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Real-time electrical variables estimation based on recursive wavelet transform

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A B S T R A C T

In frequency and phasor estimation algorithms, the undesired components are required to be filtered out from the original signals. In power systems, the undesired components are the decaying dc offset and harmonics. These components could cause delay in algorithm convergence time and deviation from the desired results to a great extent. This paper proposes a new recursive algorithm for accurate and fast estimation of the instantaneous electrical variables such as frequency, amplitude and phase angle. The new algorithm provides an improvement over the existing recursive wavelet transform and, therefore, it is called IRWT. The IRWT performance is compared with the commonly used full-cycle discrete Fourier transform (DFT) and the recursive wavelet transform (RWT) methods. Since it uses a special mother wavelet function, it reduces computational complexity compared to the conventional DFT based method. Compared to the recursive wavelet transform (RWT) method, it has a faster response time. It is shown that IRWT possesses an improvement over a wide range of decaying dc component, harmonic distortions, frequency deviation and sampling frequency compared to the previously proposed methods. This characteristic of IRWT makes it a good candidate for the real-time applications in any power systems.

Introduction

Use of phasor measurement technology in real-time monitoring, state estimation, model validation, and instability detection improve power system visualization, protection, and control. Phasor measurement accuracy and fast measurement become essential aspects that directly affect the application performance and, therefore, it may have an extensive impact on the power system [1]. Therefore, an effective measuring algorithm is necessary to mitigate blackouts and learning the power system real time behavior.

The main sources of phasor measurement uncertainties are divided in two groups: First, inherent errors related to the measuring devices and technology and second, the errors associated with the computational phasor measurement algorithms. Due to the low scanning rates and relatively slow computations of the first group, much of the delays inherent in the phasor measurement are inevitable and the present technology is incapable of removing these delays. However, the phasor measurement algorithms provide an opportunity to minimize the overall errors in the phasor estimation process [2]. Therefore, real-time and accurate measurement of the frequency and phasors of the voltage and current signals is vital for power system.

In disturbance conditions, power system voltage and current signals are not ideal sinusoids and often contain decaying dc offset, harmonics and/or noise. Any power system faults, switching operations, and transients phenomena may cause oscillations, disturbances, frequency deviation, and high-frequency interference in the magnitude and frequency of the signals. Therefore, fast and accurate estimation of the electrical variables, i.e., amplitude, phase angle and frequency, is still a contemporary research topic of interest [2–5].

In digital protection relaying, DFT is the most preferred method to extract the fundamental phasor quantities from the signals. DFT is robust when encountering integer harmonic components and has a relatively accurate response for the fundamental component calculation [6]. However, it is not robust enough when encountering some disturbances, such as decaying dc offset, frequency deviation and inter-harmonics. These disturbances can cause undesirable oscillations and time-delay in the DFT results.

Many algorithms have been proposed to deal with the dc offset problem in phasor estimation which can be divided into two

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categories [7–14]. One is dc component filtering from the original signal before the phasor estimation and the other method is calculating the dc component offset and then removing it from the original signal. High computational complexity and required time delay for estimation of the decaying dc parameters are the main drawbacks of these algorithms. In [7] a digital mimic filter based has been proposed. In this algorithm, the decaying dc component removal is complete when the time constant is equal to that implemented in the mimic filter. In [8], a DFT based method that requires one cycle plus two samples to calculate and remove the decaying dc offset was proposed. The proposed method in [9] uses the integral of the original signal for parameters estimation of the decaying dc component. This method is based on the fact that the integral of the sinusoidal signal and decaying dc offset, over one period are zero and non zero, respectively. An algorithm that uses partial summation technique to eliminate the influence of decaying dc offset on the DFT algorithm has been proposed in [10]. Reference [11] uses the periodicity of the fundamental frequency and integer harmonics using one cycle plus two samples for calculating the decaying dc component parameters. A modified DFT based full cycle phasor estimation algorithm has been proposed in [12]. The algorithm can remove the effect of decaying dc offset from the estimated phasors by means of two orthogonal digital DFT filters. However, it requires extensive amount of computations to calculate the decaying dc component parameters. An adaptive phasor estimation algorithm to suppress the effect of an exponential decaying dc component based on the weighting Least Error Squares (LES) technique is proposed in [13]. In [14] the decaying dc component magnitude and time constant are estimated by integrating the fault current signals during one cycle. The decaying dc component is eliminated by subtracting the dc value at each sampling instant.

