Wide Area Monitoring Solutions and Experience of Employing Data Obtained at Lower Voltage Levels

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Summary
In Japan, a joint research project across four universities has been developing wide area monitoring solutions. These WAM solutions, which can deal with data from PMUs with Web-based functions, are installed in areas which are supplied by ten major electric power companies. This paper describes the system architecture, whereby PMUs are connected at lower voltages such as at customer level, and the various solutions. This paper presents some methods for transmission monitoring and disturbance detection to enhance the quality of data obtained at lower voltage levels, and experiences of disturbances at transmission level, which resulted in generator trips, load trips and power system islanding.

KEYWORDS
Power system dynamics, Synchrophasor, PMU, GPS, WAMS, Fault location, Generator trip, Load trip, Islanding, Power system oscillation.

1. Introduction

In recent years, wide-area monitoring systems based on synchronized phasors have gradually become more widespread, and various applications of phasor measurement units (PMU) and phasor data concentrators (PDC) have been suggested [1]. To improve our knowledge about the disturbances that occur in power systems, and to understand their impact on network stability, it is necessary to monitor the system at many geographical locations, obtaining sufficient data and information about the network.

Authors have proceeded with a joint research project across four universities, developing wide area monitoring solutions. These WAM solutions, which can deal with data from PMUs with Web-based functions, are installed in areas which are supplied by ten major electric power companies. The project has been conducted since 2002 with continuous monitoring, storing and analyzing of enormous quantities of field data across interconnected power systems. This paper describes the various solutions that have been developed in this project, and reports on experiences of disturbances at transmission level, which resulted in generator trips, load trips and power system islanding.

Although many studies on WAMS or WAMPAC have been reported, most of their PMUs have been installed at transmission system substations, because faults or other events in transmission systems are most important as far as the entire power system is concerned. On the other hand, some studies have been reported on voltage or frequency monitoring at distribution system voltage levels [2], [3]. These studies have concluded that data obtained at distribution voltage levels also provide useful information concerning faults or other disturbances in transmission systems. Although these monitoring systems may be restricted in the quantity and quality of the inputs into their PMUs, they have several advantages such as easy installation or simple specification. For transmission monitoring and disturbance detection, authors have also studied since 2002 how we obtain appropriate information from data obtained at lower voltage levels. The focus of this paper is on solutions based on the experience of storing and analyzing large quantities of data from the PMUs.

Considering the transformation of the current electrical network into an intelligent grid, called Smart Grids, the scope of WAMS with PMUs will expand to distribution systems. Field experience of employing PMUs in a microgrid interconnected to a distribution system was already reported in [4]. In the future, our proposed solutions can be useful, not only to fault and disturbance analysis in power transmission systems in point of cost-effectiveness and flexibility, but also to control schemes for future grids such as Smart Grids. This is because on the lower voltage side, customers or distributed generators will require information on faults and disturbances that occur in transmission systems in real-time if we are to fully realize the benefits offered by these schemes.

In section 2, authors present the system architecture, whereby PMUs are connected at lower voltages, such as at customer level with the voltage phasor values being periodically sent to PDCs via the Internet. These allow easy installation of PMUs and unrestricted measurements across utility power systems. Section 3 describes some methods of transmission disturbance detection to enhance the quality of data obtained at lower voltage levels. For example, authors have developed a search strategy to extract data regarding power system faults and disturbances from databases effectively and autonomously. These techniques employ digital filtering and wavelet transforms to eliminate effects from distribution networks. In section 4, this paper reports on some of our field experiences and show a novel method for fault location, estimations of long term oscillation and other solutions. Finally, section 5 summarizes our conclusions.

