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Power System Oscillation Dynamics Analysis Based on Campus PMU/WAMS

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Abstract—The dynamics of inter-area low-frequency oscillations in the power system is investigated with real system data acquired by Campus PMU (Phasor Measurement Unit) / WAMS (Wide Area Measurement System) in Japan. The analysis method is implemented by the filtering of measured phasor data, which are synchronized by the GPS (Global Positioning System) signal, based on the spectral analysis to extract the major swing mode from fluctuating oscillations including many modes with various frequencies. The swing dynamics and the small-signal stability in the real power system are presented.

1. Introduction

Inter-area low-frequency oscillations are characteristic phenomena in interconnected power systems [1]. These oscillations have poor damping characteristics in the heavy loading condition in tie-lines mainly due to the power exchange and complex power contracts under a deregulated environment. Therefore, proper grasp of the present state with flexible wide area control and operation should become key issues to keep the power system stability.

In recent years, WAMS (Wide Area Measurement System) with PMUs (Phasor Measurement Units) attracts power system engineers for the state estimation, system protections and control. The system is introduced as an useful monitoring technology especially in widely spread power systems [2]. A direct, more precise and accurate monitoring can be achieved by the technique of synchronized phasor measurements [3] of the voltage and current phasors.

The authors have developed the Campus WAMS in Japan by using PMUs synchronized by the Global Positioning System (GPS) signal since 2001. The developed system successfully detects the dynamic characteristics of the interconnected power system. This paper presents the brief overview of the developed monitoring system and some investigated results of the electromechanical dynamics of the real power system.

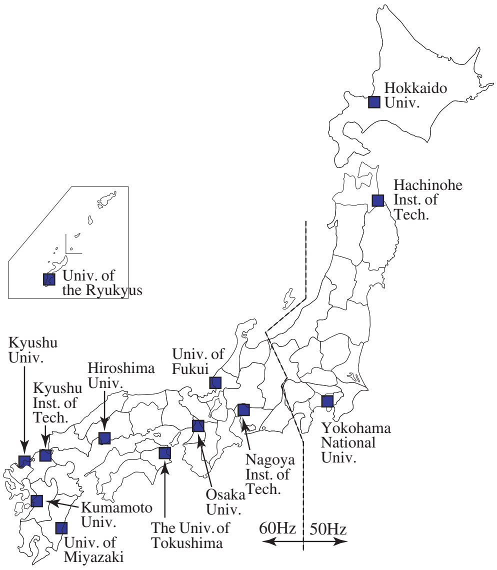


Figure 1: Configuration of Campus WAMS in Japan (at June 2011).

2. Schema of Campus PMU/WAMS

Figure 1 shows the installed location of Campus PMUs, NCT2000 manufactured by Toshiba Corp., synchronized by GPS signal. The installation of PMUs started at 2001 to develop the wide area monitoring system covering the whole power system in Japan as a collaborative work with researchers. At least one PMU has been installed within the service area of each power company. The system measures voltage phasors of 100 V outlets of the laboratory in the university campus on 24-hour schedules, while PMUs are usually installed at substations of transmission lines in the practical application. Hence, the authors call the system "Campus WAMS."

In the developed system, the measurement interval is 2/60 seconds in the western 60 Hz area, and 2/50 seconds in the eastern 50 Hz area in order to observe the dynamic characteristics of the power swing. Synchronized monitoring

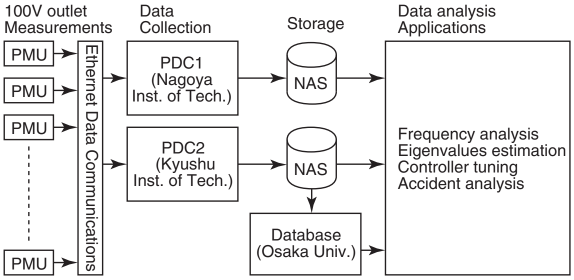


Figure 2: Schema of Campus PMU/WAMS.

can be achieved by using the precise PPS (Pulse Per Second) output of the GPS receiver even in the widely spread power system, and measured remote data can be easily concentrated via fast communication network.

Figure 2 shows the schema of the system. The measured PMU data are automatically collected by PDCs (Phasor Data Concentrators) installed at Nagoya Institute of Technology and Kyushu Institute of Technology via SINET (Science Information NETwork). Though the IEEE COMTRADE format is employed as the format of data stored in each PMU, collected data by PDCs are converted into the CSV (Comma Separated Value) format for the usability, and then converted data are stored in NAS (Network Attached Storage) with the large capacity.

