Visualization of Wide Area Dynamics in Power Network for Oscillatory Stability Assessment

Chun-Lien Su, *Member, IEEE*, and Bo-Yuan Jau

Abstract-- **Many countries around the world had suffered blackout incidents due to inter-area oscillations in recent decades. Analysis of system wide oscillatory stability requires a more effective engineering tool for modeling the wide area dynamics in power network. This paper proposes a data visualization based method for assessing the wide area power oscillatory stability. The phasor measurements are used and estimated to obtain more real-time system operating data by using a linear state estimator. The phasor data are then used as the input data for visualizing wide area dynamics. Several visualization modules for displaying the phased angle dynamics are discussed and implemented. Test results of application of the proposed method to an inter-area oscillation event are reported. Sensitivity of the performance of the proposed visualization modules to different system sizes is illustrated.**

Index Terms-- **Power system dynamics, Inter-area oscillation, PMUs, and Visualization.**

I. Introduction

TAIWAN power (Taipower) system is a longitudinal and isolated system with three major areas, namely, North, Central, and South, connected by a number of 345kV transmission lines. Load centers are located in the north and most generating plants are in the central and south areas. A large amount of powers are transferred from south and central areas to the north through several trunk lines during peak loads, which has caused the degradation of the system stability [1].

Since the 1980s, the Taipower system has suffered several blackout incidents due to inter-area low frequency oscillations [2]. The inter-area low frequency oscillation is a phenomenon that the phase angles, power flows, voltages, and frequency slowly and periodically oscillate following small or large disturbances due to the deficiency of the dynamic damping [3,4]. This oscillation phenomenon that significantly varies with system structure, operating conditions, and excitation systems is associated with groups of generators, or groups of plants in a range of 0.1 to 0.8 Hz [5]. Generally, its impact is extensive and it is more complex to study and control, which results in system-wide blackout incidents.

In order to avoid the blackout incident due to the inter-area oscillation to occur again, a phasor measurement units (PMUs) based wide area monitoring system (WAMS) was designed and built by Taipower company to collect the real-time data regarding the system dynamics. The digital signal processing algorithms based on-line analysis technique is used to extract the measurement data for assessing the power oscillatory stability [6]. The analysis result is represented by a numerical form, curve chart, or spreadsheet. For an inter-area low frequency oscillation that covers a wide area, the existing traditional representations may be not enough effective. In this situation, a data visualization technique that could adequately represent the changes in dynamic behavior of the whole grid and provide a quick and intuitive way to view the wide area dynamics in power network may be an effective way to assess the inter-area oscillatory stability [7,8].

This paper proposes a visualization approach for presenting small signal oscillatory behavior to system operators. The visualization is based on a set, possibly small, of PMUs to provide phasor information. The phasor measurements are estimated to obtain more real-time system operating data through a linear state estimator. The phasor data are then used as the input data for visualizing wide area dynamics in power network for assessing oscillatory stability. An inter-area oscillation event occurred in Taipower system is used for the study. The Taipower WAMS system structure and the visualization techniques used are described in this paper.

II. Taipower Wide Area Measurement System

A. System Structure

To well understand the system dynamic performance for devising proper control actions to maintain system dynamic stability, a PMUs based WAMS was designed and implemented by the Taipower company. Fig. 1 shows the WAMS system structure. This system was completed and it was in service in November 2001. It covers nine PMUs that all are installed in critical substations including 3rd Nuclear power

This work was supported by the National Science Council of Taiwan under Grant NSC 93-2213-E-022-004.

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station, South Lungchi extra high voltage substation (E/S), North Lungchi E/S, Chiamin E/S, South Chungliao E/S, North Chungliao E/S, Omei E/S, North Lungtan E/S, and 2rd Nuclear power station. The master stations installed in the Taipower central dispatch control center (CDCC) and electric power research institute located in the north area of Taiwan capture the real-time phasor data for remote control and further study. The system functions include monitoring and analysis of system dynamics measurements, disturbance events, and steady-state system operation data. Through Intranet and Internet, the users in different offices can view, access, and analyze the data. The parameter updates or modifications, data acquisition, and supervisory of the PMUs can be remotely performed at the master stations via data communications of fiber optical cable and digital communication channel.