Many algorithms have been developed for the estimation of the power system frequency. A good number of these algorithms are DFT based methods and have satisfactory dynamic responses. However, in these methods, any deviation from the rated frequency generates inter-harmonics will cause error and oscillation in the frequency estimation. Various methods have been proposed to overcome the DFT based algorithms drawbacks in frequency estimation. Zero crossing (ZC) technique is one of the commonly used frequency estimation methods [15–17]. ZC is a time-domain based method which uses the samples in half or one cycle to estimate the power system frequency. The major shortcoming of this technique is its sensitivity to harmonics and noise. The LES [18] and Newton-type [19] algorithms are additional frequency estimation techniques. Due to the nonlinear terms approximation by Taylor series expansions, the accuracy is only a narrow band around the fundamental frequency. Reference [20] proposes a method based on three consecutive samples of the instantaneous input signal. The main issues in this method are noise and zero crossings which cause high errors at the output. Artificial intelligent (AI) based techniques like neural network and genetic algorithm are also employed to phasor and frequency estimation [21–23]. Performance of these methods depends on training and optimization techniques, and usually their implementations and computations are complex.

The wavelet transform approach has been used for frequency and phasor computation in protective relaying [24–26]. The recursive WT based methods are more suitable for real-time applications. The recursive wavelet transform can be implemented for extracting the band energy of any center frequency with low computation [27]. In [28] a recursive algorithm based on continuous wavelet transform is proposed. This algorithm needs future output samples to update the new estimating sample, thus it is not applicable for real-time applications. In [29] a recursive band-pass filter is proposed to compute the phasor of the fundamental and symmetrical components. This filtering is performed using several previous samples and filtering outputs. However, the high decaying dc offsets cause error and high initial overshoot in the filter output. This algorithm is sensitive to frequency deviation and does not always produce an appropriate dynamic response. Also the output will usually converge to the final value after more than five cycles that is a high time-delay for the real-time protective relays.

In this paper, an improved recursive wavelet transform (IRWT) for real-time estimation of the amplitude, phase angle and frequency is proposed. A new mother wavelet function based on a recursive equation is constructed. The recursive algorithm is developed for bandpass filtering. The filter output is updated only using few previous sample values and filtering outputs. Therefore, computational complexity of the proposed filter, which is the most issue of the wavelet based methods, is greatly reduced. Subtracting the WT even set samples from the WT odd set samples (SEO) is considered for frequency and phasor estimation. The SEO set samples greatly reduces the effect of decaying dc component in phasor computation and prevents the initial overshoot in the filter output. This overshoot is common in most algorithms. The proposed algorithm is compared with the full cycle DFT technique and the RWT based method in [29]. The proposed IRWT is an improvement over a wide range of decaying dc component, harmonic distortions, frequency deviation and sampling frequency compared to the previously proposed methods. This characteristic of IRWT makes it a good candidate for the real-time applications in any power systems. The static, dynamic, transient, and noise tests are performed to demonstrate the effectiveness and superiority of the proposed algorithm.

Real-time phasor estimation based on IRWT

In order to propose the IRWT algorithm a new mother wavelet is constructed in Section "Mother wavelet construction". A brief introduction to wavelet transform and criteria for the mother wavelets will be presented in this section. Then, a new wavelet function is introduced in general form and will be analyzed for different cases based on our application. Finally, the optimized function is selected as th mother wavelet. In Section "Proposed IRWT based on even and odd samples" the coefficients of the proposed mother wavelet are extracted and splited in two sets samples. The proposed algorithm based on these two sets of coeffiecients are presented accordingly. Finally, the error calculations for wide range of main parameters will be proposed in Section "Error analysis".

Mother wavelet construction

Let $\psi_{s,\tau}(t), s \in \mathbb{R} \setminus \{0\}, \tau \in \mathbb{R}$ be a set of functions defined as translation and re-scales of a single function $\psi(t)$,

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{|s|}}\psi\left(\frac{t-\tau}{s}\right) \tag{1}$$

The function ψ, which is called the mother wavelet, is assumed to satisfy the admissibility condition [30],

$$C_\psi = \int_{\mathbb{R}} \frac{|\Psi(\omega)|^2}{\omega} d\omega < \infty, \tag{2}$$

where $\Psi(\omega)$ is the Fourier transformation of $\psi(t)$ and C_ψ is called admissibility constant. Also, the admissibility condition requires that the wavelet to be oscillatory in time and satisfy the followings.

$$\Psi(\omega)|_{\omega=0} = 0 \text{ i.e. } \int_{-\infty}^{+\infty} \psi(t)dt = 0 \tag{3}$$

Therefore, any mother wavelet should satisfy the admissibility conditions in (3).

In our application, mother wavelets with short time and frequency duration are more efficient. For this reason, we construct a mother wavelet, $\psi(t)$, as described below.