3. Low-frequency Oscillation Dynamics

Dynamic characteristics of power system oscillations are investigated by using measured PMU data. Many electromechanical modes exist in power system oscillations due to the nonlinear nature of the system. Inter-area low-frequency oscillations with poor damping characteristics are well known problem in the interconnected power system. The characteristics of such dominant modes should be analyzed to keep the power system reliability. The system takes with relatively linear behavior in the steady-state operating condition; therefore, small-signal dynamics could be investigated by using linear system concepts [1].

3.1. Characteristics of Electromechanical Modes

Figure 3 shows phase differences between Univ. of Miyazaki (Miyazaki) and Nagoya Institute of Technology (Nagoya), where are located at both ends of the 60 Hz system. Small-signal fluctuations caused by continuous small disturbances such as load variations are observed in PMU data. Many oscillation modes are superimposed; however a few dominant modes should be important to investigate the power system dynamics.

Figure 4 shows results of the spectrum analysis. Low-frequency oscillations with frequency of about 0.37 Hz are detected distinctly by phase differences between Miyazaki and Nagoya. In addition, this mode can be detected by phase differences between Hiroshima and Osaka, where these two are located in the middle part of the system, though the amplitude of the mode is comparatively small. On the other hand, another quasi-dominant mode can be detected by data between Miyazaki and Tokushima, where these are located in the one end and the central region of the system, respectively.

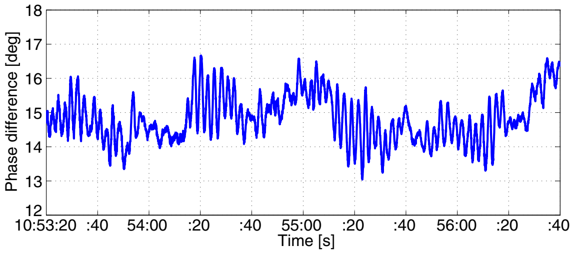
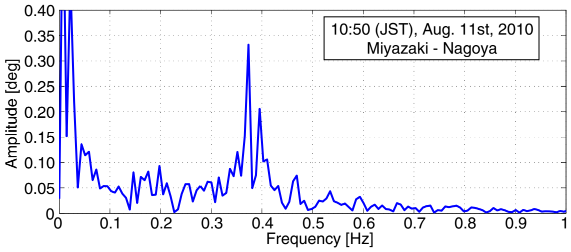
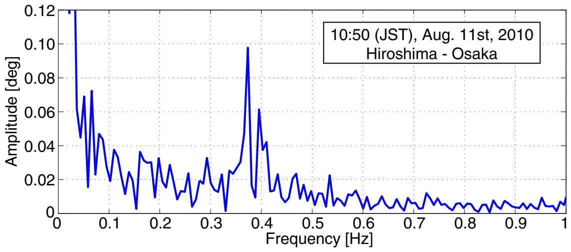


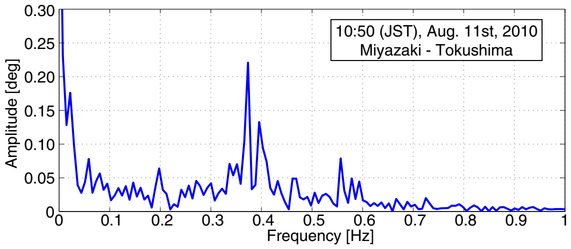
Figure 3: Phase difference between Miyazaki and Nagoya on August 11, 2010.



(a) Both ends.



(b) Middle.



(c) End and middle.

Figure 4: Fourier spectrum of phase differences.

