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Review

Analysis of low frequency oscillations in power system using EMO ESPRIT

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ABSTRACT

Identification of poorly damped low frequency oscillations present in the densely interconnected power system is of paramount importance to maintain its stable operation. Estimation of signal parameters via rotational invariance technique (ESPRIT) is a parametric method used for analysing such signals even under noisy conditions. However, this method requires precise information about the number of modes present in the signal. Hence, this work uses a combination of Exact Model Order (EMO) algorithm and ESPRIT for analysing these low frequency oscillations. The performance of the proposed method is tested using various synthetic signals with different levels of noise and PMU reporting rates. Further, the robustness of the proposed method towards noise resistance is compared with modified Prony, TLS-ESPRIT and ARMA methods. Finally, the proposed method is tested using real time probing test data obtained from Western Electricity Coordinating Council (WECC) network. Results reveal that the proposed method is accurate, precise and outperforms the other methods.

Contents

1. Introduction

The modern day power systems are highly interconnected for effectively sharing the increasing load demand. These complex interconnected networks pose many challenges to the power system engineers such as monitoring and detection of poorly damped low frequency oscillations [1]. Traditionally, these low frequency modes are identified through Eigen value analysis by linearizing the power system model around the operating point of the system [2]. The main disadvantage of this method is that it is inaccurate and requires extensive information about the modelling of the system. With the advent of Phasor Measurement Unit (PMU) and Wide Area Measurement System (WAMS), it is possible to estimate and monitor these modes based on the data from the Phasor Data Concentrator (PDC). Such methods are collectively known as measurement based methods [3,4].

Some of the common measurement based methods used for small signal estimation are Prony analysis [5–10], ARMA [11], Fast Fourier Transform (FFT) [12], Continuous Wavelet Transform (CWT) [13,14], Discrete Wavelet Transform (DWT) [15], Hilbert-Huang transform [16] ESPRIT [17–19], Matrix Pencil [20] and Complex-Singular Value Decomposition (C-SVD) [21].

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Among these methods, Prony method [5–8] estimates the frequency and damping of signals accurately when noise content of the signal is low but fails under highly noisy conditions. Modified Prony methods are proposed in [9,10] but the issue of sensitivity to noise is not fully removed. Times series techniques like AR, ARMA [11,22] assumes a predefined time series order and fits its free parameters such that the difference between the original signal and the time series is minimized. The practical application of these methods are limited as they cannot estimate closely spaced modes present in a signal. Moreover, these methods are computationally intensive. FFT based methods [12] extract only the frequency information of the modes present in the signal whereas damping ratio of these modes cannot be estimated. Wavelet techniques like CWT, DWT [13–15] are based on multi-resolution analysis where wavelets of variable sizes are used to extract the modal information present in the signal. These methods are easy to implement and can extract modal information of non stationary signals effectively but their accuracy is dependent on the shape of the mother wavelet and decomposition levels. HHT based methods [16] use a combination of EMD and Hilbert's transform for estimating the modes in the low frequency oscillations. The frequency and damping estimation of this method is accurate only if the modes extracted using the EMD are mono frequency components.

Of late, ESPRIT based methods are used for low frequency mode identification in [17–19,23]. These methods decompose the autocorrelation matrix into signal and noise subspaces and the modes are identified from the signal subspace. ESPRIT based methods has the ability to detect close modes and provide good accuracy for modal estimation especially in noisy environments. However, they require precise information about model order or the number of modes present in the signal for successful modal estimation, which is one of their drawbacks.

From the aforementioned literature, it can be concluded that the ESPRIT coupled with a good model order algorithm could overcome most of the drawbacks of other measurement based methods. The ESPRIT models in [17,18] uses a method based on singular value of autocorrelation matrix for estimating the model order. Though this method is simple, it provides inaccurate estimates of model order when the number of modes present in the signal is less or modes are closely spaced. A detailed explanation of the same is given in Section 2. Considering these facts, an attempt has been made in this paper to develop an ESPRIT based modal estimation method with a better model order algorithm to accurately estimate low frequency modes at varying levels of noise and PMU reporting rates. The low frequency oscillations under consideration are inter area (<1 Hz), intra plant (2–3 Hz), local plant(1–2 Hz) and torsional and control modes. The proposed method uses Exact Model Order algorithm [24] to estimate the number of frequency components present in the signal. The effectiveness of this method is tested using synthetic test signals and the results are compared with modified Prony method [9], ARMA based method [11] and TLS-ESPRIT [17] method. Further, the proposed method is used to estimate the modes of a practical probing test data of the WECC system.

