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Robust estimation of fundamental frequency positive-sequence component for grid-integration applications in energy systems

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Abstract

This article studies the problem of fundamental frequency positive-sequence component separation in unbalanced three-phase systems for grid-integration applications. We propose a-simple-to-implement approach involving a modified delayed signal cancellation method and moving average filtering. A delay-based linear-regression framework is considered to make the sequence component separation frequency-adaptive, providing fast and accurate frequency estimation. Comparative experimental results demonstrate the suitability of the proposed method over conventional approaches.

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Keywords: Sequence estimation; Unbalanced voltage; Delayed signal cancellation

1. Introduction

Fast and accurate separation of sequence components is essential for controlling converters operating in an unbalanced grid [1–9]. It motivated the development of numerous grid-synchronizing sequence component separation methods. Most approaches are built around the traditional synchronous reference frame phase-locked loop (SRF-PLL) [10].

Delayed signal cancellation (DSC) [11] is a popular choice among the various sequence separation methods available in the literature. This method can be applied either as an in-loop or pre-loop filter in conjunction with SRF-PLL. A DSC with a quarter-cycle delay is suggested in [12] to reject the fundamental frequency negative-sequence component (FFNS). Several modifications are proposed in the literature to speed up the convergence of DSC-based PLL. A modified DSC is proposed in [13], where the required delay is significantly lower than a quarter-cycle. However, this approach requires a pre-loop filter to reduce the effect of noise and harmonics. Another solution is reported in [14], where an additional phase compensator is used in the PLL to speed up the

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convergence. However, this deteriorates the transient performance in the presence of large voltage sag and/or phase jump. Moreover, numerous parameters also need to be tuned.

In [15], a combination of modified DSC and moving average filter (MAF) is used in conjunction with quasi type-1 PLL (QT1- PLL) [16,17]. Thanks to the proportional loop-filter of QT1-PLL, this method can significantly decrease the convergence time, however, at the cost of sensitivity to harmonics and noise. A similar hybrid DSC and MAF approach and an open-loop frequency estimator are considered in [18]. However, it is very complicated to implement.

This article proposes applying a modified DSC method for fundamental frequency positive sequence (FFPS) separation. The FFPS component is converted into SRF through demodulation, where MAF enhances harmonic robustness. Finally, the proposed method is made frequency adaptive by considering unknown frequency estimation under a delay-based linear-regression framework [19,20]. The contributions of this work are twofold. Firstly, the FFPS separation method uses lower delay, resulting in a fast estimation of the sequence components. Secondly, the frequency evaluation is decoupled from the sequence separation, resulting in a fast frequency estimation, unlike conventional methods, which depend on the sequence separation.

The rest of this article is organized as follows: The development of the proposed estimator is given in Section 2, experimental results are provided in Section 3, and finally, concluding remarks are given in Section 4.

2. Proposed estimator design

Unbalanced three-phase grid voltages with measurement offset in the stationary reference frame are given by:

$$y_\alpha(t) = Y_{\alpha 0} + Y^+ \cos\left(\omega t + \varphi^+\right) + Y^- \cos\left(\omega t + \varphi^-\right), \tag{1a}$$

$$y_\beta(t) = Y_{\beta 0} + Y^+ \sin\left(\omega t + \varphi^+\right) - Y^- \sin\left(\omega t + \varphi^-\right), \tag{1b}$$

where the superscript $+$ and $-$ denotes the positive and negative sequence, $\phi^\pm = \omega t + \varphi^\pm$ is the total phase, $Y^\pm$, ω, $\varphi^\pm$, $Y_{\alpha 0}$, and $Y_{\beta 0}$ represent the amplitude, angular frequency, phase angle, and DC offsets in phases α and β, respectively. The extraction of the FFPS component, i.e., $y_\alpha^+ = Y^+ \cos\left(\omega t + \varphi^+\right)$ and $y_\beta^+ = Y^+ \sin\left(\omega t + \varphi^+\right)$, and the estimation of ϕ^+ are considered in this work. In the remainder of this article, the time-dependence of a signal is often not explicitly stated for convenience. Moreover, continuous- and discrete-time signals and notation of filtered signals are often mixed for brevity.

