Extended Kalman Filter Based Grid Synchronization in the Presence of Voltage Unbalance for Smart Grid

Sun, M.; Sahinoglu, Z.

TR2011-068 January 17, 2011

Abstract

In this paper, grid synchronization for gird-connected power generation systems in the presence of voltage unbalance and frequency variation is considered. A new extended Kalman filter based synchronization algorithm is proposed to track the phase angle of the utility network. Instead of processing the three-phase voltage signal in the abc natural reference frame and resorting to the symmetrical component transformation as in the traditional way, the proposed algorithm separates the positive and negative sequences in the transformed alpha-beta stationary reference frame. Based on the obtained expressions in alpha-beta domain, an EKF is developed to track both the in-phase and quadrature sinusoidal signals together with the unknown frequency. An estimate of the phase angle of the positive sequence is then obtained. As a by-product, estimates of phase angle of negative sequence and grid frequency are also computed. Compared to the commonly used scheme, the proposed algorithm has a simplified structure. The good performance is supported by computer simulations.

IEEE PES Innovative Smart Grid Technologies Conference (ISGT) 2011

Extended Kalman Filter Based Grid Synchronization in the Presence of Voltage Unbalance for Smart Grid

Ming Sun, *Student Member, IEEE,* and Zafer Sahinoglu, *Senior Member, IEEE*

***Abstract*—In this paper, grid synchronization for gird-connected power generation systems in the presence of voltage unbalance and frequency variation is considered. A new extended Kalman filter based synchronization algorithm is proposed to track the phase angle of the utility network. Instead of processing the three-phase voltage signal in the abc natural reference frame and resorting to the symmetrical component transformation as in the traditional way, the proposed algorithm separates the positive and negative sequences in the transformed $\alpha\beta$ stationary reference frame. Based on the obtained expressions in $\alpha\beta$ domain, an EKF is developed to track both the in-phase and quadrature sinusoidal signals together with the unknown frequency. An estimate of the phase angle of the positive sequence is then obtained. As a by-product, estimates of phase angle of negative sequence and grid frequency are also computed. Compared to the commonly used scheme, the proposed algorithm has a simplified structure. The good performance is supported by computer simulations.**

***Index Terms*—Frequency estimation, grid-connected power systems, grid synchronization, phase angle estimation.**

I. INTRODUCTION

Grid synchronization to the utility network is a very critical issue for the purpose of control and operation when more and more distributed power generation systems are in use and connected to the utility network [1]. The basic task of grid synchronization is to compute the phase angle of the three-phase voltage signal in utility grid [2]. In the presence of voltage unbalance, this becomes very challenging because the unbalanced three-phase signal is composed of positive, negative and zero sequences and the aim is to detect the phase angle of the positive sequence instead of the original signal. For example, although the state-of-the-art phase locked loop (PLL) has already proven to work well under most abnormal grid conditions, it suffers from performance degradation in the presence of voltage unbalance because a double frequency component is introduced due to the existence of negative sequence [3]. In addition, the grid frequency may deviate from the nominal frequency in practice, which makes the task even difficult. In this paper, we consider the grid synchronization in the presence of voltage unbalance and frequency variation.

A number of algorithms have been proposed to detect the phase angle of the grid signal in the presence of unbalance. Among them, a commonly used scheme is based on the extraction of the positive sequence through the application of symmetrical component transformation [4]–[7]. This scheme accomplishes the synchronization task in three steps: 1) obtain the noise reduced three-phase input signal and its 90-degree phase-shifted version first by certain techniques; 2) extract the positive sequence from the obtained three-phase input signal and its 90-degree phase shift by symmetrical components transformation; 3) estimate the phase angle from the positive sequence by applying some methods originally designed for balanced signal, such as PLL. To obtain an appropriate 90-degree phase-shifted signal is not easy. All-pass filter and Kalman filter have been applied when the grid frequency is known exactly [4], [5]. If there is frequency variation, the grid frequency should also be tracked to improve the performance. The enhanced PLL (EPLL) [6] and adaptive notch filter (ANF) [7] belong to this case. Note that the phase angle detection is accomplished in the abc natural reference frame. Three EPLLs or ANFs are needed to obtain the 90-degree phase shift (one for each phase) and a fourth one is used to compute the phase angle from the positive sequence. Therefore, this approach has a high computational complexity. In addition, since the negative sequence voltage and the phase angle between the positive and negative sequence voltages are sensitive to estimation errors, these methods may suffer from inaccuracies due to the presence of noise and harmonic distortions [5].

