Electrical Power and Energy Systems 96 (2018) 222–237

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Multichannel continuous wavelet transform approach to estimate electromechanical oscillation modes, mode shapes and coherent groups from synchrophasors in bulk power grids

Xue Li[a], Hantao Cui[b], Tao Jiang[a,*], Yao Xu[c], Hongjie Jia[d,*], Fangxing Li[b]

[a] Department of Electrical Engineering, Northeast Electric Power University, Jilin, JL 132012, China
[b] Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville, TN 37996, USA
[c] Department of Electrical and Computer Engineering, Purdue University Northwest, Westville, IN 46391, USA
[d] Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China

ARTICLE INFO

Keywords:
Continuous wavelet transform (CWT)
Mode estimation
Dominant mode
Mode shape
Coherent generators
Phasor measurement units (PMUs)

ABSTRACT

Continuous Wavelet Transform (CWT) is a traditional single-channel method to estimate the dominant mode from measurements, but it is rarely applied to estimate mode shapes and coherent generators. On the other hand, estimation accuracy of traditional CWT is significantly affected by the observability of oscillations. This paper develops a multichannel CWT which is based on multichannel measurements and is less observability constrained so as to estimate not only dominant modes, but also mode shapes and coherent generators. First, wavelet power spectrum (WPS) is applied to wavelet coefficient matrices (WCMs) of multichannel measurements obtained by CWT to detect the critical scale ranges associated with the dominate modes. Then, the WCMs with the same scales in the detected ranges extracted from the raw WCMs are used to estimate the dominant modes and mode shapes. Meanwhile, the measurements that only contains the information of dominant modes are reformed by inverse CWT to detect the coherent groups of generators using direction cosines. The proposed approach is applied and evaluated with the simulation data from the 16-generator 68-bus test system and field measurements from Phasor Measurement Units (PMUs) in China Southern Power Grid (CSG). Results show that the proposed approach is accurate and efficient in estimating dominant modes, mode shapes and coherent groups of generators from synchrophasor measurements.

1. Introduction

Electromechanical oscillations are inherent in power systems, and can be described by frequency, damping, mode shapes and coherency [1,2]. Correct identification of these modal properties exerts great influences to the power grid operator. The Western Electricity Coordinating Council (WECC) blackout happened on 10 August 1996 was caused by falsely estimating one unstable inter-area mode as stable [3]. Such false estimation was mainly due to the inaccuracy of the system model and parameters. Because of the extreme complexity in power systems, accurate models and parameters are not easy to obtain [3]. Consequently, researchers began to adopt the measurement-based methods, which seized the system status better to estimate the mode, mode shapes and coherent generators [4–19].

To estimate the dominant mode from the phasor measurement unit (PMU) data in power grids, Prony was initiated by Hauer et al. [6] and further extended by Zhou et al. [7] to detect the dominant modes automatically with a stepwise regression method. Peng et al. [8] and Chauduri et al. [9] used Kalman filter to estimate the dominant modes, Kamwa et al. [10] proposed a multi-band modal analysis (MBMA), a hybrid of parametric and nonparametric methods, to estimate the modes. Zhou et al. [11,12]developed autoregressive moving average exogenous (ARMAX)-based robust recursive least square (RRLS) and regularized robust recursive least squares (R3LS) to detect the dominant modes. In addition, empirical mode decomposition (EMD) [13], stochastic subspace identification (SSI) [14,15], eigensystem realization algorithm (ERA) [16], and continuous wavelet transform (CWT) [17,18] were applied to estimate the dominant modes from the PMU data.