2.1. Separation of FF1PS component

The first step in developing the proposed estimator is to separate the FFPS component from (1). For this purpose, the DSC method is a very suitable choice. In the case of unbiased voltage measurement, a traditional $\alpha\beta$-DSC operator can separate the FPPS with a delay of $T/4$, where T is the signal period. However, this makes the convergence slower. A modified DSC method is proposed in [13] to overcome this issue. However, as shown in [13, Table 1], the separation of sequences requires many arithmetic operations involving trigonometric quantities. Here, we propose a simplified version that significantly reduces the computational complexity. For this purpose, let us denote that $y_\alpha^{\phi_d} = y_\alpha(\phi - \phi_d)$ and $y_\beta^{\phi_d} = y_\beta(\phi - \phi_d)$ with $\phi = \omega t$, $\phi_d = 2\pi f N_d T_s$, where $f = \omega/2\pi$ is the frequency, N_d is the number of delayed samples, and T_s is the sampling time. Then, the FFPS can be extracted by a modified first-order DSC operation inspired from [15]:

$$\hat{y}_\alpha^+ = \frac{1}{2}\left(y_\alpha + \cot(\phi_d)\, y_\beta - \csc(\phi_d)\, y_\beta^{\phi_d}\right), \tag{2a}$$

$$\hat{y}_\beta^+ = \frac{1}{2}\left(y_\beta - \cot(\phi_d)\, y_\beta + \csc(\phi_d)\, y_\alpha^{\phi_d}\right), \tag{2b}$$

where $\hat{y}_\alpha^+$ and $\hat{y}_\beta^+$ are the estimated FFPS components. In theory, (2) can extract the FFPS component for any value of N_d. However, a higher value provides better robustness against harmonic disturbances at the cost of a slow dynamic response. So, $N_d = 10$ for $f = 50$ Hz ($f_s = 1/T_s = 10$ kHz) can be considered as a good compromise value. To provide additional robustness to grid frequency variation, a two first-order frequency-adaptive DSC operation (2) can be cascaded and this issue is considered in this work.

2.2. Phase angle estimation

The FFPS component separation process described in Section 2.1 is not very robust to noise and grid harmonics. According to IEEE 519-2014 standard, the total harmonic distortion of the terminal voltage of grid-connected converters should be below 5%, and individual harmonic components should be less than 3%. To respect these limits, moving average filters are considered in this work. To apply these filters, a separated FFPS component is converted to a synchronous reference frame through demodulation and is given by [21]:

$$\begin{bmatrix} \hat{Y}_d^+ \\ \hat{Y}_q^+ \end{bmatrix} = \begin{bmatrix} \cos(\hat{\omega}t) & \sin(\hat{\omega}t) \\ -\sin(\hat{\omega}t) & cos(\hat{\omega}t) \end{bmatrix} \begin{bmatrix} \hat{y}_\alpha^+ \\ \hat{y}_\beta^+ \end{bmatrix}, \tag{3}$$

$$\begin{bmatrix} \hat{Y}_d^+ \\ \hat{Y}_q^+ \end{bmatrix} = \begin{bmatrix} \hat{Y}^+ \cos(\hat{\varphi}^+) \\ \hat{Y}^+ \sin(\hat{\varphi}^+) \end{bmatrix}. \tag{4}$$

where $\hat{\omega}$ is the estimated frequency, $\hat{Y}_d^+$ and $\hat{Y}_q^+$ are the estimated FFPS voltages, and $\hat{Y}^+$ is the estimated FFPS voltage amplitude. In the $\alpha\beta$ to $dq-$ frame conversion through (3), the estimated value of the grid frequency $\hat{\omega}$ is used. Details of the used estimation approach are given in Section 2.3. From (4), the phase angle of the FFPS component can be estimated as:

