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Global oscillation mode analysis using phasor measurement units-based real data

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ABSTRACT

This study employs the Hilbert–Huang transform (HHT), the wavelet transform (WLT) and the fast Fourier transform (FFT) to analyze the inter-area (global) oscillation characteristics of Western Japan 60 Hz power system. The data are collected from a network of distributed phasor measurement units (PMUs) through a national project called Campus wide area monitoring system (Campus WAMS). In the present paper the Campus WAMS is introduced, and then the recorded phase difference data are analyzed using WLT, FFT and HHT methods, respectively. A comprehensive comparison is performed, and it is demonstrated that HHT offers more flexibility in terms of detailed profile and enough description, which can be beneficial for power system small signal stability analysts following estimation of system low-frequency oscillation. The results could be useful for on-line tuning of power system stabilizers.

Introduction

Experiences from the latest blackouts in the North America and Europe have revealed that partial or complete blackouts can arise from sustaining small disturbance angle instability. Therefore, online monitoring and estimation of the inter-area power oscillation characteristic in the presence of various disturbances such as frequent load changes or unexpected line tripping is of great importance for power system stable operation and preventive control [1]. Over past decade, the wide area monitoring system (WAMS) using a network of phasor measurement units (PMUs) has been put into commission in some large interconnected power system [2]. In WAMS projects, the multiple synchronized phasor measurements, which contain rich and precise information of system wide dynamics of transmission at high voltage level, can be utilized to implement online monitoring and estimation of inter-area global low-frequency oscillation mode.

For this purpose, a Campus wide area monitoring system (Campus WAMS) is developed based on a network of distributed PMUs, across the Western Japan 60-Hz power system, Eastern Japan 50-Hz power system, Thailand, Singapore and Malaysia power systems.

With increasing application of WAMS, the measurement-based approaches to estimate the low-frequency oscillation parameters became prevailing. Without knowledge of generators and line parameters (dynamical model), the measurement-based approaches primarily employ statistical signal processing techniques and system identification theory to discover the characteristic of low-frequency oscillation mode which usually buries in the bus voltage, phase angle or tie line power variations due to random and constant load variations.

The Fourier transformer has been already used for estimating parameters of various oscillation modes, simultaneously [3]. However, the power system oscillation should change in frequency from location to location, and time to time, even within one oscillation cycle. This intra-frequency oscillation is the hallmark of nonlinear systems. In the past, when the analysis was based on the linear Fourier analysis, this intra-wave frequency variation could not be depicted, except by resorting the harmonics. Thus, any nonlinear distorted waveform can be referred as a "harmonic distortion." Harmonics distortions are a mathematical artifact resulting from imposing a linear structure on a nonlinear system. They may have mathematical meaning, but physically meaningless.

Wavelet analysis with high resolution is also known as a temporal frequency analysis method, which also shows the discrete transform is made in time domain and spectra analysis is made in time frequency domain. Although the wavelet transform was introduced to solve the problem by presentation of frequency and energy content in the time domain, it still suffers from the convolution of a priori basis functions with the original signal. The wavelet base (or mother wavelet) selection is an important problem for wavelet anal-

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ysis applied in engineering, because using different mother wavelets to analyze same problem will produce different results. Therefore, wavelet analysis results are limited by mother wavelet, and wavelet components and wavelet spectra are meaningful only to the selected mother wavelet. Although these problems exist in wavelet analysis, it is still an effective method to analyze non-stationary data [4].

Hilbert-Huang Transform (HHT) is a fully adaptive time–frequency analysis methods, suitable for both non-linear and non-stationary signal analysis as well as for linear and stationary signal analysis [5]. The HHT applies empirical model decomposition (EMD) to decompose the low frequency oscillation signals and calculate the instantaneous parameters including frequency of every model component. Then, it calculates the damping ratio of every model component based on above parameters and the derived formulas. This method can be applied to analyze strong non-linear oscillation models in power systems and design damping controllers.

This paper analyzes the global (inter-area) oscillation modes estimated by wavelet transform (WLT), Hilbert–Huang transform (HHT) and Fast Fourier transform (FFT) using the PMU-based data for Japanese 60 Hz power system via the Campus WAMS project. The proposed analysis shows that the HHT is more effective in obtaining the required data from phase difference and being used to monitor oscillation mode in small signal system. The results could be useful for on-line tuning of power system stabilizers.