In this paper, we propose a different scheme to accomplish the synchronization task in the presence of unbalance. Both amplitude and phase unbalance are considered. Instead of processing the three-phase voltage signal in the abc natural reference frame, we separate the positive and negative sequences in the transformed $\alpha\beta$ stationary reference frame by the application of Clarke transformation. As a result, an explicit expression of the phase angle of the positive sequence is obtained. By choosing the in-phase and quadrature sinusoidal signals together with the grid frequency as the state variables, an extended Kalman filter based solution is developed. The proposed algorithm simplifies the structure of the estimation: the number of variables to be estimated and processing units are reduced and the symmetrical component transformation and the following processing are not required. It also succeeds in tracking the step change of the grid frequency.

II. PROBLEM FORMULATION

The three-phase voltage signal of utility grid is measured and utilized for the purpose of grid localization. In the presence of unbalance, the discrete three-phase voltage signal corrupted by additive noise is expressed as

$$\begin{aligned} v_a(n) &= V_a \cos(n\omega + \varphi_a) + e_a(n) \\ v_b(n) &= V_b \cos(n\omega + \varphi_b) + e_b(n) \\ v_c(n) &= V_c \cos(n\omega + \varphi_c) + e_c(n) \end{aligned} \tag{1}$$

where n is the time instant $n = 0, 1, 2, ...$, V_i and φ_i for $i = a, b, c$ are the amplitude and initial phase angle of the phase i. The values of V_a, V_b and V_c may be different from each other and φ_a, φ_b and φ_c may not obey the relationship $\varphi_b = \varphi_a - 2\pi/3$ and $\varphi_c = \varphi_a + 2\pi/3$. As a result, (1) models the unbalance in amplitude, phase or both. Nevertheless, All V_i and φ_i are not known. In (1), ω is the angular frequency of the grid and $\omega = 2\pi f/f_s$, where f and f_s are the grid frequency and the sampling frequency respectively. It is well known that ideally f is equal to its nominal value f_o that is 50 or 60 Hz. In practice, the grid frequency f may deviate from its nominal value f_o. Hence ω is also treated as an unknown parameter. The additive noise vector at time instant n is $\mathbf{e}(n) = [e_a(n), e_b(n), e_c(n)]^T$ and it is assumed to be a zero-mean Gaussian random vector with covariance matrix $\mathbf{Q}$. The noise vectors at different time instants are uncorrelated, i.e., $E[\mathbf{e}(n)\mathbf{e}(m)^T] = \mathbf{O}, n \neq m$. Although all V_i, φ_i and ω in (1) are unknown parameters. However, none of them is the

M. Sun is with the Department of Electrical and Computer Engineering, University of Missouri, Columbia, MO 65211, USA (e-mail: msxqc@mail.missouri.edu).

Z. Sahinoglu is with Mitsubishi Electric Research Laboratories (MERL), Cambridge, MA 02139, USA (e-mail: zafer@merl.com).

interested parameter since the phase angle of the positive sequence is the unknown to be estimated for synchronization in the presence of unbalance.

We next present an alternative expression of (1) where an explicit expression of the phase angle of positive sequence is available. According to the Fortescue theorem [8], [9], the three-phase grid voltage signal $\mathbf{v}(n) = [v_a(n), v_b(n), v_c(n)]^T$ can be rewritten as

$$\mathbf{v}(n) = \mathbf{v}_p(n) + \mathbf{v}_n(n) + \mathbf{v}_0(n) + \mathbf{e}(n) \tag{2}$$

where $\mathbf{v}_p(n)$, $\mathbf{v}_n(n)$ and $\mathbf{v}_0(n)$ represent the positive, negative and zero sequences respectively defined by

