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# PJM Case Studies of System Events Using Synchrophasor Data

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## SUMMARY

More than 370 phasor measurement units (PMUs) have been installed in the PJM Interconnection grid in recent years. Phasor data is being used to monitor real-time power system status and to identify grid disturbances for post-event analysis using the phasor data. This paper describes the event detection process that incorporates the use of SCADA and PMU data and discusses the metric reports that are automatically generated. These reports are displayed in an operations dashboard and used by the daily review team to evaluate performance metrics for the previous day. Several case studies of post-event analysis using phasor data with a resolution of 30 samples per second are discussed in this paper.

## KEYWORDS

PMU – Phasor - Event Detection – Post Event Analysis - Oscillation

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## 1. Introduction

PJM Interconnection is a regional transmission organization (RTO) that monitors and coordinates the movement of wholesale electricity in all or part of 13 states and the District of Columbia. Acting as neutral, independent party, PJM operates a competitive wholesale electricity market and manages the bulk electric system to ensure reliability for more than 61 million people. PJM has 183,604 MW of installed electric generating capacity available and 11,175 MW of demand response and energy efficiency, with an all-time peak demand of 165,492 MW. The PJM bulk transmission system is built around a backbone of 765kV/345kV in the western and 500kV/230kV in the eastern part of the grid, with a total 62,556 miles of transmission lines. As a NERC-registered Reliability Coordinator, Balancing Authority and Transmission Operator, PJM ensures the safety, reliability and security of the bulk electric power system.

The August 14, 2003, blackout in parts of the northeastern and midwestern United States and Canada led to 50 million people losing power, accompanied by significant social and economic impacts. One of the leading contributors to the blackout was the absence of real-time information for wide area monitoring of the system [1]. In response, the North American Synchro-Phasor Initiative was organized by the North American Electric Reliability Corporation (NERC) to expand the use of synchrophasor data and advance synchrophasor applications and practices that improve grid engineering analysis [2]. A large number of PMUs and Phasor Data Concentrators, which collect the information, have been installed in the interconnection. In the last few years, much research has been developed to utilize PMU data for real-time monitoring, wide area visualization and post-event analyses [3-6].

PJM continues to work with its members and industry organizations to support research and the deployment of PMUs. Currently, there are more than 370 PMUs installed in more than 100 substations across the PJM footprint, as shown in Fig.1. PJM has recently implemented the exchange of real-time PMU data with two neighboring RTOs, the Midcontinent Independent System Operator and the New York ISO. In a collaborative effort with the Electric Power Group, PJM has implemented a real-time situational awareness tool and an off-line application to support wide area monitoring, power system planning and the analysis of grid disturbances.

This paper focuses on the event detection tools and post-event analysis that have been developed and are being performed at PJM. This paper is organized as follows. Section 2 describes the grid disturbance event triggers that initiate post-event analysis using phasor data and related tools to perform that analysis. Section 3 discusses several grid disturbances that occurred in the PJM balancing area in the first half of 2014 and the post-event analyses for those events. Section 4 summarizes PJM's experience to date in off-line analysis and discusses future objectives and initiatives.