To estimate the mode shape from PMU data, a theoretical basis and signal-processing approach were initiated by Trudnowski [19]. Tashman et al. [20] developed a multi-dimensional Fourier ringdown analyzer (MFRA) to carry out modes and mode shapes analysis. Dosiek et al. [21] used multichannel ARMAX to estimate the mode shapes and

* Corresponding authors.
E-mail addresses: tjiang@neepu.edu.cn (T. Jiang), hjjia@tju.edu.cn (H. Jia).

http://dx.doi.org/10.1016/j.ijepes.2017.09.043
Received 14 February 2017; Received in revised form 1 August 2017; Accepted 29 September 2017

Ni et al. [22] applied SSI to mode shapes estimation. Further, Dosiek et al. [23] comparatively reviewed the existing ambient mode shapes estimation approaches including transfer function (TF), spectral method, frequency domain decomposition (FDD), channel matching, and subspace methods, and pointed out that spectral, FDD and channel matching methods were all special cases of the more general TF Method, which may cause high estimation bias, while the subspace method exhibited a good performance in the mode shape estimation.

To estimate the coherent groups of generators from PMU data, Senroy et al. [24] used Hilbert-Huang Transform (HHT) to track the system coherency. In [25], Fast-Fourier Transform (FFT) was employed to identify the coherent generators. Signal correlation coefficient was defined by Vahidnia et al. [26] to explore the coherent generators and the related buses. Anaparthi et al. [27] conducted the principal component analysis (PCA) to find the coherent generators. Moreover, to suppress the noise in the field measurements, independent component analysis (ICA) was investigated by Ariff et al. [28] to identify the coherent areas. In [29], wavelet phase difference (WPD) was applied to separate the power system areas with coherent generator groups by using the CWT. In [30], the Koopman mode (KM) was used to identify the coherent groups by comparing the amplitude coefficients and initial phases of the Koopman modes. Based on [30], a dynamic mode decomposition (DMD) algorithm was further proposed in [31] to detect the coherent groups.

These abovementioned methods focus on the estimation of one or two facts among dominant modes, mode shapes and coherent groups, but only DMD discussed estimating them all. Although DMD is reliable in estimating dominant modes, mode shapes and coherent groups of generators, it still has a major limitation that DMD assumed the PMU data to be noise-free and stationary, which is a less realistic assumption in power system small signal stability studies.

Motivated by the MBMA proposed in [10], a multichannel CWT based modal analysis is developed in this paper to estimate not only dominant modes, but also mode shapes and coherent groups of generators from synchrophasor measurements. The major contributions of this work are as follows.

(1) An improved multichannel CWT-based dominant mode estimation is proposed. It is based on the multichannel CWT proposed in [18]. However, the process is simplied in this work and the improved process solves the problem of critical information loss in the data process reported in [16].
(2) Using multichannel CWT to estimate mode shapes is proposed in this work for the first time.
(3) This work also proposes an estimation method of coherent groups of generator by the use of inversed CWT (ICWT) to reform the multichannel synchronphasor measurements.

The rest of this paper is organized as follows. Section 2 reviews the CWT-based modal analysis. Section 3 develops a multichannel CWT based modal analysis to estimate the dominant mode, mode shapes, and coherent groups of generators from synchrophasor measurements. Section 4 validates the performance of the developed methods using the simulation data from the 16-generator 68-bus test system and field measurements from the PMUs in China Southern Grid (CSG). Section 5 draws the conclusions.

2. Continuous wavelet transform

The CWT of measurement $\boldsymbol{y}(t)$ can be expressed by the following inner product:

$$W(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}\boldsymbol{y}(t)\phi^*\left(\frac{t-b}{a}\right)dt = \int_{-\infty}^{+\infty}\boldsymbol{y}(t)\phi_{a,b}^*(t)dt = \langle\boldsymbol{y}(t),\phi_{a,b}(t)\rangle \quad (1)$$

where $W(a, b)$ is the wavelet coefficient of $\boldsymbol{y}(t)$; a is a scale factor; b is a translation factor; $\phi_{a,b}$ is named daughter wavelet, obtained by scaling and translating $\phi(t)$ with a and b, respectively. The detailed representation of $\phi_{a,b}$ is expressed as:

$$\phi_{a,b}(t) = \frac{1}{\sqrt{a}}\phi\left(\frac{t-b}{a}\right) \quad (2)$$

where $\phi(t)$ is defined as a mother wavelet.