2. ESPRIT and model order estimation

ESPRIT is a signal processing technique which decomposes complex signals into sum of sinusoids using a subspace based approach. It can be mathematically represented as

$$x(t) = \sum_{i=1}^{K} a_i \cos(2\pi * f_i t + \phi_i) + w_t \quad (1)$$

Here, $x(t)$ is the signal to be decomposed. In this paper, it is assumed that x(t) is obtained from different PMUs placed in the power system. f_i and ϕ_i are the frequency and phase of the i^{th} sinusoidal component decomposed from $x(t)$. w_t represents the white Gaussian noise present in the signal and K is the total number of frequency components present in the signal. For exact estimation of frequency components, this technique demands prior information of the number of modes present in the signal. It can be achieved using a model order estimation algorithm, which is described in the next sub-section.

2.1. Model order estimation

The model order estimation considers the dominant singular values of the autocorrelation matrix generated from the signal. A commonly used method for model order estimation was proposed in [17]. In this method, the auto correlation matrix is formed using the data from the PMU. Singular Value Decomposition (SVD) is performed on this matrix. The singular values are arranged in decreasing order and K(i), which is an index used for separating the signal and noise subspace is obtained using the following equation

$$K(i) = \frac{\rho_1 + \rho_2 + \rho_3 + \dots \rho_i}{\rho_1 + \rho_2 + \rho_3 + \dots \rho_l} \quad (2)$$

Here, ρ_i is the i^{th} singular value of the auto correlation matrix and l is the total number of singular values of the autocorrelation matrix. The value of i for which $K(i)$ is closest to one is selected as the model order of the system. The main limitation of this method is that it cannot accurately estimate the model order when the number of modes present in the signal is less or modes are closely spaced. This can be explained with the help of an example.

Let us consider a power system signal as in the following equation.

$$\begin{aligned} x1 = {} & ((1\cos(2\pi * 0.4t)\exp(-0.0909t)) + (0.9\cos(2\pi * 0.5t) \\ & \times \exp(-0.35t)) + (0.7\cos(2\pi * 0.6t + (\pi/6)) \\ & \times \exp(-0.2001t)) + (0.4\cos(2\pi * 1.1t + (\pi/4)) \\ & * \exp(-0.666t))); \end{aligned} \quad (3)$$

This signal is sampled at 50 Hz. It is corrupted by adding white Gaussian noise at 40 dB. The value of $K(i)$ of the signal is determined from the singular values of its autocorrelation matrix and $K(i)$ vs i graph is plotted. It is shown in Fig. 1.

It is observed that the value of $K(i)$ is closest to one at $i = 5$. So the model order is estimated as 5. But this estimation is incorrect as the signal in (3) has only four frequency components. Also the estimate further deviates if the signal is highly noise contaminated and contains close frequency components. Therefore, this paper employs the Exact Model Order algorithm proposed in [24] for precise estimation of number of modes.

The proposed algorithm is based on the fact that there will be considerable difference between the eigen values of the signal

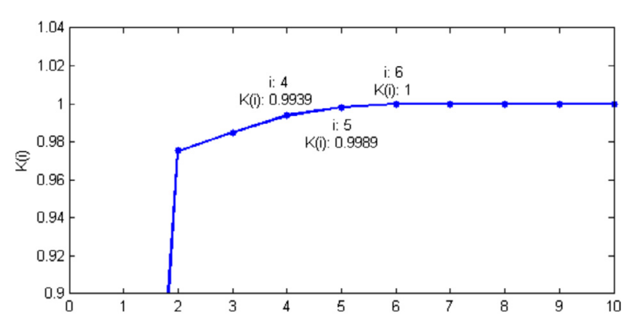

Fig. 1. K(i) vs i plot.