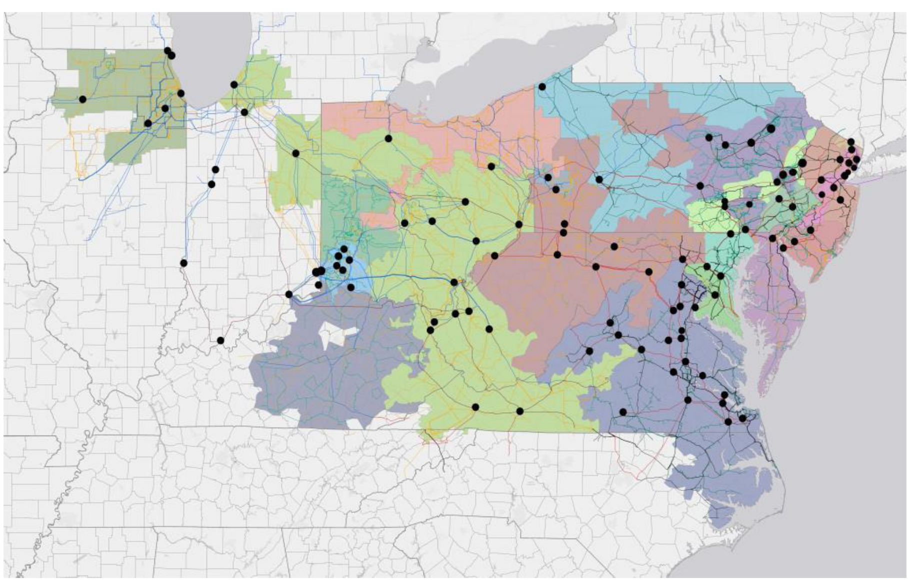

Fig. 1. PMUs in PJM Grid Map

## 2. Event Detection and Reporting

A daily review team works with power system operators to identify grid disturbances and performance metrics from the previous day. Events are studied by using traditional SCADA data in addition to high-resolution PMU data. Three criteria are currently used to detect grid disturbances that trigger post-event analysis using PMU data. The triggers detect large frequency deviations, large unit trips and extra high voltage (EHV) transmission line trips on the transfer interfaces. The triggers for frequency deviations and unit trips align with criteria for NERC reliability standards BAL-002-1, Disturbance Control Performance and BAL-003-1, Frequency Response and Frequency Bias Setting.

The trigger for frequency events is a frequency deviation greater than or equal to 40 mHz in any 16-second window. This is consistent with the criteria used by the NERC Frequency Working Group when selecting candidate frequency events for BAL-003-1 compliance [7]. Each of the 370 PMUs in PJM measures its own local frequency. Five frequency sources across the PJM footprint, four at the boundaries with adjacent Balancing Authorities and one near the electrical center of the Mid-Atlantic Region, are monitored and used as the default frequency signals for post-event analysis. The trigger for large generator trips is a loss of 900 MW or more, which is consistent with the criteria currently proposed by the NERC for the BAL-002-2 reliability standard [7]. The EHV transmission trigger monitors PMUs at substations that are components of the PJM transfer interfaces that define Interconnection Reliability Operating Limits. With several thousand generation resources and hundreds of transmission lines in the PJM grid, the percentage of locations with PMUs is small by comparison. It proved most effective to use a combination of SCADA and PMU data to define the event triggers that then initiate stability analysis using phasor data.

A SAS program runs automatically each morning on the SAS server and retrieves the data from the Energy Management System and PMU databases to identify grid disturbance events from the previous day. If any of the trigger events is detected, the program will push the event information to a SQL server where the event calculations are saved and the online dashboard is displayed. Operators can review the results on their own laptop through a web link connected to the server. Engineers can use a variety of tools, such as PI Historian, Phasor Grid Dynamic Analyzer and/or Real Time Dynamics Monitoring System, to drill down for a more detailed analysis and then attach their findings through the web link. An example report is shown in Fig. 2, which includes the summary report and detail information.

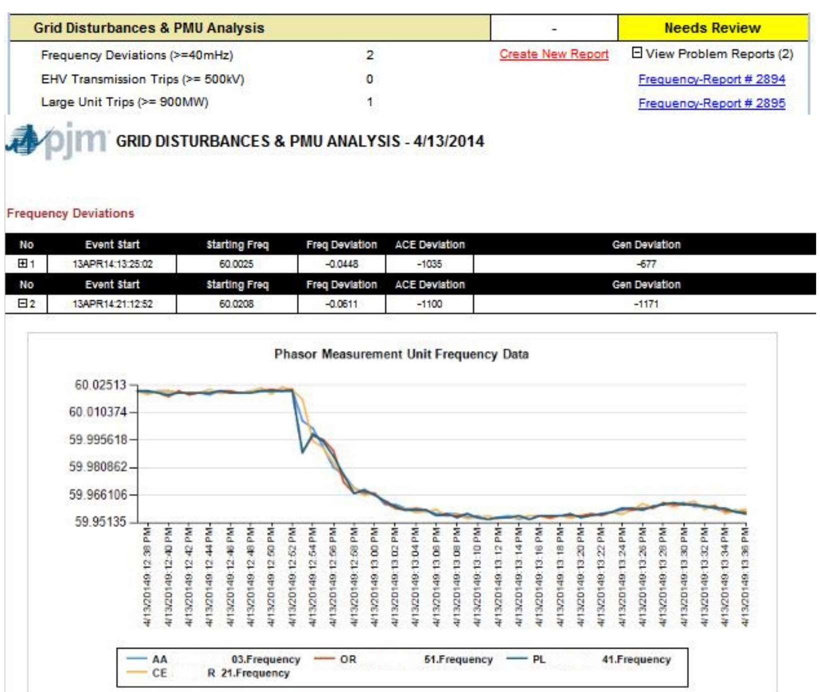


Fig. 2. Dashboard Reports

## 3. Post-Event Analysis

This section presents the results of phasor analysis for several disturbance events recorded in the PJM region since January 2014. The PMU data can be applied to the study of disturbance propagation in addition to voltage and current oscillations.

