PMU Based Monitoring of Inter-Area Oscillation in Thailand Power System via Home Power Outlets

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ABSTRACT

This paper proposes a wide-area monitoring system of the inter-area oscillation between central and southern areas of Thailand power system using GPS-based synchronized phasor measurement units (PMUs). The PMUs are installed at two universities representing both areas. The phasor data of a single phase voltage 220 V are measured by PMU via a wall outlet. The phase difference data between two universities recorded by PMUs are validated by comparing with the actual tie-line power flow during steady-state conditions. The wavelet decomposition and least-squares regression are applied to identify the eigenvalue corresponding to the dominant inter-area mode. Monitoring of variation of damping ratio and oscillation frequency of the eigenvalue in any period not only indicates the oscillatory behavior of the inter-area mode, but also provides useful information of the wide-area dynamic stability.

Keywords: Synchronized phasor measurement unit, Wide area monitoring, Power system oscillation, Wavelet decomposition, Least square regression.

1. INTRODUCTION

The interconnection between central and southern areas of Thailand 50 Hz power system by 230 kV tie-line formulates a longitudinal structure. It is well known that this interconnection may cause an inter-area oscillation. However, the inter-area oscillation between both areas has never been analyzed before. To monitor wide-area power system oscillations, the phasor measurement units (PMUs) which are synchronized based on the time stamp of the global positioning system (GPS) \cite{1,2} have been applied \cite{3-7}. In these works, phasor measurement systems are constructed in a transmission level. To increase the feasibility of the wide-area monitoring of power system oscillations, a new PMU-based monitoring system with convenient installation at a distribution level, Internet based data transmission, easy access for university researchers and cost-effective system is significantly expected.

This paper focuses on a practical monitoring system of the inter-area oscillation based on GPS-synchronized PMUs developed in Thailand power system. The salient feature of the presented system is the convenient installation of PMUs at 220 V domestic outlets. Additionally, the initial installation cost is extremely low. In the proposed system, PMUs are located at two universities which represent central and southern areas of Thailand power system. The PMU data transmission between both universities is performed via the Internet. Based on phasor voltages collected by PMUs, the phase difference between two universities can be calculated. The validity of the phase difference data of PMU is verified by comparing with the actual tie-line power flow data of the Electricity Generation Authority of Thailand (EGAT) during steady-state conditions. Using the phase difference data, the physical characteristics of inter-area oscillation can be analyzed by Fast Fourier Transform (FFT). Besides, the discrete wavelet decomposition and the least-squares regression are applied for system identification. Consequently, the eigenvalue corresponding to the inter-area mode can be determined. Analyzed results yield physical behavior information of the inter-area oscillation.

2. OVERVIEW OF PROPOSED MONITORING SYSTEM

An overview of the PMU based monitoring system is delineated in Fig. 1. PMUs are located at Thammasat University (TU), Bangkok and Prince of Songkla University (PSU), Songkla. The purpose of the monitoring system is to detect the inter-area oscillation between central and southern areas. Here it is assumed that generators in each area oscillate in the same fashion or are in the same coherent group. Both coherent groups are connected by a 230 kV tie-line. As a result, the phase angles at PSU and TU are used as the representative phase angles of the southern area and the remaining areas of EGAT system, respectively.

The phasor measurement system employs a man-

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manufactured PMU as a commercial product, which is a Network Computing Terminal Type-A, NCT2000 of Toshiba [8]. The PMU can measure a single-phase instantaneous voltage at 220 V outlets, with correcting its clock based on the time stamps 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 voltages every 40 ms (2 cycles) and measures at the domestic outlets for 20 minutes twice an hour, for example, 0.20-0.40 a.m. and 0.50-1.10 a.m. etc. The measured phasor voltages at PSU are transmitted via the Internet to a server at TU.

The measurement data of PMU is taken from 220 V outlet. Therefore, they may be influenced by the phase shift due to distribution transformers. This problem can be solved as follows. As shown in Fig. 2, the phasor voltages at TU and PSU are measured from common wall outlets of a 220 V distribution level. There are several transformers between an outlet and its upper high voltage bus. The transformers bring some phase shift with a multiple of 30 degrees. This phase shift is not a problem since we do not use phase angle itself but rather use phase difference $\Delta \delta$.

The effect of phase shifts due to distribution transformers has been taken into account in the phase difference $\Delta \delta$.

