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Measurement based analysis of electromechanical modes with Second Order Blind Identification

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ABSTRACT

The Measurement based modal analysis is an effective tool for obtaining essential information on the stability of power systems. This paper proposes a novel multivariate method for the measurement based modal analysis. The proposed method is based on a Blind Source Separation (BSS) technique called Second Order Blind Identification (SOBI), and it utilizes multiple signals measured from several locations in the power system. In addition to the SOBI algorithm, the proposed method uses the Random Decrement (RD) technique and the Eigensystem Realization Algorithm (ERA) to estimate the frequencies and damping ratios of the existing electromechanical modes. The performance of the SOBI–RD–ERA method is analyzed using both simulated data and measurement data collected from the Nordic power system. The results indicate that the frequencies and damping ratios of electromechanical modes can be estimated with high accuracy using the proposed method. Thus, the SOBI–RD–ERA method is a promising analysis tool for wide-area monitoring of electromechanical oscillations.

1. Introduction

Electromechanical oscillations are characteristic of interconnected power systems. The oscillations cannot be entirely eliminated and the damping of the oscillatory modes may set the limits to the power transfer capacity of the system. Typically, the oscillations are effectively damped but in certain situations poorly damped oscillations may lead to large scale disturbances, such as the WECC (Western Electricity Coordinating Council) breakup of August 10, 1996 [1]. Thus, monitoring the oscillatory stability is of high importance and may provide valuable information on the dynamic properties of the system.

The oscillatory stability can be monitored by utilizing measurements from phasor measurement units (PMU). Recently, wide area monitoring systems (WAMS) consisting of several PMUs have enabled using multiple synchronized measurement signals received from different locations in the power system for the measurement based modal analysis. Measurement based modal analysis is usually performed with ambient measurement data collected in real time from the power system. Ambient data are obtained during the normal operation of the power system (i.e., when the primary disturbance is caused by the load changes in the system).

Several previously published measurement based modal analysis methods estimate the system dynamics by using a single ambient measurement signal [2–8]. However, the best observability of the oscillatory modes cannot always be achieved by utilizing a single measurement signal [9–12]. The observability of the oscillatory modes can be improved when several measurement signals from different locations are analyzed simultaneously with multivariate analysis methods [9–14].

This paper proposes a new multivariate method for the measurement based analysis of electromechanical modes. The method is based on a Blind Source Separation (BSS) technique called Second Order Blind Identification (SOBI) [15–17], and uses the SOBI algorithm to recover the oscillatory signals from the noisy ambient measurement data collected from the power system. After processing the signals with SOBI, the method estimates the impulse response of the system with the Random Decrement (RD) technique [18,19] and identifies the modal parameters (modal frequency and damping ratio) with the Eigensystem Realization Algorithm (ERA) [20].

In modal analysis, SOBI has been previously applied for oscillating structures [21–23] but the algorithm has not been applied for

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power systems. This paper shows that the SOBI algorithm, along with RD and ERA, is applicable for analyzing the electromechanical modes of power systems and that the proposed method is robust against measurement noise. The performance of the method is analyzed with simulated data as well as real PMU measurement data collected from the Nordic power system.

This paper is structured as follows. Section 2 describes the theoretical background of the SOBI–RD–ERA method. In Section 3, the performance of the proposed method is investigated with a simple simulation model. In Section 4, the functionality of the method is analyzed using simulated measurements generated with a dynamic version of the IEEE three area reliability test system [24,25]. In Section 5, the SOBI–RD–ERA method is applied to actual PMU measurement data received from the Nordic power system. Section 6 illustrates the applicability of the SOBI–RD–ERA method by using it to analyze different sets of measured PMU data. Section 7 discusses the applicability of the method for analyzing electromechanical oscillations, and Section 8 presents the conclusions of this paper.

2. Methodology

The method proposed in this paper for the measurement based modal analysis of power systems consists of the SOBI, RD and ERA techniques. These techniques will be elaborated further in Sections 2.1–2.3. To illustrate the application of the SOBI–RD–ERA method to measurement data received from a power system, a block diagram of the method is presented in Fig. 1.