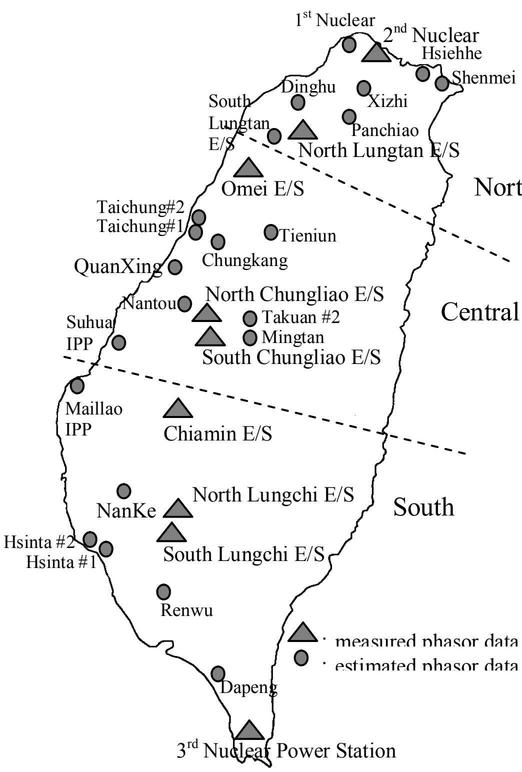


Fig. 1 Taipower WAMS system structure

In the normal condition, the PMUs record three phase voltages, currents and frequency at a rate of twenty samples per second and convert the voltage and current phase quantities to positive sequence phasor data. With global positioning systems (GPSs), the PMUs tag the phasors recorded at different locations with a high degree of accuracy (1μS). The phasor data is transferred to the master stations every second to update the database based on the time stamp. When an event or a disturbance that fits with the predefined condition is detected, the PMUs will be synchronously triggered to record the event data at a rate of 3840 samples per second.

B. Linear State Estimation

The measurements from Taipower WAMS can be used in the visualizations of wide area dynamics for assessing wide area power oscillatory stability. However, the number of measurements is possibly minimal due to high capital cost of PMUs and/or communication unavailability. This generally leads to a less number of phasor measurements, which may not reflect the actual system dynamics and represent the enough exact analysis result. To obtain more real-time system operating data for adequately understanding and analyzing the dynamics of the system, the phasor measurements located in a number of substations can be extended by using a linear state estimation.

Considering a system equipped with a number of PMUs that have m measurements of voltage phasor and current phasor, the linear state estimate model can be written as follows [9]:

$$\begin{bmatrix} \mathbf{Z}_V \\ \mathbf{Z}_I \end{bmatrix} = \begin{bmatrix} \mathbf{I} & 0 \\ \mathbf{Y}_M & \mathbf{Y}_C \end{bmatrix} \begin{bmatrix} \mathbf{V}_M \\ \mathbf{V}_C \end{bmatrix} + \begin{bmatrix} \mathbf{v}_V \\ \mathbf{v}_I \end{bmatrix} \tag{1}$$

where $\mathbf{Z}_v$ is the vector of voltage phasor measurements
$\mathbf{Z}_I$ is the vector of branch current phasor measurements
$\mathbf{I}$ is the identity matrix
$\mathbf{Y}_M$ is the matrix which entry is series admittance of the network branches
$\mathbf{Y}_C$ is the matrix which entry is shunt admittance of the network branches
$\mathbf{V}_M$ is the measured state vector
$\mathbf{V}_C$ is the calculated state vector
$\mathbf{v}_V$ is the measurement errors of voltage phasor
$\mathbf{v}_I$ is the measurement errors of branch current phasor

Equation (1) can be rewritten as follows:

$$\mathbf{Z} = \mathbf{BV} + \mathbf{v} \tag{2}$$

where $\mathbf{B} = \begin{bmatrix} \mathbf{I} & 0 \\ \mathbf{Y}_M & \mathbf{Y}_C \end{bmatrix}$, $\mathbf{V} = \begin{bmatrix} \mathbf{V}_M \\ \mathbf{V}_C \end{bmatrix}$, $\mathbf{v} = \begin{bmatrix} \mathbf{v}_V \\ \mathbf{v}_I \end{bmatrix}$

According to the weighted least squares principle, the estimate of the state vector $\mathbf{V}$ obtained from the measurement vector $\mathbf{Z}$ can be calculated by

$$\mathbf{V} = \mathbf{G}^{-1}\mathbf{B}^T\mathbf{R}^{-1}\mathbf{Z} \tag{3}$$

where $\mathbf{G} = \mathbf{B}^T\mathbf{R}^{-1}\mathbf{B}$ is the gain matrix, $\mathbf{R}$=*diag*(σ_i^2) is the covariance matrix, and σ_i is the standard deviation of measurement error v_i.