2. System Architecture

The measurement system that authors and colleagues have constructed consists of more than ten PMUs and two PDCs as shown in Fig. 1. The PMUs have been deployed in areas which are supplied by ten major electric power companies, and each PMU measures single phase voltage of a 100V outlet on the wall at laboratories which collaborate with our project as shown in Fig. 2. The PMU (NCT2000) has PMU functions and Web server functions [5], [6]. The system architecture is shown in Fig. 3. The PDCs periodically download synchrophasor data files from the PMUs via LANs of the campuses and the Internet. These files are stored with a period of twenty minutes in the PMUs, containing synchronized phasors calculated with the time-tag rate of 30 per second for a 60 Hz system. The PDCs (Nagoya PDC and Kyushu PDC) access the PMUs according to a schedule to avoid collisions, and complement each other in case of data loss caused by system failures. The number of data collected per a day can be more than 40,000,000. The amount of data per day is more than 121G byte, which is an enormous quantity for data management. To realize easy management, a database management system for the PDCs has been developed.

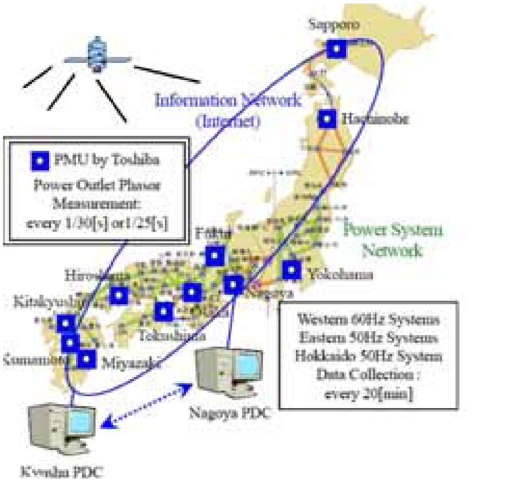


FIg. 1. PMU distribution MAP.

Fig. 2. PMU, UPS, PDC and 100V Outlet.

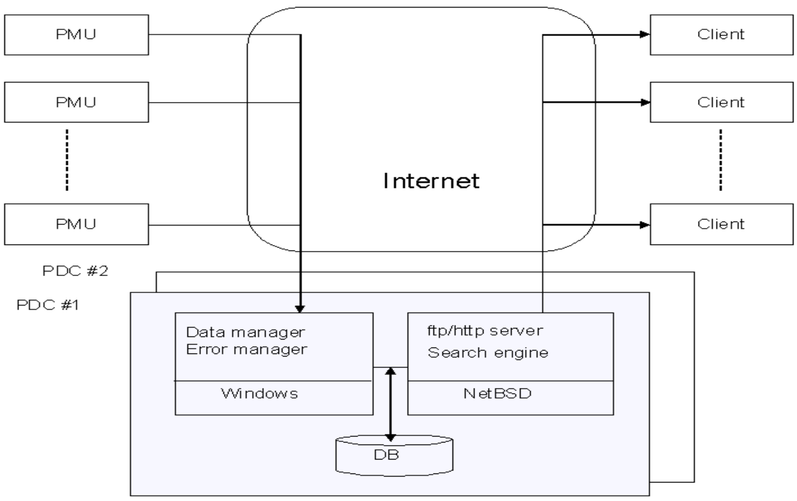


Fig. 3. System architecture.

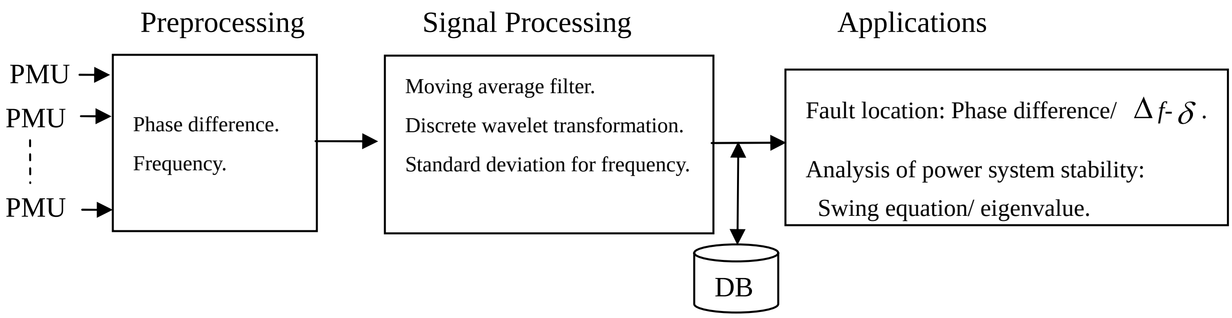


Fig. 4. Software Framework.

