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# Distributed oscillation damping estimation to large scale power systems: A multi-area online empirical approach

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ABSTRACT

Online extraction and characterization algorithms to the distributed damping factor that can accurately monitoring the transient response in large interconnected power systems has attracted much attention, principally to maximize the multi-area functions in energy control centers. In this paper we present an online estimation algorithm to the distributed damping factor of inter-area electromechanical oscillations in power systems. The method is based on a statistical analysis of multi-area matching patterns (MPs) modes from spatially coupled empirical coefficients, and derived with a network partitioning method by coherent signal blocks into data clusters from the phase domain. This provides a distributed global picture on the modal behavior, which is derived using synchronized-time multi-area signals simultaneously recording from wide-area monitoring schemes (WAMS). For purposes as our multi-area online approach, a sliding data window frame for estimating the distributed damping factor of low-frequency electromechanical oscillations based on Prony and Fourier methods with multiple empirical orthogonal functions (EOFs) analysis is presented. In order to demonstrate the usefulness and adaptivity to obtain an online damping factor estimation and global picture of inter-area electromechanical modes from dynamic oscillations in distributed power systems, the proposed algorithm is applied in detail to the 16 machine-68 bus New England test system.



## 1. Introduction

Recent improvements to wide-area monitoring schemes (WAMS) in power networks have led to renewed investigation on techniques of identification, characterization and analysis to the damping associated to inter-area electromechanical oscillations. Many methods and applications have been introduced to take appropriate control actions to maintain the balance of the system and prevent instabilities and blackouts [1–11]. Advanced processing techniques can be adopted to maximize the capabilities and overcome the computational burden in energy control center functions, due to the large data sets collected from multiple locations during the use of WAMS into electrical grids. The measurement-based methods are suitable for online applications and are less expensive than the model-based methods to the large scale power systems analysis. Some of the existing techniques such as Hilbert–Huang analysis, Wavelet analysis, the Teager–Kaiser operator, dynamic harmonic regression, multi-signal Prony analysis, Koopman analysis, Fourier-based algorithms, adaptive filter, Matrix Pencil method, have been reported in [5,12–21]. Limitations such as its usefulness and adaptivity of existing methods make the parameters estimation of electromechanical oscillations still an active field of research. In [13–18], both Prony and Fourier based methods have been proposed to the estimation of online modal damping factor from measured data, and have been applied to approach electromechanical oscillation modes from these measurements. It is known that Prony's method can process multiple signals simultaneously, but it is not able to use large amount of data and characterize its distributed traveling waveform components from the used data set, principally because of its trade-off between accuracy and the computational burden, by itself tends to have quite poor numerical conditioning to solve the lineal prediction equation [13–15]. More difficulties that this method present are associated to its low performance at low signal-to-noise ratio (SNRs), and the tuning of parameters to use, like the polynomial order, sampling rate, and the lineal prediction model. It has been noted that the use of Prony analysis on multi-area signals

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of the entire record make the computational burden very expensive into centralized global analysis systems in network powers. On the other hand, the Fourier-based algorithm, which is derived from the use of an orthogonal window method, estimates damping factor with consecutive multiple orthogonal time windows. The advantage is that the ratio of the Fourier amplitudes in consecutive windows is dependent on the rate of modal decay and that least-square averaging techniques can be properly applied later to combine the obtained results [16–18]. It is seen that the main drawback of this method to its practical application into large power networks, is associated with the number of signals to analyze and its online recursive application, which is limited to a single signal. These damping factor estimation techniques are useful to analyze signals from certain regions in the power system, but cannot be used to estimate and characterize a global picture to the distributed damping factor from multi-area signals of a complete system with highly geographical dispersion [13–18]. Additionally, these methods tend to perform poorly in its online application to large data sets, which is treated in this paper. For any particular transmission grid, a comprehensive analysis to simulate, design, and test the adequacy of a centralized computation system in energy control center functions for power systems is of an extreme importance.

