Using Synchrophasor Data for Phase Angle Monitoring

NASPI Control Room Solutions Task Team Paper

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Background

The North American Synchrophasor Initiative (NASPI) is a collaborative effort between the U.S. Department of Energy, North American Electric Reliability Corporation, and electric utilities, vendors, consultants, federal and private researchers, and academics. The NASPI mission is to improve power system reliability and visibility through wide area measurement and control. The NASPI community is working to advance the deployment and use of networked phasor measurement devices, phasor data-sharing, applications development and use, and research and analysis. Important applications today include wide-area monitoring, real-time operations, power system planning, and forensic analysis of grid disturbances.

The NASPI Control Room Solutions Task Team (CRSTT) mission is to work collectively with other NASPI task teams to advance the use of real-time synchrophasor applications for the purpose of improving control room operations and grid reliability. This team utilizes its experience and regional diversity to provide advice, direction, support and guidance to NASPI stakeholders and other organizations involved in the development and implementation of real-time synchrophasor applications.

This is one of a series of papers being developed by CRSTT members to explore the following areas of interest and determine if value can be added in the near future by using synchrophasor data and applications: oscillation detection, system islanding detection and blackstart restoration, determining disturbance locations, voltage stability assessment, and monitoring of reactive power balance. Existing versions of these papers can be found on the CRSTT page of the NASPI website (https://www.naspi.org/crstt). An overview of the NASPI Work Group structure is provided below:

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1   Introduction

This paper addresses how synchrophasor technology can be used for phase angle monitoring and describes the various synchrophasor-based applications being used by electric utilities and grid operators presently. Uses for phase angle monitoring include:

- Wide-area situational awareness and visualization
- Line reclosing
- Verifying operation of synch check relays
- Setting alarms and alerts
- Improving state estimator solutions.

This paper may be updated in the future to include additional applications, update features of existing applications, functionality and methodologies as new information is received.

2   Overview of Synchrophasor Technology

A synchrophasor is a time-synchronized measurement of a quantity described by a phasor. Like a vector, a phasor has magnitude and phase information. Devices called Phasor Measurement Units (PMU) measure voltage and current and with these measurements derive parameters such as frequency and phase angle. The measurements may be either fundamental components (50 or 60 Hz) and of the Positive Sequence for the 3-phase representation. Data reporting rates are typically 30 to 60 records per second. In contrast, current Supervisory Control and Data Acquisition (SCADA) systems often report data every four to six seconds – over a hundred times slower than PMUs.

PMU measurements are time-stamped to a precision of a microsecond, synchronized using the timing signal available from Global Positioning System (GPS) satellites or other equivalent time sources. Measurements taken by PMUs in different locations are therefore accurately synchronized with each other and can be time-aligned, allowing the relative phase angles between different points in the system to be derived from directly measured quantities. Synchrophasor measurements can thus be combined to provide a precise and comprehensive "view" of an entire Interconnection.

The accurate time resolution of synchrophasor measurements allows unprecedented visibility into system conditions, including rapid identification of details such as oscillations and voltage instability that cannot be seen from SCADA measurements. Complex data

networks and sophisticated data analytics and applications convert PMU field data into high-value operational and planning information.[1]

3   Using Synchrophasor Data for Phase Angle Monitoring

Consider the voltage signal shown in Fig. 1(a). It is a sinusoidal signal that can be represented by a unique complex number known as phasor. Let the signal be represented mathematically as shown below:

$$x(t) = X_m \cos(\omega t + \delta) \tag{1}$$

where ω is the frequency of the signal in radians per second, δ is the phase angle in radians, X_m is the peak amplitude of the signal and the root mean square (RMS) value of the signal is $(X_m/\sqrt{2})$.
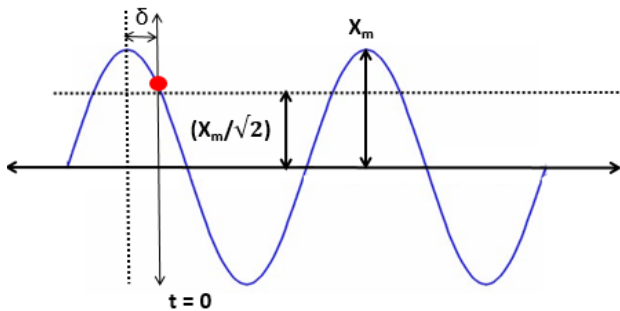
Fig. 1 (a): Sinusoidal Signal   Fig. 1(b): Phasor representation
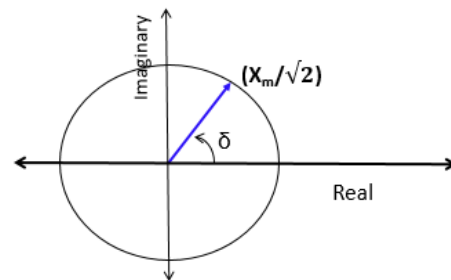
Figure 1 Phasor Representation of a sinusoidal signal

The phasor representation of this sinusoidal signal can be explained as follows.[2] [3] Using Euler's formula for relating trigonometric functions with complex exponentials[4], the sinusoidal signal (1) can be rewritten as:

$$x(t) = \text{Re}[X_m e^{-j(\omega t + \delta)}] = \text{Re}\left[\{ e^{-j(\omega t)} \} X_m e^{-j(\delta)}\right] \tag{2}$$

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[1] Refer to the *Synchrophasor Fact Sheet* dated October 2014 for additional information about synchrophasor technology and its uses: https://www.naspi.org/File.aspx?fileID=1326

[2] A.G. Phadke, J.S. Thorp, "Synchronized Phasor Measurements and Their Applications", Springer Publications, 2008.

[3] Jaime De La Ree, Virgilio Centeno, James J Thorp and A.G. Phadke, "Synchronized Phasor Measurements Applications in Power Systems", IEEE Transactions on Smart Grid, Vol 1, No. 1, June 2010, pp 20-27.

[4] $e^{jx} = \cos x + j \sin x$, where x is a real number

It is customary to suppress the term $e^{-j(\omega t)}$ in the above expression (2), with the understanding that the frequency is ω. The sinusoid of equation (1) can then be represented by a single complex number **X** known as its phasor representation:

$$x(t) \rightarrow \mathbf{X} = \frac{X_m}{\sqrt{2}} e^{-j\delta} = \frac{X_m}{\sqrt{2}} [\cos \delta + j \sin \delta] \qquad (3)$$

This phasor representation of the sinusoidal signal is illustrated in Fig. 1. Magnitude of the phasor is set to be equal to the RMS value ($X_m/\sqrt{2}$) of the sine wave. The phase angle of the phasor is arbitrary, as it depends upon the choice of the reference axis $t = 0$.

