ANALYSIS OF LOAD FREQUENCY CONTROL DYNAMICS BASED ON MULTIPLE SYNCHRONIZED PHASOR MEASUREMENTS

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Abstract - In recent years time stamps of the Global Positioning System can be utilized for precise time synchronization at different remote locations. By the time synchronization and information technology, it becomes available to execute synchronized measurements of large power system. Authors have constructed an online global monitoring system of the Western Japan 60Hz power system.

This paper investigates dynamic characteristics of frequency oscillation after a disturbance based on measurement results. First, by observing the frequency oscillations at each point and phase differences among them, global behaviors of the power system are investigated. It is considered how power flow varied in the power system just after the disturbance. Secondly, transient behaviors are studied in detail through the Wavelet analysis. Some interesting interactions among the local power systems can be observed and system performances originated from a Load Frequency Control (LFC) can be extracted. Finally, frequency variation characteristics by the LFC are studied on a plane of frequency deviation versus phase difference. Then the stiffness and controlled behaviors of the power system are carefully considered.

From these analyses, it is confirmed that the multiple synchronized phasor measurement system has a great possibility to investigate the global power system in an easy way.

Keywords - Global Positioning System, Interconnected power systems, Phase measurement, Load frequency control, Synchronization, Time-frequency analysis, Wavelet transform.

1 INTRODUCTION

WESTERN Japan 60Hz power system is a longitudinal and huge power system which consists of six major electric power companies interconnected with each other by high-voltage ac or dc transmission lines. Due to its longitudinal structure the power system is known to have some significant long term oscillation modes. As concerns frequency oscillation characteristics, the power system may indicate some interesting dynamics because of a situation surrounding Load Frequency Control (LFC). First, the all six companies in the power system have recently adopted Tie-line Bias Control (TBC) for increasing importance of tie-line power flow regulation. Secondly, the system dynamics are also affected by independent power producers which do not contribute anything to the LFC. In the circumstances, dynamics of the frequency oscillation and its control become not only interesting but also important issue for power system engineers to keep the power system reliability.

However, it used to be difficult for most of researchers to observe the dynamics of a whole power system because of difficulties in measuring system variables synchronously at appropriate points which are distant from each other. In recent years time stamps of the Global Positioning System (GPS) can be utilized for precise time synchronization at different locations even if the measurement point is far from the other. Based on the time synchronizing method and recursive Discrete Fourier Transform (DFT) algorithm, time synchronized voltage phasor measurement technologies have been developed [1, 2]. In the circumstances, useful application studies have just started all over the world [3, 4].

Authors have constructed an online global monitoring system of the Western Japan 60Hz power system [5, 6] based on the time synchronized phasor measurement techniques. In the system, seven Phasor Measurement Units (PMUs) [7], which can accumulate time sequential data of the voltage phasors synchronously using the time stamps of GPS, are located at seven universities, respectively. The universities are in large cities and each of them belongs to the demand area supplied by the different major electric power company. The PMU uses an outlet on the wall of laboratory for single-phase terminal voltage measurement. Additionally, the PMUs have a network interface for remote access via Internet. The universities are equipped with campus information networks and interconnected with each other, so the accumulated data are automatically collected in data servers by utilizing the well-formed campus information network. Therefore it becomes easy for us to study the power system dynamics by the global monitoring. Authors now continue the multiple phasor measurement in the power system.

This paper investigates dynamic characteristics of frequency oscillation after a disturbance based on the multiple synchronized phasor measurement. The phasor measurement provides relations between phase differences and frequency deviations.

First, by observing the relations, global behaviors of the power system are carefully investigated. It is considered by the measurement how power flows varied in the power system just after the disturbance.

Secondly, transient behaviors are studied in detail through the Wavelet analysis. It is known that a behavior which originated from the LFC is a long term variation during from a few to ten minutes. The behavior is expected to be observed in case that the frequency suddenly changes because of a disturbance. In this study time-frequency analysis based on the Wavelet transform is employed to distinguish the frequency behaviors due to the LFC. Some interesting interactions among the local power system are extracted from the transient behaviors.