The disturbances can be seen by observing the frequencies at selected PMU locations. There were about 50 frequency deviation events from January through May, with some of them listed in Table 1. By using PMU and SCADA data, the event start time, frequency deviation and estimated losses can be detected and calculated by the SAS program code. The impact of the disturbance will propagate through the transmission grid and can be observed by comparing the phasor frequency at different locations [8-9]. The proximity of the event location could then be approximated [10]. The frequency signals from the various PMUs decline rapidly after the generation trip due to the load and generation imbalance. The various distances between each PMU and the units that tripped in Events 3 and 4 (Table 1) are shown in Fig. 3 and 4. The first response is from the closest PMU, followed by PMUs located further away from the trip. When comparing the PMU frequency signal with traditional EMS sources, the high resolution of the PMU signal is apparent. The PMU measurements show sub-second transients not detected by traditional EMS data. The PMU data in Fig. 3 shows two pairs of oscillations indicating that two units tripped about 10 seconds apart, which was not visible using traditional two second EMS frequency data.

Table 1. Selected Frequency Deviation Events

| No | Event Start time | Starting Freq (Hz) | Freq Deviation (mHz) | Reason | Estimate Loss (MW) |
|---|---|---|---|---|---|
| 1 | 1/18/2014 9:30:38 | 60.001 | 38 | External BA | |
| 2 | 1/21/2014 13:50:24 | 60.013 | 57 | Gen Trip | 1262 |
| **3** | **1/21/2014 21:25:28** | **59.978** | **40** | **Gen Trip** | **1719** |
| **4** | **1/26/2014 12:09:24** | **59.999** | **51** | **Gen Trip** | **1071** |
| 5 | 2/27/2014 10:14:22 | 59.966 | 37 | External BA | |
| 6 | 3/13/2014 16:34:10 | 60.021 | 55 | Gen Trip | 889 |
| 7 | 4/8/2014 4:28:22 | 60.004 | 63 | External BA | |
| 8 | 4/13/2014 13:25:02 | 60.003 | 45 | Gen Trip | 677 |
| **9** | **4/13/2014 21:12:52** | **60.021** | **61** | **Gen Trip** | **1171** |
| 10 | 4/25/2014 13:30:48 | 60.001 | 62 | Gen Trip | 1624 |