Now let us consider a second sinusoidal (voltage) signal with the same frequency and same peak amplitude but a different phase angle as shown in Fig. 2. This signal may be represented mathematically as follows:

$$x_2(t) = X_m \cos(\omega t + \delta_2) \qquad (4)$$

We can say that these two sinusoidal voltage signals have a phase angle difference equal to ($\delta_2 - \delta$). Note that for both the signals, same time reference is chosen. If the reference point (t = 0) changes, phase angles of both the signals would change. However, the difference between the two phase angles would remain the same (see Fig. 2).
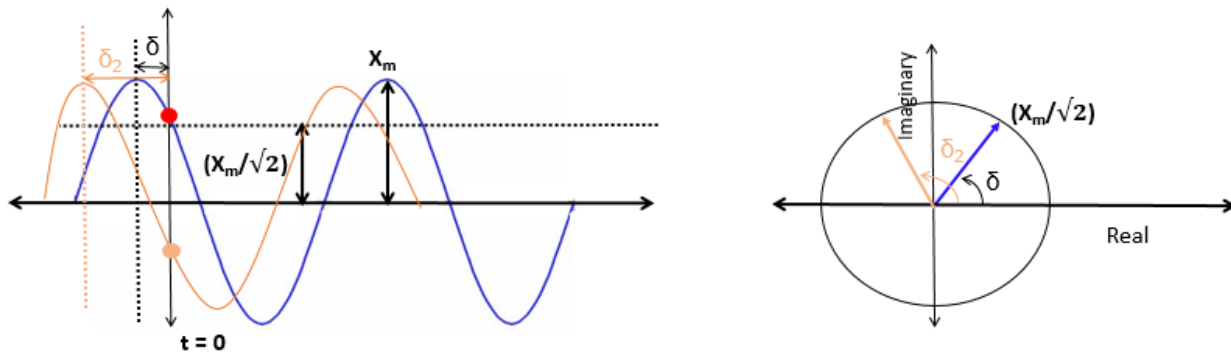
Figure 2: Phasor representation of two sinusoidal signals

Two different voltages from different locations in the system can be represented individually with respect to their own references according to equations (1) − (3). However, if both signals are tagged to a common reference point in time (for example, all signals were time-tagged to UTC[5]), then one of the signals can be used as a reference point from which the relative phase angle differences for all other signals could be

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[5] Universal Coordinated Time, often provided by a Global Positioning System (GPS) satellite receiver and clock.

calculated. This is the basis of the phase angle difference monitoring that is the subject of this report.

A PMU reports measured values synchronized with, and time-tagged to, UTC. These measured parameters are the amplitude of the signal, x, the frequency, f, the rate-of-change of frequency, ROCOF, and the phase angle, ϕ. The power system operates approximately at a nominal frequency (50 or 60 Hz). However, system frequency is constantly changing as the balance between load and generation changes. PMU is designed to report these values, typically many times per second, in accordance with IEEE Standard C37.118-1 (2011).

When we compare the voltage and current signals, the angle by which the voltage in a circuit leads or lags the current is also a phase angle difference. But this difference is the power factor angle of that particular location and not the subject of this section. In the context of this document, we are concerned with the differences between voltage phase angles at different locations in the system. This phase angle difference drives (and is driven by) the power flows between the respective locations.

The phase angle between two points on the grid changes as grid conditions change. In an AC system, power flows from a higher voltage phase angle to a lower voltage phase angle. The larger the phase angle difference between the source and sink, the greater the power flow between those points. Real Power Flow (Watts) drives phase angle differences (or vice-versa) between locations on the system.

Greater phase angle differences across the system imply larger stress in the underlying grid; larger stress could move the grid closer to instability.[6] Phase angle differences are also a function of system topology and may change as topology changes, even if the power flows between two points do not change. A monotonic, rapidly changing phase angle difference between two points may indicate a problem in the corresponding area of the grid. Because PMUs measure grid conditions precisely with all measurements synchronized to a common time reference (unlike SCADA), phase angle data from PMUs in different locations on the grid can be used to determine the angle differences between those points in real time.

Note that there is no technical limitation preventing SCADA systems from recording local phase angles referenced to a standard, or local frequency. However, SCADA measurements are taken about a hundred times slower than PMU measurements and are not time-stamped and synchronized, making it more difficult to calculate phase angles directly or to monitor high-speed phenomena such as power oscillations.

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[6] NERC Report titled *Real-Time Application of Synchrophasors for Improving Reliability* dated 10/18/2010: http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf

Since phase angle differences are an indicator of system stress, they can be used to detect conditions that could lead to a grid disturbance.[7] Since the phase angle difference between two points is an indicator of effective power flow between those points, phase angle difference monitoring across a transmission line or interface can be used to manage relay reclosing, and resynchronization of electrical islands. Phase angle differences are also useful for post-disturbance analysis of oscillatory operating states.

Monitoring the Phase Angle Difference between Transmission Line Terminals

Following a transmission line relay and trip operation, electric utilities and grid operators have traditionally waited until a line is energized to scope across the open terminal and determine if the line is within the maximum allowable closing angle. PMU-based phase angle measurements – using PMUs from opposite sides of the bus or transmission line in question -- allows a transmission owner or operator to measure the voltage angle difference between the transmission line breaker terminals or connecting busses and determine if the line is within phase angle limits, before acting to close the line. This gives the operator better information about whether any corrective action is needed to reduce the phase angle within acceptable limits and when it is safe to close the line.

Monitoring Phase Angle Measurements across the Interconnection

With synchrophasor technology, utilities can also measure phase angle differences across the wider electrical system to provide wide-area visibility of both their service area and also beyond. Significant divergence in phase angles across the system indicates an increase in system stress and may be the precursor to a significant disturbance event.

It's believed that a lack of wide-area visibility prevented early identification of the August 14, 2003 Northeast blackout. The U.S.-Canada investigation report into the blackout hypothesized that if a synchrophasor system had been in operation at that time, the blackout preconditions — in particular, the growing voltage problems in Ohio — could have been identified and understood earlier in the day. In the last few minutes before the cascade, there was a significant divergence in phase angles between Cleveland and Michigan, as shown in Figure 3 below.[8]

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[7] Damir Novosel, Vahid Madani, Bharat Bhargava, Khoi Vu and Jim Cole, "Dawn of the Grid Synchronization", IEEE Power and Energy Magazine, January/February 2008, pp 49-60.
[8] See NERC Report titled Real-Time Application of Synchrophasors for Improving Reliability dated 10/18/2010: http://www.nerc.com/docs/oc/rapirtf/RAPIR%20final%20101710.pdf