Finally, frequency variation characteristics associated with the LFC are studied on a plane of frequency deviation versus phase difference. There is an attractive literature which deals with statistical studies about relations between tie-line power flow and frequency deviation under the LFC [8]. The result of the phasor measurement is expected to show some similar behaviors discussed in the literature because the phase difference between some two areas is closely related to the power flow between them. This paper also presents that the extracted LFC behavior shows similar dynamics known as relations between tie-line power flow and frequency deviations under the LFC. Then the stiffness and controlled behaviors of the power system are carefully considered by a statistically method.

From these analyses, it is confirmed that the multiple phasor measurement system has a great possibility to investigate the global power system dynamics in an easy way.

2 MULTIPLE SYNCHRONIZED PHASOR MEASUREMENT SYSTEM

2.1 System Configuration

As shown in Fig. 1, authors have constructed the multiple synchronized phasor measurement system for Western Japan 60Hz power system. The power system consists of six power systems depicted as circles in Fig. 1. The six local power systems belong to different six major electric power company, respectively, and they are interconnected by ac tie-line (solid line) or high-voltage dc transmission lines (doted line) with each other. PMUs are located at seven laboratories of university in each of six power systems as summarized in Table 1. The power system including Osaka University supplies the largest demands in the six local power systems.

The phasor measurement system employs PMUs manufactured as commercial products, NCT2000. The PMU can measure a single-phase instantaneous voltage at 100V outlets on the wall, with correcting its internal clock based on the time stamps of GPS. As the PMU uses the time stamps of GPS, the time synchronization among PMUs located at distant place can be easily accomplished.

In order to continue the synchronized phasor measurement even if an interruption or a voltage sag occurs at the outlet, each PMU has an Uninterruptible Power Supply (UPS). By the UPS, the PMU can continue the synchronized phasor measurement for at least 15 minutes in case of losing its power source.

The PMU has 10BaseT network interface and we can download the data accumulated in the PMU through the well-formed campus information network. Data servers are located at Osaka University, Nagoya Institute of Technology (NIT), and Kyushu Institute of Technology (KIT) in order to classify the enormous data by PMUs. The phasor data accumulated in the PMUs are automatically collected from every PMU to the data servers by utilizing the campus network. We can also browse the measured data by every one second on an internet browser, therefore the measurement system can be operated as an online monitoring system.

A measurement process in this system has been carefully designed. To be available for analysis of both short and long term power system dynamics, one cycle of measurement is decided as 20 minutes and a sampling interval of the phasor data is 2/60 sec. As the phasor data stored in the PMUs must be transferred to the data servers, the measurement cycle is accompanied by 10 minutes idling interval, which is used for data transmission from the PMU to the data servers. Then the 20 minutes mesurement and 10 minutes data transmission are repeated alternately by every PMU. Although continuous measurement is limited less than 20 minutes by the data transmission interval, most of LFC dynamics can be caught within the measurement interval.

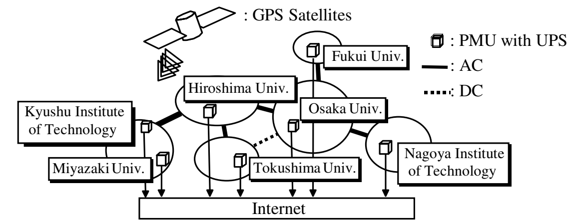

Figure 1: Multiple phasor measurement system.

Area	Universities with a PMU
Chubu	Nagoya Institute of Technology (NIT)
Kansai	Osaka University
Hokuriku	Fukui University
Shikoku	the University of Tokushima
Chugoku	Hiroshima University
Kyushu	Kyushu Institute of Technology (KIT)
	Miyazaki University

Table 1: PMU distributions.

2.2 Phasor Measurement Technique

Based on the recursive DFT algorithm, the voltage phasor is given by

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

where v_k is sequential data of the instantaneous voltage of 100V outlet measured through A/D transformer, M is the number of times for sampling of the voltage and θ is the sampling angle. In the case of this apparatus, $M = 96$ and

$\theta = 3.75$ [deg]. From (1), we have the phase angle δ as follows:

$$\delta = \tan^{-1}\left[\frac{\Im\{\dot{V}\}}{\Re\{\dot{V}\}}\right]. \tag{2}$$

The phase angle δ is accumulated in the PMU as time sequential data.