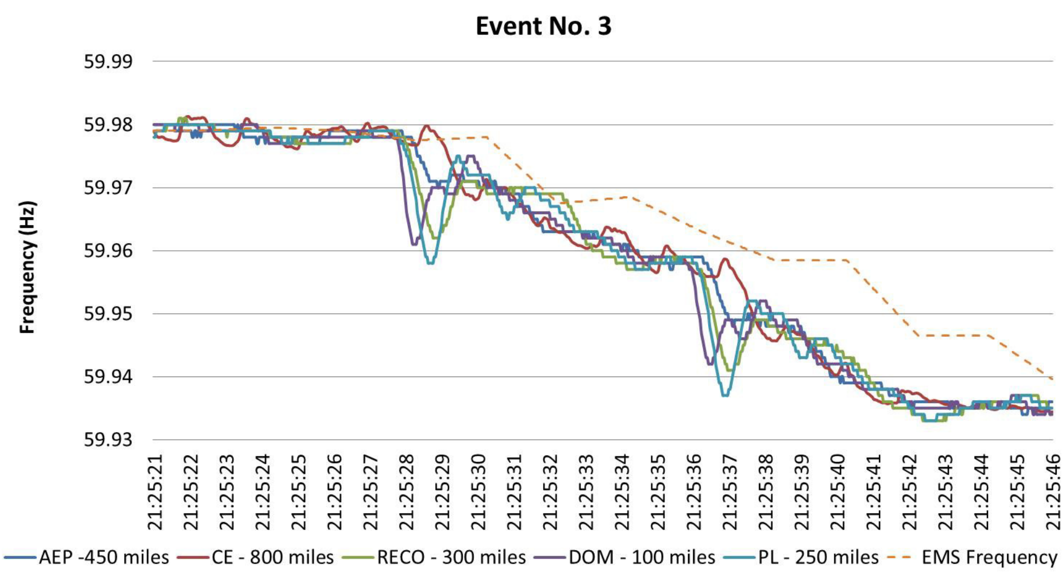


Fig. 3. Frequency Deviation Caused by Double Gen Trip

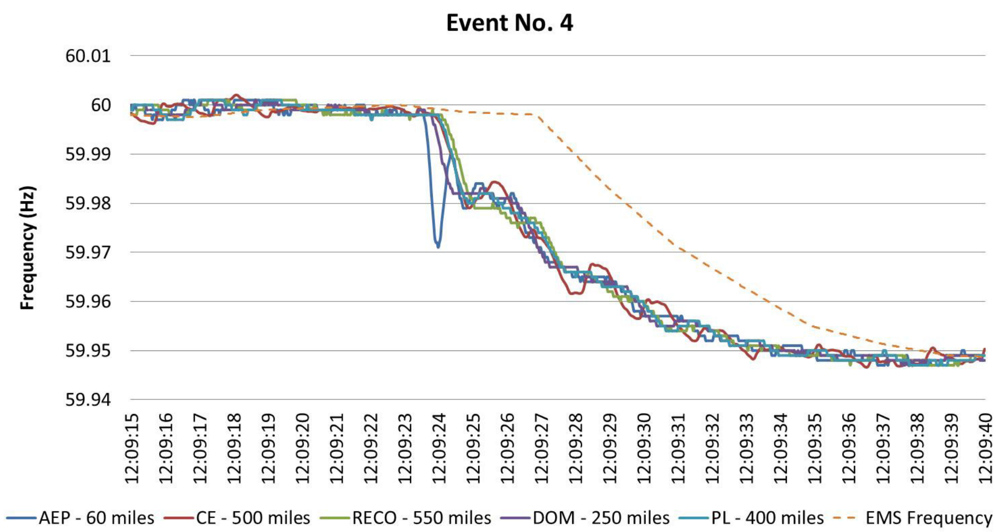


Fig. 4. Frequency Deviation Caused by Gen Trip

RTOs/ISOs typically have very detailed models of their own grid in their SCADA/EMS systems. However, they may have limited real-time modelling of their neighbouring systems, particularly when large external generators trip. PMU data can help to improve situational awareness at such times. A large generation trip is usually captured by the rate-of-frequency changes [11]. PJM may detect the estimated location of an external generation trip through PMU data.

The propagation of a disturbance caused by a generation trip can also be seen in the oscillations of voltage and current measured by different PMUs. The apparent power flow cannot be directly measured by PMU devices, but can be calculated based on the magnitude of voltage and current phasor measurements. Fig. 5 shows how the flows in the transmission system are redistributed after the loss of generation. The calculated apparent power flow values were confirmed by comparing them to SCADA data as the dash lines shown. SCADA scan rates for the transmission lines are up to 10 seconds; however, the PMU data provides much higher resolution at 30 samples of data per second. The oscillation after the loss of generation is observed in the PMU data, but not in the SCADA data. In order to compare them, the X-axis (time) of SCADA data was shifted by nearly 18 seconds. The shift in flows using SCADA data was observed at 21:13:10, but the phasor data reflected the change at 21:12:52.

