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Power system frequency estimation using morphological prediction of Clarke components

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ABSTRACT

This paper presents a new frequency estimator algorithm for electric power systems that uses the Mathematical Morphology operators of dilation and erosion to predict the Clarke Components from voltage signals of three phases of the system. The frequency is obtained as a function of phase shift between the predicted complex signal and the received complex signal given by the $\alpha\beta$-Transformation. The proposed method presented great accuracy and fast convergence for a wide range of different operational conditions involving transitory events of frequency deviation, amplitude variations, signal phase shifts and stable power swings. In addition, signals distorted by noises, harmonics and inter-harmonics were also tested. In order to demonstrate the quality of the new frequency estimator in each analyzed case, its estimation was compared with the responses obtained by four other methods, in terms of performance indices based on the estimation of transitory error and response convergence time. For all analyzed cases, the proposed methodology presented better results, showing great robustness and high accuracy for its task.

1. Introduction

Frequency is one of the most important variables in the operation of an electric power system. Its estimation is important to a wide range of applications such as in the system protection, control and energy quality. Although the normal operation of an electric power system does not produce major changes in frequency, a large unbalance between generation and load affects the frequency of the system significantly.

During a transient in an electric power system, the frequency may change and its estimation must be as fast and accurate as possible for the correct relays operation. In [1] it is presented the effects of frequency tracking in the protective relays, and it is also shown that the magnitude of differential currents and the impedances seen by the protection elements are influenced by the accuracy and velocity of this procedure. Furthermore, frequency estimation is essential for phasorial measurement because it depends on the power system frequency. As it occurs for the protection relays, frequency must be accurately estimated to ensure a good performance of the phasorial measurement elements.

In this context, it is necessary to develop precise and robust methodologies to perform the frequency estimation. Most of the relays use zero crossing detection for this task. However, this procedure is inaccurate when the signals processed have a significant amount of noise or harmonic content.

Many algorithms for frequency estimation have been proposed in recent specialized literature, among which many are based on the Discrete Fourier Transform (DFT). Such methods work well when the signal frequency is close to its nominal value, but during major frequency variations, errors tend to occur due to the spectral leakage effect. To minimize this drawback, a recursive method to compute the phase difference is proposed in [2]. Also, in [3] it is proposed a Shifting Window Average Method, which uses a one-cycle DFT and one-cycle integration in the frequency answer. Both methodologies presented in [2,3] have good precision in steady state condition, but suffer with time delay in transients.

Another improvement to DFT based frequency estimators appears in Ref. [4], which proposes a hybrid method using Taylor series. Despite the improvements achieved, this method has higher estimation errors for signals containing noises.

Other frequency estimators using different mathematical and computational tools have also been proposed over the years, among which may be mentioned the methods based on Kalman filters, as in [5] and [6]; the methodology using recursive Newton type algorithms, as in [7]; and least mean square (LMS) based algorithms, as

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shown in [8,9]. Besides, a frequency estimator based on demodulation of two complex signals was proposed in [10]. Also, the Clarke components of the voltage signals has been used to compute the system frequency in an iterative process proposed in [11], which uses a proportional-integral-derivative controller. These algorithms also present some problems and frequently demand an additional answer filtering for better accuracy and robustness.

Considering this context, this paper proposes a new technique for frequency estimation, which can be applied as a frequency tracker in numeric relays for protection purposes or as a frequency measurement function. The methodology uses the Mathematical Morphology operators of dilation and erosion to predict the Clarke Components from the voltage signals of the three phases of the system. Furthermore, the frequency is obtained as a function of the phase shift between the predicted complex signal and the received complex signal given by the αβ-Transformation.

In order to validate the quality of this proposed methodology, some performance indices, such as convergence time, transitory error and overshoot, were obtained. The objective was to compare the response of the proposed method against four other frequency estimators. A wide range of signals including different conditions of frequency and amplitude variation were tested, which simulated different operational conditions of the power system. Besides, signals with noise and harmonics were also tested. In all analyzed cases, the proposed method based on the Morphological Predict of Clarke Components (MPCC) showed better convergence times and great accuracy in frequency estimation for all sampling rates tested, demonstrating the robustness of the proposed methodology. The following sections describe the method, the results, and the conclusions.

