A Simple Frequency Estimator for Power Systems

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A Simple Frequency Estimator For Power Systems

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***Abstract*—Fast and accurate frequency estimation of an unbalanced three-phase power system in the presence of measurement offset is a challenging task. A simple to implement and tune method is proposed in this work through a delay-based linear-regression framework. Using two challenging scenarios, we verify the performance of our procedure in the presence of severe grid abnormalities, including voltage unbalance, harmonics, frequency jump, and DC offset. Comparative hardware-in-the-loop experimental results demonstrate the suitability of the proposed approach.**

***Index Terms*—Frequency estimation; Power systems**

I. Introduction

Frequency plays an important role in monitoring the electric power grid. Various abnormalities such as unbalance, DC-offset, and voltage sag/swell often make the frequency estimation challenging. Moreover, fast estimation is also required to take any potential preventive action. Numerous techniques are available in the literature that deal with fast and accurate frequency estimation. Some popular tools are: phase-locked loop (PLL) ([1], [2]) frequency-locked loop (FLL) [3], demodulation [4], least-square [5], Kalman filter [6], neural network [7] and so on.

PLLs [2] dynamic performance depends on the loop-filter (proportional-integral-type) tuning parameters. A fast dynamic response comes at the cost of reduced harmonics robustness. Total quasi type-1 PLL (TQT1-PLL) [1] uses a proportional controller-based loop-filter, increasing the dynamic response without sacrificing much the harmonic robustness. FLL [3] and its many variants [7] use an integral controller to estimate the frequency. This approach is sensitive to the grid harmonics components. So, additional filters are required. Demodulation [4] and least-square [5] use an initial phase-angle-based technique for frequency estimation. The demodulation technique applies additional moving average filters, and adaptive tuning of the filter's window length can be challenging and computationally demanding. Kalman filter [6] can provide good robustness to measurement noise. However, it requires accurate information of the process and measurement noise covariance matrices. Moreover, results in [6] show that the least-square technique has a better statistical performance than the Kalman filter.

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From the brief literature review, it can be found that there is a demand for a simple frequency estimator that can handle various grid abnormalities without requiring additional pre- and or post-filtering stages. One such simple solution has been proposed in [8], where the unknown frequency estimation problem has been solved through linear regression. However, it works only for single-phase cases and can not handle DC offset. In this work, we have applied the idea of [8] to estimate the unknown frequency of an unbalanced three-phase grid and our proposed approach can handle DC offset without any additional filtering stages.

The rest of this letter is organized as follows: the linear-regression-based model of the three-phase unbalanced voltages and the design of the unknown frequency estimator are given in Section II, comparative experimental results are in Section III, and finally, Section IV concludes this letter.

II. Signal Modeling and Estimator Design

Unbalanced three-phase grid voltages in the stationary reference are given by:

$$v_\alpha(t) = V_{\alpha 0} + V_p \cos(\omega t + \phi_p) + V_n \cos(\omega t + \phi_n), \quad (1)$$

$$v_\beta(t) = V_{\beta 0} + V_p \sin(\omega t + \phi_p) - V_n \sin(\omega t + \phi_n), \quad (2)$$

where the subscript p and n denote the positive and negative sequence for $i \in \{p, n\}$, $\theta_i = \omega t + \phi_i$ is the total phase, V_i, ω, ϕ_i, $V_{\alpha 0}$, and $V_{\beta 0}$ represent the amplitude, angular frequency, phase angle, and DC offsets in phases α and β, respectively. Let us first consider the signal v_α and its delayed versions $v_\alpha^\tau(t) = v_\alpha(t-\tau)$ with $\tau > 0$ as given by:

$$\begin{aligned} v_\alpha^\tau(t) &= V_{\alpha 0} + V_p \cos(\omega(t-\tau) + \phi_p) + V_n \cos(\omega(t-\tau) + \phi_n), \\ &= V_{\alpha 0} + V_p \cos(\theta_p)\cos(\omega\tau) + V_p \sin(\theta_p)\sin(\omega\tau) \\ &\quad + V_n \cos(\theta_n)\cos(\omega\tau) + V_n \sin(\theta_n)\sin(\omega\tau). \end{aligned} \quad (3)$$

Similarly, the delayed signals $v_\alpha^{2\tau}(t) = V_\alpha(t-2\tau)$ and $v_\alpha^{3\tau}(t) = V_\alpha(t-3\tau)$ are given by:

$$\begin{aligned} v_\alpha^{2\tau}(t) &= V_{\alpha 0} + V_p \cos(\theta_p)\cos(2\omega\tau) + V_p \sin(\theta_p)\sin(2\omega\tau) \\ &\quad + V_n \cos(\theta_n)\cos(2\omega\tau) + V_n \sin(\theta_n)\sin(2\omega\tau). \end{aligned} \quad (4)$$

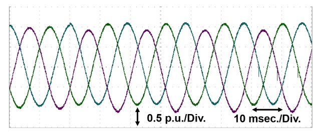
$$\begin{aligned} v_\alpha^{3\tau}(t) &= V_{\alpha 0} + V_p \cos(\theta_p)\cos(3\omega\tau) + V_p \sin(\theta_p)\sin(3\omega\tau) \\ &\quad + V_n \cos(\theta_n)\cos(3\omega\tau) + V_n \sin(\theta_n)\sin(3\omega\tau). \end{aligned} \quad (5)$$

Using (1) and (3)-(5), one can obtain that:

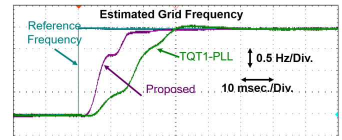
$$v_\alpha^{2\tau}(1 + 2\cos(\omega\tau)) - v_\alpha^\tau(1 + 2\cos(\omega\tau)) = -v_\alpha + v_\alpha^{3\tau}.$$

This leads to the following relationship:

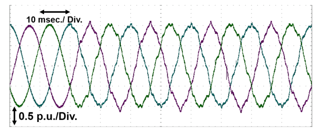
$$v_\alpha - v_\alpha^\tau + v_\alpha^{2\tau} - v_\alpha^{3\tau} - 2\cos(\omega\tau)(v_\alpha^\tau - v_\alpha^{2\tau}) = 0. \quad (6)$$



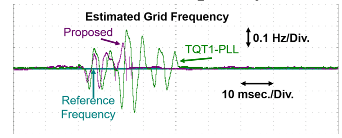
(a) Grid voltage: Test-I



(b) Estimated frequency: Test-I



(c) Grid voltage: Test-II



(d) Estimated frequency: Test-II

Figure 1. Comparative experimental results with TQT1-PLL [1].

The above calculations are equally applicable to the signal v_β and one can write that:

$$v_\beta - v_\beta^\tau + v_\beta^{2\tau} - v_\beta^{3\tau} - 2\cos(\omega\tau)(v_\beta^\tau - v_\beta^{2\tau}) = 0. \tag{7}$$

By combining (6) and (7), the following first-order linear regression model can be obtained:

$$y = \varphi\Omega, \tag{8}$$

where $y = v_\alpha + v_\beta - v_\alpha^\tau - v_\beta^\tau + v_\alpha^{2\tau} + v_\beta^{2\tau} - v_\alpha^{3\tau} - v_\beta^{3\tau}$, $\varphi = 2(v_\alpha^\tau + v_\beta^\tau - v_\alpha^{2\tau} - v_\beta^{2\tau})$, and $\Omega = \cos(\omega\tau)$. As a result, the unknown grid frequency can be easily estimated from the parameter Ω in eq. (8). The unknown parameter Ω in (8) can be estimated by applying the gradient method [9] and is given by:

$$\dot{\hat{\Omega}} = \varepsilon\varphi(t)(y(t) - \varphi(t)\hat{\Omega}), \tag{9}$$

where $\varepsilon > 0$ is the tuning parameter. From $\hat{\Omega}$, the unknown frequency can be evaluated as:

$$\hat{\omega} = \arccos(\hat{\Omega})/\tau.$$

It is well-known that the regressor φ is persistently exciting if $\tau < \pi/\omega$ [9]. As a result, exponential convergence of the estimator (9), and consequently, the frequency ω can easily be established.

Note that instead of combining (6) and (7), two separate frequency estimators can be designed by writing these equations into the linear regression form (8). Then, by taking an average of the estimated frequencies, the effect of noise can be reduced. However, this will increase the computational complexity as an additional integrator will be required.

The estimator (9) has two parameters to tune: the delay τ and the gain ε. The delay can be selected as $\tau = T/4$, where T is the fundamental signal period. The tuning gain ε has to be selected as a trade-off between fast convergence speed and disturbance rejection property. Through an extensive numerical simulation, it has been found that $\varepsilon = 10$ can be a good choice.

III. Results and Discussions

dSPACE 1104 board-based hardware-in-the-loop experimental studies are considered in this section. Details of the experimental setup are given in [10]. As a comparison technique, TQT1-PLL [1] is used. Parameters of the TQT1-PLL are selected the same as in [1]. Both techniques are discretized using the explicit Euler method with a sampling frequency of 10 kHz.

In Test-I, we consider 2 Hz frequency step change and a sudden addition of 0.05 p.u., −0.06 p.u., and 0.07 p.u. DC offsets in phases a, b, and c, respectively. Experimental results are given in Fig. 1 (a) and (b). The proposed technique converged in ≈ 20 msec. while TQT1-PLL took ≈ 40 msec. In Test-II, suddenly the grid become distorted with $\overrightarrow{V}^{+1} = 1\angle 0°$, $\overrightarrow{V}^{-5} = 0.04\angle 45°$, $\overrightarrow{V}^{+7} = 0.03\angle 60°$, $\overrightarrow{V}^{-11} = 0.02\angle 90°$, and $\overrightarrow{V}^{+19} = 0.01\angle 90°$ [p.u.]. This corresponds to a total harmonic distortion of $\approx 0.5\%$. Experimental results in Fig. 1 (c) and (d) show that the developed method has faster convergence (less than 1 cycle) to the actual value with an excellent harmonic robustness property. Results in Fig. 1 show that the developed method is very suitable as a real-time frequency monitoring tool for smart grid. In addition, it can also be used as the frequency estimator for stationary reference frame-based grid-synchronization methods [3], [7].

IV. Conclusion

This letter studied the frequency estimation problem of an unbalanced three-phase electric power grid with DC offset. First, using consecutive delays, the unknown frequency estimation problem has been converted into a problem of a delay-based linear regression. Then, a simple gradient estimator is used to estimate the unknown frequency in real-time. Since the proposed method is linear, it is very simple to implement and tune. Comparative experimental studies demonstrated the suitability of the proposed method in estimating the unknown grid frequency from unbalanced and distorted grid voltage measurements.

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