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Monitoring the Wide Area Power System Dynamics by Phasor Measurement Units Based on Campus WAMS Strategy

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Abstract: This paper presents the applications of Phasor Measurement Unit (PMU) for assessing the dynamics and stability of wide area interconnected power system. Wide area measurement system for the power system dynamical assessment which has been developed by our group is installed at the power outlets in some university campuses in Japan. Thus, it is called Campus WAMS, and the system was also applied to Singapore-Malaysia power system. Some results based on the long term continuous monitoring are described in this paper.

1. INTRODUCTION

Assessment of power system dynamic stability is important issue with the installation explosion of renewable energy power generators such as Photovoltaic and Wind Power. Phasor measurement technology has to be a powerful tool for it. Thus, the PMU technology is categorized as a significant tool to realize the Smart Grid. Our group has developed a wide area monitoring system for power system inter area dynamics by installing PMUs with collaborations among some research groups associated with power system engineering in universities, which is called “Campus WAMS”. Even from the user power outlets they are surely connected to the power system with AC synchronization. In such a way we can monitor the power system dynamical phenomena based on the phasor data which are collected via Internet.

Once we get synchronized phasor data useful signal can be extracted from them with FFT analysis, Wavelet analysis and some other signal processing schemes. Especially wide area power system stability which tends to shift toward unstable side can be easily monitored. We have already stored data more than ten years. As a result we can analyse the variation of stability year by year manner. These results are ready to be applied to the PMU systems which are installed at substations, that is, the analytical method in this paper are not limited to the campus WAMS data. The reason why we have developed the campus WAMS is that we can get the phasor data by ourselves. In this paper some results to analyse the real power system stability are presented in detail based on our ten years experiences.

Electric power supply and distribution systems are continuously growing along with expansions of power systems. Accordingly, these large scale interconnections of power systems cause power system inter-area stability degrading toward lower level. The power system in West Japan has a longitudinal structure due to its geographical constraints. The instability arises as a problem of low-frequency oscillation with weak damping characteristic originated from this power system structure. There are some examples of longitudinal power system such as Italy, Malay Peninsula and so on. As an application the Campus WAMS was installed in the Malay power system.

A number of PMUs are located in different universities in Japan as shown in Fig.1 and in Malay as shown in Fig.2, and data are collected automatically via the Internet. By installing PMUs at multiple locations in a power system, time synchronized measurements with accuracy within ±1μs can be achieved by the use of GPS signal. Measured data from PMUs directly show local frequency variations and phase difference between areas. From the measured data, low-frequency oscillations and power system stability that are useful for analysing power system dynamics can be investigated and examined. With proposed methods, we can analyse the inter area power system stability in West Japan power system and compare them with those in Malay.

2. MONITORING OF WIDE AREA POWER SYSTEM DYNAMICS BY PMU

2.1 Campus WAMS in Japan

Figure 1 shows PMU locations in the Campus WAMS developed by our group in Japan power system, where the installations of PUMs are in the university campuses, and presently we have installed 12 PMUs: 9 of them are installed in the supply area of West Japan 60 [Hz] system and another 3 in the supply area of East Japan 50 [Hz] system (Hashiguchi T.. et al., 2008). The West 60 [Hz] system and the East 50 [Hz] system are linked by DC back-to-back frequency converters and in 50 [Hz] area the main land system and Hokkaido system are connected by DC transmission line. Okinawa system is isolated. This paper's results are on the West 60 [Hz] system analysis. The phasor measurement system consists of a commercial PMU product, which is Network Computing Terminal Type-A, NCT2000 (Tsukui, R. et al., 2001). The PMU measures the single-phase voltage phasor of 100V outlets, and corrects its clock based on the time stamp of GPS. The phase angle of the measured voltage is accumulated in the PMU as the time sequential data. The PMU records the calculated phasor every 40 or 33 ms (2 cycles) and for every 20 minutes, the measured data is saved in a data file. The measured phasor data are transmitted via the internet to server at Kyushu Institute of Technology.

From the measured phasor data of the Campus WAMS, two kinds of useful signals can be computed: voltage phase difference between two locations and frequency deviation of each location. Increasing phase angle represents that the frequency of the observed voltage is higher than the correct 50-Hz or 60-Hz frequency calculated from the GPS signal. Decreasing phase angle means that frequency of the observed voltage is lower. The time derivative of phase angle corresponds to the deviations of system frequency, which can be calculated by

$$\Delta f_n = \frac{\delta_{n+1} - \delta_n}{360 \Delta t_n} \tag{1}$$

where, Δt_n [s] is the sampling interval of sequential phase data δ_n and n is the number of accumulated phase angle data. And the frequency variation can be observed by the PMU with accumulating the sequential frequency deviations Δf_n.