The management system allows the clients easily to deal with the data obtained at different places at the same time, creating a new file based on the time that a disturbance occurs, detecting and compensating synchronous error data.

The software framework of the WAMS is shown in Fig. 4. Basic values, phase differences and frequencies, are derived through the preprocessing of synchrophasors. In the subsequent signal processing stage, disturbances can be detected by a number of methods, such as moving average filter, discrete wavelet transformation and standard deviation for frequency. The data files are created and stored in the database such that the clients can easily access and analyze the data related to each application software. These processes are conducted in the PDCs. In the application stage, application programs of the clients are executed at each user computer. Section 3 and 4 will describe these processes in more detail.

3. Methods of monitoring at customer level

Two issues need to be considered for the monitoring scheme at lower/customer voltage levels such as the outlets in the laboratories: One is how to eliminate disturbances caused by local load variations around the outlets, the other is how to represent dynamics across transmission systems. To assure the quality of the monitoring data, authors have introduced a number of methods to monitor synchrophasors at lower voltage levels.

3.1 Phase difference and frequency

Authors employ time-varying phase differences and frequencies derived from synchrophasor data of the PMUs as the basic values for analysis of power systems. A phase angle itself isn't useful because authors don't have information on system configurations such as the effect of transformer phase shifts around the monitoring points. On the other hand, a phase difference and a frequency are independent of the system configurations at lower voltage levels. The PMUs sample input voltage signals and convert the sampled data to voltage phasors.

Using the DFT algorithm, the voltage phasor *V* is given by

$$\dot{V} = \frac{\sqrt{2}}{M}\left(\sum_{k=1}^{M} v_k \sin k\theta + j\sum_{k=1}^{M} v_k \cos k\theta\right) \quad (1)$$

where M is 96.

From equation (1), the phase angle δ can be derived as follows:

$$\delta = \tan^{-1}\left\{\frac{\Im\{\dot{V}\}}{\Re\{\dot{V}\}}\right\} \quad (2)$$

The phase differences between any two monitoring points and frequencies can be calculated at the preprocessing stage. Frequencies and rates of change of frequencies at a local location can be estimated from the phase angles of the synchrophasors. Frequency deviation from the nominal frequency is also given by

$$\Delta f_n = \frac{\delta_{n+1} - \delta_n}{360\Delta t_n} \quad (3)$$

The results of these preprocessing operations are fed to the next stage, the signal processing. The magnitude of the synchrophasors at lower voltage levels has been used only as supplemental information, because the magnitude can be considerably affected by disturbances of distribution systems.

3.2 Moving average filter

Moving average filters allow elimination of an oscillation with constant frequency. It has already been revealed that the western Japan power system has a long-term oscillation with a cycle of about 2.5 sec [7] as shown in Fig. 5. To deal with system dynamics data precisely, the effect of the long-term oscillation can be eliminated from phase differences obtained at the preprocessing stage, using a moving average filter [8].

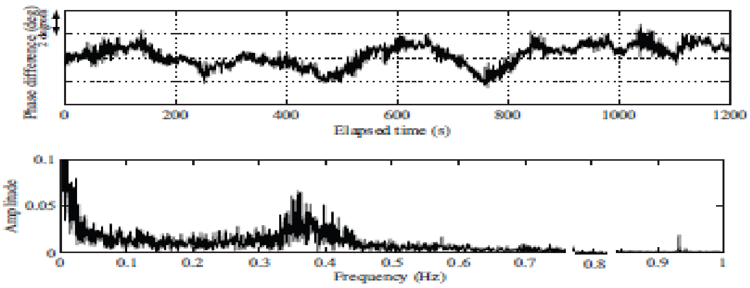


Fig. 5. Phase difference between Kyushu and Osaka, and its spectra.