Since the computation of the estimation algorithm in (3) is straightforward and the gain matrix $\mathbf{G}$ is a constant matrix, the computation performance of the linear state estimator is efficient [9]. This is helpful for "on-line" power oscillatory stability assessment. Using the phasor measurements of bus voltage and branch current, the number of real-time system states can be extended by using (3). For the Taipower WAMS, there are 22 estimated phasor data obtained from the linear state estimation while 9 measured phasor data are considered. The geographic allocation of the estimated and measured phasor data is shown in Fig. 1.

III. Power System Dynamics Visualization

A. Data Visualization Technique

The inter-area oscillation that covers a wide area affects the operations of the utility's system as well as the neighboring power systems. From a system-wide dynamic security monitoring standpoint, the assessment of the wide area power oscillatory stability should consider the dynamic behavior of different buses in the whole grid. The data visualization technique that could provide the visual data rather than numeric data and integrate geographic information in a computer graph is an effective way to present the inter-area oscillation phenomenon for operators.

"Visualization" firstly appeared in the visualization in scientific computing (ViSC) report in July 1987. It is defined by the National Science Foundation (NSF) as an alternative way to find out the phenomena or messages that cannot be found by using traditional methods [10]. Some data visualization techniques are used by many scientists for data mining, so called visualized data mining. The visualized data mining method that utilizes the thinking, discriminative, and creative capability of human can be used to improve traditional computer algorithm computations. Generally, the data visualization technique can handle complex and numerous data and allow users to extract the useful information from the data.

The analysis procedure of the proposed visualization based inter-area power oscillatory stability assessment approach is shown in Fig. 2. The measured phasor data about the power system are obtained from the PMUs. The phasor data are estimated by using the linear state estimation and converted into the graphic data by using the data transformation techniques such as data simplification methods and dimension reduction methods. The graphic data are then converted into the images with the computer drawing and/or image processing techniques. With the processed images, the operators can observe them by interactive techniques to extract the useful or meaning information or phenomenon for assessing oscillatory stability.

B. Visualization Modules of Power System Dynamics

Since the whole analysis procedure of the inter-area power oscillation is based on the computer graphs, an effective visualization model is essential. It should be able to thoroughly present the process of changes in the real system dynamics.

Phase angle that is the voltage angle of a bus relative to the reference bus is an important parameter in the dynamic operation of power systems. The magnitude of the phase angle reflects the margin of the power system steady state stability. The period of changes in the phase angle represents the status of the power system dynamic stability and is usually used to indicate the status of oscillatory instability. Since the frequency of the inter-area oscillation is very low (0.1~0.8 Hz) and the duration is relatively long, the dynamic visualization of phase angles reflects the inter-area power oscillatory stability situation.

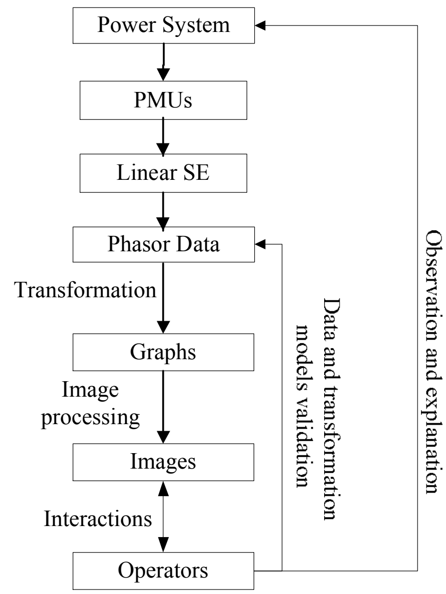
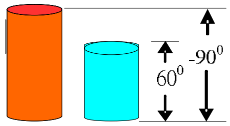