3. VALIDATION OF PMU DATA

Fig. 3 depicts waveforms of the phase differences between TU and PSU from 7.20 a.m. to 7.40 a.m. and 7.20 p.m. to 7.40 p.m. on Aug 30, 2005. In this part, the variation of the average phase difference between TU and PSU is considered. The average value of phase differences for 20 minutes twice an hour in each day is calculated. Thus, there are 48 average phase difference data per day. Fig. 4 shows the variation of the average phase difference between TU and PSU from
Aug 25 to 31, 2005. Generally, the phase difference between two interconnected areas reflects the active power flow in tie-line between both areas. The positive average phase difference implies that the active power flows to the southern area from the remaining parts of the EGAT network and vice versa. To verify the validity of the PMU data, the average phase difference is compared to the actual power flow data of 230 kV tie-lines between central and southern areas of EGAT during steady-state conditions from Aug 25 to 31, 2005, as demonstrated in Fig. 5. Since the power flow data of EGAT are measured at every half an hour, there are also 48 data per day same as the number of the average phase difference data of PMUs. Obviously, the phase difference changes in the same way as the power flow.

Next, the correlation between the power flow data of EGAT and the average phase difference data between TU and PSU measured by PMUs is evaluated by a least-squares regression. The linear equation with two variables is used as a regression model. The resulted least-squares linear equation of the power flow and the average phase difference from Aug 25 to 31, 2005 can be delineated in Fig. 6. To evaluate the fitness of data, the correlation coefficient between two variables is calculated by

\[
R^2 = \frac{n\left(\sum xy\right) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{n\sum x^2 - \left(\sum x\right)^2}\sqrt{n\sum y^2 - \left(\sum y\right)^2}}\]

where \(x\) is average phase difference data, \(y\) is power flow data, and \(n\) is the number of data. The correlation coefficient \(R^2\) indicates the fitness of data. If \(R^2\) is close to unity, then the power flow strongly correlates with the average phase difference. If not, the correlation is weak. As given in Fig. 6, the correlation coefficient of two variables is nearly equal to one. The phase difference data measured by PMUs strongly correlate with the power flow data of EGAT during steady-state condition.

4. DETECTION OF INTER-AREA OSCILLATION

It can be seen in Fig.3 that the phase differences are composed of many oscillatory components with different frequencies. To detect the dominant oscillation frequency, the FFT is applied. Fig.7 shows the FFT results of phase differences between TU and PSU corresponding to two periods in Fig.3. The FFT results signify that the dominant power oscillations at each elapsed time are observed at a frequency around 0.5 - 0.6 Hz, which is in the vicinity of the inter-area oscillation mode [9]. In addition, the oscillation frequency of the inter-area mode varies with the elapsed time. This is due to the variation of power consumptions in each elapsed time. Note that the Fast-Fourier Transform (FFT) can be used to analyze the frequency characteristic of the dominant oscillation mode in the frequency domain only. To show the oscillation of the dominant mode in the time domain, the wavelet transform can be applied to extract the signal containing the dominant mode from the phase difference signal.

Here, the Symlet wavelet function [10] with 12 levels is applied to decompose the phase difference signal into one approximate component and twelve detail components as depicted in Fig.8. It can be observed that the wavelet component with the oscillation frequency around 0.5 - 0.6 Hz is the detail component \(d_5\). Fig. 9 outlines the enlarged view of the \(d_5\) component. Clearly, the oscillation period is about 2.0 sec. To investigate the oscillation frequency of the \(d_5\) component, the FFT is employed. As depicted in Fig.10, the dominant power spectrum of the FFT result occurs at frequency around 0.5 - 0.6 Hz. This implies that the wavelet \(d_5\) component corresponds to the dominant inter-area oscillation.

5. IDENTIFICATION OF INTER-AREA OSCILLATION

To determine the eigenvalue corresponding to the inter-area oscillation mode from the phase difference
data, the least-squares regression with multiple variables is applied to identify the mathematical model of the study system. Here it is assumed that generators in each area are in the same coherent group. The phase angles at PSU and TU are used as the representative phase angles of the southern area and the remaining areas of EGAT system, respectively. As a result, the southern area and the remaining areas of EGAT can be modelled as an equivalent two-machine system. The swing equation can be represented by

\[ M(\ddot{\delta} + \ddot{\delta}_0) + D(\dot{\delta} - \dot{\delta}_0) + K(\delta - \delta_0) = 0 \]  