2.3 General Characteristics of Accumulated Data

The phase angle δ is calculated as a phase difference between observed instantaneous voltage and 60Hz reference signal produced by the PMU based on the time stamps of GPS. Without information about system parameters and configuration, both the phase angle value itself and the phase difference value itself are not so useful because, for example, the phase angle can be directly shifted by an angular displacement at a wye-delta transformer.

On the other hand both varying phase angle and varying phase difference between two points give us a very useful information. Increasing phase angle represents that the frequency of the observed voltage is higher than the system nominal frequency, 60Hz. Decreasing phase angle means that the frequency of the observed voltage is lower than 60Hz. The time derivative of phase angle corresponds to the deviations of system frequency. So the frequency deviations can be calculated as

$$\Delta f_n = \frac{\delta_{n+1} - \delta_n}{360\Delta t_n}, \tag{3}$$

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

The variation of phase difference between two points means that the power flow between the two points has changed. Increasing the phase difference represents the power flow has been increased, and decreasing the phase difference means the power flow has been decreased, conversely.

2.4 Accuracy of Measured Data

The PMU corrects its internal clock by the time stamps of GPS. A time error of the clock is guaranteed within 1 μs. In this case, phase angle δ of the terminal voltage at the outlet on the wall is used as measured data. An error of phase angle is guaranteed less than 0.1 deg. The accuracy of time and phase angle is enough to analyze the frequency oscillations as a whole power system because oscillations with short term or small amplitude less than the error are out of the range for the LFC.

3 OBSERVATION OF FREQUENCY OSCILLATIONS AFTER A DISTURBANCE

It is known by a press release from an Electric Power Company that a generator of the company was dropped out by an accident at 10:00 on May 19, 2004. The generator is in Shikoku where the University of Tokushima is, and its generating power was 566MW at that time. The press release also says that, although a generating power decreased by 536MW with the accident, there was no supply problem and the power system continued its proper operation. The decreased power 536MW was 7.8 % of 6860MW, which is the available power of the local system.

Then, this paper picks up the measured data from the stocked data in the data server, which includes at the time of the accident. The measurement system accumulated from 9:50 to 10:10 on Wednesday, May 19, 2004, in Japan Standard Time, by every 0.033 seconds. Measurement conditions are summarized in Table 2. Unfortunately, we do not have mesurement results for 10 minutes both just before 9:50 and after 10:10 because the 10 minutes durations were reserved for data transmission interval. However, the 20 minutes measurement interval gives us a lot of information about the system dynamics and the following sections reveal them.

Date	Wednesday, May 19, 2004
Interval	20 minutes from 9:50 to 10:10
Sampling interval	2/60sec
Number of data	36000
Accuracy of angle	$\pm$ 0.1 deg.
Accuracy of clock	1 μs

Table 2: Measurement conditions.

Fig. 2 shows frequency deviations calculated by (3) with phase angle data measured at each university. As concerns about the frequency oscillation measured at the University of Tokushima, the maximum value of the frequency deviations is 0.0833Hz, the minimum value is -0.1358Hz, and the averaged frequency is 59.936Hz.

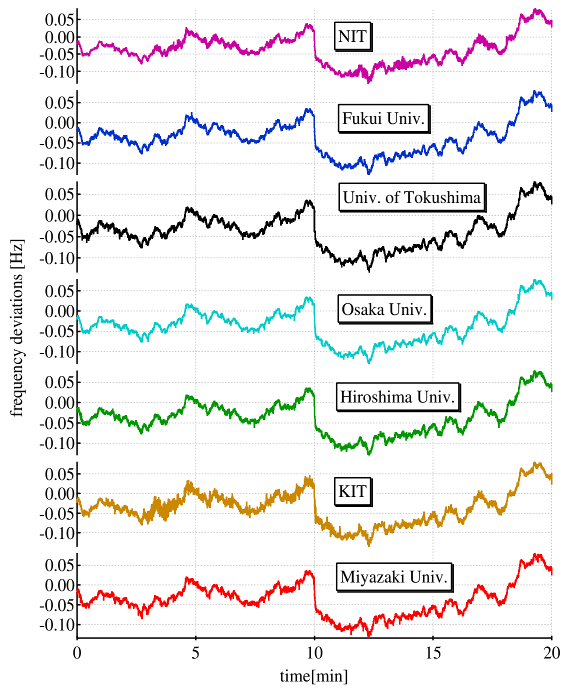

Figure 2: Frequency variations in the power system.