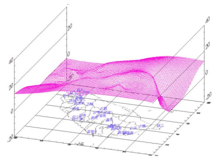
Fig. 2 Analysis procedure of the proposed approach

Visualization modules of the phase angle can be classified as two-dimensional (2D) or three-dimensional (3D) modules. Two-dimensional visualization displays the changes in the data on a plane. Three-dimension visualization represents the changes in data dynamics on x-y-z axes. Generally, the 3D visualization model is more effective than two-dimension model but it requires more computation efforts. In this paper, the three-dimensional visualization model is designed. They are:

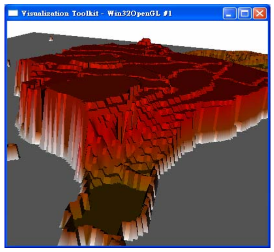
- 3D cylinder: The altitude of the 3D cylinder indicates the magnitude of the phase angle. The color represents the positive or negative value of the phase angle. For instance, as can be seen from Fig. 3(a) that the color of the cylinder is blue if the phase angle is positive and it is red for a negative phase angle.
- 3D surface: The power grid is first divided into hundreds or thousands of small grids. The phase angles on the grids are interpolated to a large region by using space stochastic approaches [11] to form a continuous plane. This plane is then converted to a 3D surface and the changes in phase angles can be observed from the z axis. Fig. 3(b) shows the 3D surface visualization module of the phase angle.
- 3D contour: This module shown in Fig. 3(c) is similar to the 3D surface except that the terrain altitude is used to indicate the phase angle changes to represent the system dynamics.



(a) 3D cylinder



(b) 3D surface



(c) 3D contour

Fig. 3 Visualization modules of power system dynamics

The visualization modules described above are integrated with the network topology and geographic information in a graphic user interface (GUI). For a large-scale power system, inclusion of detailed network topology in the GUI is ineffective and impossible. Therefore, main transmission trunks and critical buses of the Taipower system are selected and used for the GUI designed.

IV. Test Results and Discussions

The proposed visualization based inter-area oscillatory stability assessment approach is developed on a PC with Pentium IV 3.2GHz CPU and 1024 Mbytes memory. A data visualization development package [12] that supports multi-dimensional plots, interactive displays, sophisticated and accurate forecasting tools, and animations is used. An inter-area oscillation event occurred in the Taipower system due to the trip of Panchiao-Lungtan 345 kV transmission line located in the north area is used for the study. This oscillation event started at 11:59:43 am and stopped at 12:03:00 pm. The duration of the event is about four minutes. The recorded measurements had shown that it is an oscillation event between the north area and central and south areas with main damping frequency of 0.45 Hz. The phasor data of the Taipower WAMS shown in Fig. 1 are estimated by (3) and used as the input data for the visualization modules shown in Fig. 3.

Using the phase angle of the 2nd Nuclear power station as a reference, the changes in the phase angles of some selected buses are shown in Fig. 4. It can be seen from Fig. 4 that this oscillation event contains three main oscillation stages including increased oscillation, sustained oscillation, and decreased oscillation. The phase angle visualization modules shown in Fig. 3 are tested using the signals of different oscillation stages. Due to the limited space, only the meaning test results are selected and reported.

Fig. 5 shows the test result of the 3D surface module for the increased oscillation stage. For this oscillatory signal, the damping constant is 0.08 and main oscillation frequency is 0.45 Hz. Fig. 5(a) shows the phase angles at 11:59:42.95 am before the event and the phase angles after the event are shown in Fig. 5(b) and 5(c). From Fig. 5(a), it can be seen that the phase angles in the north area are smaller than that of the central and south areas. This is because larger powers are transferred from the central and south areas to the north area of the Taipower system during this time period. Comparing Fig. 5(a) to Fig. 5(b) and Fig. 5(C), it can be seen that the phase angles change when the oscillation event occurs. The change in oscillation of the phase angles for the north area is opposite to that of the central and south areas. It also can be found that the magnitude of the oscillation is continuously becoming large and the changes in the phase angles in the north area seem to be larger than that of other areas. Through observation of the dynamic displays, the operators can quickly and intuitively detect the occurrence of inter-area oscillation event at the initial stage and may find out the location of the oscillation event.

