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A quadratic polynomial signal model and fuzzy adaptive filter for frequency and parameter estimation of nonstationary power signals

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ABSTRACT

Accurate estimation of amplitude, phase and frequency of a sinusoid in the presence of harmonics/inter harmonics and noise plays an important role in a wide variety of power system applications, like protection, control and state monitoring. With this objective, the paper presents a novel hybrid approach for the accurate estimation of dynamic power system frequency, phasor and in addition to suppressing the effect of harmonics/interharmonics and noise in the voltage and current signals. The algorithm assumes that the current during a fault occurring on a power system consists of a decaying dc component, and time variant fundamental and harmonic phasors. For accurate estimation of fundamental frequency, phasor, decaying dc and ac components in the fault current or voltage signal, the algorithm uses a quadratic polynomial signal model and a fuzzy adaptive ADALINE filter with a modified Gauss–Newton algorithm. Extensive study has been carried out to demonstrate the performance analysis and fast convergence characteristic of the proposed algorithm. The proposed method can also be implemented for accurate estimation of dynamic variations in the amplitude and phase angles of the harmonics and inter harmonics mixed with high noise conditions.

1. Introduction

Real-time dynamic state monitoring, state estimation and islanding detection. are essential for wide area monitoring, protection and control applications in power networks. Nonstationary sinusoids occur in electrical power networks due to the proliferation of power electronic equipments, computers and microcontrollers. Further the integration of renewable energy sources in the utility grid results in the generation of harmonics, interharmonics, and severe waveform distortions [1,2]. It is well known that the harmonics/interharmonics interfere with sensitive electronic equipments and cause undesired power loss, overheating, and frequent fuse blowing. Also the speed and accuracy of the estimation algorithms are adversely affected by the presence of harmonics/interharmonics and noise in the signal [3]. Thus, there is an utmost need of an algorithm which can be efficient for accurate real-time dynamic phasor estimation that plays an important role in the area of protection and control application in power networks.

In recent years a large number of techniques have been proposed for the estimation of the power network phasor and frequency accurately. The simplest way to estimate the frequency of a signal is to measure the time of its zero

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crossing [4]. However, the voltage and current waveforms are usually distorted and noisy. Most of the digital relays adopt discrete Fourier Transform (DFT) like Full cycle DFT [5,6], and its modifications [7–9] for phasor estimation of the voltage and current signals. Although Fourier based algorithms are efficient in estimating phasors accurately for time invariant signals, their performance deteriorates for time varying signals contaminated with noise and harmonic distortions. Another widely used algorithm for signal parameter estimation is the least squares algorithm [10], which, however, suffers from higher computational overhead since it requires matrix inversion at every iteration. Other methods like, Prony analysis technique [11], Kalman filters [12,13] and weighted least squares method [14] are based on the nonlinear curve fitting techniques and therefore suffer from inaccuracies when the signal frequency deviates widely from its nominal value. Parametric approaches [15], ESPRIT method [16], Improved Prony method [17], Fourier analysis [18], window based methods [19], are able to compute damping coefficients, but they are highly sensitive to noise and computationally expensive due to the finding of roots of higher order polynomials. Methods like orthogonal filtering [20], Taylor series expansion [21], wavelet transform [22,23], adaptive notch filter [24], Filter bank approach [25] require dedicated filters for removal of harmonic components before applying the algorithms for signal parameter estimation. Comparison of different adaptive algorithms for frequency and phasor estimation are provided in [26].

In recent years, artificial neural network based techniques [27,28] have been used for fundamental and harmonic phasor estimation due to their simplicity in structure and ease of computation in comparison to other well known techniques. Further the adaptive linear neuron known as ADALINE [29–31] has been used widely as a powerful tool for signal parameter estimation. But the conventional ADALINE was used for single output systems with tracking error, introduced due to non-stationary nature of the signal. Further, the arbitrary choice of the weights connecting the inputs to the computing neurons of the ADALINE gives rise to different tracking performance. A two-stage ADALINE discussed in [32] is capable of estimating fundamental frequency and phasor of a time varying signal under frequency deviation conditions but its computational cost is very high. In addition to this Fuzzy Logic and Neural network approaches have been employed for nonlinear systems including the power system applications, MIMO [33–35], SISO [36,37] and aerospace applications [38] where the state variables are difficult to be measured. Also to achieve wider operating conditions under uncertainties and to adopt to the nonlinear uncertainties Fuzzy Control has been used in [39,40] which emphasize the applicability of Fuzzy control to power system applications

Hence this paper proposes a hybrid approach for estimating the time varying amplitude, phase, and frequency of a sinusoid during fault condition to deal with time varying signal waveforms subjected to amplitude modulation, phase modulation, step change, and fundamental frequency deviations. Generally in case of a power network faults, the voltage and current signals comprise decaying dc and fundamental components and hence in the proposed approach they have been expressed as a time series using Taylor series expansion. The parameters of the expanded Taylor series are computed using the fuzzy variable step size ADALINE (FVSS ADALINE) where the learning parameters are made adaptive to compel the resultant error of the desired and estimated output to satisfy a stable difference error equation. As a result this approach, allows one to achieve better accuracy on the rate of convergence and stability by suitable selection of parameters of the error difference equation. The FVSS ADALINE approach is proposed for frequency estimation of time varying power signals and the modified recursive Gauss–Newton approach is used for phasor estimation [41,42] This hybrid approach using the quadratic polynomial signal model performs very well in terms of accuracy for signals with dynamic variations. In case of fast changes in signal dynamics, a new adaptive fuzzy logic based approach is proposed in this paper to update the step size of the ADALINE and cope up with the abrupt large and small deviations thereby providing significant noise rejection and faster convergence. The modified recursive Gauss–Newton ADALINE used for phasor estimation has been simplified by Hessian matrix approximation and also the need for matrix inversion at every iteration. This procedure results in reducing the computational complexity of the algorithm and in addition it also exhibits accurate tracking results in non-stationary environment using the objective function for error minimization. Moreover as per the demand in some real power signal application scenarios both the frequency estimation using FVSS and phasor estimation using modified recursive Gauss–Newton algorithm (MRGNA) approach can proceed simultaneously in the same iteration to detect any change either in the amplitude, phase or frequency of the time varying signal. Further for a three phase power system application, a multi-output ADALINE structure is discussed for the simultaneous estimation of amplitude and phase angle of three-phase current and voltage signals. A detailed study of the global convergence of the proposed FVSS ADALINE approach is presented in this paper. Extensive simulations are carried out to test the accuracy and speed of the proposed algorithm in various scenarios as observed in real power system applications. Simulation and experimental results show superiority of the proposed algorithm in estimating the dynamic behavior of the signal in presence of harmonic/interharmonic and noise over many conventional algorithms like DFT and ADALINE based methods.

The rest of the paper is organized as follows: Section 2 is divided into two parts, describing the proposed frequency and phasor estimation of the power signal, respectively. The performance analysis and global convergence characteristics of the proposed method are studied in Section 3 Numerous simulation and experimental results are presented in Section 4, while Section 5 outlines the conclusion.

2. Proposed algorithm

ADALINE based methods show inaccuracy in estimating fundamental frequency deviations in the presence of