It can be seen in Fig. 2 that frequency oscillations with short term and small amplitude indicate some individualities. The short term oscillation may be influenced by local load variations on the abrupt shifts of phasor because the PMU measured at 100V outlets on the wall of laboratory. Then the individualities are supposed to originate from the measurement system. On the other hand, frequency oscillations with long term indicate some important behavior as a global system. In order to investigate global system behaviors, frequency oscillations with short term and small amplitude are neglected and the long term frequency oscillations are carefully investigated in this paper.

In Fig. 2, every frequency deviation shows a remarkable sudden decrease at 10min. It is the time when the generator dropped out as described above, therefore the decrease of frequency deviation is assumed to be caused by a shortage of supplied electric power, which originated in the accident.

On the other hand, long term frequency oscillations are almost identical with each other regardless of the disturbance. This means that the all local power systems kept synchronization and the interconnected power system operated properly, too. The fact corresponds with the press release by the electric power company.

Variations of phase difference between each university and NIT are shown in Fig. 3. In Fig. 3, the only phase difference between the University of Tokushima and NIT shows a sudden change at 10min. It is the time when the accident occurred at the power plant, therefore the change of phase difference is also caused by the accident. On the other hand, it is known that a phase difference and a power flow between two point have a close relation to each other. Changing power flow between Shikoku and Chubu area results in varying the phase difference between the Univ. of Tokushima and NIT. Taking these into account, it can be said that the shortage of supplied power was caused in Shikoku area by the accident and some amount of power flowed into Shikoku area, resulting in the change of phase difference between the Univ. of Tokushima and NIT.

Fig. 3 also indicates behaviors of the other local area. Chubu, Kansai, Chugoku and Shikoku is interconnected by AC tie-line from east to west in this order, as shown in Fig. 1 and Table 1. However, phase differences between NIT and the local areas except Shikoku display little change at the time of accident. Accordingly, it can be said from the results that the change of phase difference between the Univ. of Tokushima and NIT is nearly equal to the one between the Univ. of Tokushima and Hiroshima Univ. in Chugoku. This mentions that changes of power flow hardly occur among the local areas except Shikoku at that time and it happened just between Shikoku and Chugoku. Therefore, it can be concluded that, after the shortage of supplied power in Shikoku occurred by the accident, power flow from Chugoku and Kansai to Shikoku increased and the increased power flow appeared as a sudden change of phase angle difference only between Shikoku and Chugoku.

However, it is difficult to decide the increased amount of power flow. The value of phase difference cannot be straightly translated to the value of power flow with knowing neither the system parameters and configurations which lie among the PMUs nor a value of steady-state power flow.

There is a HVDC transmission line between Shikoku and Kansai, and it normally carries electric power generated at a power plant in Shikoku to Kansai which is a large demand area. If the HVDC transmission line compensated somewhat of the shortage of supplied power in Shikoku, the multiple phasor measurement system could hardly observed a power flow variation on a HVDC transmission line because the power flow variation does not appear as a change of phase angle.

Although these difficulties are left, it should be noted that the above qualitative considerations can be drawn only by the data measured with PMUs which are placed at the laboratories of university. The multiple phasor measurement system is useful to consider such a large power system behavior based on observed actual data.