2.1. Second Order Blind Identification

Second Order Blind Identification (SOBI) [15–17] is a Blind Source Separation (BSS) technique. The fundamental objective of BSS is to retrieve unobserved source signals from their observed mixtures [21]. A well-known example of BSS is the cocktail party problem, where the individual speech signals of several people speaking simultaneously in a room are retrieved utilizing only the signals recorded by a set of microphones located in the room. In modal analysis, BSS has been widely applied for analyzing oscillating structures [26]. Recently, a BSS technique called Independent Component Analysis (ICA) was also applied to analyze the electromechanical modes in power systems [14]. The SOBI technique, however, has not been previously used in the field of electromechanical oscillation analysis.

The goal of the SOBI algorithm is to identify and separate the blind sources utilizing their temporal structure. SOBI relies entirely on second order statistics, whereas ICA techniques are based on higher order statistics (non-Gaussianity of the sources). Therefore, SOBI has an advantage compared to ICA techniques since the calculation of higher-order statistics is laborious and also difficult in the case of scarce data [21].

The model underlying behind the SOBI algorithm assumes that the observations $\boldsymbol{x}(t)$ gathered from the studied system consist of mixed independent source signals $\boldsymbol{s}(t)$ and additive noise $\boldsymbol{e}(t)$. The goal of the algorithm is to recover the unobserved source signals $\boldsymbol{s}(t)$ (i.e., the electromechanical modes) from the observed mixtures of the source signals and noise. The model considered in SOBI can be written

$$\boldsymbol{x}(t) = \boldsymbol{y}(t) + \boldsymbol{e}(t) = \boldsymbol{A}\boldsymbol{s}(t) + \boldsymbol{e}(t), \tag{1}$$

where $\boldsymbol{y}(t)$ is the signal part of the observations, and $\boldsymbol{A}$ is referred to as the mixing matrix [15,21].

In SOBI, the sources are assumed to be mutually uncorrelated and stationary. If the sources are scaled to have a unit variance, their covariance matrix is

$$\boldsymbol{R_S}(0) = E[\boldsymbol{S}(t)\boldsymbol{S}^*(t)] = \boldsymbol{I}, \tag{2}$$

where * denotes the conjugate transpose of a vector. The covariance matrix of the observations is

$$\boldsymbol{R_x}(0) = E[\boldsymbol{x}(t)\boldsymbol{x}^*(t)] = \boldsymbol{A}\boldsymbol{A}^H + [\boldsymbol{\sigma}(t)\boldsymbol{\sigma}^*(t)] = \boldsymbol{A}\boldsymbol{A}^H + \boldsymbol{\sigma}^2\boldsymbol{I}, \tag{3}$$

where $\boldsymbol{\sigma}$ is a vector consisting of the variance of the noise, and H denotes the complex conjugate transpose of a matrix [15,21].

The first step of SOBI consists of whitening the signal part $\boldsymbol{y}(t)$ of the observation such that

$$E[\boldsymbol{W}\boldsymbol{y}(t)\boldsymbol{y}^*(t)\boldsymbol{W}^H] = \boldsymbol{W}\boldsymbol{A}\boldsymbol{A}^H\boldsymbol{W}^H = \mathbf{I} \tag{4}$$