$$\begin{aligned}\mathbf{v}_p(n) &= V_p\left[\cos\theta_p(n), \cos(\theta_p(n) - \frac{2\pi}{3}), \cos(\theta_p(n) + \frac{2\pi}{3})\right]^T\\ \mathbf{v}_n(n) &= V_n\left[\cos\theta_n(n), \cos(\theta_n(n) + \frac{2\pi}{3}), \cos(\theta_n(n) - \frac{2\pi}{3})\right]^T\\ \mathbf{v}_0(n) &= V_0\left[\cos\theta_0(n), \cos\theta_0(n), \cos\theta_0(n)\right]^T\end{aligned}$$

where V_i and $\theta_i(n) = n\omega + \varphi_i, i = p, n, 0$ are the amplitude and phase angle of each sequence, where φ_i is the corresponding initial phase angle.

Given the observations $v_i(n), i = a, b, c$, the problem of interest is to estimate the unknown parameter $\theta_p(n)$, the phase angle of the positive sequence at time instant n.

III. Proposed Algorithm

It can be seen that (2) is highly non-linear with respect to $\theta_p(n)$ and together with several nuisance variables it is difficult to estimate $\theta_p(n)$ by solving (2) directly. As a result, many algorithms in literature obtain the three-phase input signal and its 90 degree phase-shifted version from (1) and then resort to symmetrical component transformation to extract the positive sequence component for phase angle computation later on [4]–[7]. Different from the existing work, a novel scheme is developed to solve this synchronization problem in this Section. The proposed algorithm obtains $\theta_p(n)$ in a three-step approach: 1) transform the three-phase input signal to $\alpha\beta$ stationary reference frame; 2) estimate the sinusoidal signals themselves and their quadrature signals using extended Kalman filter; 3) compute the phase angle of the positive sequence based on its relationship to the estimates of the sinusoidal signals.

A. Transform signals to $\alpha\beta$ stationary reference frame

After applying the Clarke transformation to (1), we obtain the corresponding signal in $\alpha\beta$ stationary reference frame as

$$[v_\alpha(n), v_\beta(n)]^T = \mathbf{T}[v_a(n), v_b(n), v_c(n)]^T \tag{3}$$

where $\mathbf{T}$ is the Clarke transformation defined as

$$\mathbf{T} = \frac{2}{3}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}. \tag{4}$$

By applying (2), (3) can be rewritten as

$$\begin{bmatrix}v_\alpha(n)\\ v_\beta(n)\end{bmatrix} = V_p\begin{bmatrix}\cos\theta_p(n)\\ \sin\theta_p(n)\end{bmatrix} + V_n\begin{bmatrix}\cos\theta_n(n)\\ -\sin\theta_n(n)\end{bmatrix} + \begin{bmatrix}e_\alpha(n)\\ e_\beta(n)\end{bmatrix} \tag{5}$$

The covariance of the noise vector $\mathbf{e}_{\alpha\beta}(n) = [e_\alpha(n), e_\beta(n)]^T$ is $\mathbf{Q}_{\alpha\beta} = \mathbf{TQT}^T$. The benefit of applying Clarke transformation is clear since the zero sequence is canceled out and the number of unknown nuisance parameters is reduced by two. (5) is a general form in $\alpha\beta$ domain in the presence of voltage unbalance. If there is no unbalance existing, then V_n becomes $V_n = 0$ and (5) is degenerated to the ideal case.

Although the number of unknown parameters in (5) is reduced, it is still difficult to solve because (5) still contains two sinusoidal signals and is highly non-linear with respect to the unknown parameters. Based on the fact that $\theta_p(n)$ and $\theta_n(n)$ have the same frequency, (5) can be rewritten as

$$\begin{aligned}v_\alpha(n) =&(V_p\cos\varphi_p + V_n\cos\varphi_n)\cos(n\omega)\\ &- (V_p\sin\varphi_p + V_n\sin\varphi_n)\sin(n\omega) + e_\alpha(n)\\ \triangleq& V_\alpha\cos(n\omega + \varphi_\alpha) + e_\alpha(n)\\ v_\beta(n) =&(V_p\sin\varphi_p - V_n\sin\varphi_n)\cos(n\omega)\\ &- (-V_p\cos\varphi_p + V_n\cos\varphi_n)\sin(n\omega) + e_\beta(n)\\ \triangleq& V_\beta\cos(n\omega + \varphi_\beta) + e_\beta(n)\end{aligned} \tag{6}$$

It can be seen from (6) that each phase in $\alpha\beta$ domain includes only one noise corrupted sinusoidal signal. The problem becomes estimating parameters of a single-tone sinusoidal signal. Once the parameters $V_i, \varphi_i, i = \alpha, \beta$ and ω are obtained from $v_\alpha(n)$ and $v_\beta(n)$, an estimate of $\theta_p(n)$ can be easily computed based on their relationship given in (6).