$$\hat{\varphi}^+ = \text{atan2}\left(\hat{Y}_q^+, \hat{Y}_d^+\right), \tag{5}$$

where atan2 is the double quadrant arctangent function. To obtain (4), we assume that the grid voltage does not contain any harmonics. However, in practice, the grid voltage contains harmonics. The IEEE 519-2014 standard puts particular emphasis on odd-order harmonics. The presence of odd-order harmonics in the grid voltage will generate even-order AC ripple in the estimated DC quantities $\hat{Y}_d^+$ and $\hat{Y}_q^+$. A MAF can eliminate these even-order harmonics in the $dq-$ frame with a half-cycle window length. The transfer function of the discrete-time MAF is given by:

$$G_{MAF}(z) = \frac{1}{N_m}\frac{1 - z^{-N_m}}{1 - z^{-1}}, \tag{6}$$

where $N_m = f_s/2f_n$ is the half-cycle window length with f_n the nominal frequency. The non-adaptive window length MAF (6) introduces a small-amplitude estimation ripple in the off-nominal grid frequency case. In this work, we consider a frequency-adaptive MAF where fractional delays are implemented through linear interpolation as suggested in [14].

2.3. Unknown frequency estimation

In implementing the demodulation (3), an estimate of the unknown grid frequency is required. SRF-based PLLs pass the estimated phase angle through a loop-filter to estimate the grid frequency variation. However, this makes the frequency estimation dependent on the FFPS component separation dynamics. A direct frequency estimation is considered here to break this loop within a delay-based linear-regression framework. For this purpose, let us consider that for $n = 1, 2, 3$ [19]:

$$y_\alpha^{n\tau}(t) = y_\alpha(t - n\tau) \text{ and } y_\beta^{n\tau}(t) = y_\beta(t - n\tau), \tau > 0. \tag{7}$$

Using the measured grid voltages (1) and delayed versions (7), the following relationships can be obtained [19]:

$$y_\alpha - y_\alpha^\tau + y_\alpha^{2\tau} - y_\alpha^{3\tau} - 2\cos(\omega\tau)\left(y_\alpha^\tau - y_\alpha^{2\tau}\right) = 0. \tag{8a}$$

$$y_\beta - y_\beta^\tau + y_\beta^{2\tau} - y_\beta^{3\tau} - 2\cos(\omega\tau)\left(y_\beta^\tau - y_\beta^{2\tau}\right) = 0. \tag{8b}$$

The above equation can be rewritten as the following linear regression model:

$$v_\alpha = x_\alpha\theta_\alpha \text{ and } v_\beta = x_\beta\theta_\beta, \tag{9}$$

where $v_\alpha = y_\alpha - y_\alpha^\tau + y_\alpha^{2\tau} - y_\alpha^{3\tau}$, $v_\beta = y_\beta - y_\beta^\tau + y_\beta^{2\tau} - y_\beta^{3\tau}$, $x_\alpha = 2\left(y_\alpha^\tau - y_\alpha^{2\tau}\right)$, $x_\beta = 2\left(y_\beta^\tau - y_\beta^{2\tau}\right)$, and $\theta_\alpha = \theta_\beta = \cos(\omega\tau)$. From the unknown parameters θ_α and θ_β in (9), the unknown grid frequency ω can easily be estimated. The estimates $\hat{\theta}_\alpha$ and $\hat{\theta}_\beta$ can be derived by using the gradient method and is given by:

$$\dot{\hat{\theta}}_\alpha = \eta x_\alpha \left(v_\alpha - x_\alpha \hat{\theta}_\alpha\right), \tag{10a}$$

$$\dot{\hat{\theta}}_\beta = \eta x_\beta \left(v_\beta - x_\beta \hat{\theta}_\beta\right), \tag{10b}$$

where $\eta > 0$ is the rate control gain. From the estimated unknown parameters, the unknown frequency is evaluated as [19]:

$$\hat{\omega} = \frac{1}{2\tau}\left(\arccos\left(\hat{\theta}_\alpha\right) + \arccos\left(\hat{\theta}_\beta\right)\right). \tag{11}$$