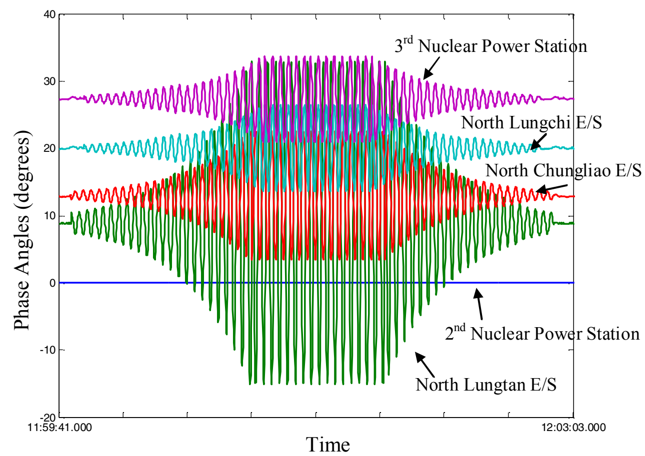
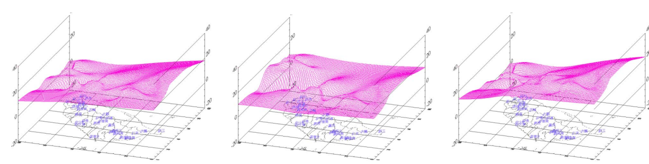


Fig. 4 Signals of phase angles during an inter-area oscillation event

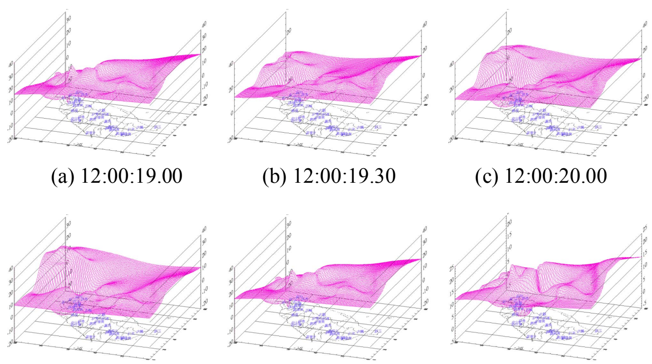


(a) 11:59:42.95 (b) 11:59:54.80 (c) 11:59:56.00

Fig. 5 3D surface visualization of phase angles for the initial stage of an inter-area oscillation event

The proposed method are also tested by using the sustained oscillation signals to ensure the performance of the visualization modules during a sustained oscillation. The results are reported in Fig. 6, Fig. 7, and Fig. 8, which depict the 3D surface, 3D cylinder, and 3D contour visualizations of the phase angles, respectively. It can be seen from Fig. 6 that the phase angles change significantly when there is a large disturbance. The phase angles in the north, central, and south areas continuously change in the following time snapshots and this change for the north area and central and south areas is opposite. From Fig. 6(a) to 6(e), it also can observe that the period of this change is about 2.2 seconds and its frequency is 0.455 Hz that is very close to the actual oscillation frequency

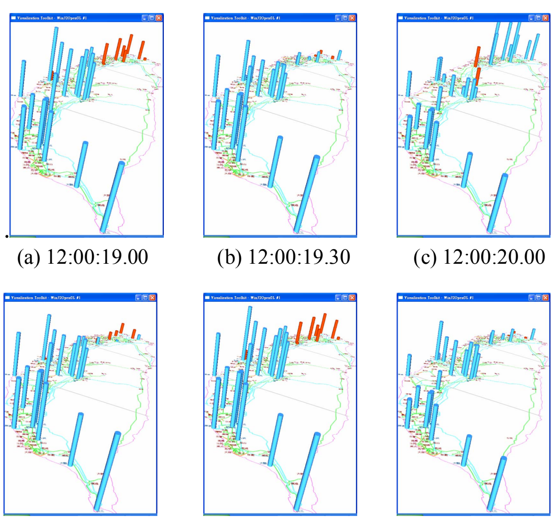
(0.45 Hz). Generally, the accuracy of the analysis result of application of visualization techniques to the inter-area oscillatory stability assessment heavily relies on the resolution of the data used in the visualization modules. For better results, the resolution of the measurements used in the visual displays should be adequately high but it requires a larger computation effort. Comparisons of Fig. 6, 7, and 8 can be seen that the 3D surface could have a good display result even for a large-scale system and a small disturbance. The 3D cylinder module could clearly present the wide area power oscillation phenomenon if the system is small and it may be ineffective for the large-scale system. The 3D contour visualization module seems to be ineffective just based on the test data. From these test results, it has shown that the 3D surface and 3D cylinder visualizations could provide the operators a more efficient way to view the oscillation phenomenon of the whole grid and possibly assess its stability.