B. Track the sinusoidal signals

The extended Kalman filter (EKF) is applied to track the sinusoidal signals in $\alpha\beta$ domain when the unbalanced signal experiences a slowly time-varying frequency. The EKF scheme has been adopted to track the frequency of a single sinusoidal signal embedded in noise [10]. Here, it is introduced to handle the synchronization of grid-connected power line signals in the presence of unbalance.

As specified in (6), the unbalanced signals in $\alpha\beta$ domain can be treated as two sinusoidal signals with unknown amplitudes, initial phases and slowly time-varying frequency. Hence, we define five state variables, where the in-phase and quadrature signals of each sinusoid are included and the last variable is the frequency, as

$$\begin{aligned}x_1(n) &= V_\alpha\cos(n\omega + \varphi_\alpha)\\ x_2(n) &= V_\alpha\sin(n\omega + \varphi_\alpha)\\ x_3(n) &= V_\beta\cos(n\omega + \varphi_\beta)\\ x_4(n) &= V_\beta\sin(n\omega + \varphi_\beta)\\ x_5(n) &= \omega\end{aligned} \tag{7}$$

As a result, the state equation can be modeled as

$$\begin{aligned}x_1(n+1) &= x_1(n)\cos(x_5(n)) - x_2(n)\sin(x_5(n))\\ x_2(n+1) &= x_1(n)\sin(x_5(n)) + x_2(n)\cos(x_5(n))\\ x_3(n+1) &= x_3(n)\cos(x_5(n)) - x_4(n)\sin(x_5(n))\\ x_4(n+1) &= x_3(n)\sin(x_5(n)) + x_4(n)\cos(x_5(n))\\ x_5(n+1) &= (1-\epsilon)x_5(n) + e_w(n)\end{aligned} \tag{8}$$

where the parameter ϵ is introduced to model the slowly time-varying characteristic of the frequency. $e_w(n)$ is modeled as a Gaussian distributed random variable with zero-mean and variance q.

According to definitions of the state variables, the observation equation from (6) is related to the state variables by

$$\begin{aligned}v_\alpha(n) &= x_1(n) + e_\alpha(n)\\ v_\beta(n) &= x_3(n) + e_\beta(n)\end{aligned} \tag{9}$$

In vector, we have

$$\mathbf{y}(n) = \mathbf{Px}(n) + \mathbf{e}(n) \tag{10}$$

where $\mathbf{y}(n)$ is the measurement vector $\mathbf{y}(n) = [v_\alpha(n), v_\beta(n)]^T$ and $\mathbf{P}$ is defined as

$$\mathbf{P} = \begin{bmatrix}1 & 0 & 0 & 0 & 0\\ 0 & 0 & 1 & 0 & 0\end{bmatrix}. \tag{11}$$

Note the state equation in (8) is nonlinear and hence the extended Kalman filter is applied.

The complete set of equations to estimate the state $\mathbf{x}(n)$ based on the measurement vector $\mathbf{y}(n)$ is

$$\begin{aligned}\hat{\mathbf{x}}(n|n) &= \mathbf{f}(\hat{\mathbf{x}}(n-1|n-1)) \\ &\quad + \mathbf{K}(n)(\mathbf{y}(n) - \mathbf{P}\mathbf{f}(\hat{\mathbf{x}}(n-1|n-1))) \\ \mathbf{K}(n) &= \mathbf{M}(n)\mathbf{P}^T(\mathbf{Q}_{\alpha\beta} + \mathbf{P}\mathbf{M}(n)\mathbf{P}^T)^{-1} \\ \mathbf{M}(n+1) &= \mathbf{F}(n)\left(\mathbf{M}(n) - \mathbf{K}(n)\mathbf{P}\mathbf{M}(n)\right)\mathbf{F}^T(n) + q\mathbf{A}\end{aligned} \tag{12}$$