According to [22], the exponential convergence of the estimator (10), and consequently, the unknown frequency ω can be established if the delay τ in (7) is selected to be less than π/ω. In this work, we consider $\tau = T_n/4$ with T_n being the nominal period which satisfies $\tau < \pi/\omega$. This value can enhance the convergence speed and reduce the effect of noise and unmodeled disturbances (e.g., harmonics) on the estimated frequency. For real-time implementation, delayed signals in (7) are implemented through delay-shift operator with $\tau = T_n/4T_s$. By passing the unknown frequency (11) through an integrator, the unknown total phase of the FFPS component can be evaluated as:

$$\hat{\omega} = \hat{\omega}t + \hat{\varphi}^+. \tag{12}$$

The block diagram of the proposed method is given in Fig. 1.

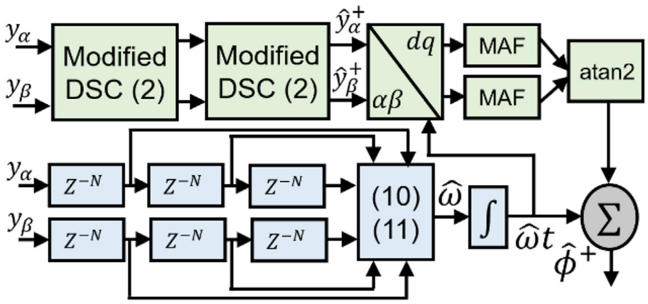


Fig. 1. Block diagram of the proposed method.

3. Results and discussions

The experimental setup, shown in Fig. 2, is used to validate the proposed method. Here, a PWM-controlled three-phase inverter is used to emulate the adverse grid voltage signal. Details of the experimental setup can be found in [16]. As comparative techniques, modified DSC-based QT1-PLL [15] and frequency-adaptive MAF-PLL [23] are selected. The proposed and comparative methods all use MAF with half-cycle window length. Parameters of QT1- and MAF-PLLs are selected the same as in [15,23]. All the techniques are implemented in Matlab/Simulink with $T_s = 100$ µs. for code generation and real-time implementation in dSPACE 1104 platform. The parameters of the proposed method are: $N_d = 10$, $N_m = f_s/2f$ (nominal), and $\eta = 35$. Zero initial conditions are used for implementing all the delay blocks. Results from dSPACE ControlDesk are exported to Matlab for further processing.

Two experimental tests are considered. In the first test, a step change of −2 Hz in frequency is considered and the results are given in Fig. 3. Results in Fig. 3(b) and (c) show that the proposed method has significantly lower peak to peak overshoot together with fast convergence speed. In the second test, diode-rectifier-based nonlinear load is connected to generate harmonically distorted and unbalanced grid voltage signals. Results in Fig. 4(b) show that the proposed method has the lowest peak overshoot and the steady-state ripple compared to QT1- and MAF-PLLs. In terms of total harmonic distortion (THD), it can be concluded that the technique developed in this work can significantly lower the THD value, which makes it a suitable tool for control of grid-connected converters. A comparative time domain performance summary is given in Table 1.