Recently, a statistical identification method established on the empirical orthogonal functions (EOFs) analysis has been widely applied to identify, characterize and extract inter-area instabilities from power system measurements. The technique is based on the correlation structure from space-time varying fields and its waveform propagation components. It allows to compress data into a few spatial patterns that contain variability modes [3–10]. It is noted that underlying applications of this technique such as its online optimal implementation to the distributed damping factor estimation and characterization based on Prony and Fourier methods has been reported little. This fact motivates us to the derivation of an online estimation algorithm in combination with the EOFs analysis in order to estimate and characterize the inter-area damping factor of exponentially decaying modes in large interconnected power systems oscillations. Thus, in this paper we present an online estimation algorithm to the distributed damping factor of inter-area electromechanical oscillations in power systems. The method is based on a statistical analysis of multi-area matching patterns (MPs) modes from spatially coupled empirical coefficients, and derived with a network partitioning method by coherent signal blocks into data clusters from the phase domain. This provides a distributed global picture on the modal behavior, which is derived using synchronized-time multi-area signals simultaneously recording from WAMS. For purposes as our multi-area online approach, a sliding data window frame of finite length for estimating the distributed damping factor of low-frequency electromechanical oscillations based in Prony and Fourier methods with multiple EOFs analysis is presented. By combining a process of synchronized identification of MPs modes, a new online optimal-global implementation and computationally efficient to the Prony and Fourier based methods is proposed to extract and characterize the distributed damping factor of multi-area oscillations into large power systems. In order to demonstrate the usefulness and adaptivity, the proposed algorithm is applied in detail to the 16 machine-68 bus New England test system.

The main original contributions of this paper are:

- The generalization of the Prony and Fourier based methods to be used to derive a distributed damping factor of inter-area electromechanical oscillations in large power systems.
- The development of an analytical framework to extract online modal information from large data sets using multi-area MPs modes and derived from its spatial correlation structure.
- Multiple EOFs analysis is introduced to guarantee the optimal modal decomposition from coherent signal blocks into data clusters from the phase domain using the WAMS.
- A sliding data window frame is included to provide a more detailed extraction and characterization to the online transient response in large interconnected power systems.

This paper is organized into the following sections: Section 2 introduces some theoretical background about the Prony and Fourier based methods and EOFs analysis; next, the proposed algorithm is described in Section 3; test results are provided in Section 4; finally, conclusions are given in Section 5. Additionally, in appendix are given some theoretical fundamentals on the proposed multi-area MPs modes method.

## 2. Theoretical framework

### 2.1. Prony Analysis

Prony analysis is a parametric fitting technique applied to the output of a linear-time invariant (LTI) system $\dot{x} = f(x)$, with initial state $x(0) = x_0$ at the time $t_0$. This method directly estimates the parameters of a dynamic system model from the output of the system by a linear combination of exponent functions (in the least-squared-error sense), with a basic form of:

$$y(k) = \sum_{i=1}^{L} A_i e^{j\theta_i} e^{\lambda_i k}, \quad k = 0, 1, 2, \ldots, N-1, \tag{1}$$

where $A_i$ is the amplitude, $\theta_i$ is the phase angle, $L$ is the model order, and $k$ is the sample index, with:

$$\lambda_i = \sigma_i \pm j2\pi f_i, \tag{2}$$

where $\lambda_i$ is the $i$-th eigenvalue, with damping factor $\sigma_i$ and frequency $f_i$. Refs. [13–15] present details to the Prony's method solution, and an extension to its online and multi-signals applications.

### 2.2. Fourier algorithm: multiple orthogonal window method

Orthogonal window method is a damping factor estimation algorithm that uses Fourier transformation of a complex exponential decaying signal on two consecutive time windows. So, the ratio of the Fourier amplitudes in each window is dependent on the rate of modal decay. The type of window is also important for the analysis, where "smooth" shaped windows such as the Kaiser Window are preferred [16–18]. In the method, it is assumed that the oscillating mode of interest is a complex exponential of the form:

$$z_r(n) = Ae^{j(\omega_0 n + \phi) - \alpha n} + \varepsilon(n), \tag{3}$$

with amplitude $A$, damping factor $\alpha$, modal frequency $\omega_0$, initial phase $\phi$, $\varepsilon(n)$ being additive complex Gaussian noise, and $n$ that represents the discrete-time. Then, two orthogonal windows are applied to the signal at different time positions to obtain:

$$y_{r1}^k = z_r(n) w_k(n), \quad (\text{for} \quad 0 \leqslant n \leqslant N_w - 1, \quad k = 1, 2, \ldots, K) \tag{4}$$

and

$$y_{r2}^k = z_r(n + N_g) w_k(n), \quad (\text{for} \quad 0 \leqslant n \leqslant N_w - 1, \quad k = 1, 2, \ldots, K), \tag{5}$$

where $w_n$ is the window to the $k$-th sliding block, $N_g$ is the number of samples between windows, and $N_w$ is the number of samples in both windows. Thus, the damping factor can be determined using:

$$\hat{\alpha}_k = \frac{1}{N} \log \left[ \text{Re} \left( \frac{Y_{r1}^k(\hat{\omega}_0)}{Y_{r2}^k(\hat{\omega}_0) e^{(-j\hat{\omega}_0 N_g)}} \right) \right], (\text{for} \quad k = 1, 2, \ldots, K), \tag{6}$$