The filter function used is given by

$$y(n) = \frac{1}{2N+1}\{x(n-N)+\cdots+x(n)+\cdots+x(n+N)\} \qquad (4)$$

Each output $y(n)$ is the average of (2N+1) sequential inputs, $x(n-N)\cdots x(n)\cdots x(n+N)$. The effect of this filtering has been confirmed by our project experiences.

3.3 Discrete wavelet transformation

Operations of a power system around the monitoring points induce step changes in the phase differences as shown in Fig. 6. The moving average filters described above cannot eliminate these effects well. Thus, a discrete wavelet transformation is introduced to detect harmonic components caused by operations of the power system [8]. When phase difference data include harmonic components above 10 Hz, the PDCs decide that the step change is caused by an operation of the power system, and can eliminate the step change data from the monitored data. To estimate these harmonic components, a discrete wavelet transform has been employed to decompose a frequency deviation as shown in (3) into 12 different wavelet components (D1, D2, … D12).

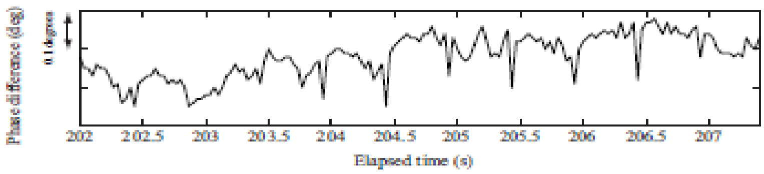


Fig. 6. Phase difference between Tokushima and Osaka.

The moving average filters mentioned above and the discrete wavelet transformation allow for precise detection of the time at which disturbances occur in a transmission system.

3.4 Standard deviation of frequencies

To detect disturbances with fluctuating frequency, the rate of change of frequency or fluctuation width of the frequency have been used as a measure for detection. However, it is difficult to distinguish between frequency fluctuations under steady state conditions and those during disturbances. Therefore, a method employing standard deviation of frequencies has been developed. Fig. 7 shows frequency monitored during a disturbance. The standard deviation is shown in Fig. 8. Considering that the time for which the frequency remains in the disturbance state is about 5 to 10 seconds, according to the control schemes of power systems in western Japan, the standard deviation can be calculated as follows, using the frequencies obtained during a ten second time window:

$$\delta = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \overline{x})^2} \qquad (5)$$

Where $\overline{x}$ is a moving average of frequencies observed in the window, n is the number of data in the window. The method is useful to detect a disturbance as shown in Fig. 8, where the standard deviations of the disturbance are much higher than those of steady state.

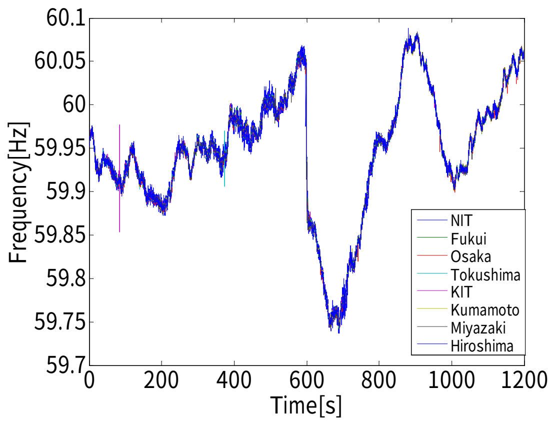


Fig. 7. Frequency during disturbance.

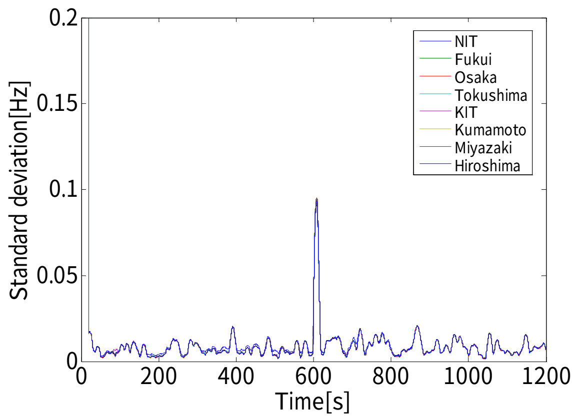


Fig. 8. Standard deviation during disturbance.