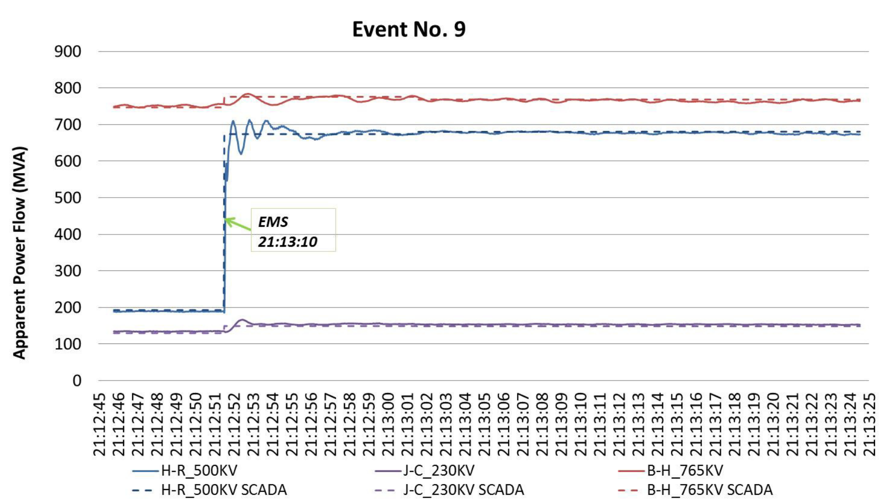


Fig. 5. Apparent Power Flow Changes Caused by Gen Trip

In another case, a local oscillation was observed at several nearby generators twice within a 30-day period. Using the PGDA analysis tool, which applied the Prony method, an oscillation mode of 1.4 Hz was identified. Table 2 lists the parameters of those oscillations, one of which was due to opening a nearby breaker to reduce the actual flows on the transformer. Once the flows were reduced and the breaker was closed a few hours later, the generators' oscillation disappeared, as shown in Fig. 6. This situation was mitigated by changing the automatic voltage regulator settings of one of units.

Table 2. Oscillation Parameters

| **Event Time** | **Mode Frequency** (Hz) | **Shape - Imaginary** | **Shape - Real** | **Damping** |
|---|---|---|---|---|
| 5/17/2014 2:00 | 1.412 | 0.5805 | -0.4253 | -0.0409 |
| 6/16/2014 9:46 | 1.427 | -0.4592 | 0.0191 | -0.0029 |

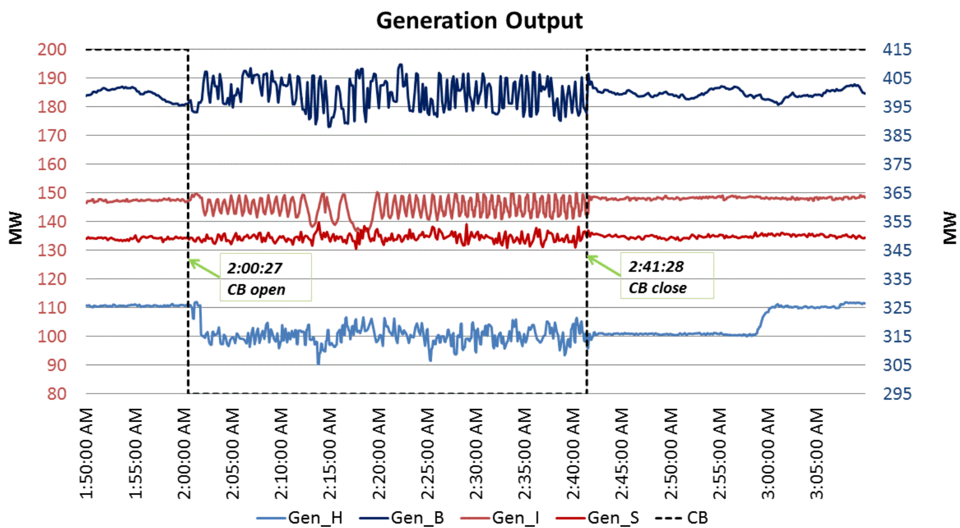


Fig. 6. Generators' Oscillation

In the example shown in Fig. 7 below, PMU data detected the oscillations about 10 minutes before large generator output swings. This was not detected in SCADA data. Once detected, the findings were provided to the generating plant to assist in modifying the control settings.