(2)

where \( M \) is an inertia constant, \( D \) is a damping coefficient, \( K \) is a synchronizing power coefficient, \( \delta \) and \( \delta_0 \) are phase angles at PSU and TU, respectively, \( \dot{\delta} \) and \( \dot{\delta}_0 \) are the first derivatives of phase angles at PSU and TU, respectively, \( \ddot{\delta} \) and \( \ddot{\delta}_0 \) are the second derivatives of phase angles at PSU and TU, respectively. Note that \( \delta - \delta_0 \) and \( \ddot{\delta} + \ddot{\delta}_0 \) can be directly calculated from the first and second derivative of \( \delta - \delta_0 \). Rewriting (2) as

\[ \ddot{\delta} + \ddot{\delta}_0 = \frac{D}{M}(\dot{\delta} - \dot{\delta}_0) - \frac{K}{M}(\delta - \delta_0) \]  

(3)

By applying the wavelet decomposition with 12 levels to the measured data \( \dot{\delta} + \dot{\delta}_0 \), \( \delta - \delta_0 \) and \( \ddot{\delta} - \ddot{\delta}_0 \), extracting the d5 component of each term and substituting in (3), the coefficients \( D/M \) and \( K/M \) can be estimated by a least-squares regression.

As an example, the phase difference from 7:20 p.m. to 7:40 p.m. on Aug 30, 2005 is employed to identify
an equivalent two-machine system. Accordingly, the estimated values of $D/M$ and $K/M$ are equal to 0.519 and 12.1313, respectively. To evaluate the regression results, the $d_5$ component of $\ddot{\delta} + \dot{\delta}_0$ is substituted in the left side of (3), while the estimated $D/M$, $K/M$, and the $d_5$ components of $\ddot{\delta} - \dot{\delta}_0$ and $\dot{\delta} - \delta_0$ are substituted in the right side of (3). Fig. 11 shows the comparison results of the measured values (the left side of (3)) and the estimated values (the right side of (3)). Clearly, the measured values are almost equal to the estimated values.

Because (3) is a second-order system, the characteristic equation can be represented by

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0$$

Fig.11: Comparison of measured and estimated values

Hence, the undamped natural frequency $\omega_n$ and the damping ratio ($\zeta$) are determined by

$$\omega_n = \sqrt{\frac{K}{M}}$$

$$\zeta = \frac{D}{2N\omega_n}$$

The undamped natural frequency and the damping ratio lead to the calculation of the eigenvalue. Suppose that the eigenvalues corresponding to the oscillation mode are $-\sigma \pm j\omega_d$, the real part ($\sigma$) and the imaginary part ($\omega_d$) of the eigenvalues can be determined by

$$\sigma = \zeta\omega_n$$

$$\omega_d = \omega_n\sqrt{1 - \zeta^2}$$

It should be noted that the proposed identification technique can use the steady-state phasor fluctuation to model the system dynamics. In other words, a large disturbance like a line fault is not necessary since the stability of the major mode can be investigated by using eigenvalues of the approximate model.

Consequently, the eigenvalues corresponding to the oscillation mode from 7.20 p.m. to 7.40 p.m. on Aug 30, 2005 are $-0.2594 \pm j3.4744$. The oscillation frequency is 3.4744 rad/sec or 0.553 Hz and the damping ratio is 0.0745.

Next, the characteristics of the oscillation mode are monitored by the variations of damping ratio and oscillation frequency. Fig. 12 illustrates the variation of damping ratio from August 25 to 31, 2005. The variation of the damping ratio on each day has almost the same pattern. In the daytime and evening, the damping ratio of the oscillation mode is lower than that in the night time. This is due to large power consumptions in the daytime and evening which deteriorate the system stability. For the oscillation frequency as shown in Fig.13, it also varies in the same way on each day. The oscillation frequency in the daytime and evening is lower than that in the night time. This is due to a lot of synchronous generators participated in the power system. As a result, this is equivalent to a larger system inertia which leads to a longer oscillation period and a lower oscillation frequency (see (5) and (8)). Based on these results, the stability monitoring of inter-area oscillation can be easily established by the PMUs data measured from power outlets.

6. CONCLUSIONS

In this paper, a wide-area monitoring system of the inter-area oscillation between central and southern areas of Thailand power network based on GPS-based
synchronized PMUs has been proposed. The convenient installation of PMUs at 220 V home power outlets is the main feature of the presented system. The validity of the measured phase difference by PMUs during steady-state conditions is verified by comparing to the actual tie-line power flow of EGAT. The eigenvalue representing the dominant inter-area mode (0.5-0.6 Hz) can be identified by the wavelet decomposition and the least-squares regression. The analyze results provide practical information of wide-area system stability for power system researchers, system operators and university students.

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