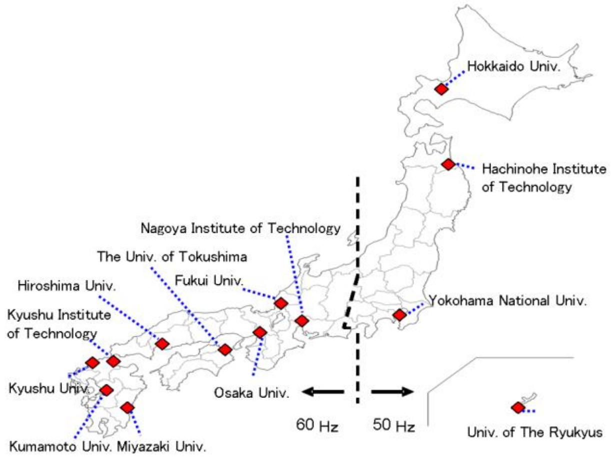
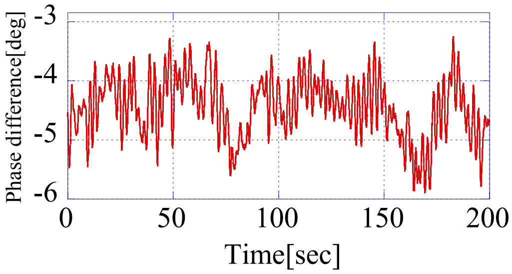
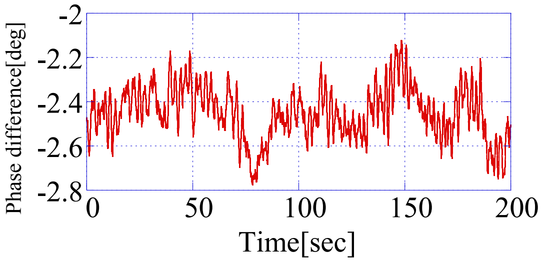


Fig. 1 Assignment of Phasor Measurement Units in Campus WAMS in Japan.

In our system the phasor is acquired from the 100 V user outlet. To confirm the similarity of oscillation components between the phasor signals in 500 kV substation and 100V user outlet we got data from the power company and compared them with time synchronization. The results are shown in Fig. 2. Good coincidence of oscillation components are observed clearly.



(a) Data acquired from the PMUs in 100 V outlets (distance is about 750 km)



(b) Data acquired from the PMUs in 500 kV substations (distance is about 200 km)

Fig.2 Data comparison between 100V and 500kV

2.2 Application to Singapore-Malaysia System

By collaborations with University Sains Malaysia, Penang and Nanyang Technological University, Singapore, we applied the Campus WAMS to the power system in Malay Peninsula. The map of Campus WAMS installation in Malay is shown in Fig. 3.

The tie-line between Malaysia and Singapore is linked by AC and the tie-line between Malaysia and Thailand is by DC, so the power system in Malay Peninsula is one large AC interconnected system with a longitudinal structure which is similar to the West Japan power system. In this longitudinal power system a low-frequency power oscillation mode around 0.3 - 0.5 Hz is observe, which is the dominant mode among some electro-mechanical oscillations.

Fig. 3 PMU installations in Malay Peninsula

3. DATA PROCSSING FOR WIDE AREA POWER SYSTEM STABILITY ANALYSIS

In this chapter a method to evaluate the stability of dominant mode based on the observed data from Campus WAMS by using the phase data of Nagoya Institute of Technology (Nagoya) and Miyazaki University (Miyazaki) located at both ends of power system in West Japan.

3.1 FFT Analysis for Low-Frequency Oscillation Mode

Result of FFT analysis of phase difference between Nagoya and Miyazaki is shown in Fig. 4. We can observe the low-frequency oscillation mode around 0.4[Hz] in the result of FFT analysis of phase difference between both ends of power system in West Japan.