There are multiple types of mother wavelets developed in CWT for different research purposes such as the complex Gaussian wavelet, complex Morlet wavelet, Mexican hat wavelet, complex Shannon wavelet, and so on. For the mode estimation in this work, the complex Morlet wavelet is chosen for (1) as the mother wavelet which has all the desired properties [17]. Detailed expression of complex Morlet wavelet $\phi(t)$ is

$$\phi(t) = \frac{1}{\sqrt{\pi f_b}}e^{-j2\pi f_c t}e^{-t^2/f_b} \quad (3)$$

where, f_b and f_c are bandwidth and center frequencies of complex Morlet wavelet, respectively. The complex Morlet wavlet $\phi(t)$ in (3) should satisfy the following admissibility condition

$$C_\phi = \int_{-\infty}^{+\infty}\frac{|\phi(\omega)|^2}{|\omega|}d\omega < \infty \quad (4)$$

where $\phi(\omega)$ is the Fourier transformation of $\phi(t)$ and C_ϕ is called admissibility constant. The admissibility condition in (4) requires that the mother wavelet $\phi(t)$ in (3) to be oscillatory in time and satisfy the followings:

$$\phi(\omega)|_{\omega=0} = \int_{-\infty}^{+\infty}\phi(t)dt = 0 \quad (5)$$

Further, substituting the mother wavelet in (3) into (2), the daughter wavelet $\phi_{a,b}$ in (2) is

$$\phi_{a,b}(t) = \frac{1}{\sqrt{a}}\phi\left(\frac{t-b}{a}\right) = \frac{1}{\sqrt{a\pi f_b}}e^{-j2\pi f_c\frac{(t-b)}{a}}e^{-\frac{1}{f_b}\left(\frac{t-b}{a}\right)^2} \quad (6)$$

If the mother wavelet $\phi(t)$ in (3) satisfies the admissibility condition in (4), the measurement $\boldsymbol{y}(t)$ in (1) can be further obtained via the following inverse CWT (ICWT).

$$\boldsymbol{y}(t) = \frac{1}{C_\phi}\int_{-\infty}^{+\infty}db\int_{-\infty}^{+\infty}\frac{1}{a^2}W(a,b)\phi_{a,b}(t)da \quad (7)$$

Since the small signal oscillations in the power system can be expressed as a linear combination of its embedded modes [17], the measurement $\boldsymbol{y}(t)$ containing n dominant oscillation modes can be represented as follows:

$$\boldsymbol{y}(t) = \sum_{k=1}^{n}A_k e^{-\varsigma_k\omega_{0k}t}cos(\omega_k t + \theta_k) \quad (8)$$

where A_k, ζ_k, ω_{0k}, ω_k and θ_k are the magnitude, damping, un-damped angular frequency, damped angular frequency, and phase angle of the k-th dominant mode contained in $\boldsymbol{y}(t)$, respectively.

By substituting (8) into (1), the wavelet coefficient of $\boldsymbol{y}(t)$ at the scale a_k associated with the k-th dominant mode contained in $\boldsymbol{y}(t)$ can be expressed as:

$$\begin{aligned} W(a_k,b) &= \frac{1}{\sqrt{a_k}}\int_{-\infty}^{+\infty}\boldsymbol{y}(t)\phi_{a_k,b}^*\left(\frac{t-b}{a_k}\right)dt \\ &= \frac{\sqrt{a_k}}{2}A_k e^{-\varsigma_k\omega_{0k}b}\phi_{a_k,b}^*(b\omega_{dk})e^{j\omega_k b+\theta_k} \end{aligned} \quad (9)$$

Substituting (6) into (9), the detailed representation of $W(a_k, b)$ in (9) is

$$W(a_k,b) = \frac{\sqrt{a_k}A_k e^{-\varsigma_k\omega_{0k}b}}{2}e^{-\frac{f_b}{4}(a_k\omega_k-2\pi f_c)^2+j(b\omega_k+\theta_k)} \quad (10)$$

According to (10), the detailed form of wavelet coefficient matrix $\boldsymbol{W}(a, b)$ for $\boldsymbol{y}(t)$ can be further described as: