2011 American Control Conference
on O'Farrell Street, San Francisco, CA, USA
June 29 - July 01, 2011

Overview of Wide-Area Stability Monitoring Algorithms in Power Systems using Synchrophasors

Vaithianathan “Mani” Venkatasubramanian, Xing Liu, Guoping Liu, Qiang Zhang, and Michael Sherwood

Abstract— The paper provides an overview of our recent developments in wide-area real-time stability monitoring tools for large-scale power systems. These tools are based on synchronized wide-area phasor measurements from synchrophasors. The technology is aimed at fast automatic detection of instability phenomena related to any of angle, voltage or small-signal stability phenomena in power systems. The paper will provide an overview of some of the algorithms used, and a summary of industry implementations that are currently underway.

***Index Terms*—Power system stability, Power system control, Power system dynamics, voltage stability, small-signal stability, transient stability, oscillations, synchrophasors.**

I. Introduction

Power system operation is normally required to meet the following four operational reliability properties: 1) Acceptability or viability (all bus voltages and line currents stay within specified acceptable tolerances); 2) Small-signal stability (system dynamics is able to damp out all small-scale disturbances); 3) Transient stability (system dynamics can recover from all credible contingencies); 4) Voltage stability (system dynamics continues to operate at nominal viable bus voltages without degenerating into voltage collapses or voltage declines). This paper will highlight recent efforts at Washington State University (WSU) on wide-area real-time monitoring of large-scale power systems using synchrophasors. Our research is aimed at developing real-time operational tools related to the three properties 2), 3) and 4) above, namely, small-signal stability, transient stability and voltage stability. Our formulation is aimed at developing algorithms for detecting instability mechanisms purely based on synchrophasor measurements without any real-time knowledge of underlying power system model.

Power system operation is undergoing major technological advances with many new installations of synchrophasors all across the North American grid as well in power systems all over the world. Recent initiatives by the Federal government in the general area of smart grid technology are contributing to major installations of synchrophasor monitoring systems in many utilities in North American power grid. The industry-university collaborative organization, North American SynchroPhasor Initiative (NASPI), is serving as a major coordinating group in leading the recent efforts in this direction.

Synchrophasor measuremets together with modern communication technology facilitate the monitoring of the current state of the wide-area power system in near real-time. Our research work as well as efforts by many other research teams all over the world aim to exploit the availability of such wide-area synchronized measurements from the power grid into developing new real-time tools for power system operation.

This paper is organized as follows. Section II provides overview of a voltage stability monitoring framework. Section III introduces an Oscillation Monitoring System (OMS) that is targeted for monitoring small-signal stability problems in the power grid. Section IV summarizes new algorithms for transient instability detection and mitigation using major control actions such as generation tripping and load shedding.

II. Static Voltage Stability Analysis

The objective of the tool is to estimate the proximity of the system operating conition to static voltage instability limit in the sense of the classical QV margin at any bus by using a few PMU measurements.

The authors gratefully aknowledge funding from Power System Engineering Research Center (PSERC), Tennessee Valley Authority (TVA), Entergy, Bonneville Power Administration (BPA), US Department of Energy, and Consortium for Electric Reliability Technology Solutions (CERTS).

Vaithianathan “Mani” Venkatasubramanian and Qiang Zhang are with School of Electrical Engineering and Computer Science, WSU, Pullman, WA 99164, USA. (email: mani@wsu.edu). Xing Liu is presently at Siemens Inc., Minneapolis, MN. Guoping Liu is at PJM Interconnection, Philadelphia, PA. Michael Sherwood is with Pacific Gas and Electric, San Francisco, CA. The work reported in this paper was done while the authors were students at WSU.

II.1 VSA Index and Its Motivation

A global voltage security assessment index Γ_i for bus i is defined as the slope of the QV curve:

$$\Gamma_i = \frac{\Delta Q_i}{\Delta V_i} = \sum_j \frac{\Delta Q_{ij}}{\Delta V_i} \qquad (1)$$

where ΔQ_{ij} represents reactive power change for each transmission line or transformer (equivalent line mode) connected with this bus. ΔQ_i is an incremental change in bus injection at bus i.

The well-known fact is that power flow Jacobian becomes singular when the system is at a static saddle-node bifurcation. Hence, the slope at the critical point of Q-V curve will be infinite. Or, the VSA index Γ_i will approach zero in the sense of parameter variation of Q_i at bus i when the variation iduces a saddle-node bifucarion at the nose of the QV curve.

As for the complementary limit induced bifurcation case introduced in [2], the slope $\Gamma_i = \Delta Q_i / \Delta V_i$ will likely stop at some small value instead of approaching zero when the parameter variation induces the limit induced bifurcation.

Figure 2 and Figure 3 show these two bifurcation cases in Q-V curves and the index vs. Q. Figure 1 is for bus 12 of New England 39-bus system. This is a saddle node bifurcation case. At the critical node of Q-V curve, the tangent of critical node of Q-V curve is almost vertical. Correspondingly, Γ_{12} is 1.18 which is very close to "0". Figure 3 is a complementary limit induced bifurcation case from IEEE 300-bus system. For bus 14, the power flow fails when its reactive load is approximately 470 MVAr. From Q-V curve, the slope around the critical node is apparently not infinite. This result is reflected very well on the "small" value of Γ_{14} which is seen to be 7.01 at the limit.

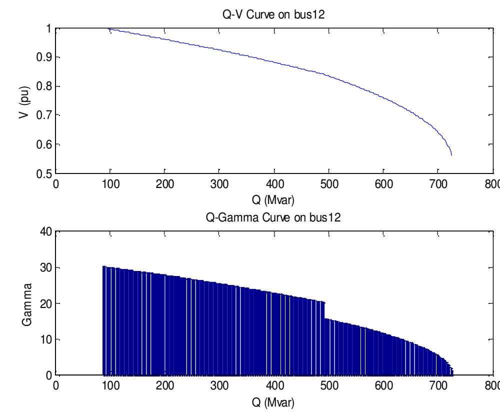

Fig.1 Saddle node bifurcation case

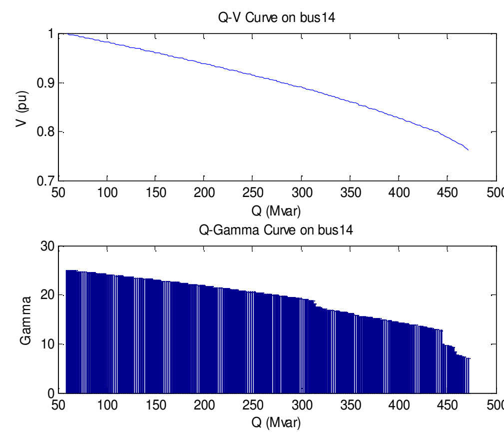

Fig.2. Complementary limit induced bifurcation

Naturally and consequently, we conjecture the following rules only using this global index Γ_i to assess the system voltage security at any bus *i*.

The index Γ_i can assess bus voltage security by the following statements:

i) A "high" value of Γ_i indicates a "strong" bus in terms of being distant from static voltage instability limit.

ii) If there is any bus with Γ_i value near "0", the system is close to static voltage stability limit related to saddle-node bifucrcation, and the bus with the lowest Γ_i is likely in the crticially voltage stressed part of the system.

iii) If one system has the bus whose Γ_i is less than some critical value, and then the system may be vulnerable towards voltage instability caused by either of saddle-node or limit induced bifurcations. We need to pay attention to this system voltage security.

In other words, *no matter which static bifurcation the* *system will encounter, the system is operating in voltage unsecure region and needs to be controlled, if some bus has low* Γ_i. In the next section, we propose techniques for computing Γ_i from real-time PMU measurements.