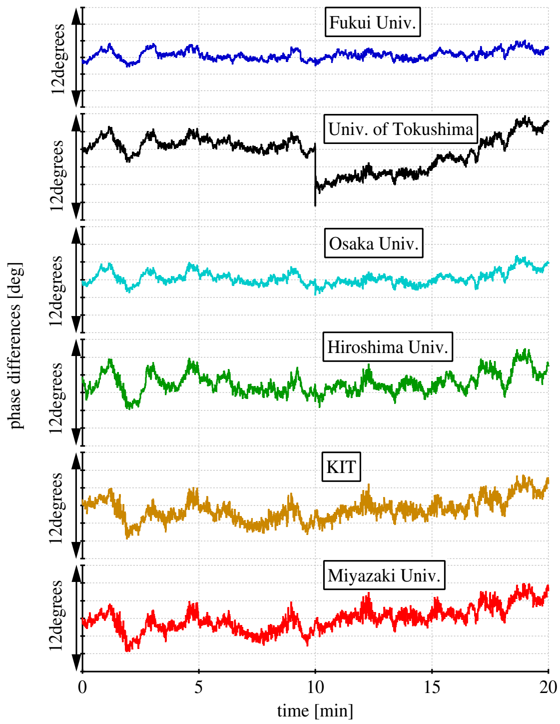

Figure 3: Variations of phase difference based on phase angle measured at NIT.

4 OBSERVATION OF TRANSIENT PHENOMENA BY WAVELET ANALYSIS

As described above, the shortage of supplied power in Shikoku might be supported by its neighboring areas with increasing the power flow from them to Shikoku. After the disturbance, phase difference between the University of Tokushima and NIT returned slowly to its initial value just before the disturbance, as shown in Fig. 3. The phase difference between the University of Tokushima and Hiroshima University can be assumed to have behaved like it, too. Fig. 2 shows that the frequency deviations also returned to zero value simultaneously. These behaviors are seemed to depend on LFC which might be applied to the power system after the disturbance.

In this section, system dynamics associated with the LFC operations are picked up from the waveforms of frequency deviation shown in Fig. 2. In order to consider the LFC dynamics, the transient behavior of the frequency oscillations just after the disturbance are extracted by Daubechies Wavelets. In this case very short term oscillations which originate from local load variations around the 100V outlet for measurement by the PMU are also eliminated.

The waveforms of frequency oscillation as results of Wavelet analysis are very similar with each other. This is why the interconnected power system could keep its synchronization before and after the disturbance. To investigate in detail, the results are displayed in Fig. 4 as the differences between them and the waveform at the University of Tokushima. The system behaviors are divided into following four stages.

The first stage is a transient mode. It starts at 600sec, when the accident occurred, and continued until 603sec.

The second stage following the transient mode begins at 603sec and continues until 620sec. The waveforms around this stage are picked up and shown in Fig. 5. It can be seen that the frequencies at the six universities oscillates with forming two groups. One is a western group which includes Miyazaki Univ., KIT, Hiroshima Univ. and Osaka Univ., and the other is an eastern group, NIT and Fukui Univ. It is interesting that the local systems except Shikoku system were divided into the western and eastern group, and they oscillated to opposite direction with periods of about two seconds. The other oscillating components which have more long period can be also seen in the waveforms. This oscillating components lasted to next stage.

The third stage is from 620sec to around 650sec. On this stage, synchronized oscillations with periods of 8.9sec can be clearly seen in Fig. 4, and this oscillations continued from the second stage. This oscillating mode with the long period is that the five local systems oscillate against Shikoku system including the University of Tokushima.

Finally, the fourth stage begins at around 650sec. On this stage, frequency oscillations have been converged to zero value, that is, the all local systems including Shikoku system attained synchronization.

From these considerations, it can be summarized that the transient behaviors are observed by Wavelet analysis, and system behaviors from around 650sec should be considered for investigation of LFC dynamics.

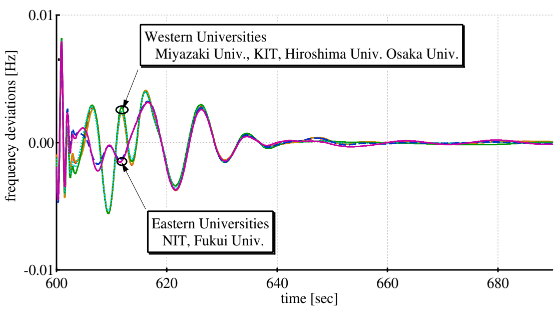

Figure 4: Behaviors of the local system derived by Wavelet analysis.