It Can Fall Apart in Three Minutes
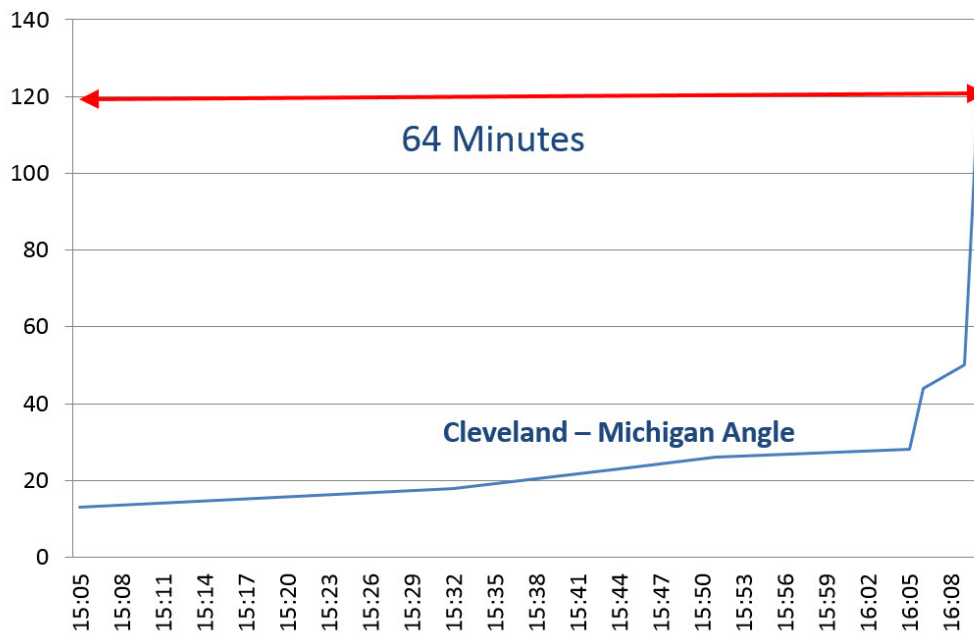
Figure 3: Divergence of Phase Angle between Cleveland and Michigan during 2003 Northeast blackout

Monitoring Phase Angles to Strengthen Compliance to Mandatory Standards

There are no current NERC Standards that specifically require electric utilities or grid operators to monitor phase angles. However, the FERC/NERC report titled *Arizona-Southern California Outages on September 8, 2011 – Causes and Recommendations,*[9] which was released in April 2012, does include a finding and recommendation specific to phase angle monitoring:

Finding 27 – Phase Angle Difference Following Loss of Transmission Line: A Transmission Operator (TOP) did not have tools in place to determine the phase angle difference between the two terminals of a 500 kV line after the line tripped. Yet, TOP informed the Reliability Coordinator (RC) and another TOP that the line would be restored quickly, when, in fact, this could not have been accomplished.

Recommendation 27 – TOPs should have: (1) the tools necessary to determine phase angle differences following the loss of lines; and (2) mitigation and operating plans for reclosing lines with large phase angle differences. TOPs should also train operators to effectively respond to phase angle differences. These plans should be developed based on the seasonal and next-day contingency analyses.

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[9] http://www.ferc.gov/legal/staff-reports/04-27-2012-ferc-nerc-report.pdf

In a settlement agreement between Arizona Public Service (APS) and FERC following the Southwest blackout, APS agreed to install PMUs at five key high voltage substations across its grid for better monitoring and situational awareness. These PMUs will support the tools used to determine when planned or actual operations may result in large phase angle differences on BES facilities that will impede normal, emergency, or restoration operations, including the delayed reclosing of transmission lines.[10]

It should be noted that *NERC Standard IRO-002-4 – Reliability Coordination – Monitoring and Analysis*, which has been approved and is subject to future enforcement, will require RCs to provide their System Operators with the capabilities necessary to monitor and analyze data needed to perform their reliability functions.

NERC's rationale for including certain requirements in Standard IRO-002-4 is described in the Standard IRO-002-4 – Guideline and Technical Basis as follows:

Changes made to the proposed definitions were made in order to respond to issues raised in NOPR paragraphs 55, 73, and 74 dealing with analysis of System Operating Limits (SOL) in all time horizons, questions on Protection Systems and Special Protection Systems in Notice of Potential Rulemaking (NOPR) paragraph 78, and recommendations on phase angles from the SW Outage Report (recommendation 27). The intent of such changes is to ensure that Real-time Assessments contain sufficient details to result in an appropriate level of situational awareness. Some examples include: 1) analyzing phase angles which may result in the implementation of an Operating Plan to adjust generation or curtail transactions so that a Transmission facility may be returned to service, or 2) evaluating the impact of a modified Contingency resulting from the status change of a Special Protection Scheme from enabled/in-service to disabled/out-of-service.

Recently, NERC came up a Technical Reference Document[11] on 'Phase Angle Monitoring: Industry Experience Following the 2011 Pacific Southwest Outage Recommendation 27' which discusses how and why to use phase angle monitoring for bulk power system reliability.

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[10] 148 FERC 61,009, "Order Approving Stipulation and Consent Agreement," Docket No. IN14-6-000, July 7, 2014, pp. 6 and 8-9.
[11] NERC Technical Document on 'Phase Angle Monitoring: Industry Experience Following the 2011 Pacific Southwest Outage Recommendation 27', June 2016.

4   Summary of Synchrophasor-Based Applications for Phase Angle Monitoring

To support the development of this paper, CRSTT members surveyed 27 separate parties, which included electric utilities, grid operators and vendors, and asked them to provide details on synchrophasor-based applications being used for phase angle monitoring. Seventeen of these parties responded to the survey and their answers are summarized below:

The goal of using phase angle monitoring and alarming tools is to provide insight into real-time grid operations, particularly with respect to grid stress across a wide area of the grid. Collectively, the respondents are using synchrophasor technology and phase angle monitoring tools to:

- Calculate and set limits for phase angle alarming across specific angle pairs in order to establish and operational early warning system
- Determine whether the phase angle difference across specific lines exceed the lines' respective sync relay settings
- Validate voltage angle values used to improve state estimator solution quality and identify modeling issues.

Most of the contributors to this paper report that phase angle monitoring tools are presently being used by operations support engineers rather than control room operators. Only XM Colombia and POSOCO are actively using a phase angle alarming tool in the control room environment. Most users report that their phase angle monitoring systems are in development and testing but not fully operational at present.

Hurdles to full operational implementation include:

- Improving data quality,
- Conducting regular baselining analyses to identify updated alarms and alert thresholds consistent with grid vulnerability,
- Extensive operator and engineer training,
- New operational procedures, and
- Integration of the phase angle monitoring tool into the EMS and SCADA systems that already manage control room alarms.

Alarm thresholds are determined using a baselining study to identify the normal, minimum and maximum values of angle differences in the system.[12]

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[12] Bill Blevins, Ajay Das, "ERCOT Synchrophasor Data Baselining Study', NASPI Working Group Meeting, March 11, 2014.

The respondents are using a variety of commercial or in-house developed applications for monitoring phase angles. The vendors of the commercial software in use by these respondents includes (ordered alphabetically):

- Alstom Grid – PhasorPoint and eterraVision
- EPG – Real-Time Dynamics Monitoring System (RTDMS)
- GE – PowerOn
- OSIsoft – PI historian
- SEL – SynchroWAVe Central
- V&R Energy – Region Of Stability Existence (ROSE)

XM Colombia has developed its own software for phase angle monitoring in the control room.

The goals and uses specific to each respondent can be found in Section 5.

5 Responses Received from Survey Participants

The Task Team received responses from the following organizations.

1. Dominion Virginia Power (DVP)
2. ISO New England (ISO-NE)
3. American Transmission Company (ATC)
4. PJM Interconnection
5. Power System Operations Corporation Ltd, India (POSOCO)
6. Peak Reliability
7. Southern California Edison (SCE)
8. Lower Colorado River Authority (LCRA)
9. Duke Energy
10. Electric Reliability Council of Texas (ERCOT)
11. XM Colombia
12. ALSTOM Grid
13. Electric Power Group (EPG)
14. Electric Power Research Institute (EPRI) and Powertech Labs
15. Quanta Technology
16. Schweitzer Engineering Laboratories (SEL)
17. V&R Energy

The responses received are presented in the following sub-sections and segregated between user responses and vendor responses. In the material below, the survey questions are shown in **bold** and the respondents' answers are in regular text. The illustrations shown were provided by the respondents.

USER RESPONSES

5.1 Dominion Virginia Power (DVP)

Application name: EPG RTDMS, OSIsoft PI Historian

Objective of the application: Provide visualization and analytical processing of synchrophasor data (real-time and historical data), including phase angles across the system, and alarming options.

Application requirements (hardware, software, visualization telecommunications, etc.): For phase angle visualization and alarming, must send synchrophasor data to each

application. Then in each tool, a number of ways to visualize phase angles, such as trend charts, polar charts and geographic displays.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): Our focus for phase-angle visualization and alarming is using synchrophasor data at a resolution of 30 phasors per second.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: Phase angles are not readily available with today's EMS/SCADA data. Having phase angles from synchrophasor data will allow more insight into the real-time operations of the grid, including new angle-based metrics for grid stress, manual breaker reclosing angles and even blackstart situations when connecting small sections of the grid back together.

Current status of the application (in development, testing, in operation): RTDMS is in operation in DVP engineering departments and in development for getting RTDMS screens in front of System Operators. PI is still under development and early implementation stages at DVP.

Application software (open source, proprietary): Both applications are proprietary.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): Our PI Historian will be the main repository for all synchrophasor data and SCADA/EMS data at DVP. This will allow PI to be one place where all data can be visualized and analyzed together with state of the art analytical tools.

Describe how the application could be operationalized (i.e. used in real-time): Phase angles are not readily available with today's EMS/SCADA data. Having phase angles from synchrophasor data will allow more insight into the real-time operations of the grid, including new angle-based metrics for grid stress, manual breaker reclosing angles, and even blackstart situations when connecting small sections of the grid back together.

Type of application GUI: Both RTDMS and PI applications have a server end that is the engine to collect all input data, store to database, and make available to client side applications. Both RTDMS and PI applications have client side applications that users use on standard Windows computers.

Identify operating entities that are using the application: Below are links to EPG and OSIsoft website which identify their respective clients:

http://www.electricpowergroup.com/solutions/rtdms/deployments.html
http://www.osisoft.com/value/industry/PowerUtilities/

Any other relevant information: Screenshot of voltage phase angle display at DVP is as shown in Figure 4.
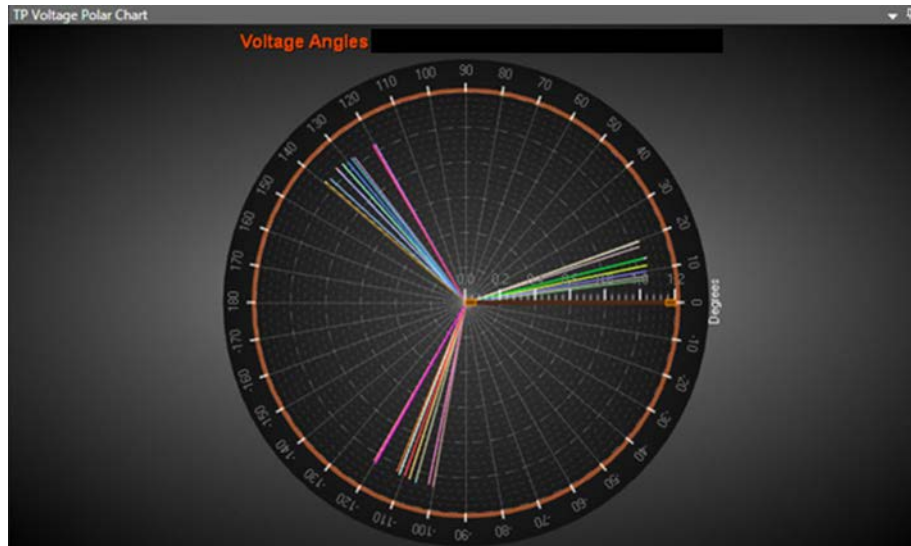
Figure 4: Display of Voltage Phase angles in Dominion Virginia Power System

5.2 ISO NEW ENGLAND

Application name: Alstom Phasor Point

Objective of the application: As communicated by Alstom, the application has the ability to collect synchrophasor data from 40 substations in New England; archive all data for three years; provide visualization of real-time and historic synchrophasor data; provide analysis of data.

Application requirements (hardware, software, visualization telecommunications, etc.): The vendor can provide this information.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): Phasor Point utilizes only synchrophasor data and provides full resolution (30 data points per second) for all functions (archiving, visualization, and analysis).

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: ISO-NE is evaluating potential benefits of using synchrophasor data in the real time environment but does not currently use this data in the real time environment.

Current status of the application (in development, testing, in operation): The Phasor Point application is currently in operation for post event analysis.

If in operation, where? Phasor Point is currently being used in post event analysis.

Application provider or developer: Alstom/Psymetrix

Application software (open source, proprietary): Proprietary software.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): The vendor can provide this information.

Describe how the application could be operationalized (i.e. used in real-time): ISO-NE is evaluating this possibility.

Type of application GUI: The vendor can provide this information.

Identify operating entities that are using the application: The vendor can provide this information.

5.3   American Transmission Company

Application name: Alstom (Psymetrix) PhasorPoint

Objective of the application: Visualization, Monitoring and Notification

Application requirements (hardware, software, visualization telecommunications, etc.): The application serves as a Phasor Data Concentrator (PDC) and visualization engine that resides on a server. I believe redundancy can be implemented but we have not pursued that at this time.

The application needs to have access to a live synchrophasor data stream. The end users run an application that connects to the server to display data. Some alarming is built into the tool that could be used to identify times when angle differences exceed defined thresholds but we are more focused on integrating the system and using EMS alarming so I can't provide much detail on those existing alarm capabilities.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): The application does not use SCADA inputs. We are currently using 30 sample/second phasor data as an input. I believe it can accept data at higher rates if desired. Phase angle pairs need to be defined but once configured they can be used for visualization displays, trending, and angle difference alarming.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: Initially the application could be used in conjunction with our existing interface monitoring tools which are based on

MVA/MWs across the interface. Having the angle data in real time to compare to the interface flows could eventually lead to changes in how we monitor the operation of the system if we determine the angle limit provides a more easily understood measure of the stress on the system.

Current status of the application (in development, testing, in operation): We've had the application running on our development network for the past year with limited operations access. We've been waiting to push the application to production/operations until we have hooks to our EMS alarm application. The intent is that the alarm system would be used to notify the Operators when they should look at the visualization displays versus expecting them to monitor this special application 24x7.

Application provider or developer: Alstom (Psymetrix)

Application software (open source, proprietary): Proprietary

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): PhasorPoint has the ability to integrate with Alstom's EMS software as well as their visualization application eterraVision. We have tested these interfaces and while they can be made to work the configuration process had some issues we needed to work through. We hope to address that in 2015.

Describe how the application could be operationalized (i.e. used in real-time):
Operationalizing the application requires good hooks to existing tools for our Operations to accept it. As stated above, we do not expect our Operators to monitor this special, stand-alone application 24x7 so it needs to integrate well with our existing operator tool set. Most notable any alarms generated by the system need to be presented to the Operators via our existing EMS alarm system.

Type of application GUI: Proprietary
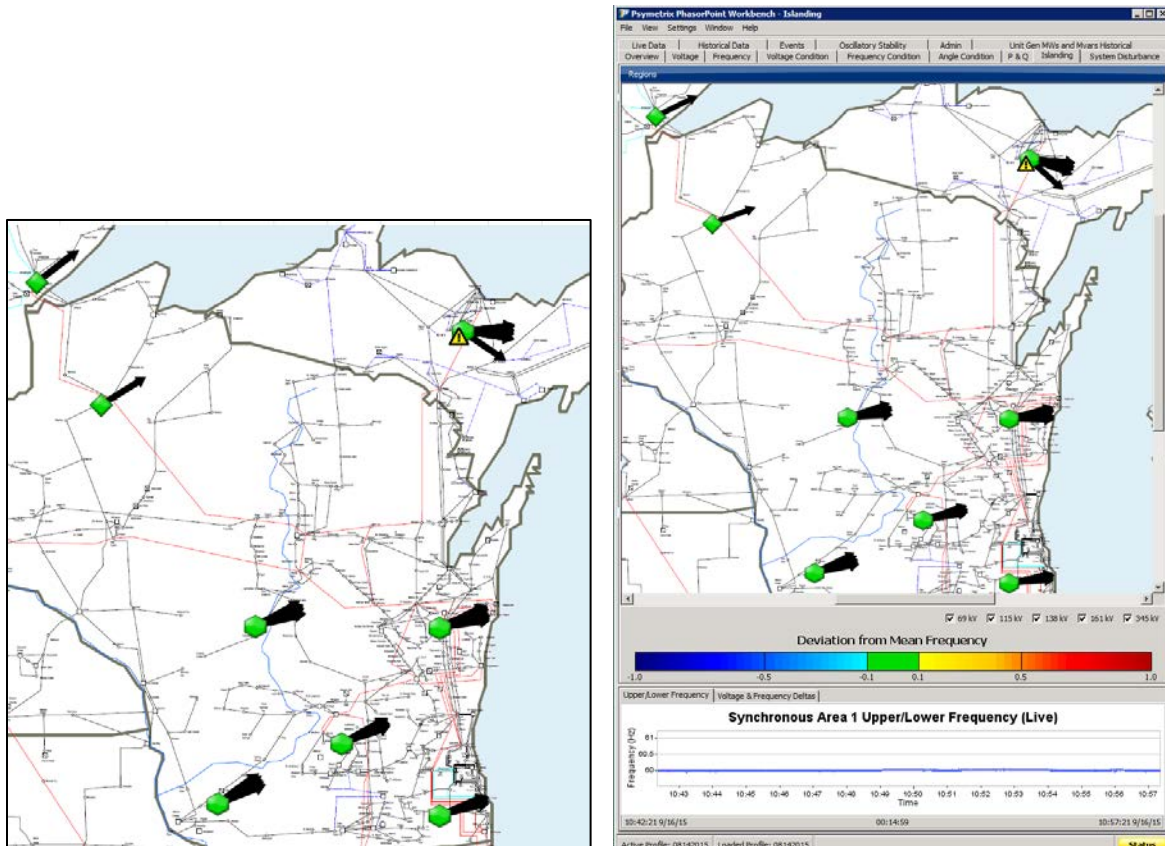
Figure 5: Display of Voltage Angle Information at ATC Using PhasorPoint

Identify operating entities that are using the application: Please contact Alstom for a list of companies using the application. I have a general idea who has it but do not have permission to share that information from the other companies.

Any other relevant information: The application has worked well with the 110 PMUs we are scanning. We have seen some issues with performance on save times with this larger configuration but the real time displays are reliable and provide timely updates.

We have been working through licensing as they are transitioning their licensing structure from the Psymetrix model to something more in line with the standard Alstom licensing scheme.

Example: Can you provide a sample video clip demonstrating the capabilities of the tool: Yes. Click here to view the video:
https://www.naspi.org/Video/TaskTeamId_12/PhasorPoint_for_NASPI_CRSTT.mp4

5.4 PJM INTERCONNECTION

Application name: EPG RTDMS

Objective of the application: RTDMS is a synchrophasor software application for providing real time, wide area situational awareness to Operators, and Engineers, as well as the capability to monitor and analyze the dynamics of the power system.

Application requirements (hardware, software, visualization telecommunications): One special need is RTDMS requires at least 1GB video card memory.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): 30samples/sec phasor data

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: Monitoring Phase angle difference will provide another type of indicator of system stress in the wide area.

Current status of the application (in development, testing, in operation): Testing

Application software (open source, proprietary): Proprietary

Applications ability to integrate with EMS/SCADA systems or data historians: Can be integrated with PI.

Describe how the application could be operationalized (i.e. used in real-time): If limitations are derived using engineering-based post-contingency limits (ideally dynamic calculated recognizing system topology) phase angle limits then could be then provide value operationally beyond being based upon statistical normal/abnormal limitations.

Type of application GUI: Windows application GUI

Identify operating entities that are using the application: The application is available to 12 PJM transmission owners and 8 of them are using it.

5.5 Power System Operation Corporation Ltd, India

Application name: Synchrophasor Central

Objective of the application: Visualization of synchrophasor data real-time as well as historical data.

Application requirements (hardware, software, visualization telecommunications, etc.): Historian, Phasor Data Concentrator, Synchrophasor Central Software of SEL.

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Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): Measured phasor voltage or phasor current.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: "Phase Angle Alarming" is very useful in real-time grid operation. It provides early warning signals.

Current status of the application (in development, testing, in operation):
In operation.

If in operation, where? At National Load Dispatch Center Control Room.

Application provider or developer: SEL

Application software (open source, proprietary): Proprietary

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): Not known

Describe how the application could be operationalized (i.e. used in real-time): It is being used in real time grid operation.

Type of application GUI: Color change indication along with text.

Identify operating entities that are using the application: Northern Regional Load Dispatch Center, Southern Regional Load Dispatch Center, Northern Regional Load Dispatch Center.

Any other relevant information:
Click here to view the video:
https://www.naspi.org/Video/TaskTeamId_12/Sel_Alarm.avi

5.6 Peak Reliability

Application name:
ALSTOM Psymetrix PhasorPoint (PP) Workbench and e-Terravision

Objective of the application:
Psymetrix PP is the engineering tool to monitor dynamic disturbance of Western Interconnection system operations, including, but not limited to:
   a) Western inter area oscillation Mode Meters (MM) (North-South modes A & B presently) e.g. oscillation mode frequency and damping ratio

b) Oscillation Detection Monitor (ODM) (forced oscillations by system switching and generating unit dynamic)
c) Wide area angle separation monitoring-generate warning/alarming when a pre-specified PMU bus voltage angle pair difference exceeds its thresholds
d) Islanding detection by PMU signals
e) System Disturbance monitoring
f) Frequency, Voltage Magnitude/Angle, P & Q flows
g) Composite event alarming
h) Live PMU data review and historical PMU data retrieval (up to ~3 months)
i) Etc.

Note items a, b use Montana Tech developed Modal Analysis Software (MAS) engine to compute MM and ODM solutions. The rest are original Psymetrix functionalities.

E-terravision is Alstom's new generation graphical visualization tool for wide area situational awareness. It has the ability to import both real-time applications and offline study results. E-terravision can import and visualize the results of the following real-time applications:
a) EMS-SCADA ICCP measurements/Quick Network Analysis (QKNET)
b) EMS-State Estimation
c) EMS-Real-Time Contingency Analysis (RTCA)
d) Raw PMU data stream from OpenPDC
e) MAS-MM and ODM results received from the PP workbench.
f) Bus voltage Angle Pair separation monitoring in the context of PMU, SE, CA and SCADA applications

Application requirements (hardware, software, visualization telecommunications, etc.): OpenPDC servers, Phasor PI servers, Data transfer/Link between EMS servers and e-terravision/OpenPDC/PP servers.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.):
- SCADA ICCP refresh rates: 10 seconds for Analog points and exceptional for Status points.
- PMU incoming streams: 30 sample per second.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment:
Major benefits achieved thus far are:
a) Validated PMU voltage angle values are used in improving SE solution quality and identify the modeling issues.
b) PMU serves independent data source for RC to gain the system situational awareness in case of EMS system fails e.g. ICCP link/OAG servers down.
c) Monitor system oscillatory events.

Current status of the application (in development, testing, in operation): In testing and validation phase.

If in operation, where? N/A

Application provider or developer: Alstom Grid (integrated with Montana Tech MAS engine) and Washington State University developed Oscillation Monitoring System (OMS) tool (on off-line validation phase).

Application software (open source, proprietary): Montana Tech MAS engine is open source.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): Alstom PhasorPoint Workbench is able to integrate with EMS/SCADA system. WSU OMS tool has interface with PI.

Describe how the application could be operationalized (i.e. used in real-time): Peak plan to complete the validation test in 6-months, and run the PMU applications in a trial mode for baselining, implement RC friendly visualization, and develop actionable operations procedures/guides in next year or two.

Type of application GUI: Vendor provided GUI and Peak costumed visualization displays in SCADA and PI

Identify operating entities that are using the application. Not sure

5.7 Southern California Edison

Application name: Power On (GE's new name for the XA/21 platform)

Objective of the application: Synchrophasor visualization, alarming and system control.

Application requirements (hardware, software, visualization telecommunications, etc.): Very detailed for a short answer. Think an EMS system requirements.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): High speed trends and 1 sample per second for general alarming and display

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: Analysis Pending

Current status of the application (in development, testing, in operation): Operation on hold pending NERC CIP verification

If in operation, where? Control room.

Application provider or developer: General Electric.

Application software (open source, proprietary): Proprietary

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): Yes

Describe how the application could be operationalized (i.e. used in real-time): Same application as our EMS system.

Type of application GUI: Same application as our EMS system.

5.8   LCRA TRANSMISSION SERVICES CORPORATION

Application name: EPG RTDMS 2012/2015

Objective of the application: Detect angle discrepancies that exceed normal values.

Application requirements (hardware, software, visualization telecommunications, etc.): Refer to EPG documentation re: RTDMS software requirements

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): 30-sample per second real-time PMU data from each bus of interest. PMU data must include a voltage source that is on the "far" side of the open line; not on the transmission line itself, otherwise the measurement will be inaccurate.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: From time to time, lines may not be able to be reclosed because the angle difference across the line exceeds the sync relay settings or some other limit. Knowledge of the angle in real-time can help Operators adjust the system to provide for system restoration. Visualizing the angle can demonstrate the angle improving or worsening as system modifications are made.

Current status of the application (in development, testing, in operation): In testing by Operations engineering staff; not yet released to Operators on a 24x7 basis.

If in operation, where? N/A. Although the Big Hill to Kendall double-circuit series compensated 138 mile 345-kV line is a prime candidate for this type of functionality.
Application software (open source, proprietary): RTDMS platform

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): Our EMS vendor has confirmed that RTDMS may be integrated within the LCRA TSC EMS system.

Describe how the application could be operationalized (i.e. used in real-time):

Angle differences will be integrated into system-wide visualization displays for system operator awareness. Under normal system conditions, this will mostly provide awareness to an operator for how and to what magnitude power is flowing across its system. When restoring lines to service, angle measurements will be used to ensure the difference in angle across an open circuit breaker will not exceed circuit breaker sync limits. Angle monitoring and visualization will be especially important to operators during Black Start restoration.

Type of application GUI: RTDMS platform with dashboard-style alerts and trended measurement values.

Identify operating entities that are using the application: Refer to EPG's customer list for RTDMS.

Any other relevant information: Functionality was documented in a section of this technical paper available on SEL's web site:

https://www.selinc.com/WorkArea/DownloadAsset.aspx?id=104253.

5.9 Duke Energy

Application name: EPG RTDMS

Objective of the application: To derive meaning from the phasor measurements installed across the system

Application requirements (hardware, software, visualization telecommunications, etc.): Multiple servers, RTDMS Software

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): Phasor data, 30x/second

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: Angles can be measured directly instead of calculated using state estimation

Current status of the application (in development, testing, in operation): Testing

Application software (open source, proprietary): License required

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): Able to send alarm data to EMS, points to PI

Describe how the application could be operationalized (i.e. used in real-time):
Alert operator to problem using integrated alarming to EMS, operator can look at phasor data to quickly determine problem.

Type of application GUI: RTDMS Application

5.10 ERCOT

Application name: EPG RTDMS

Objective of the application: To provide real-time, wide-area situational awareness and real-time dynamics monitoring of the power grid for use by Operators, Reliability Coordinators, Planners, and Operating Engineers, as well as the capability to analyze system performance and events. The major use cases of the application within ERCOT are the ability to observe and alert operators to voltage angle differences across the interconnection, detect and mitigate local and system-wide oscillations, and the ability to save and replay system events recorded by PMUs across the system.

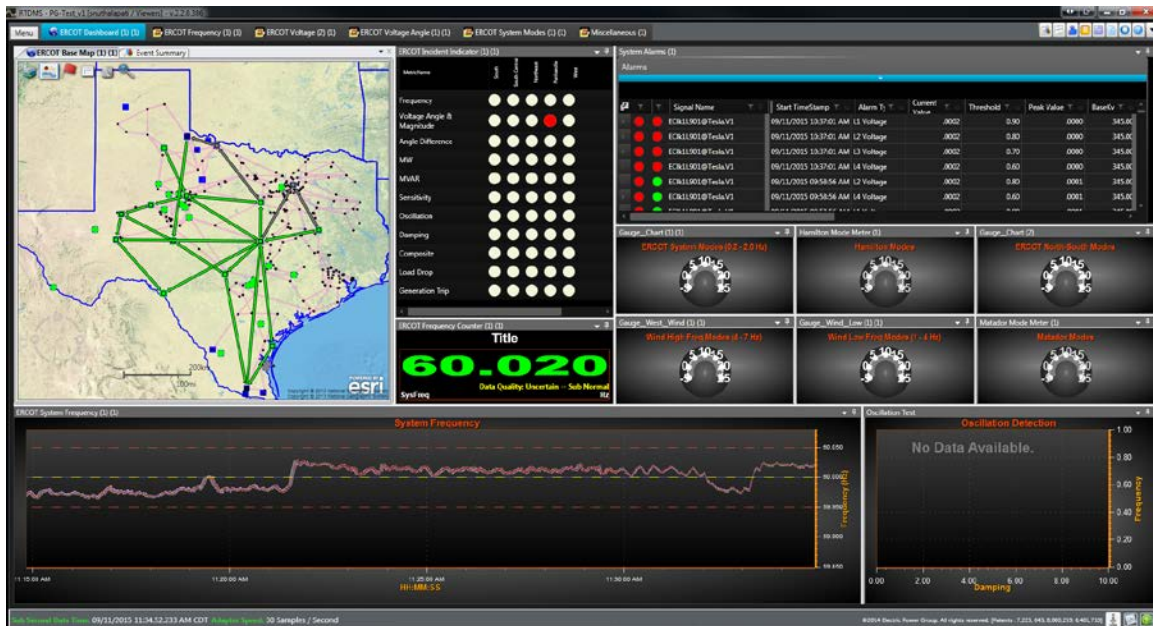Figure 6: Visualization of Phase Angles using RTDMS System at ERCOT

Application requirements (hardware, software, visualization telecommunications, etc.): Please refer to the Electric Power Group (EPG)'s requirements.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.):
Accepts phasor data input from a Phasor Data Concentrator (PDC) using either C37.118 or PDCStream data format.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment:

Current State:
- Used in control room by shift engineer as well as by support engineers to monitor voltage angles and oscillations across the system
- Developing a PMU-based operator training simulator

Future Goals:
- Build out redundant PMU monitoring system
- Develop procedures for operators and complete the PMU operator training simulator
- Add in PMU Estimation on interfaces as a backup for Interconnection Reliability Operating Limits (IROL)
- Monitor grid disturbances and notify Generators to collect data for model validation on these events
- Add PMU data into EMS for improved state estimation
- Control Room event reporting including dynamic system performance

Current status of the application (in development, testing, in operation): In use by shift engineers and operations support

If in operation, where? Control room and Operations Support Dept.

Application software (open source, proprietary): Proprietary

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): Currently, RTDMS is a completely separate system from EMS/SCADA. There are no immediate plans to integrate the two systems, although ERCOT is open to it in the future. The capability does exist, and ERCOT is in the initial stage of determining the level of integration it would like to implement.

Describe how the application could be operationalized (i.e. used in real-time): Currently, the RTDMS is being used in the control room at the shift engineer's desk and by control room support engineers. The primary purposes of the system are to monitor voltage angles and system oscillations, as well as replaying system events for post mortem analysis. There are no official procedures or protocols in place for using the system, since there is not a redundant or backup system. In the future, ERCOT is looking to implement a PMU-based monitoring system into a full production atmosphere, with a redundant system with failover capabilities, operational procedures, and an operator training simulation program.

Type of application GUI: The RTDMS user interface is made up of many tools for visualizing data and monitoring alarms. It consists of a hierarchy of layers that together provide a rich user experience for viewing data.

Any other relevant information:
Click here to view the videos:
https://www.naspi.org/Video/TaskTeamId_12/ERCOT_Oscillation_Demo_1.wmv
https://www.naspi.org/Video/TaskTeamId_12/ERCOT_Oscillation_Demo_2.wmv

5.11 XM, Colombia

Application name: Phasor Alarming Platform

Objective of the application: Real Time Monitoring of the evolution of predefined indexes based on synchronized phasor measurements supplied by the Colombian Wide-Area Monitoring System (WAMS). *Central* and *Cut Set Angles* indexes reflect the current stress of the operation. These indexes are designed to be displayed in the control room to give indications of abnormal or very stressed situation to the operator in order to take remedial actions.

On the other hand the indexes can also be used as source of information for a WAMPAC, intended to protect the integrity of the power system under events of large impact and low probability of occurrence. Currently this protection system is under research.

Application requirements (hardware, software, visualization telecommunications, etc.):
- The final implementation of this platform requires a high reliability and wide coverage WAMS which is currently under continuous development.
- A high reliable "internet" of phasors, states and commands is a mid-term goal.
- A visualization tool has been developed to show the control room operator in real time the angle indexes.
- Baselining required to relate the operation period, demand, generation of each zone, etc. to define angle limits for operation under certain conditions.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.):
- Currently there are 44 PMU installed across the Colombian Transmission system. 40 more will be installed in the following year.
- Currently the WAMS uses a rate of 10 (pps) phasors per second. It is going to be increased to 30 pps at the end of 2015.
- A new version of SCADA system is about to be implemented. This new version incorporates phasor measurements into the State Estimator along with conventional measurements.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: We expect to develop a tool that can incorporate voltage angles as a new indicator of operative problems in the system. Intuitive displays and alarms will arise in the control room to warn the operator of abnormal or much stressed operation. Automatic control actions are also planned to protect the system against partial or total blackout.