From (4), it follows that for any whitening matrix $\boldsymbol{W}$, there exists a unitary matrix $\boldsymbol{U}$ such that $\boldsymbol{W}\boldsymbol{A} = \boldsymbol{U}$. If $\boldsymbol{x}(t) \neq \boldsymbol{y}(t)$ (i.e., noise is present in the observations), the whitened process $\mathbf{z}(t) = \boldsymbol{W}\boldsymbol{x}(t)$ yields:

$$\begin{aligned} E\left[\mathbf{z}(t)\mathbf{z}^*(t)\right] &= E\left[\boldsymbol{W}\boldsymbol{x}(t)\boldsymbol{x}^*(t)\boldsymbol{W}^{\mathrm{H}}\right] = \boldsymbol{W}\boldsymbol{A}\boldsymbol{A}^{\mathrm{H}}\boldsymbol{W}^{\mathrm{H}} + \boldsymbol{W}\sigma^2\boldsymbol{W}^{\mathrm{H}} \\ &= \boldsymbol{W}\left(\boldsymbol{R_x}(0) - \sigma^2\boldsymbol{I}\right)\boldsymbol{W}^{\mathrm{H}} + \boldsymbol{W}\sigma^2\boldsymbol{W}^{\mathrm{H}} = \boldsymbol{W}\boldsymbol{R}_x(0)\boldsymbol{W}^{\mathrm{H}} \end{aligned} \tag{5}$$

Consequently, the whitening matrix $\boldsymbol{W}$ can be determined from the covariance matrix $\boldsymbol{R_x}(0)$ of the observations (readers are referred to [15] for more details).

The second step of SOBI is finding the unitary matrix $\boldsymbol{U}$. To determine $\boldsymbol{U}$, spatially whitened time lagged covariance matrices $\boldsymbol{R_{W,x}}(\tau)$ are considered:

$$\begin{aligned} \boldsymbol{R_{W,x}}(\tau)E[\mathbf{z}(t+\tau)\mathbf{z}^*(t)] &= \boldsymbol{W}E[\boldsymbol{x}(t+\tau)\boldsymbol{x}^*(t)]\boldsymbol{W}^H \\ &= \boldsymbol{W}\boldsymbol{A}E\left[\boldsymbol{s}(t+\tau)\boldsymbol{S}^*(t)\right]\boldsymbol{A}^H\boldsymbol{W}^H \\ &= \boldsymbol{U}\boldsymbol{R}_s(\tau)\boldsymbol{U}^H \quad \forall\tau \neq 0 \end{aligned} \tag{6}$$

Since $\boldsymbol{U}$ is unitary and $\boldsymbol{R_s}(\tau)$ is diagonal, (6) shows that any whitened covariance matrix $\boldsymbol{R_{W,x}}(\tau)$ can be diagonalized with the unitary transform $\boldsymbol{U}$. Consequently, the matrix $\boldsymbol{U}$ can be determined through the eigenvalue decomposition of the time-lagged whitened covariance matrices. After determining $\boldsymbol{U}$, the mixing matrix $\boldsymbol{A}$, and the sources $\boldsymbol{S}(t)$ can be easily calculated since $\boldsymbol{U} = \boldsymbol{W}\boldsymbol{A}$, and $\boldsymbol{x}(t) = \boldsymbol{A}\boldsymbol{s}(t)$ [15,21].

To estimate the unitary matrix $\boldsymbol{U}$, the SOBI algorithm jointly diagonalizes several whitened covariance matrices $\boldsymbol{R_{W,x}}(\tau)$ with

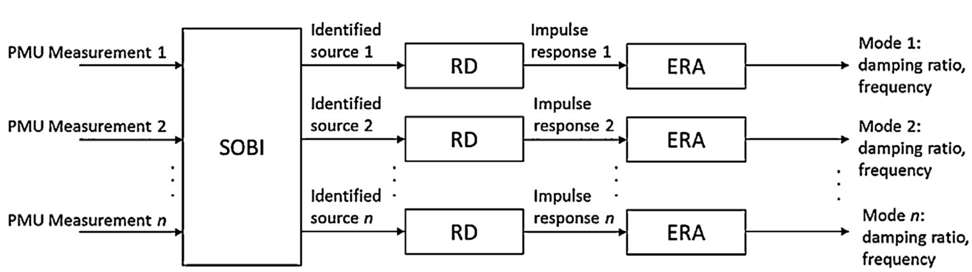

Fig. 1. A block diagram of the SOBI–RD–ERA method (two column figure).