4. FIELD EXPERIENCES AND ANALYSES

4.1 Fault location

4.1.1 Phase difference method

This section discusses a fault location method and the results of verification with the data of actual disturbances that occurred from 2006 to 2008. The method firstly identifies the fault mode by the standard deviation of the frequency. Faults are divided into three categories: generator isolated, load isolated and utilities interconnection split. When a generator area is isolated, the frequencies obtained at all monitoring points decrease. Conversely, when the load area is isolated, the frequencies at all monitoring points increase. In the case of utilities interconnection split, some areas suffer frequency increasing, the other areas suffer frequency decreasing. Thus, the frequency deviation monitored allows us to decide the fault mode.

Secondly the method determines the fault location, employing the phase differences, where phase difference relationships between all monitoring points indicate the faulted area. When a generator area is isolated, the phase difference of the generator area, where the reference point is fixed, is delayed compared to those of the other areas. When a load area is isolated, the phase difference of the load area is advanced compared to those of the other areas.

The fault locations and occurrence times of six disturbances, estimated by this method, which occurred from 2006 to 2008, accurately corresponded with press releases. Standard deviations of frequency monitored during 2006 are shown in Fig. 9, where the outstanding deviations greater than 0.05 Hz indicate fault occurrences. In the month of June 2006, a generator area was isolated. Fig. 10 shows frequencies monitored in that case, where the frequencies decreased in all areas. Fig. 11 shows that the fault occurred in Nagoya area because the phase difference is delayed compared to those of the other areas. Fig. 12 shows phase differences under a fault that occurred in Osaka area, where the phase difference of Osaka area is advanced compared to those of the other areas.

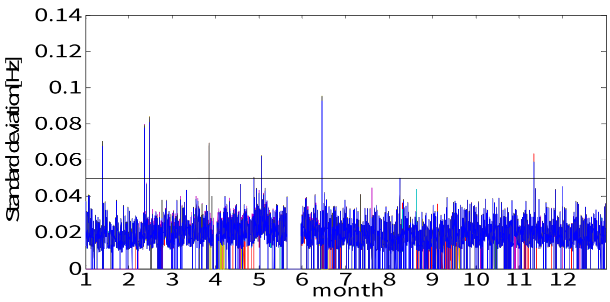


Fig. 9. Standard deviation of frequency in 2006.

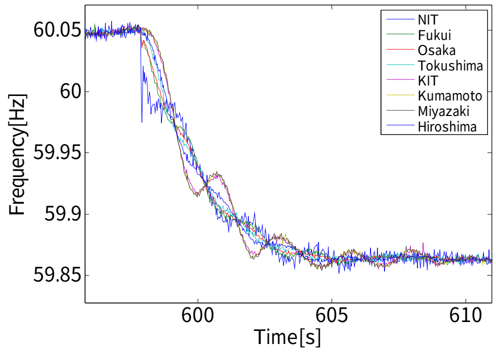


Fig. 10. Frequency under generator trip.

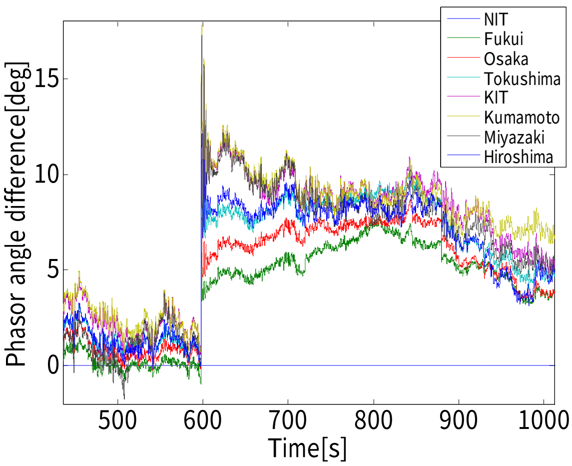


Fig. 11. Phasor differences under generator trip.