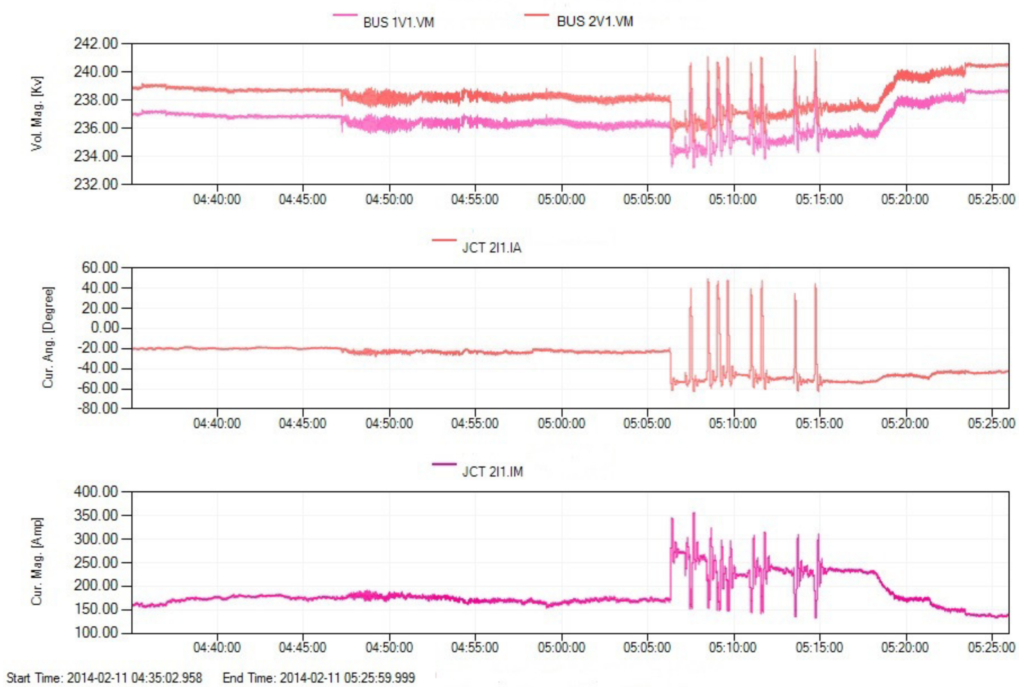


Fig. 7. Generator Oscillation

## 4. Conclusion

In this paper, we have described the process that was developed at PJM for detecting grid disturbances that trigger post-event analysis using phasor data, as well as the preliminary findings for several events that occurred in 2014. We have demonstrated the benefits of high resolution PMU data in detecting transient conditions that are not evident using traditional SCADA data. We have also demonstrated the propagation effects of large disturbances through the transmission grid.

PJM will continue to develop tools and processes that utilize the benefits of high speed PMU data to enhance situational awareness and post-event analysis. Future projects could include model validation using PMU data and further development of local and inter-area oscillation detection.

## BIBLIOGRAPHY


[1] NERC. "A Review of System Operations Leading up to the Blackout of August 14, 2003" (Available: http://www.nerc.com/docs/docs/blackout/Operations_Report_FINAL.pdf)

[2] NASPI. "NASPI Reorganization Plan October 2013"

[3] J. H. Chow, L. Vanfretti, et al "Preliminary Synchronized Phasor Data Analysis of Disturbance Events in the US Eastern Interconnection" (IEEE PES Power Systerms Conference and Exposition, March 2009)

[4] R. Moxley and D. Dolezilek "Case Studies: Synchrophasors for Wide-Area Monitoring, Protection, and Control" (Innovative Smart Grid Technologies ISGT Europe, 2011 2nd IEEE PES International Conference and Exhibition on, December 2011)

[5] J. Chen, P. Shrestha, et al "Use of Synchronized Phasor Measurements for Dynamic Stability Monitoring and Model Validation in ERCOT" (Power and Energy Society General Meeting, 2012 IEEE, July 2012)

[6] G. Zhang, S. Lee, et al "Wide Area Power System Visualization Using Real-Time SynchroPhasor Measurements" (Power and Energy Society General Meeting, 2010 IEEE, July 2010)

[7] NERC. "BAL-002-1, BAL-003-1 and Procedure for ERO Support of Frequency Response and Frequency Bias Setting Standard"

[8] R. L. Cresap and J. f. Hauer "Emergence of a New Swing Mode in the Western Power System" (IEEE Transactions on Power Apparatus and Systems, vol. PAS-100, No. 4, April 1981, pages 2037-2045)

[9] M. Parashar, J. S. Thorp, and C. E. Seyler "Continuum Modeling of Electromechanical Dynamics in Large-scale Power Systems" (IEEE Transactions on Circuits and Systems I: Regular Papers, vol. 51, No. 9, September 2004, pages 1848-1858)

[10] J. Zuo, M. Baldwin, H. Zhang, J. Dong, K. Kook, K. Soo and Y. Liu "Use of Frequency Oscillations to Improve Event Location Estimations in Power Systems" (IEEE Power Engineering Society General Meeting, June 2007)

[11] J. Ingleson and M. Nagle "Decline of Eastern Interconnection Frequency Response" (1999 Fault and Disturbance Conference at Georgia Tech, May 1999)