where $\mathbf{K}(n)$ is the weighting matrix, $\mathbf{M}(n+1)$ is the prediction MSE matrix,

$$\mathbf{f}(\hat{\mathbf{x}}(n|n)) = \begin{bmatrix} \hat{x}_1(n|n)\cos(\hat{x}_5(n|n)) - \hat{x}_2(n|n)\sin(\hat{x}_5(n|n)) \\ \hat{x}_1(n|n)\sin(\hat{x}_5(n|n)) + \hat{x}_2(n|n)\cos(\hat{x}_5(n|n)) \\ \hat{x}_3(n|n)\cos(\hat{x}_5(n|n)) - \hat{x}_4(n|n)\sin(\hat{x}_5(n|n)) \\ \hat{x}_3(n|n)\sin(\hat{x}_5(n|n)) + \hat{x}_4(n|n)\cos(\hat{x}_5(n|n)) \\ (1-\epsilon)\hat{x}_5(n|n) \end{bmatrix} \tag{13}$$

and

$$\mathbf{F}(n) = \left.\frac{\partial \mathbf{f}(\mathbf{x})}{\partial \mathbf{x}}\right|_{\mathbf{x}=\hat{\mathbf{x}}(n|n)} = \left.[\mathbf{F}_1(n), \mathbf{F}_2(n)]\right|_{\mathbf{x}=\hat{\mathbf{x}}(n|n)} \tag{14}$$

where

$$\mathbf{F}_1(n) = \begin{bmatrix} \cos x_5 & -\sin x_5 & 0 & 0 \\ \sin x_5 & \cos x_5 & 0 & 0 \\ 0 & 0 & \cos x_5 & -\sin x_5 \\ 0 & 0 & \sin x_5 & \cos x_5 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{15}$$

$$\begin{aligned}\mathbf{F}_2(n) = [&-x_1\sin x_5 - x_2\cos x_5,\ x_1\cos x_5 - x_2\sin x_5, \\ &-x_3\sin x_5 - x_4\cos x_5,\ x_3\cos x_5 - x_4\sin x_5, \\ &1-\epsilon]^T\end{aligned} \tag{16}$$

$\mathbf{A}$ is a 5×5 matrix with zero elements except the most right bottom element is one.

C. Compute the phase angles

Once an estimate of $\mathbf{x}$ at each time instant n, $\hat{\mathbf{x}}(n|n)$, is obtained, it is used to compute the initial phase angle and amplitude of the positive sequence component according to (6)

$$\hat{\varphi}_p = \tan^{-1}\frac{\hat{V}_\alpha\sin\hat{\varphi}_\alpha + \hat{V}_\beta\cos\hat{\varphi}_\beta}{\hat{V}_\alpha\cos\hat{\varphi}_\alpha - \hat{V}_\beta\sin\hat{\varphi}_\beta} \tag{17}$$

and

$$\hat{V}_p = \frac{1}{2}\sqrt{(\hat{V}_\alpha\sin\hat{\varphi}_\alpha + \hat{V}_\beta\cos\hat{\varphi}_\beta)^2 + (\hat{V}_\alpha\cos\hat{\varphi}_\alpha - \hat{V}_\beta\sin\hat{\varphi}_\beta)^2} \tag{18}$$

where

$$\begin{aligned}\hat{V}_\alpha\sin(\hat{\varphi}_\alpha) &= \hat{x}_2(n|n)\cos((n-1)\hat{x}_5(n|n)) \\ &\quad - \hat{x}_1(n|n)\sin((n-1)\hat{x}_5(n|n)) \\ \hat{V}_\alpha\cos(\hat{\varphi}_\alpha) &= \hat{x}_2(n|n)\sin((n-1)\hat{x}_5(n|n)) \\ &\quad + \hat{x}_1(n|n)\cos((n-1)\hat{x}_5(n|n)) \\ \hat{V}_\beta\sin(\hat{\varphi}_\beta) &= \hat{x}_4(n|n)\cos((n-1)\hat{x}_5(n|n)) \\ &\quad - \hat{x}_3(n|n)\sin((n-1)\hat{x}_5(n|n)) \\ \hat{V}_\beta\cos(\hat{\varphi}_\beta) &= \hat{x}_4(n|n)\sin((n-1)\hat{x}_5(n|n)) \\ &\quad + \hat{x}_3(n|n)\cos((n-1)\hat{x}_5(n|n))\end{aligned} \tag{19}$$