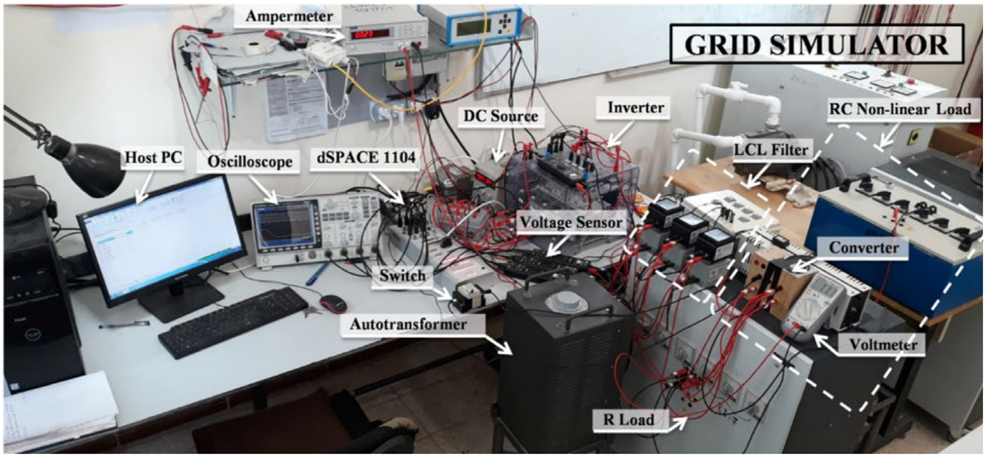
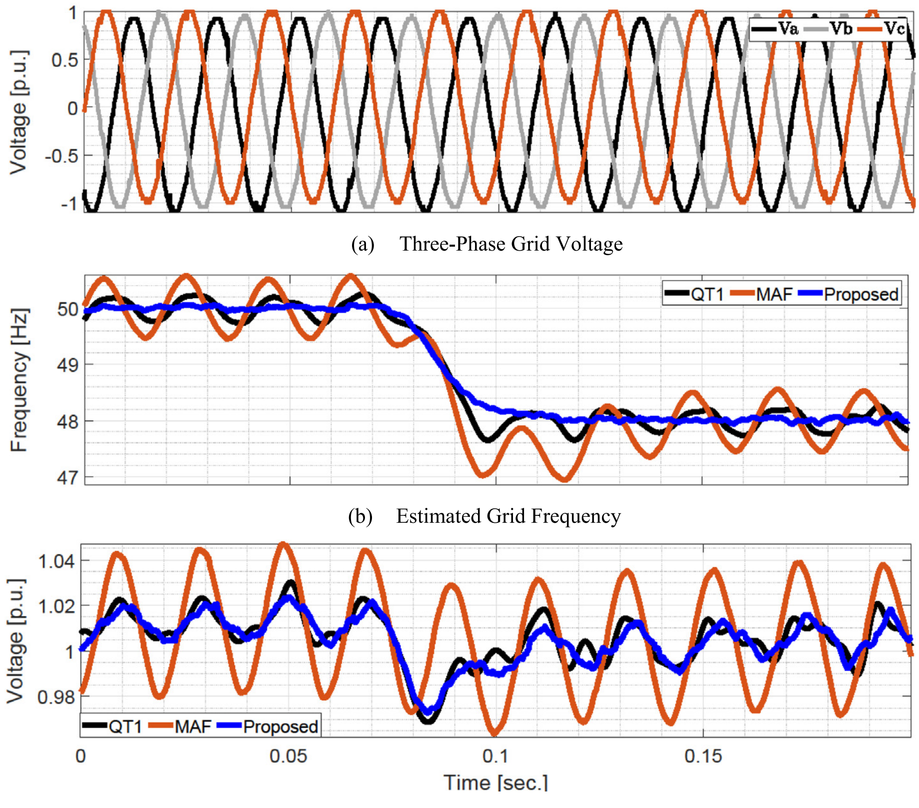


Fig. 2. Test setup [16].



