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Estimation of dominant mode parameters in power systems using correlation analysis

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ABSTRACT

This paper proposes a hybrid Prony-cross-correlation real-time tracking dominant mode and parameter estimation using simulated and phasor measurement unit (PMU) data. It proposes a new method for detecting the dominant mode during the transient phenomena in electrical power systems. The performance of the proposed method has been compared to some of the existing methods for estimating the frequency and damping factor of a signal under noisy conditions, such as the Prony and EKF methods. In contrast to the traditional Prony and EKF methods for estimating the modes parameters, which require the order of the model and the initial parameters of the mode, the hybrid Prony-cross-correlation does not require any previous information. Three Brazilian systems (reduced, north and NIS) have been studied for both stationary and transient phenomena in power systems to determine the robustness and the accurate estimates even in the presence of noise in the measured signal by the proposed method.

1. Introduction

Currently, modern power system is composed of several generators supplying power to heavy loads far away from generation centers, all connected through transmission lines. These systems are continuously disturbed by load variations and severe faults, such as short circuits and tripping generators. When abrupt load variations or faults occur, oscillations are generated. These oscillations are called a post-disturbance or *ringdown* [1] response, and they are associated with the oscillatory modes.

The electromechanical oscillations are properties of alternating current transmission systems. They cannot be eliminated but can be properly estimated. They are observed in most power systems, and the parameters of the modes can provide important information about the system stability [2]. By monitoring these power systems in near real time, the tracking of these parameters may prevent instabilities and allow corrective measures to maintain the stability and safety of the system.

According to Trudnowski et al. [3], electromechanical modes can be classified into two groups: local and inter-area. The former is related to the single generator swinging against the rest of the system, whereas the latter is associated with a group of generators in one area swinging against a group of generators in another area [2]. To study these modes, that is, for assessing stability, two method classes are available: the spectral and parametric methods [4]. Spectral methods use the fast Fourier transform (FFT) on a response signal to extract information about frequencies and their magnitudes, whereas parametric methods employ a model for the system or signal to extract the modes and their respective parameters. The nature of electromechanical oscillations is a nonlinear phenomenon; however, this study is performed in the context of small signal stability using linear system techniques [5,6]. If the linearized model is stable, this implies that the operating point is stable [6]. Meanwhile, in the case of large oscillations, the best approach is to use nonlinear techniques to draw inferences about the stability.

Power system linear models are formed by state-space equations of high order, which may take hundreds of thousands of states. Several analytical techniques of sparse linear systems are generally applied, which can reduce the order of the models, preserving the main system dynamic features in the frequency range of interest [7–10].

In the real-time context, to estimate dominant system modes, measurements can be obtained from phasor measurement unity (PMU) data. Thus, according of the type of data used, the measurement-based methods are classified into three groups [1,5]. The first group, called ambient data, is characterized by stochastic load changes that excite the existing oscillation modes [11,12]. The second group, called probing signals, consists of transient signals generated by injecting a test signal into the system under study [13]. The third group, called *ringdown* data, consists

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of transient signals of high energy caused by a major disturbance, such as line tripping, abrupt adding/removing of loads and tripping generators [13–15]. *Ringdown* and probe signals are characterized by presenting system oscillation modes with greater intensity than environmental data [3].

Several identification methods have been proposed in the literature for estimating the parameters of disturbance signals. These methods include the eigen analysis on system model [2], minimal realization algorithm [16], matrix pencil method [17], Hankel total least squares [18], the maximum likelihood method [19], and the numerical algorithm for sub-space state-space system identification [13]. In addition to these methods, the Prony method proposed in [20] has been used for identifying model parameters from time-domain responses. Other methodologies for electromechanical mode estimations have used a combination of the Prony method and Kalman filter [21] or extended Kalman filter [22].

Dominant system modes can be also extracted in the frequency domain using FFT [23,24] and the correlation analysis technique [25]. *Ringdown* signals are obtained through simulation or measured from PMUs. In the latter case, measurements may contain noise originating from electronic devices and other sources that can hinder the identification of the dominant modes. To improve the accuracy in noisy environments, correlation analysis can be applied to the system model.

In this paper, a hybrid method that combines the Prony method and correlation analysis is proposed for estimating the frequency and the damping factor of the dominant system mode of the *ringdown* signals. The proposed method uses nonlinear techniques to estimate the dominant mode parameters.

The remainder of this paper is organized as follows. In Section 2, the theoretical foundations for the Prony analysis and cross-correlation are presented. Section 3 describes the proposed hybrid Prony-cross-correlation method, and Section 4 discusses the performance of the proposed method for synthetic and real signals compared to the Prony method and the extended Kalman filter (EKF). Finally, conclusions are summarized in Section 5, as well as suggestions for future works.