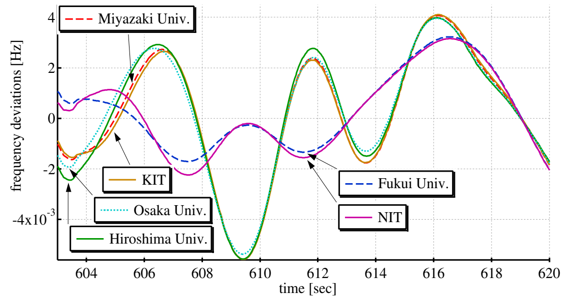

Figure 5: Enlarged waveforms shown in Fig. 4.

5 SYSTEM BEHAVIORS ON FREQUENCY-PHASE ANGLE PLOT

5.1 *Relations between Frequency Deviation and Power Flow Deviation*

In this subsection, the relations between frequency deviation and power flow deviation on a tie-line is reviewed by a two-areas interconnected power system model shown in Fig. 6.

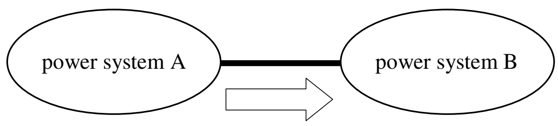

Figure 6: Two-areas interconnected power system model.

The system frequency is assumed to be f[Hz] in both area A and B, f_0[Hz] is a nominal frequency of the system, Δf[Hz] is a frequency deviation, P_T[MW] is a power flow on the tie-line and its deviation from an initial value P_0 is ΔP_T. Then the frequency deviation Δf and the tie-line power flow deviation ΔP_T are written as

$$\Delta f = -\frac{\Delta R_A + \Delta R_B}{KP}, \tag{4}$$

$$\Delta P_T = \frac{K_A P_A \Delta R_B + K_B P_B \Delta R_A}{KP}, \tag{5}$$

where ΔR_A and ΔR_B are the area control error, that is, the control error of active power for area A and B, respectively. As the LFC employed in the Western Japan 60Hz power system is based on the TBC, each system behaves to reduce the area control error.

It is proved by the reference [8] that a plot of probability density $g(\Delta P_T, \Delta f)$ shows a shape of concentric circle or ellipse when distributions of ΔR_A and ΔR_B are normal distributions.

5.2 *Possibility of Studies on Relations between Frequency and Power Flow by the Phasor Measurement System*

The method described above is useful for considering 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 calculated by the PMU, the latter can be hardly obtained, especially for a personal research. However, the phase difference between two points can be calculated by the result of measurements by PMUs. Then it is expected to indicate the power flow because a phase difference and a power flow between two point have a close relation to each other as discussed above.

From this point of view, the measured data are plotted on a plane whose vertical axis is for frequency deviation Δf and whose horizontal axis is for phase difference δ_{AB}, where $\delta_{AB} = \delta_A - \delta_B$. In the following discussion, the measured data are observed in detail based on the $\Delta f - \delta_{AB}$ plots.

5.2.1 Observation of steady-state characteristics

Examples of plot are shown in Figs. 7 and 9, which are depicted from measurement from 8:50 to 9:10 on Wednesday, May 19, 2004, in Japan Standard Time, when it is one hour before the disturbance. As shown in Figs. 7 and 9, each result presents almost a shape of concentric ellipse. In order to investigate in detail, frequency distributions of plotted data in Fig. 7 and 9 by 0.04 deg steps of δ are displayed in Figs. 8 and 10, respectively. By both histograms, it can be seen that both distribution are approximated as normal distributions.

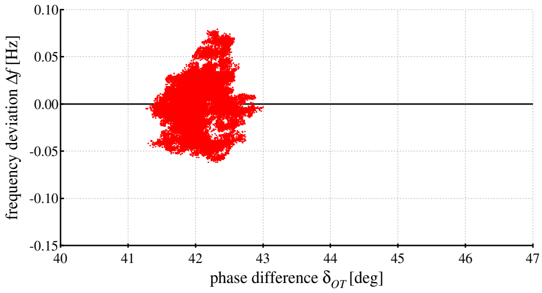

Figure 7: $\Delta f - \delta$ plot between Osaka University and the University of Tokushima

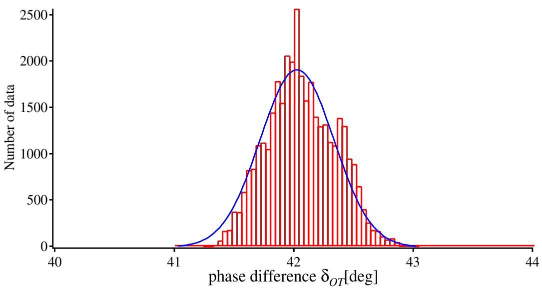

Figure 8: Histogram of the plot of Fig. 7.