II.2 VSA Index from PMU data

In this section, we plan to estimate the QV slope Γ_i from real-time PMU data by individually estimating QV line sensitivity on each of the lines connected to bus *i* and by taking the sum:

$$\Gamma_i = \frac{\Delta Q_i}{\Delta V_i} = \sum_j \frac{\Delta Q_{ij}}{\Delta V_i}$$

Philosophically, we are processing line sensitivities to detect proximity to static stability limits as in [3]. However, our approach is clearly different because we are directly extracting the QV slope Γ_i from the line sensitivities by the sum (1). The subequent relationship of Γ_i to system static stability limit is well-defined as discussed in II.1. Moreover, the novel contribution of this paper is the direct estimation of the line sensitivities $\Delta Q_{ij}/\Delta V_i$ from PMU data by exploiting fundamental nature of power system causality.

There have been many other recent papers (e.g. [4]) on voltage stability monitoring using PMU data which all use a combination of system model data (such as line parameters and state estimation solution) together with PMU data. Whereas our approach proposed in this paper is purely based on PMU measurement data and does not need system model information for real-time voltage stability analysis.

First, let us try to extract the slope $\Delta Q_{ij}/\Delta V_i$ for some transmission line from the sample recorded PMU data which is from an actual PMU in the eastern system. Looking at Fig 3, a statisticl fit of a linear slope on the QV data for the line shows the slope to be near zero. Even the density plot does not point to any meaningful slope $\Delta Q_{ij}/\Delta V_i$ for this line.

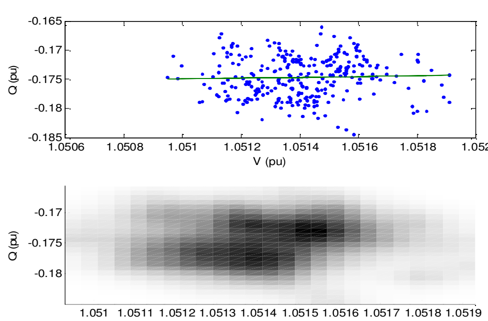

Fig. 3. V-Q data points and the density plot for 10 seconds of PMU data for an Eastern System PMU

However, based on capacitor bank switching near the bus, we could conclude that the slope $\Delta Q_{ij}/\Delta V_i$ was definitely not zero. The apparent inconsistency why the statistical fit failed to reveal the slope could be explained by causality of Q-V relationship. In the real system, note that there are actually two slopes $\Delta Q_{ij}/\Delta V_i$ related to the transmission line from bus i to bus j. Whether the change in line-flow is effected by changes in sending end of the line or the receiving end of the line will result in two different slopes with opposite signs. Therefore, the slope can be estimated only by first dividing the data into two sets accordingly as shown next.

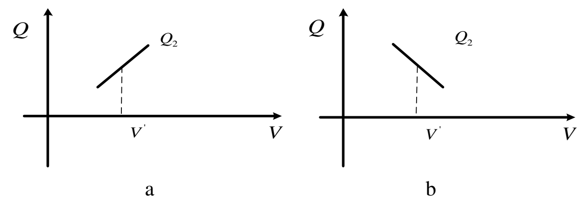

Fig. 4 The V-Q relationship for reactive power Q_{ij} to bus voltage V_i in a small time interval

When the same data in Fig 3 is split according to positive slopes and negative slopes, we can clearly see the trend of the data points lining up along a definite positive slope versus a clearly defined negative slope for the sensitivity. Using statistical analysis, the two slopes can then be estimated. The slopes from these "ambient" PMU responses also match very well with sensitivities calculated from discrete switching events.

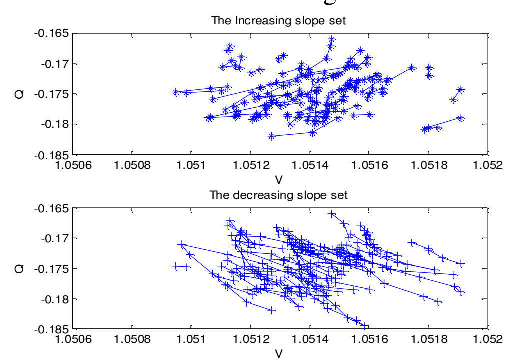

Fig.5 Points of V-Q with increasing and decreasing slopes

Based on similar analysis, the line sensitivities $\Delta Q_{ij}/\Delta V_i$ can be calculated for each of the lines connected to bus *i* giving us the net sum Γ_i in (1) which is then the VSA index for bus *i*. Whenever the value Γ_i goes below a predefined threshold, say "10", the system near the monitored bus is approaching static voltage stability limit as discussed earlier in section II.1.

Details on the statistical analysis as well as simulation results on test systems will be presented elsewhere. The algorithms have also been implemented into openPDC platform in a prototype fashion at Tennessee Valley Authority (TVA), and the results will be presented elsewhere. We are also implementing the voltage stability monitor framework at Entergy.

III. Oscillation Monitoring System

Oscillation Monitoring System (OMS) is being developed as a real-time operations toolbox for monitoring the damping ratio, frequency, as well as mode shape [5] of poorly damped electromechanical oscillations in the power system from wide-area PMU measurements. A prototype version of OMS has been implemented as part of the Phasor Data Concentrator at Tennessee Valley Authority (TVA)[1].

OMS includes two engines as shown in the flowchart in Figure 6. The event analysis engine shown in the right side of the flowchart in Figure 6 carries out an automatic Prony type analysis of system responses following disturbances in the system. The complementary damping monitor engine in the left side of the flowchart estimates the damping, frequency as well as mode shape of poorly damped oscillatory modes from ambient PMU measurements whenever such oscillations appear. Details on the two engines can be seen in [5], [6]. Figure 7 shows an example of the results from the two engines for a recent event near a major generating plant at TVA. In Figure 7, the system encountered a routine event at about 830 seconds. The event analysis engine of OMS then carries out moving time-window analysis of the PMU measurements towards real-time Prony analysis and concludes the oscillation to be from a local mode (involving mainly one PMU or few nearby PMUs) of 1.2 Hz oscillations with +1.5% damping ratio. On the other hand, the damping monitor engine of OMS analyzes the real-time ambient PMU data continuously, and can estimate the dominant oscillatory mode to be the same local mode identified by Prony at 1.2 Hz with damping ratio of +1.8%. The two engines, namely, the event analysis engine and damping monitor engine serve as complementary engines in identifying the dominant poorly damped oscillatory modes of a power system whenever such modes exist.

Figure 8 shows an example of damping monitor webpage captured from the TVA implementation. In the damping monitor display, there are three major areas. Left top is a frequency vs. damping ratio point chart. It clearly shows all the modes in the frequency domain, and their damping ration on y-axis. From damping monitor result history over the previous five minutes, average values are calculated, and shown by asteriks denoting each of the dominant modes in the power system at that time. The damping ranges over the past five minutes are displayed as white bars in Figure 8.

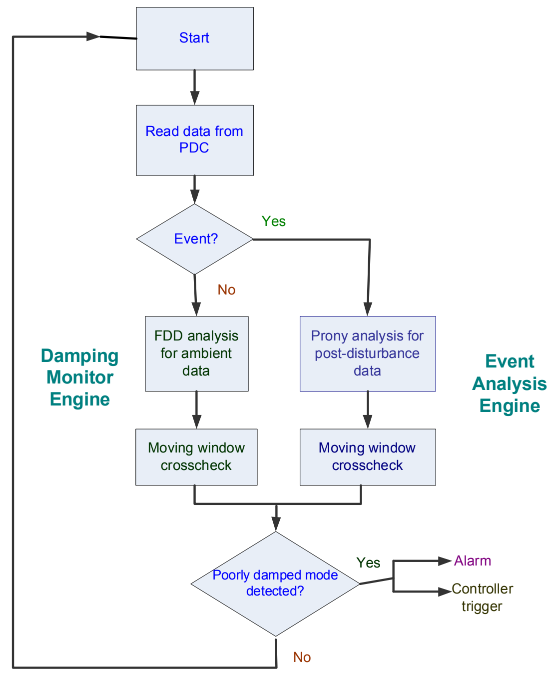

Fig. 6 Flowchart of Oscillation Monitoring System

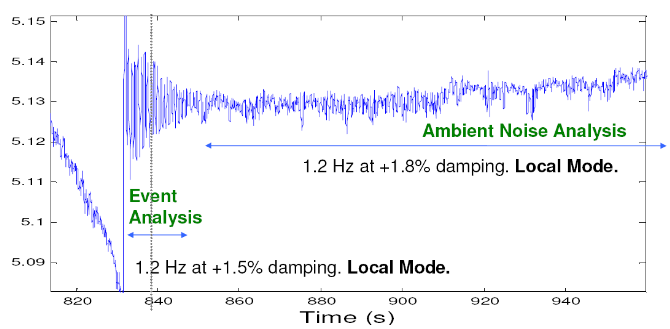

Fig.7 Illustration of analysis results from the OMS engines

The right top corner shows the time and a brief summary of the dominant modes, which includes the status of each mode. The summary will change color according to the status of each mode. For instance, the system had a poorly damped interarea mode at 0.8 Hz with estimated damping around 2.4% at the time when the snapshot was taken. Bottom part of Figure 8 summarizes mode shape information for each of the modes, which shows mode shapes of up to 4 modes, in a

[1] The authors thank Ritchie Carroll, Ryan Zuo, Lisa Beard and Gary Kobet for their help in implementing OMS at TVA.

radial fashion. Mode shape shows how different parts of the system are swinging against each other for each of the modes under study. This information is crucial for understanding the nature of the mode and for taking potential control actions. Different colors represent different signals, and the legends are listed on the right side.

IV. Transient Stability Analysis

Three algorithms have been proposed recently by us in recent papers [7] for fast detection of transient stability from wide-area monitoring of bus voltage phase angles and frequency measurements. The first algorithm uses the synchronized phase angles to detect whether any of the area phase angles start to move away from the center of inertia phase angle reference of the system. The second method approximates the potential and kinetic energies of synchronous machines from nearby PMU bus voltage phase angle and frequency measurements. The third method introduces a concept of system effort to quantify the stability versus instability thresholds for transient stability along system trajectories. The three algorithms can also initiate suitable control actions, namely, generation tripping and/or load shedding, at appropriate locations depending on whether the specific area is accelerating or decelerating, respectively.

Fig.8 Snapshot Example of a Damping Monitor Webpage

V. Conclusions

This paper provides a brief overview of recent research work at WSU on real-time monitoring and control of large power systems using wide area PMU measurements. With increasing number of PMU installations in North America as well as the other parts of the world, there is an urgent need to develop real-time tools which utilize the dynamic monitoring capability and real-time computational potential of fast growing synchrophasor technology.

References

[1] P. Kundur, Power System Stability and Control, McGraw-Hill, New York, 1994.

[2] X.Yue and V. Venkatasubramanian, “Complementary Limit Induced Bifurcation Theorem and Analysis of Q limits in Power-Flow Studies”, *Bulk Power System Dynamics and Control-VII. Revitalizing Operational Reliability, 2007 iREP Symposium*, pp. 1-8, 19-24 Aug. 2007.

[3] B. C. Raczkowski and P. W. Sauer, “Identification of Critical Cutsets for Static Collapse Analysis", *Bulk Power System Dynamics and Control-VII, Revitalizing Operational Reliability, 2007 IREP Symposium*, pp. 1-8, 19-24 Aug, 2007.

[4] M. Glavic and T. Van Cutsem, “Detecting with PMUs the onset of voltage instability caused by a large disturbance”, Proc. IEEE PES General Meeting, July 2008.

[5] G. Liu, J. Quintero, and V. Venkatasubramanian, “Oscillation Monitoring System based on wide area synchrophasors in power systems,” *Proc. IREP symposium 2007*. Bulk Power System Dynamics and Control - VII, August 19-24, 2007, Charleston, South Carolina, USA.

[6] G. Liu and V. Venkatasubramanian, "Oscillation monitoring from ambient PMU measurements by Frequency Domain Decomposition," *Proc. IEEE International Symposium on Circuits and Systems*, Seattle, WA, May 2008, pp. 2821-2824.

[7] M.Sherwood, D. Hu and V.Venkatasubramanian, “Real-Time Detection of Angle Instability using Synchrophasors and Action Principle”, Bulk Power System Dynamics and Control-VII, August 2007, Charleston SC.