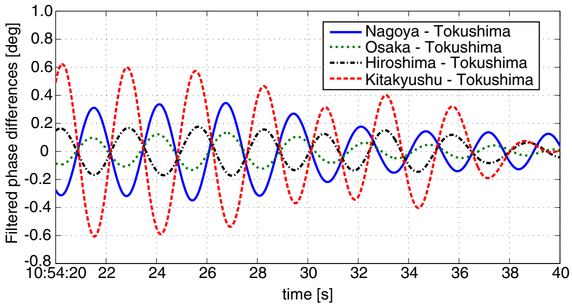
Here, a procedure to extract oscillations of the specific mode is considered:

1. Analyze the Fourier spectrum of phase differences
2. Determine the center frequency f_c of the band-pass filter by the above spectrum
3. Extract oscillation components from original phase difference data with the FFT (Fast Fourier Transform)

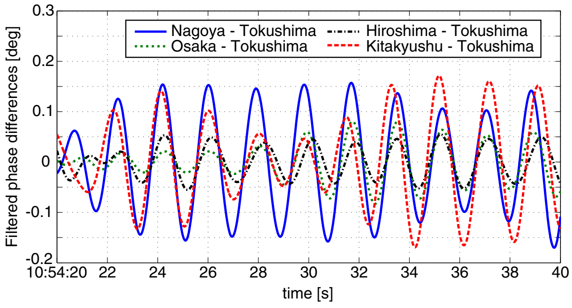
based band-pass filter with $f_c \pm 0.1$ Hz.

The amplitude and the phase characteristics of the original data are conserved by the FFT-based filtering with flexible determination of the pass band.

Figure 5 shows waveforms of the most and the quasi dominant modes extracted by the FFT-based filtering. These waveforms are depicted by taking Tokushima, where it locates roughly in the central region of the system, as the reference of the phase angle. Figure 5 (a) is the most dominant mode (mode 1) with the frequency of about 0.37 Hz. This mode oscillates over the whole system in opposite phase with respect to one another with one node located around the central region of the system. On the other hand, Figure 5 (b) shows waveforms of the quasi-dominant mode (mode 2) with the frequency of about 0.56 Hz, which oscillates in the same phase. This means that this swing has two nodes, where both ends oscillate in opposite phase with respect to the central region of the system. Consequently, the quasi-dominant mode has been detected in Figure 4 (c), while it has not been detected in Figures 4 (a) and (b) since the mode has disappeared by taking the difference of each phase. These characteristics could be explained by the participation factor [4] and the mode shape [5], which provide critical information for operational control actions. The participation weight estimation based on WAMS has been developed so far [6].



(a) Mode 1.



(b) Mode 2.

Figure 5: Low-frequency oscillations.

3.2. Stability Monitoring of the Dominant Mode

Here, the method for monitoring the stability of the low-frequency oscillation based on the eigenanalysis is considered by modeling measured oscillations as a simplified oscillation model. The model (1), which originates in the swing equation of a generator, represents the electromechanical dynamics of the dominant low-frequency oscillation.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} a_1 & a_2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \tag{1}$$

where, $x_1 = \dot{\delta}_1 - \dot{\delta}_s$, $x_2 = \delta_1 - \delta_s - (\delta_{1e} - \delta_{se})$. The subscript 1 denotes the phase angle of the object area, the subscript s denotes the reference of the phase angle, and the subscript e denotes the initial value of the phase angle. Fluctuating voltage phasors in the normal condition are used to estimate the model by assuming that random load variations as the white noise stimulate the system. Here, the FFT-based band-pass filter described above is applied to extract a low-frequency mode since measured phasors include many oscillation modes, for example, local modes which oscillate between close generators and many noises with high frequencies. Coefficients a_1 and a_2 are determined by the least squares method with measured x_2, calculated x_1 and $\dot{x}_1$. Consequently, the damping ratio ζ and the angular frequency ω (rad/s) of the mode are given by:

$$\zeta = \frac{-a_1}{2\omega_n} \tag{2}$$

$$\omega = \omega_n \sqrt{1 - \zeta^2} \tag{3}$$

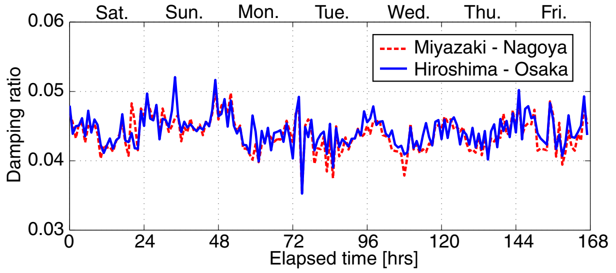
$$\omega_n = \sqrt{-a_2} \tag{4}$$

where ω_n (rad/s) represents the natural angular frequency. Note that $a_1 < 0$, $a_2 < 0$, and $0 < \zeta < 1$ are assumed.