The histograms can provide an approximated steady-state value of phase difference between two points. In case of the phase difference between Hiroshima University and the University of Tokushima, the initial value Δ_{HT0} can be estimated as 104.3deg by calculating based on Fig. 10. In addition to this, the stiffness of the two tie-lines can be also guessed by comparison with both histogram. As the power system has a HVDC transmission line between Kansai and Shikoku, the phase difference does not directly indicate the power flow between them. However, it can be said by the histogram that the interconnection between Kansai and Shikoku is very tight.

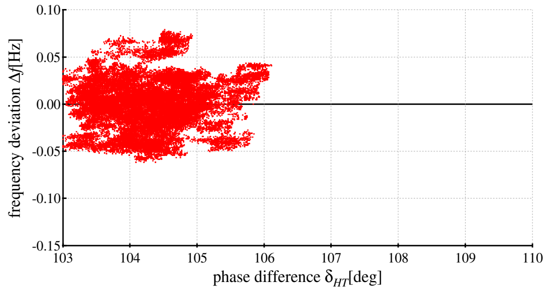

Figure 9: $\Delta f - \delta$ plot between Hiroshima University and the University of Tokushima

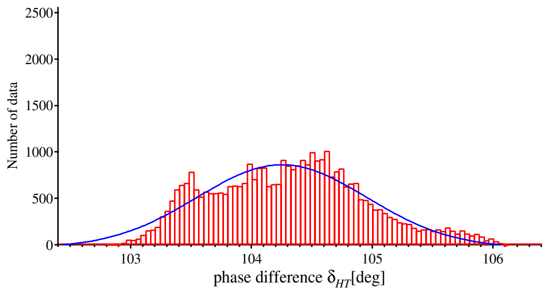

Figure 10: Histogram of the plot of Fig. 9.

5.2.2 Observation of system characteristics including transient behaviors

Fig. 11 shows the plot of the measured data used in the above discussion between Hiroshima University and the University of Tokushima in case that the disturbance occurred.

This figure shows an ellipse on the left side of the plot, on the other hand, some data expand toward right bottom of the plane. As the measured data can be divided into two groups, steady-state and the other, by the time of the disturbance, the ellipse and expanding group of data are assumed to correspond to each, respectively.

First, it can be noticed that the center of the ellipse is near $\delta_{HT} = 104.3$deg, which is defined in previous studies based on Fig 10. Therefore, it can be said that the ellipse corresponds to steady-state operation.

Next, the expanding group of data is investigated. By the above consideration, it is known that the all local systems synchronized with each other from 650sec. From this result, the data from 650sec to 1000sec should be extracted from the plots as LFC operation. In the duration, the system frequency deviations were returning to zero. The extracted data is shown in Fig. 12 with a fitted line of

$$\Delta f = -0.00184\delta_{HT} + 1.891. \qquad (6)$$

Fig. 12 shows the expanding group shown in Fig. 11, therefore, the expanding group indicate the behavior which originated from the LFC.

Adding to this, the line (6) also indicates the interconnected power system characteristics. In Fig. 6, it is assumed that the system A is Chugoku and the system B is Shikoku. Considering the fact that the shortage of supplied power occurred in Shikoku only, by substituting

$\Delta R_A = 0$ to (4) and (5), the relation

$$\Delta f = -\frac{1}{K_A P_A}\Delta P_T \tag{7}$$

can be derived.

(7) means that, when the unbalanced power was left in one system, frequency deviation Δf and power flow deviation on a tie-line ΔP_T represented a linear relation between them. As the power flow deviation is closely related to the phase angle difference between two areas, frequency deviation and phase angle difference are expected to show the same linear relation. (6) indicates this linear relation of frequency deviation and phase angle difference.