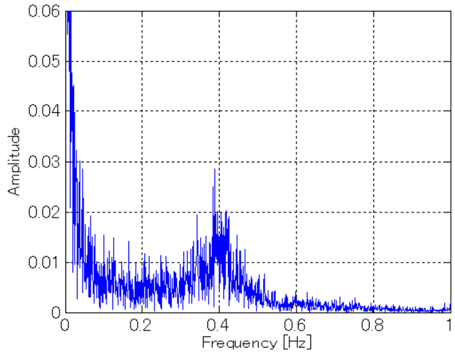


Fig. 4 FFT Analysis of Oscillation Modes

3.2 FFT Filtering for Extracting the Low-Frequency Oscillation

In order to focus our attention to the low-frequency oscillation for the analysis of the stability, the FFT filtering method is available. The FFT filtering is a method to extract the frequency components we want in the FFT domain by replacing all of unused data with zeros and the inverse FFT method is applied to the extracted FFT data. After proceeding the FFT filtering, an oscillation waveform just associated with the dominant frequency can be extracted.

Figure 5 shows the original phase difference waveform after a power system disturbance occurred. Extracted phase difference waveform after the FFT filtering is applied is shown in Fig.6, and an oscillation with exponential damping can be observed, which is corresponding to the low frequency mode with around 0.4 Hz.

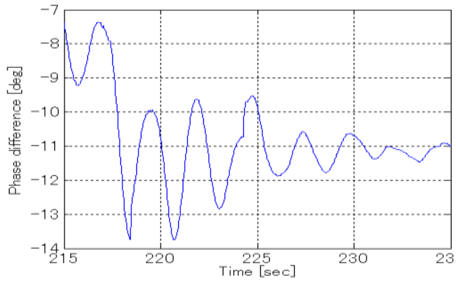


Fig. 5 Phase difference of original data after a disturbance in the power system

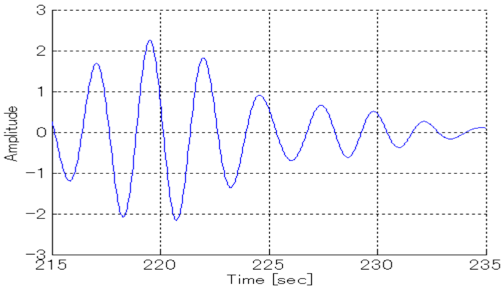


Fig.6 Extracted low frequency mode by applying FFT filtering.

4. SOME RESULTS OBSERVED FROM THE CAMPUS WAMS DATA

4.1 Analysis of Low Frequency Oscillation Mode

By using some filtering method such as wavelet transformation or FFT filtering we can extract the low frequency mode clearly. Since data are time-synchronized the geographical mode shape of the oscillation can be analysed. Figure 7 shows comparison of the waveforms of the low frequency mode referred to the phasor at Osaka observed at various places in West Japan power system. The result shows that Nagoya and Miyazaki, which are the both ends of West Japan system, swing in reverse phase followed by another places according to the geographical sequences..

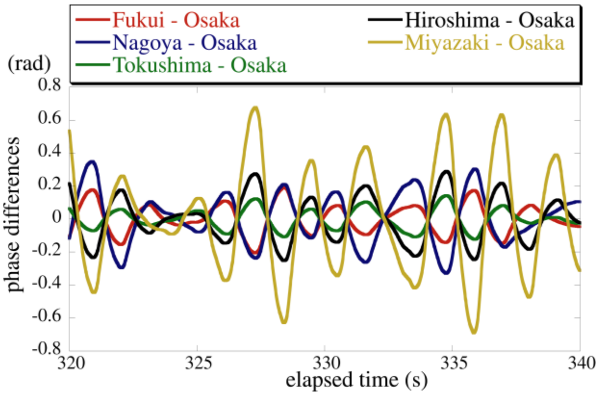


Fig. 7 Extracted waveforms of low frequency mode

The oscillation features of the dominant mode from the view point of the magnitudes and phase of waveforms are explained with the analogy of seesaw shown in Fig. 7, where note that the correct position of Osaka is not sure in Fig. 8 since Osaka is used as a reference of phasor in Fig. 7.

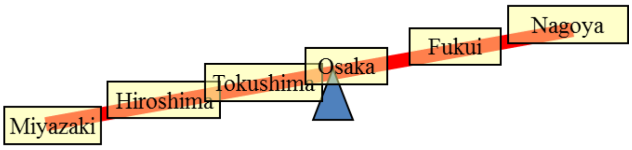


Fig. 8 Analogy of dominant inter-area oscillation

4.2 Response of Frequency Drop after a Large Disturbance

We can evaluate the propagation of frequency drops with GPS time resolution. There are some data when a large power plant was shut down due to protective actions against large events such as earthquakes or short circuits.