2. Methodology description

The proposed methodology is based on the Morphological Predict of Clarke Components obtained from the αβ-Transformation. Using the voltages or currents of the system three-phase and applying the referred transform in these signals, it is possible to obtain a complex signal composed by α and β components [10]. Voltage signals were used in this study, so V_α and V_β are defined as stated in the following equation:

$$\begin{bmatrix} V_\alpha(n) \\ V_\beta(n) \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_A(n) \\ V_B(n) \\ V_C(n) \end{bmatrix} \tag{1}$$

In (1), (n) represents the actual sample and V_A, V_B and V_C correspond to the voltage samples of phase A, B and C, respectively. Hence, the complex resultant signal is given by the following equation:

$$u(n) = V_\alpha(n) + jV_\beta(n) \tag{2}$$

Since V_α and V_β have sinusoidal waveforms, as shown in Fig. 1, the future values of these signals can be predicted using the Mathematical Morphology operators of dilation and erosion, which are functions of a structuring element (SE) that reproduces these characteristics [12].

A SE is a value or a set of values that are used to make a comparison with the central term of a data window. An appropriate SE to be applied in frequency estimation is represented by the following equations:

$$SE = \cos(2 \times \pi \times f \times \Delta t) \tag{3}$$

In (3), f represents the nominal frequency of the power system, and Δt the sampling interval.

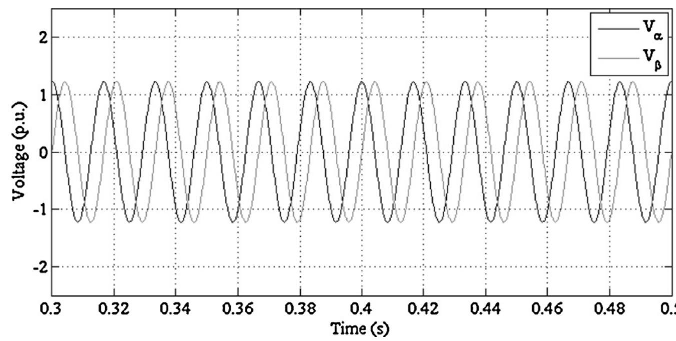

Fig. 1. Signals obtained from αβ-Transformation of three-phase voltage signals.

The frequency estimator proposed in this article uses morphological predict of V_α and V_β signals. This can be made using two moving data windows with three samples, one for each signal. These data windows are given in the following equations:

$$w_\alpha(n) = \begin{bmatrix} V_\alpha(n-2) & V_\alpha(n-1) & V_\alpha(n) \end{bmatrix} \tag{4}$$

$$w_\beta(n) = \begin{bmatrix} V_\beta(n-2) & V_\beta(n-1) & V_\beta(n) \end{bmatrix} \tag{5}$$

At each new sample, both windows are updated and the left $(n-2)$ elements are discarded. The other elements are shifted to the left and the new sample enters in the right position (n). For each window, a prediction is made using the dilation and erosion morphological operator which were modified for this application. These operators are respectively given by the following equations:

$$(w \oplus SE)(n) = \frac{V(n)}{SE} \tag{6}$$

$$(w \ominus SE)(n) = \frac{V(n-2)}{SE} \tag{7}$$

where w represents one of the data windows; V represents V_α or V_β samples inside their respective data windows.

After calculating the erosions and dilations of $V_\alpha(n)$ and $V_\beta(n)$, the future values of these quantities are estimated according to the following equation:

$$P(n) = \frac{1}{2}(w \oplus SE + w \ominus SE) \tag{8}$$

Then, the calculated values for P_α and P_β are used to form the complex estimated signal given by Eq. (9), which is applied to perform the phase shift calculation between $u_{est}(n)$ and $u(n)$, according to the following equation:

$$u_{est}(n) = P_\alpha(n) + jP_\beta(n) \tag{9}$$

$$\Delta\phi(n) = u_{est}(n) \times u(n)^* \tag{10}$$

In (10), $u(n)^*$ represents the complex conjugate of $u(n)$. The system frequency estimation is given by Eq. (11), which is a function of phase shift $\Delta\phi(n)$ and sampling frequency (f_s) [13].

$$f(n) = \frac{f_s}{2\pi} \times \tan^{-1}\left\{\frac{\mathrm{Im}[\Delta\phi(n)]}{Re[\Delta\phi(n)]}\right\} \tag{11}$$

At Eq. (11), Im and Re represent, respectively, the imaginary and the real parts of $\Delta\phi(n)$. The flowchart of this proposed methodology can be seen in Fig. 2.

The above technique was tested in a wide range of computationally generated signals with different frequency variation types, harmonical content, and noise. Also, the proposed methodology was tested for signals simulating stable power swings. In all cases, this estimator often showed excellent results compared to four other methods cited in Section 3 according to the performance indices presented in Section 4. The results of this comparison are presented in Section 5.