Overviews of the Campus WAMS project

Fig. 1 shows the PMU locations in the Japan power system for the project called Campus WAMS, consisting of twelve commercial PMUs. The PMUs are installed at thirteen universities respectively, covering the regions of all ten existing electric power companies of Japan power system [6]. Since each power company is an independent operating entity, currently there is no way to collect synchronized phasor measurements of transmission high voltage level from all power companies. However, using the Campus WAMS, it becomes possible to observe and analysis system wide dynamics for overall Japan power system, simultaneously.

For convenience of following analysis, three groups are defined for eight PMUs in the Western Japan power system. The lower-end group includes University of Miyazaki, Kumamoto University, Kyushu University and Kyushu Institute of Technology. The upper-end group includes University of Fukui and Nagoya Institute of Technology. The center group includes Hiroshima University, University of Tokushima and Osaka University.

All PMUs measure the single phase voltage phasor of 100 V (in Japan) outlet on the wall of laboratory with GPS-synchronized time tag. The voltage phasor is calculated by using 96 sample data per voltage sine-wave cycle. The calculated voltage phasor data are saved in the PMUs at interval of 1/30 s from 50 min to 10 min, from 10 min to 30 min, and from 30 min to 50 min in every hour. All phasor measurements of all locations are automatically collected into a data server through internet. The background application program running in other computers reads data from server and performs analysis. Thus a wide area measuring and monitoring system is constructed.

Preliminary analysis of oscillation records

From phasor measurement of the Campus WAMS, the following signals can be computed: voltage phase difference between two locations and frequency deviation at each location. In general, either phase difference signal or frequency deviation signal can be used to monitor/estimate the characteristic of the inter-area oscillation mode. Here, the phase difference signals are used for this purpose. Fig. 2 shows waveforms of phase difference measured between Kyushu University and Osaka University in 6:50–7:10 of July 16, 2011. It presents a normal situation without a big fluctuation in power system oscillation. It is noteworthy that the FFT cannot be applied to the non-stationary and non-linear data and the WLT cannot be applied to the non-linear data.

Extraction of low-frequency oscillation

The FFT method

The Fourier series are made up of sines and cosines; the Fourier transform is a generalization of the Fourier series, and is performed by exponentials and complex numbers. The Fourier analysis has wide applications in mathematics and engineering such as heat transfer, wave propagation, circuit analysis, electronic circuit analysis, and vibrations. Interesting to note is the Fourier kernel, $e^{2\pi i\omega t}$, which is a solution to an nth order linear differential equation which, in turn, is used to model various physical; it is one reason why Fourier analysis has such wide applications.

On the interval $[-\pi, \pi]$, and arbitrary function $f(t)$ which is periodic and single-valued could be represented by the trigonometric series:

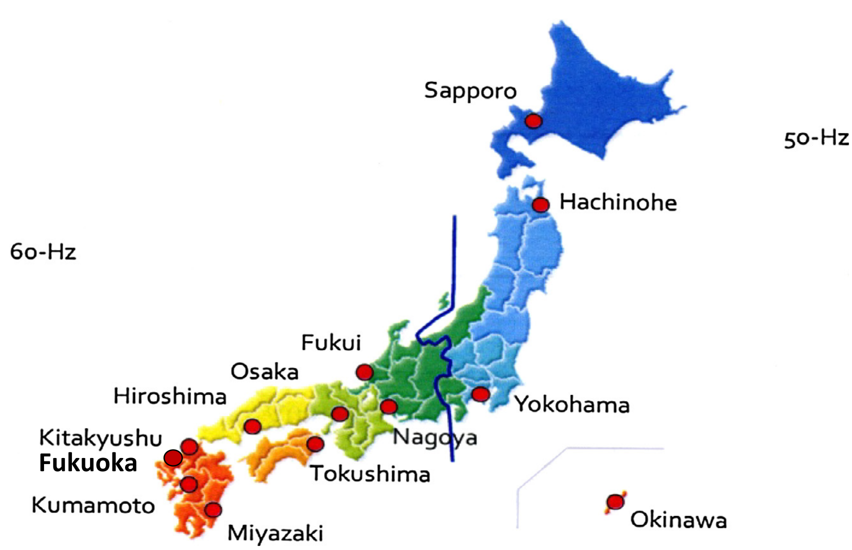

Fig. 1. PMUs locations for the Campus WAMS project in Japan.