On 16th August, 2005 a large Nuclear Power Plants shutdown occurred in 50 Hz east power system in Japan. Consequently the frequency of 50 Hz system dropped in large amount (see Fig. 9). After then an emergency action in Back to Back DC (BTB) system between 50 Hz and 60 Hz systems is taken to send a pre-determined amount of large power from 60 Hz system to 50 Hz system as a support. For the West 60 Hz system it was a kind of step response test. The responses in frequencies in local are shown in Fig. 10.

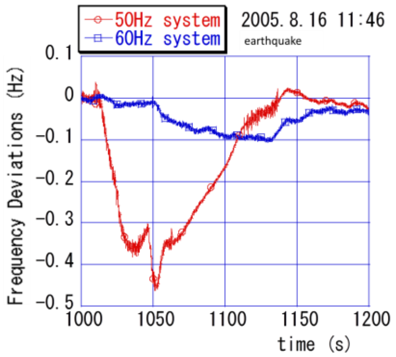


Fig.9 Frequency deviations in 50 Hz and 60 Hz systems after a large nuclear power plant shutdown in 50 Hz system

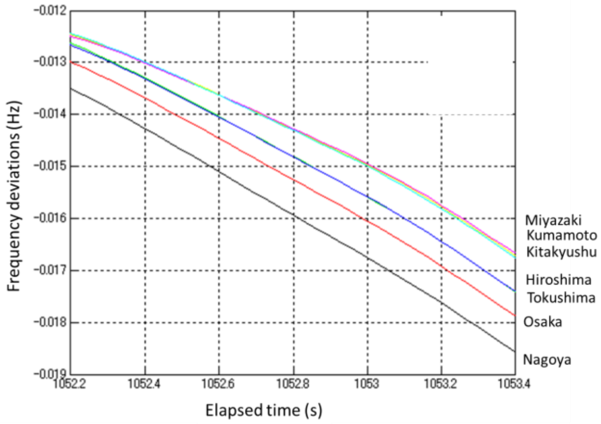


Fig. 10 Response of frequency deviations.

4.3 Some comparisons between West Japan and Malay

The distance between Kyushu Institute of Technology (Kyutech) and Nagoya Institute of Technology (NIT) is around 750 km which is similar as that between Penang and Singapore, around 600 km. Thus, we compared some features on power system dynamics with these data comparison.

Both power systems have a geographically longitudinal structure. As a result each power system has a dominant oscillation mode associated with inter area power oscillation. Figure 12 shows the FFT analysis results. The center frequency is 0.34 [Hz] in Malay and 0.39 [Hz] in West Japan. The peak in spectrum is higher in Malay.

By applying the FFT filtering method the dominant modes are extracted and compared. Figure 13 shows the result.

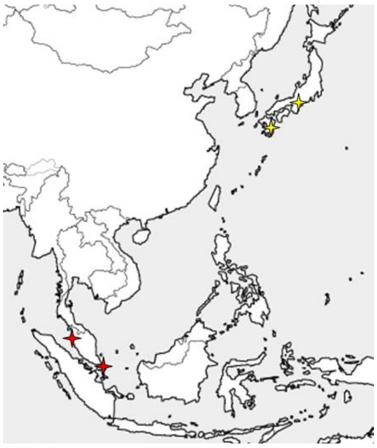


Fig. 11 Locations of PMUs in comparison

As it can be guess from the peak in FFT results the amplitude of the dominant oscillation is larger in Malay. Thus, the power system stability associated with the dominant mode can be evaluated from the FFT spectrum. The detail of stability analysis based on the FFT analysis will be shown in the sequent chapter.

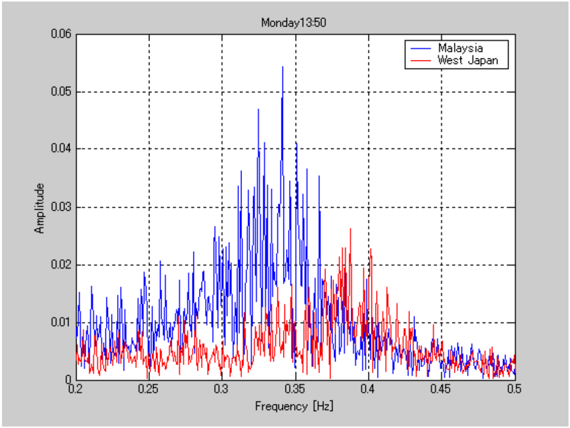


Fig. 12 Results of FFT analysis in West Japan and Malay.