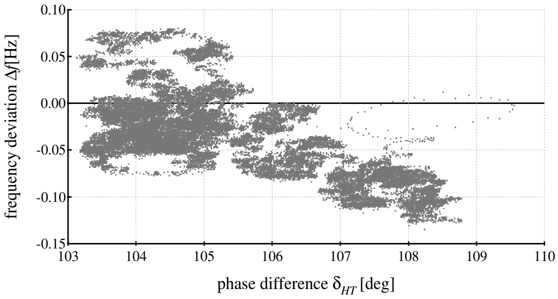

Figure 11: $\Delta f - \delta$ plot between Hiroshima University and the University of Tokushima when the disturbance occurred.

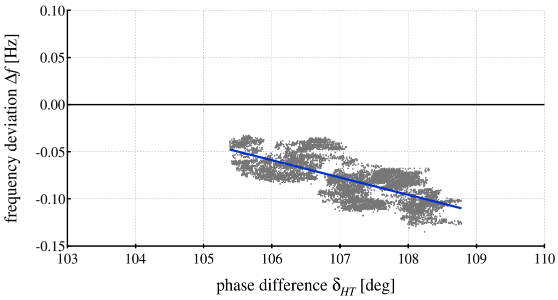

Figure 12: δ-Δf plot extracted as the LFC operated interval from Fig. 11.

The above analyses such as an investigation of stiffness or system behaviors used not to execute without receiving the data about actual power flow. As shown here, the phasor measurement system has a great possibility to provide a new method for a global system analysis.

6 CONCLUSIONS

This paper introduces the online global monitoring system for Western Japan 60Hz power system based on multiple synchronized phasor measurement techniques. With observing the terminal voltage at the end of power system, which is just an outlet on a wall, we can observe some dynamics of a global system, even if the parameters and configuration of power system are unknown.

It is confirmed that the measured data by PMUs provide a useful method to observe the global system behaviors after a disturbance. By applying appropriate signal processing method based on Wavelet transform, transient behavior can be also investigated in detail. As a result, some interesting interaction among the local systems can be observed. In addition to this, system behaviors which are considered as results of LFC can be observed and analyzed on frequency deviation versus phase difference plot. The studies shows a great possibility of the measurement system to provide a new method for investigation of stiffness and behaviors of the global system.

This technology gives us a method to investigate the power system dynamics individually and free. As the terminal for measurement is just an outlet on the wall, the method will be available for one of customers with advancement of information technologies, and it may be one of the key technology in the coming deregulated power system.

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REFERENCES

[1] A. G. Phadke, “Synchronized Phasor Measurements,” IEEE Computer Applications in Power, vol. 6, pp.10-15, Apr. 1993.

[2] A. G. Phadke, “Synchronized Phasor Measurements A Historical Overview,” in Proc. IEEE/PES Transmission and Distribution Conf., vol. 1, pp.476-479, 2002.

[3] H. Saitoh, “GPS Synchronized Measurement Applications in Japan,” in Proc. IEEE/PES Transmission and Distribution Conf., vol. 1, pp.494-499, 2002.

[4] M. Akke, “Phasor Measurement Applications in Scandinavia,” in Proc. IEEE/PES Transmission and Distribution Conf., vol. 1, pp.480-484, 2002.

[5] M. Hojo, T. Ohnishi, Y. Mitani, O. Saeki and H. Ukai, “Observation of Frequency Oscillation in Western Japan 60Hz Power System Based on Multiple Synchronized Phasor Measurements,” IEEE Bologna PowerTech Proceedings (CD-ROM), No.405, 2003.

[6] T. Hashiguchi, Y. Mitani, O. Saeki, K. Tsuji, M. Hojo and H. Ukai “Monitoring Power System Dynamics Based on Phasor Measurements from Demand Side Outlets Developed in Japan Western 60 Hz System,” Proceedings of 2004 IEEE PES Power Systems Conference & Exposition (CD-ROM), 2004.

[7] R. Tsukui, P. Beaumont, T. Tanaka and K. Sekiguchi, ”Intranet-Based Protection and Control,” IEEE Computer Applications in Power, vol. 14, pp.14-17, Apr. 2001.

[8] T. Sasaki and K. Enomoto, “Study of Generation Control and Generation Control Performance Standards,” Transactions on IEE Japan, Vol.121-B, No.3, pp.307-318, 2001. (in Japanese)