(a) 12:00:19.00 (b) 12:00:19.30 (c) 12:00:20.00

(d) 12:00:20.30 (e) 12:00:21.20 (f) 12:00:21.90

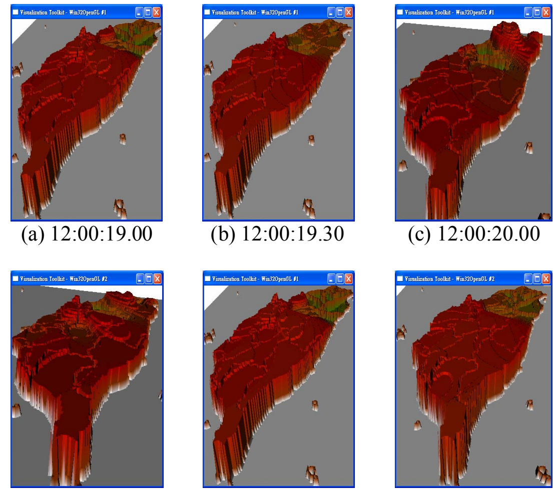
Fig. 6 3D surface visualization of phase angles during a sustained oscillation



(a) 12:00:19.00 (b) 12:00:19.30 (c) 12:00:20.00

(d) 12:00:20.30 (e) 12:00:21.20 (f) 12:00:21.90

Fig. 7 3D cylinder visualization of phase angles during a sustained oscillation



(a) 12:00:19.00 (b) 12:00:19.30 (c) 12:00:20.00

(d) 12:00:20.30 (e) 12:00:21.20 (f) 12:00:21.90

Fig. 8 3D contour visualization of phase angles during a sustained oscillation

To determine the effects of system sizes on the performance of the proposed visualization approach, a sensitivity analysis is also performed. In the test, different numbers of phasor measurements including 10, 30, 50, 100, and 200 are used to represent different system sizes. The test result is shown in Table I. It can be seen from Table I that the execution times of these visualization modules increase with an increase in system size. When 200 phasor measurements are considered, the execution times of 3D cylinder, 3D surface, and 3D contour modules are 1.28 seconds, 0.072 seconds, and 3.602 seconds, respectively. The 3D surface module could have a lowest execution time while the 3D contour module has a largest execution time. This is because the 3D surface module uses 2D graphic command and the 3D graphic command is used in the 3D contour module. It can also be found that the execution time of 3D cylinder module significantly increases with an increase in system size. The system size slightly affects the execution times of the 3D surface and 3D contour modules. This is since the 3D surface and 3D contour modules use a continuous plane to visualize data, the increase in number of the data due to an increase in system size has been considered in these two modules and it doesn't require additional computational efforts.

TABLE I
EFFECTS OF SYSTEM SIZES ON PERFORMANCE OF THE PROPOSED VISUALIZATION MODULES

Execution Times (seconds/each data sample) / Number of Phasor Data	Visualization Modules		
	3D Cylinder	3D Surface	3D Contour
10	0.208	0.050	3.304
30	0.284	0.060	3.320
50	0.376	0.066	3.350
100	0.700	0.070	3.384
200	1.280	0.072	3.602

V. CONCLUSIONS

A visualization based wide area power oscillatory stability assessment approach has been proposed. Different visualization modules of phase angle for displaying power system dynamics have been implemented. Performance of the proposed approach using phasor measurements from an actual inter-area oscillation event has been presented. Test results have shown that the proposed approach could thoroughly present the dynamic behavior of the wide area power oscillation and allow the operators to quickly and intuitively assess the inter-area power oscillatory stability.

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VII. BIOGRAPHIES

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