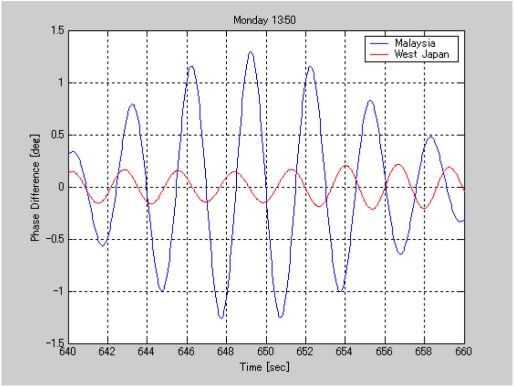


Fig. 13 The dominant modes in both systems

5. ANALYSIS OF POWER SYSTEM STABILITY

5.1 Stability Analysis Based on Resonant Mode Spectrum

The system stability can be analysed based on the resonant mode shape in FFT domain. If the stability of a mode is low the peak shape of FFT power spectrum corresponding to the mode frequency is high. Figure 14 shows an example of phasor difference waveform during 20 minutes between Kyutech and NIT, which implies that the waveform includes the power system fluctuations between two ends in West Japan power system.

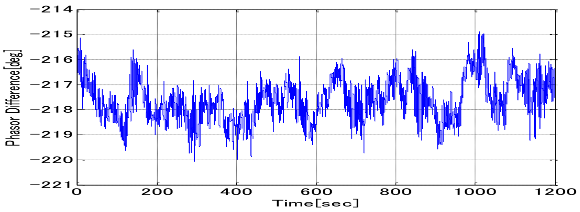


Fig. 14 Phasor difference between Kyutech and NIT

Here, the results of FFT analysis on this waveform are shown in Fig.15. This result shows a typical spectrum with a resonant mode, where we can find a peak around 0.4 Hz which corresponds to the dominant power oscillation mode associated with the inter-area oscillation in West 60 [Hz] system. Here, it is easily guessed that the peak shape is available to evaluate the stability of the mode.

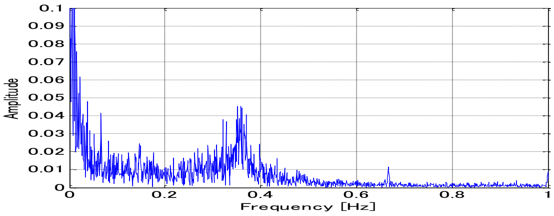
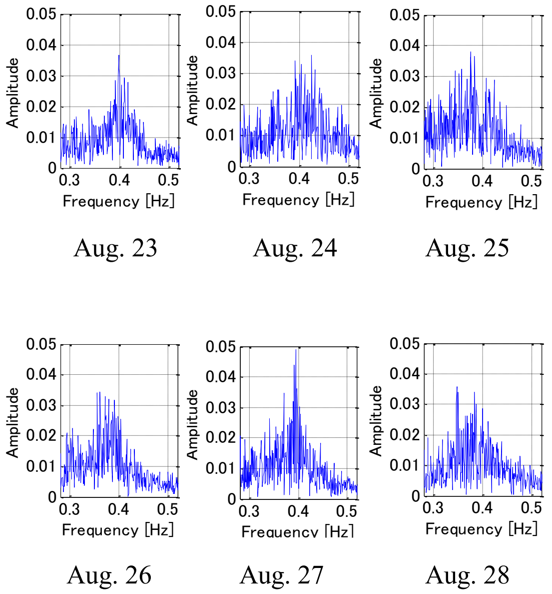


Fig. 15 FFT result for Fig. 11 waveform.