(c) Estimated Direct-Axis Voltage

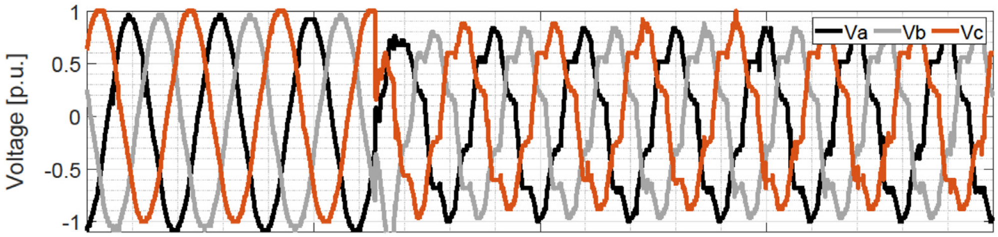
Fig. 3. Comparative experimental results for −2 Hz frequency step change.

4. Conclusion and future works

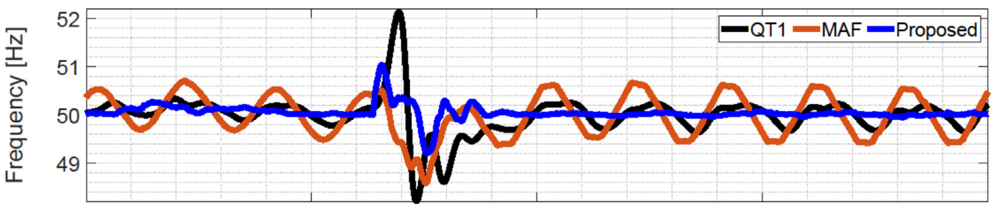
In this article, an enhanced grid-synchronizing sequence component separation method was proposed, where a modified, delayed signal cancellation method was applied for the sequence separation. Moving average filters working in the synchronous reference frame were implemented to enhance harmonic robustness. Finally, our method was made frequency-adaptive by estimating the unknown grid frequency using gradient estimator under delay-based

Table 1. Comparative steady-state performance summary.

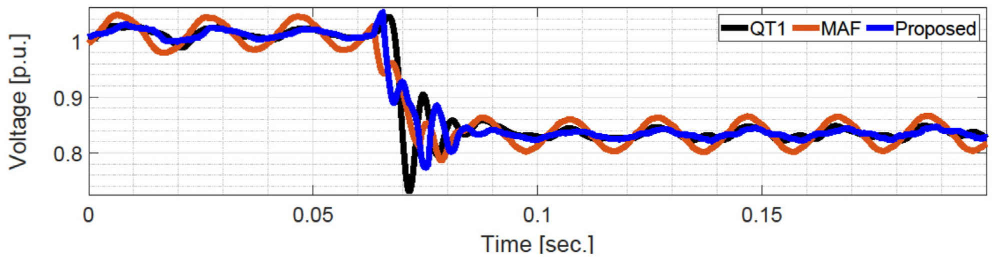
Performance indicators	MAF	QT1	Proposed
Test-I: −2 Hz Frequency step change			
Frequency ripple (peak-to-peak) (Hz)	1.03	0.48	0.15
Voltage ripple (peak-to-peak) (p.u.)	0.06	0.03	0.02
Test-II: Unbalanced and distorted grid			
Frequency ripple (peak-to-peak) (Hz)	1.17	0.58	0.17
Voltage ripple (peak-to-peak) (p.u.)	0.065	0.032	0.023
THD (%) (Grid-15.79%)	0.82	1.22	0.75



(a) Three-Phase Grid Voltage



(b) Estimated Grid Frequency



(c) Estimated Direct-Axis Voltage

Fig. 4. Comparative experimental results for unbalanced and distorted grid.

linear-regression framework. Comparative experimental results show that the FFPS voltage amplitude estimation ripple by the proposed method is at least 50% better than the next best comparative technique.

In this work, we have studied the grid-synchronization problem for grid-connected converters. Extraction of frequency, phase and FFPS components are important for monitoring the transmission power grid. Several issues in the transmission grid, such as decaying offset, transformer saturation, low- and sub-synchronous oscillations, and dynamic change in grid inertia, make the parameter extraction very challenging. These issues will be considered in future work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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