2. Prony analysis and cross-correlation

As previously mentioned, the dominant modes of a power system can be extracted from a system model or a transient response signal that represents it. During the online operating and monitoring of systems, PMUs have been used; thus, the transient response signals or *ringdown* signals play an important role for the estimation of modes since they are high-density data.

2.1. Prony analysis

According to Hauer et al. [20], the *ringdown* signal can be expressed as the sum of exponentially damped sinusoidals and an error, as described in Eq. (1),

$$y(t) = \sum_{i=1}^{N_c} A_i e^{-\sigma_i t} \cos(\omega_i t + \phi_i) + \epsilon(t) \tag{1}$$

where the amplitude A_i, damping factor σ_i, angular frequency ω_i and phase angle ϕ_i are real and unknown, and $\epsilon(t)$ is a zero-mean white noise.

The identification procedure primarily consists of determining the parameters σ_i and ω_i and then calculating the eigenvalues $\lambda_i = \sigma_i \pm j\omega_i$. In fact, $y(t)$ may be measured system variables, such as active and reactive power [13], frequency or angular difference. Generally, the discretization of the signal response shown in Eq. (1) results in N samples, where the sampling frequency is given by $F = 1/T_s$. The unknown coefficients A_i, σ_i, ω_i and ϕ_i are calculated by solving the following nonlinear least squares problem,

$$r = \min\left(\sum_{n=0}^{N-1}\left(y[n] - \hat{y}[n]\right)^2\right) \tag{2}$$

where r and $\hat{y}[n]$ are the residual and predicted data of the nth sample, respectively.

Applying the Prony algorithm to the modal analysis of low-frequency oscillation can identify stationary signals, but it is sensitive to noise and cannot adaptively reflect the time-varying performance of the oscillation mode [20]. In response to these limitations, an improved Prony algorithm was proposed in [26], but it still suffered from low anti-noise performance and difficulty in model order determination. Thus, in [27], another algorithm that presents high performance in the presence of high noise is evaluated. The noise restrained in transient responses justifies the hybrid method proposed in this paper.

2.2. Cross-correlation

During identification of the electromechanical oscillation mode, Prony methods can be used as a filter; however, such methods are sensitive to noise. According to Grund et al. [28], for noise levels above 40 dB, no accurate results can be obtained. The previous subsection showed that the Prony method involves the estimation of the mode parameters of a nonlinear dynamic system given by Eq. (1). For convenience, Eq. (1) is repeated in the form

$$y(t) = x(t) + \epsilon(t), \tag{3}$$

where $x(t)$ is the first term of Eq. (1) and $\epsilon(t)$ is the zero-mean white noise.

The approximation of the parameters could be performed using only the signal $x(t)$ directly, without the need of the correlation, and this is possible only for the case of a noiseless signal. However, the use of the correlation function allows the estimation of the signal parameters even if it contains additive white noise.

Conceptually, there are two types of correlation functions: autocorrelation function and cross-correlation function. The cross-correlation function of any signals $x(t)$ and $y(t)$ can be written as

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} x(u+\tau)\bar{y}(u)du, \tag{4}$$

where τ is the time delay and $\bar{y}$ means the complex conjugate of y. The physical interpretation of the cross-correlation function is the product of two signals in which one signal leads or lags τ seconds. Conversely, the autocorrelation function can be obtained when we make both signals equal in Eq. (4). Thus, autocorrelation from the signal shown in Eq. (3) can be written as

$$R_{yy}(\tau) = R_{xx}(\tau) + R_{\epsilon\epsilon}(\tau) + 2R_{x\epsilon}(\tau). \tag{5}$$

When the signal $x(t)$ and the noise are uncorrelated, the term $R_{x\epsilon}(\tau)$ is zero and the term $R_{\epsilon\epsilon}(\tau)$ corresponds to a Dirac delta function in $\tau = 0$; therefore, both terms R_{xx} and R_{yy} will have peaks at the same points. Thus, the method presented in Section 3 can be applied to signals with additive white noise.

3. Proposed hybrid Prony-cross-correlation method

3.1. Preliminary definitions

Consider a damped signal $x(t)$ with amplitude A, damping coefficient $\sigma > 0$, angular frequency $\omega \neq 0$, and shifted ϕ radians. Such a signal can be written as shown in Eq. (6)

$$x(t) = Ae^{(-\sigma+i\omega)t}e^{\phi i}, \tag{6}$$