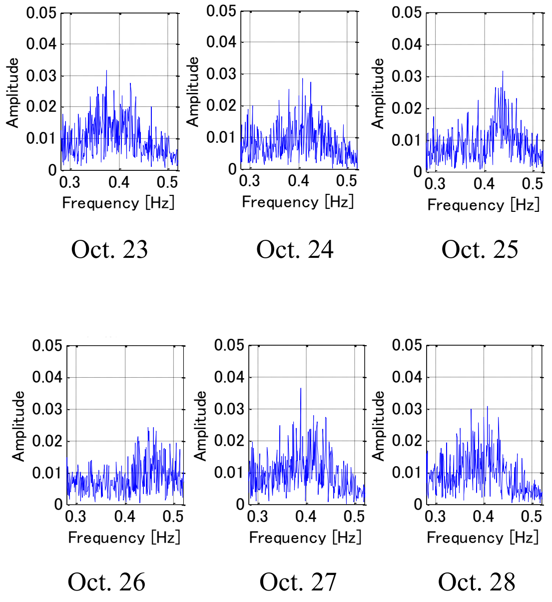
Figures 16 and 17 show some typical examples to demonstrate the differences of the peak power spectrum by comparing results in a high demand season and in a low demand one. In Japan we have a high demand in the end of August since it is just after the summer holiday week in the middle of August in addition that the temperature is very much high with around 35 C degree at the highest. On the other hand in October we have a moderate season with no air conditioner operation. Thus, October is an off-peak demand season. The power spectrums are calculated by using the phasor difference data between Kyutech and NIT during 20 minutes from 13:50 to 14:10 which corresponds to the peak hour in a day.



Aug. 23 Aug. 24 Aug. 25

Aug. 26 Aug. 27 Aug. 28

Fig. 16 FFT spectrums in August (in a high demand season)



Oct. 23 Oct. 24 Oct. 25

Oct. 26 Oct. 27 Oct. 28

Fig. 17 FFT spectrums in October (in a low demand season)

The results apparently show that the peaks around 0.4 [Hz] are comparatively sharp during high demand season, which implies that the stability of dominant power oscillation mode tends to become worse with the increase of power demand as it is usually known.

5.2 Rough Estimation of Damping Factor

Once the power spectrum is obtained we can estimate the damping factor from its shape around the peak frequency. The method is explained with an FFT power spectrum example. Suppose that the power spectrum in Fig. 18 is obtained.

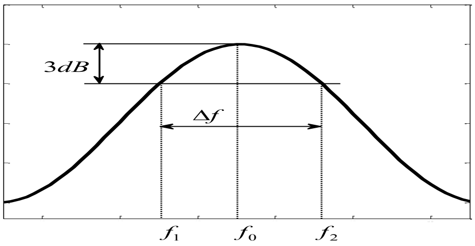


Fig. 18 A power spectrum example

Here, the Q factor is calculated as

$$Q = \frac{1}{2\zeta} = \frac{f_0}{\Delta f} = \frac{f_0}{f_2 - f_1} \tag{2}$$

That is, the damping factor can be obtained with a simple calculation,

$$\zeta = \frac{f_2 - f_1}{2 f_0} \tag{3}$$

However, the actual spectrum is not smooth one like Fig. 18 but some discrete noisy one like Figs. 16 and 17. Thus, a rough estimation to grasp the stability change is carried out as follows by using the fitting as normal distribution curve applied to the discrete FFT results. Figure 19 shows the results, where the FFT is obtained as the average of FFTs of four partial 300 [s] results.

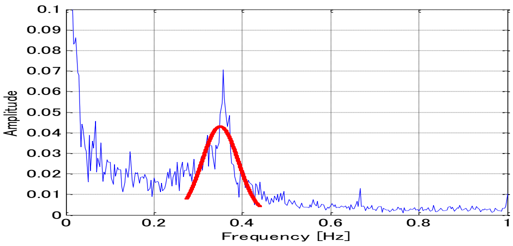


Fig. 19 A power spectrum after applying the moving average with 0.025 [Hz]

From the smooth spectrum after the curve fitting is applied the damping factors can be evaluated. The results are shown in Table 1, where α and β are the real and imaginary parts of eigenvalue calculated from ζ and ω_0 as

$$\alpha = -\zeta\omega_0,\ \beta = \sqrt{1-\zeta^2}\,\omega_0 \tag{4}$$

Table 1 Results of damping factor estimation

	August (high demand season)	October (low demand season)
α [1/sec]	−0.2158	−0.2324
β [rad/sec]	2.1884	2.5716
ζ	0.0981	0.0900
ω_0[rad/sec]	2.1990	2.6075

6. CONCLUSIONS

A monitoring system for wide area power system dynamics based on the user power outlet phasor measurements has been developed. Various analyses with some signal processing demonstrate its effects on the observation of some dynamical phenomena which occur in the transmission system and inter area power system stability. The system in this paper is versatile and simple to install since it is the Campus WAMS system. The technique developed here can be also applied to the PMU installed at the substations.

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