I^T(t_i)u_I(t_i)$$  \hspace{1cm} (14)

$$y_I(t_i) = \hat{w}_R^T(t_i)u_I(t_i) + \hat{w}_I^T(t_i)u_R(t_i)$$  \hspace{1cm} (15)

$$e_R(t_i) = d_R(t_i) - y_R(t_i)$$  \hspace{1cm} (16)

$$e_I(t_i) = d_I(t_i) - y_I(t_i)$$  \hspace{1cm} (17)

The weights in the above equations are updated in a way of eq. (18)(19) where $\mu$ is the step length of the LMS algorithm. When $0<\mu<1/\lambda_{\text{max}}$, the algorithm is convergent. $\lambda_{\text{max}}$ is the largest eigenvalue of the coefficient matrix of input signal. In this study, we set $\mu=0.5/\lambda_{\text{max}}$

$$\hat{w}_R(t_{i+1}) = \hat{w}_R(t_i) + \mu[e_R(t_i)u_R(t_i) - e_I(t_i)u_I(t_i)]$$  \hspace{1cm} (18)

$$\hat{w}_I(t_{i+1}) = \hat{w}_I(t_i) + \mu[e_R(t_i)u_I(t_i) + e_I(t_i)u_R(t_i)]$$  \hspace{1cm} (19)
Eqs (14-17) consist of the transversal filter in the LMS algorithm, which can be expressed by a cross-coupling signal flow diagram (Figure 2.). Likewise, eqs. (18-19), used for updating the weights, can be expressed with a signal flow diagram (Figure 3.).

When the output of the transversal filter tracks the expected input $d(t_i)$, i.e., $E_d(t_i)$ and $E_q(t_i)$ derived from the 3-2 transformation of three-phase voltage signal, the positive sequence component and initial phase can be estimated through eq. (11). That is, we have

$$\hat{\phi}(t_i) = \tan^{-1}\left[\frac{E_p(t_i)}{E_q(t_i)}\right]$$

(20)

**Adjustment of Frequency**

For the algorithm to measure phase, the frequency of a power grid is vital. In Eq. (9), $\omega$ in $u(t_i)$ is the $\omega$ of a given power grid. Also the positive sequence component of voltage signal $\hat{E}_{dq_p}^p(t_i)$ is estimated as a constant vector in a complex coordinate. The initial phase of the positive sequence component eq. 20 is a constant. The offset between the estimate frequency $\hat{\omega}$ and the voltage frequency in a given power system is $\Delta \omega = \omega - \hat{\omega}$. Below we discuss how the positive sequence component $\hat{E}_{dq_p}^p(t_i)$ is used to evaluate $\Delta \omega$ and finally to adjust the frequency estimation. In the dq coordinate, the rotation of $\hat{E}_{dq_p}^p(t_i)$ by $\Delta \omega$ can be broken down as

$$\hat{E}_{dq_p}^p(t_i) = x_1(t_i) = E \sin(\Delta \omega t_i + \phi)$$

(21)

$$\hat{E}_{dq_p}^p(t_i) = x_2(t_i) = E \cos(\Delta \omega t_i + \phi)$$

(22)

where $E$ and $\phi$ are the module of $\hat{E}_{dq_p}^p(t_i)$ and the phase of this module, respectively. With the DSPOS principle [16], we have

$$\Delta \omega = \frac{x_2(t_i)x_1(t_i') - x_1(t_i)x_2(t_i')}{x_1^2(t_i') + x_2^2(t_i')}$$

(23)

Using this equation, we adjust the $\omega$ in $u(t_i)$, and finally arrive at $\hat{\omega} = \omega$.

**Simulation Results**

A comparative simulation among the proposed method, Kalman-filter-based[12] and dqPLL-based phase-estimation algorithms [13] is carried out to examine the effectiveness of the proposed method in this section.

**Simulation Results of Phase Measurement**

To examine the proposed algorithm of phase measurement in a harmonic detection, we compared this algorithm with a Kalman filter based method and dqPLL in simulation tests. We generated unbalanced voltage power through adding the positive (311V) and the negative sequence component (50V)

![Figure 4. The phase estimation results with algorithms.](image1.png)

![Figure 5. The frequency tracking results different with different algorithms.](image2.png)
The parameters of Kalman filter used in this paper can be found in [12]. The parameters of PI controller in dqPLL can be found in [13]. As shown in this figure 4, the proposed complex LMS algorithm (represented by a red solid line) respond faster than other methods. The settling time is around 20ms. A simulation under frequency step change condition is also carried out as shown in Fig.5. The grid frequency jump from 50Hz to 51Hz at 0.06s. As shown in Fig.5, the proposed algorithm also provide a more satisfactory performance than other two.

Figure 6. The waveform of simulation.

Simulation Analysis of APF Harmonic Detection

We also carried out the simulation using Matlab/Simulink. The simulations started with balanced three-phase loads. At the time point of 0.05s, APF was used for harmonic compensation. At 0.1s, a non-linear load was added. At 0.15s, our simulation power system became unbalanced, coupling with the frequency shift of 0.5 Hz. At this time point, the conventional method was used for harmonic compensation. At 0.2s, we used the proposed harmonic compensation method. At 0.25s, another non-linear load was added to the power system. (Figure 6.) demonstrates our simulation results.

As shown in (Figure 6.) , the conventional APF performed well under the conditions of balanced voltage in that total harmonic distortion is around 3%. However in the case of un-balanced loads, the conventional APFs delivered the disappointed results with total harmonic distortion roaring up to 22.49%, which was even worse than the one without harmonic compensation. After applying the proposed method in the APF, we approached the promising harmonic compensation since the total harmonic distortion is around 3%.

Conclusion

To address the challenge posed by voltage unbalance to harmonic detection, we present a complex LMS based harmonic detection method for APF in this paper. Our method is capable of accurately extracting the phase and frequency of the positive sequence component in a given power system, and of effectively deal with voltage unbalance in a power system. The simulation and experiment results show that, as compared to the APF with a traditional harmonic detection algorithms, the APF using the proposed method delivers a better result of harmonic compensation, suggesting the contribution and advantage of the proposed harmonic detection method.
References