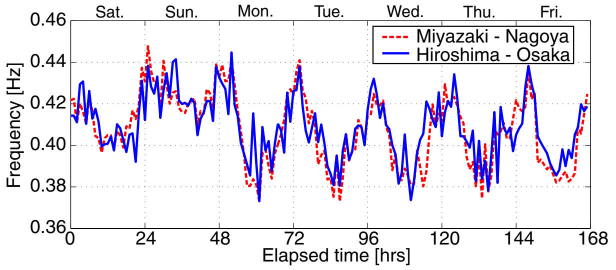
Both ends group of generators mainly participate in the low-frequency mode; therefore, the analysis with data measured at both ends should be desired. As mentioned above, this mode oscillates over the whole system, therefore, measured data between more close sites, for example, within the service area of a power company, might be utilized.

Figure 6 shows an example of monitoring the stability of the low-frequency mode for a week. The transition of the stability depends on the load demand. In addition, estimated stability by using data between close sites, where Hiroshima and Osaka, coincide well with that of both ends sites, where Miyazaki and Nagoya. The result demonstrates that the flexible location of PMUs is possible to be allowed for monitoring inter-area modes with the appropriate filtering algorithm.

Figure 7 shows yearly variations of the stability of the low-frequency oscillations, where each estimated damping and frequency is depicted by averaging 24 values per day. Here, phase differences between Miyazaki and Nagoya are used. The stability deteriorates during the wintertime and the summertime due to the demand for the air conditioning. In addition, the stability seems to be slightly shifted toward the unstable level year by year. Especially the growth of electricity demands for the heating during the wintertime might be related to the stability deterioration. Assumed



(a) Damping ratio.



(b) Frequency.

Figure 6: Comparison of the small-signal stability change for one week.

causes related to the stability change are the price of the heating oil, and the change of average temperature, the worldwide simultaneous economic slowdown, and so on. Thus, more flexible monitoring, control, and operation of the power system can be achieved by investigating identified oscillation characteristics derived by the method.

4. Conclusions

In this paper, the brief overview of developed Campus PMU/WAMS has been presented. Although real-time monitoring, protection, and control of the power system by applying PMU technology are in practical use, the authors have developed unique Campus WAMS for the sake of the academic research. Some analysis results by using measured data have been presented especially by investigating the dynamic characteristics of low-frequency oscillations.

Acknowledgments

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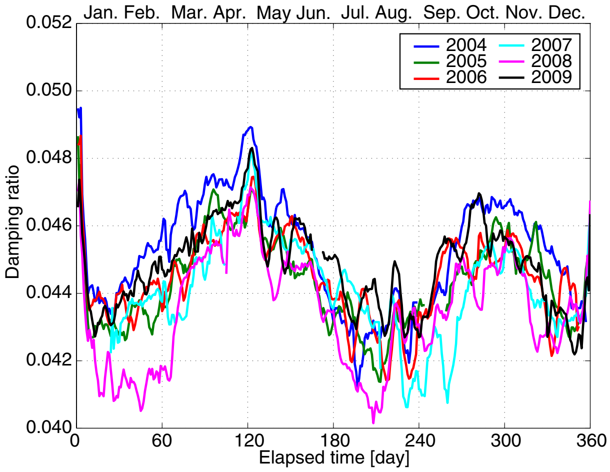
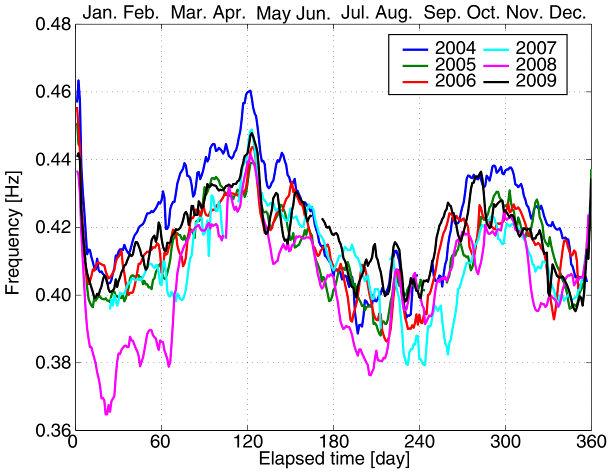


(a) Damping ratio.



(b) Frequency.

Figure 7: Long term observation results in the stability change of low frequency power oscillation mode.

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