Finally, the phase angle of the positive sequence component is obtained as

$$\hat{\theta}_p(n) = (n-1)\hat{x}_5(n|n) + \hat{\varphi}_p. \tag{20}$$

As a by-product, the initial phase angle and amplitude of the negative sequence component are given as

$$\hat{\varphi}_n = \tan^{-1}\frac{\hat{V}_\alpha\sin\hat{\varphi}_\alpha - \hat{V}_\beta\cos\hat{\varphi}_\beta}{\hat{V}_\alpha\cos\hat{\varphi}_\alpha + \hat{V}_\beta\sin\hat{\varphi}_\beta} \tag{21}$$

and

$$\hat{V}_n = \frac{1}{2}\sqrt{(\hat{V}_\alpha\sin\hat{\varphi}_\alpha - \hat{V}_\beta\cos\hat{\varphi}_\beta)^2 + (\hat{V}_\alpha\cos\hat{\varphi}_\alpha + \hat{V}_\beta\sin\hat{\varphi}_\beta)^2} \tag{22}$$

Accordingly, the phase angle of the negative sequence component is

$$\hat{\theta}_n(n) = (n-1)\hat{x}_5(n|n) + \hat{\varphi}_n. \tag{23}$$

An alternate approach to compute the phase angle of the positive sequence component is based on the following equalities

$$\begin{aligned}V_p\cos\theta_p(n) &= \frac{V_\alpha\cos(n\omega+\varphi_\alpha) - V_\beta\sin(n\omega+\varphi_\beta)}{2} \\ V_p\sin\theta_p(n) &= \frac{V_\alpha\sin(n\omega+\varphi_\alpha) + V_\beta\cos(n\omega+\varphi_\beta)}{2} \\ V_n\cos\theta_n(n) &= \frac{V_\alpha\cos(n\omega+\varphi_\alpha) + V_\beta\sin(n\omega+\varphi_\beta)}{2} \\ V_n\sin\theta_n(n) &= \frac{V_\alpha\sin(n\omega+\varphi_\alpha) - V_\beta\cos(n\omega+\varphi_\beta)}{2}\end{aligned} \tag{24}$$

This can be easily verified from (6) if the noises are not present. Also note the state variables defined in (8). Hence, an estimate of the phase angle of the positive sequence component is obtained, based on the state variable estimate $\hat{\mathbf{x}}(n|n)$, as

$$\hat{\theta}_p(n) = \tan^{-1}\frac{\hat{x}_2(n|n) + \hat{x}_3(n|n)}{\hat{x}_1(n|n) - \hat{x}_4(n|n)} \tag{25}$$

and an estimate of the phase angle of the negative sequence component is

$$\hat{\theta}_n(n) = \tan^{-1}\frac{\hat{x}_2(n|n) - \hat{x}_3(n|n)}{\hat{x}_1(n|n) + \hat{x}_4(n|n)}. \tag{26}$$

IV. Simulations

In this Section, simulation results are provided to evaluate the performance of the proposed algorithm using simulated waveforms. Monte Carlo simulations are conducted and the number of ensemble runs is 200. The mean squared error (MSE) results are computed and provided.

The entire simulation time period is 500 ms and the sampling frequency f_s is set to 1200 Hz. To simulate the voltage unbalance, the amplitudes and initial phase angles of the three-phase voltage signal are set to $1.0, 1.2, 0.8$ and $0, -\pi/3, 2\pi/3$ respectively. Besides the voltage unbalance, an additive white Gaussian noise vector with zero-mean and covariance matrix $\mathbf{Q} = \sigma^2\mathbf{I}$, where $\sigma = 10^{-2}/\sqrt{2}$ is the noise standard deviation, is superimposed on the three-phase voltage signal. The nominal fundamental frequency is 60 Hz. To testify the performance of the proposed algorithm handling the frequency change, a step frequency change from 61 Hz to 57 Hz occurs at the time 250 ms.