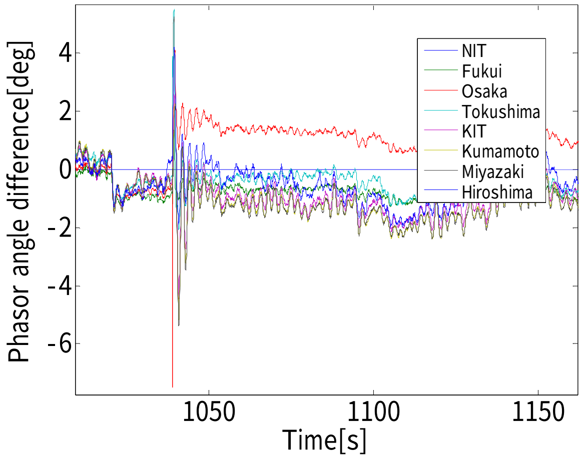


Fig. 12. Phasor differences under load trip.

4.1.2 Δf-δ_{ab} method

Another method has been developed for the fault location employing the relationship between frequency and phase difference of the power system, focusing on interconnected systems [9], [10]. Fig. 13 shows a simple model of two interconnected local power systems, A and B. The interconnected power system is monitored by two PMUs which are deployed in each local system. When the interconnected power system is operated synchronously without any large disturbances, frequency deviations at every monitoring point are the same. In general, the frequency deviation Δf and the tie-line power flow deviation ΔP_T are given as follows:

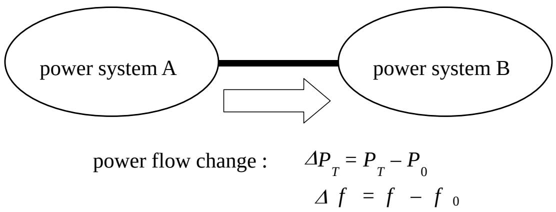


Fig. 13. Model of two interconnected power systems.

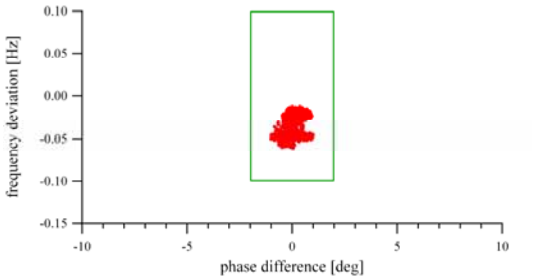


Fig. 14 (a). The first ten seconds.

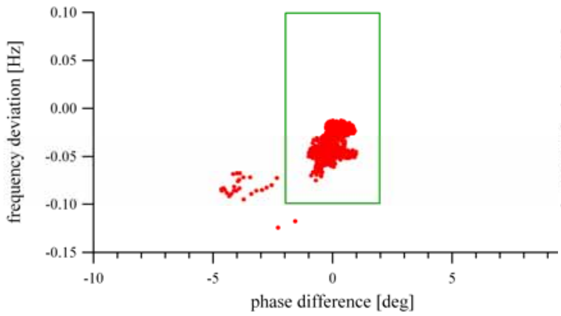


Fig. 14 (b). The second ten seconds.

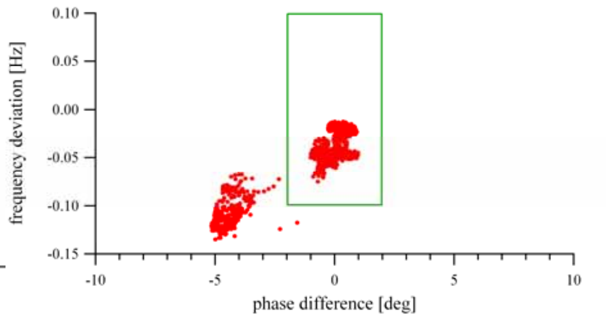


Fig. 14 (c). The third ten seconds.

Fig. 14. Δf- δ_{ab} plots during a generator disconnection.

$$\Delta f = -\frac{\Delta R_A + \Delta R_B}{KP} \tag{6}$$

$$\Delta P_T = \frac{K_A P_A \Delta R_B + K_B P_B \Delta R_A}{KP} \tag{7}$$

where ΔR_A and ΔR_B are control errors of active power for area A and B, respectively. Load frequency control systems employed in the western Japan 60Hz power system are based on the tie-line bias control scheme. Thus, each power system behaves so as to reduce the control error of the area. It has already been proved that a plot of probability density g (ΔP_T, Δf) in a power system takes the shape of a circle or ellipse when distributions of ΔR_A and ΔR_B are normal distributions. The method is useful for considering the characteristics of an interconnected power system, but it requires the actual value of the frequency deviation Δf and the tie-line power flow deviation ΔP_T. Although the former can be obtained by PMUs, the latter is difficult to obtain, especially for ordinary users. However, the phase difference between two points has close positive correlation with the tie-line power flow. Therefore, the phase differences δ_{ab} obtained by PMUs can be used instead of the actual tie-line power flow. The Δf- δ_{ab} plots in the case that a generator was removed from the power system are time-sequentially shown in Fig. 14 (a), (b) and (c). Although, under steady state conditions, the cluster plot hardly moves, new cluster plots appear progressively with time at the left side after a fault. The position of the cluster depends on the fault mode, such as generators isolated. This suggests that detection of large disturbances and fault location can be realized by observation of the movement of these clusters. Moreover, one of features of the method is robustness against noise caused by load fluctuations or incorrect data due to loss of time-synchronization. The criterion regarding fault location using the method requires further study.

4.2 Analysis of power system stability

Analysis of long-term oscillation enables us to increase the reliability and the accuracy of power system stabilizers (PSS). Therefore, two methods have been developed to estimate the parameters of power systems as follows.

4.2.1 *Swing equation model*

A method has been developed to identify the parameters of a two-machine equivalent swing equation model with synchronized phasor measurement during disturbances [11]. Identification of the model will be useful to power system control and stability systems. When the western Japan power system is described as a two-machine equivalent swing equation model, the swing equation is as follows:

$$M_{eq}\frac{d^2\delta_{ab}}{dt^2}+D_{eq}\frac{d\delta_{ab}}{dt}+K_{ab}\delta_{ab}=\frac{M_b\Delta P_a-M_a\Delta P_b}{M_a+M_b} \tag{8}$$

where

$$M_{eq}=\frac{M_aM_b}{M_a+M_b}$$

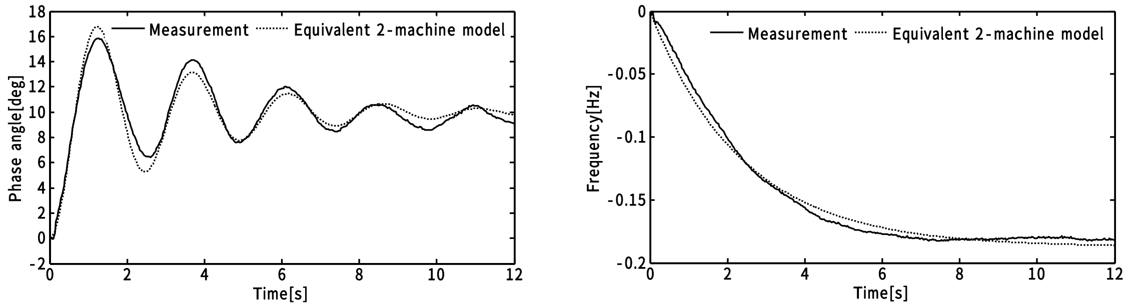
M_a and M_b are generator inertia, D_a and D_b are generator damping, K_{ab} is synchronizing power coefficient, ΔP_a and ΔP_b are the reduction in power of generators or loads during a disturbance. From (8), when the generators or loads drop, P_a and P_b cause a stepwise change, the time response of the phase difference δ_{ab} $(=\theta_a-\theta_b)$ is as follows:

$$\delta_{ab}(t)=A\left\{1-\frac{e^{-\omega_n\zeta t}}{\sqrt{1-\zeta^2}}\sin\left(\omega_n\sqrt{1-\zeta^2}\,t+\tan^{-1}\frac{\sqrt{1-\zeta^2}}{\zeta}\right)\right\} \tag{9}$$

Where, ω_n is natural frequency and ζ is damping rate. In the same way, the frequency of the center of inertia is as follow:

$$f_{ab}(t)=\frac{\Delta P_a+\Delta P_b}{D_a+D_b}\left(1-e^{-\frac{D_a+D_b}{M_a+M_b}t}\right) \tag{10}$$

The model parameter M_a, M_b, D_a, D_b and K_{ab} are calculated with data of a disturbance during the month of June 2006, using (8), (9) and some approximated curves. Using the parameters, δ_{ab} and f_{ab} were estimated under this disturbance. The calculated values correspond closely with the measurement values as shown in Fig. 15. This suggests that the method can identify the parameters of a two-machine equivalent swing equation model.



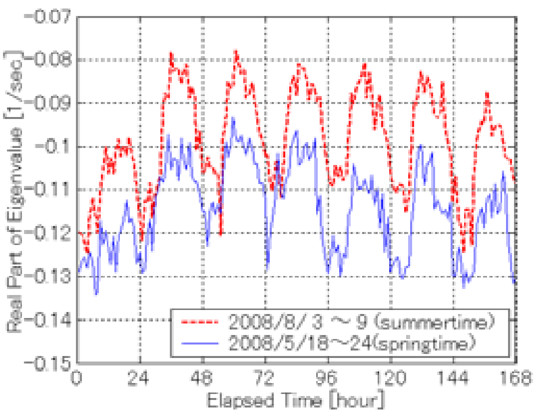
(a). phase angle. (b). Frequency

Fig. 15. Phase angle and frequency transient after fault.

4. 2. 2 *Estimation of eigenvalue of long-term oscillation*

Knowledge of the eigenvalues of long term periodical oscillation will be important for wide area power system steady state stability. In the western Japan power system, the period is 2 to 3 seconds as mentioned above. A method has been developed to estimate the eigenvalue of the oscillation using the monitoring data [12]. The eigenvalue is calculated with a simple oscillation model as follows:

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ a_1 & a_2 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} \quad (11)$$



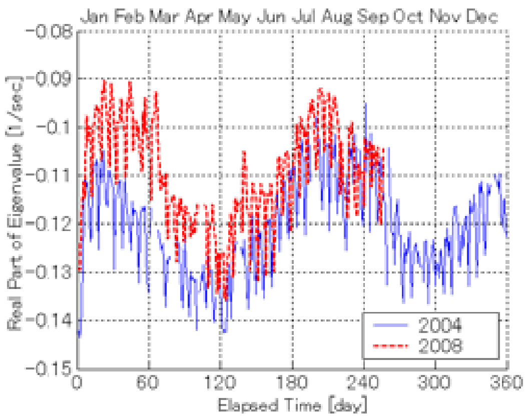


Fig. 16. Variations of eigenvalues during a week. Fig. 17. Variations of eigenvalues during a year.

The coefficient matrix can be obtained by LMS using phase differences through FFT bandpass filters. The real part of the complex eigenvalue of the state matrix indicates the stability, and the imaginary part indicates the damping frequency. Eigenvalues monitored during one week and one year are shown in Fig. 16 and Fig. 17. Understanding the trend of eigenvalues is useful for designing a PSS.

5. CONCLUSIONS

This paper demonstrates that the WAMS across interconnected power systems, employing data obtained at lower voltage levels provide useful information. Authors have been developing WAMS and various solutions since 2002. The solutions developed and experiences gained are useful, not only to fault and disturbance analysis in power transmission systems in point of cost-effectiveness and flexibility, but also to control schemes for future grids such as Smart Grids. Further development and an increase in the sophistication of the proposed methods and the extension to the wide area protection and control (WAMPAC) require more advanced study and enhancement of the database.

6. ACKNOWLEGEMENT

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BIOGRAPHIES

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