The proposed algorithm is implemented to detect the phase angle where $\epsilon = 10^{-16}$ and $q = 10^{-7}$. Fig. 1 shows the phase angle estimate for a single run as blue solid line. The ground truth is also computed by applying the symmetrical component transformation to the noisy free signal and shown as solid black line in Fig. 1. The corresponding MSE result is shown in Fig. 2. At most of the time, the MSE is around -50 dB, which means that the proposed algorithm can detect the phase angle with high accuracy.

Fig. 3 and Fig. 4 show a single run and the MSE result for frequency estimate respectively. Although the estimate fluctuates around the truth, it succeeds in tracking the frequency change. The estimation results for the phase angle of the negative sequence and the amplitudes are neglected here.

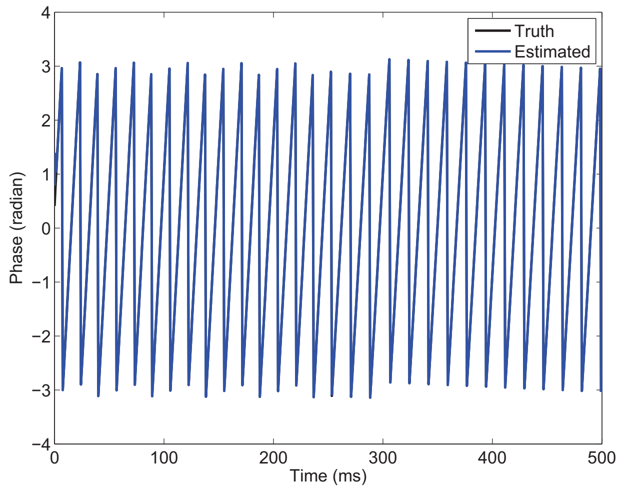

Fig. 1. Phase angle estimate for a single run.

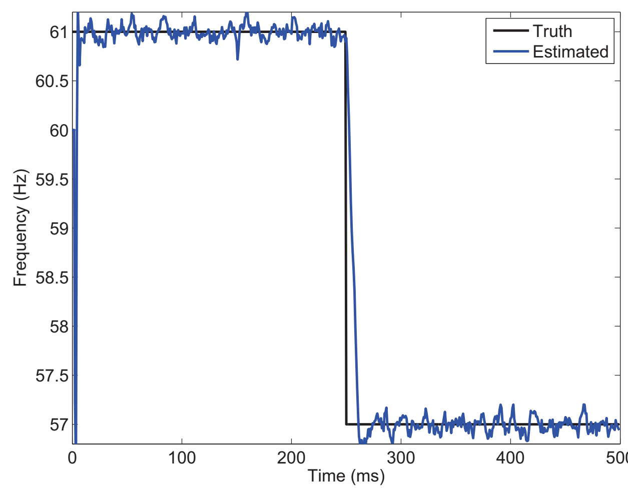

Fig. 3. Frequency estimates for a single run.

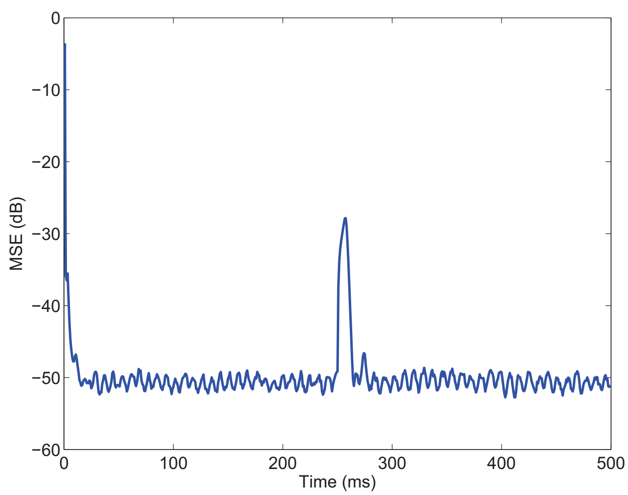

Fig. 2. MSE result of the phase angle estimation.

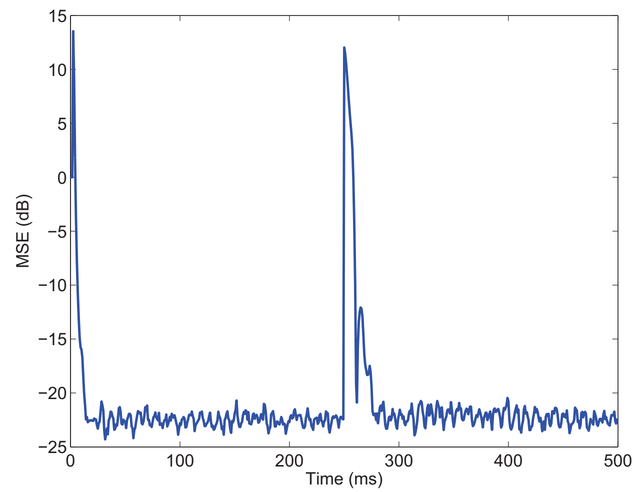

Fig. 4. MSE results of the frequency estimation.

V. Conclusion

This paper proposed a new grid synchronization scheme for grid-connected power generation systems in the presence of voltage unbalance and frequency variation. The proposed scheme transforms the three-phase voltage signal in abc natural reference frame to $\alpha\beta$ stationary reference frame. In-phase and quadrature sinusoidal signals together with grid frequency are chosen as state variables and estimated using the extended Kalman filter. The phase angle of the positive sequence is then computed. The simulation results confirm the good performance of the proposed algorithm.

References

[1] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of control and grid synchronization for distributed power generation systems," *IEEE Trans. Ind. Electron.*, vol. 53, pp. 1398–1409, Oct. 2006.

[2] A. V. Timbus, M. Liserre, R. Teodorescu, and F. Blaabjerg, "Synchronization methods for three phase distributed power generation systems. an overview and evaluation," in *Proc. IEEE Power Electronics Specialists Conference (PESC'05)*, Jun. 2005, pp. 2474 – 2481.

[3] M. Kusljevic, J. Tomic, and L. Jovanovic, "Frequency estimation of three-phase power system using weighted-least-square algorithm and adaptive FIR filtering," *IEEE Trans. Instrum. Meas.*, vol. 59, pp. 322 – 329, Feb. 2010.

[4] S. J. Lee, J. K. Kang, and S. K. Sul, "A new phase detecting method for power conversion systems considering distorted conditions in power system," in *Proc. Industry Applications Conference. Thirty-Fourth IAS Annual Meeting*, Oct. 1999, pp. 2167–2172.

[5] R. A. Flores, I. Y. H. Gu, and M. H. J. Bollen, "Positive and negative sequence estimation for unbalanced voltage dips," in *Proc. IEEE Power Eng. Soc. General Meeting*, Jul. 2003, pp. 2498–2502.

[6] M. Karimi-Ghartemani and M. Iravani, "A method for synchronization of power electronic converters in polluted and variable-frequency environments," *IEEE Trans. Power Syst.*, vol. 19, pp. 1263–1270, Aug. 2004.

[7] D. Yazdani, A. Bakhshai, G. Joos, and M. Mojiri, "A nonlinear adaptive synchronization techniquefor grid-connected distributed energy sources," *IEEE Trans. Power Electron.*, vol. 23, pp. 2181 – 2186, Jul. 2008.

[8] C. Fortescue, "Method of symmetrical coordinates applied to the solution of polyphase netwotks," *Trans. AIEE*, vol. 37, pp. 1027–1140, 1918.

[9] F. D. Freijedo, J. Doval-Gandoy, O. Lopez, and E. Acha, "A generic open-loop algorithm for three-phase grid voltage/current synchronization with particular reference to phase, frequency, and amplitude estimation," *IEEE Trans. Power Electron.*, vol. 24, pp. 94 – 107, Jan. 2009.

[10] S. Bittanti and S. M. Savaresi, "On the parameterization and design of an extended kalman filter frequency tracker," *IEEE Trans. Autom. Control*, vol. 45, pp. 1718 – 1724, Sep. 2000.