Current status of the application (in development, testing, in operation): In development

Application provider or developer: The developer is XM in collaboration with UPB University (Medellin, Colombia).

Application software (open source, proprietary): The application is being developed on top of GPA's OpenPDC using its action adapter.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): So far the application is not integrated with EMS/SCADA, and is developed externally in Microsoft Visual Studio due to the need of specialized calculation to obtain the proposed indexes. Some adjustments are going on to integrate the application to the EMS State Estimation.

Describe how the application could be operationalized (i.e. used in real-time): In order to obtain a complete visualization of phasor alarming indicators, it is necessary to deploy the PMUs needed by Cutset angles (AngC) and Center of Angles (COA) theory applied to Colombian power system. Besides, telecommunication infrastructure and architecture that has to be updated to transmit all the phasor data measures to the National Dispatch Center. Also, the angle characterization of Colombian power system has to be done in order to obtain the angle alarms for a specific situation.

Once all the information is available, the visualization platform is able to illustrate the behavior of the indicators.

Type of application GUI: The user interface and some displays of the tool are shown below.

Identify operating entities that are using the application: The application is not being used yet, it is in a development state. The idea is to be used in the future by The Colombian National Dispatch Center.

Any other relevant information:

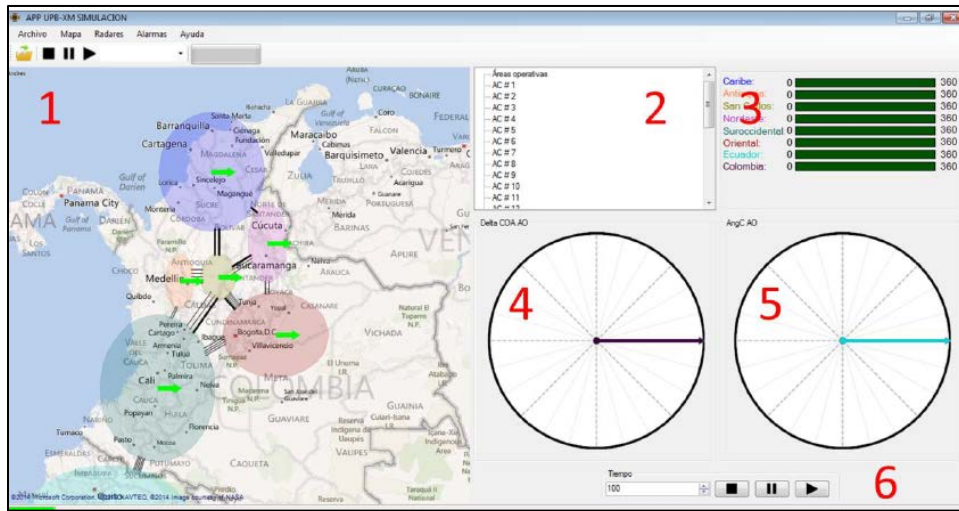*Some snapshots are as shown below in Figures 7 and 8.*

Figure 7: Typical Overview of WAMS XM, Columbia

Figure 8: Typical Display of Phase angles at XM, Columbia

VENDOR RESPONSES

5.12 ALSTOM Grid

Application name: e-terra*phasorpoint*; e-terra*vision*

Objective of the application: Ability to monitor and alarm on:
1. Phase Angle Differences as an indicator of grid stress.
2. Phase Angle Rate-of-Change to detect and characterize grid disturbances.

Application requirements (hardware, software, visualization telecommunications, etc.):
- Hardware: Physical Servers or Virtual Machines (requirements depends WAMS system sizing such as number of PMUs).
- Software: Windows or Linux
- Telecommunications/Formats: PMU/PDC data streamed in C37.118 format.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.):
- Phase Angle Difference: Sub-second phasor data (alternately, down-sampled via SCADA or State Estimator phase angles).
- Phase Angle Rate-of-Change: Sub-second phasor data.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment:
- Phase angle differences to indicate increased grid stress (due to greater power transfers or line outages) between major sources and sinks in the grid on a wide area basis.
- Phase angle rate-of-change to detect and characterize events on the grid (e.g. location, event type such as line trip or generator loss). This is especially valuable to identify a disturbance outside the SCADA/EMS footprint where PMU data may be available.

Current status of the application (in development, testing, in operation): The functionality described above is part of our WAMS products which are deployed at over 40 ISOs/TOs across 6 continents including North America, South America, Europe, Africa, Asia and Australia.

If in operation, where? The application is being used in real-time operations in Iceland, ScottishPower and Australia.

Application software (open source, proprietary): Proprietary software, however can utilize standard interfaces such as IEC 60870-5-104.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): The application can be integrated with ALSTOM or 3rd party EMS/SCADA systems,

or historians (e.g. PI) using standard interfaces such as IEC 60870-5-104 or IEEE C37.118 protocols.

Describe how the application could be operationalized (i.e. used in real-time): To operationalize the application, in addition to monitoring and alarming capabilities, operators need the ability it predict potential risks along with appropriate guidance.

As a leading EMS vendor, our WAMS applications integrate with the EMS applications such as Contingency Analysis and Dynamic Security Assessment capabilities to be able to alert operators when certain outages may cause angles to exceed their stability limits, as well as suggest corrective actions to bring angles back to safe operating conditions.

Type of application GUI: Our GUI capabilities on phase angle based monitoring include:
- Geospatial displays.
- Substation one-lines.
- High-speed trending.
- Tabulars for alerts and alarms.

Identify operating entities that are using the application: The applications are being used by ISOs, Regional Transmission Operators (RTO) and Transmission Owners.

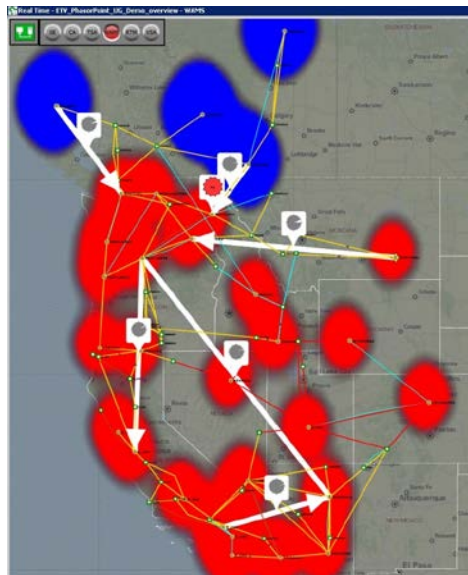**Any other relevant information:** Examples of screenshots provided below.

Figure 9: Geospatial displays showing angle difference monitoring in ALSTOM Grid Tool
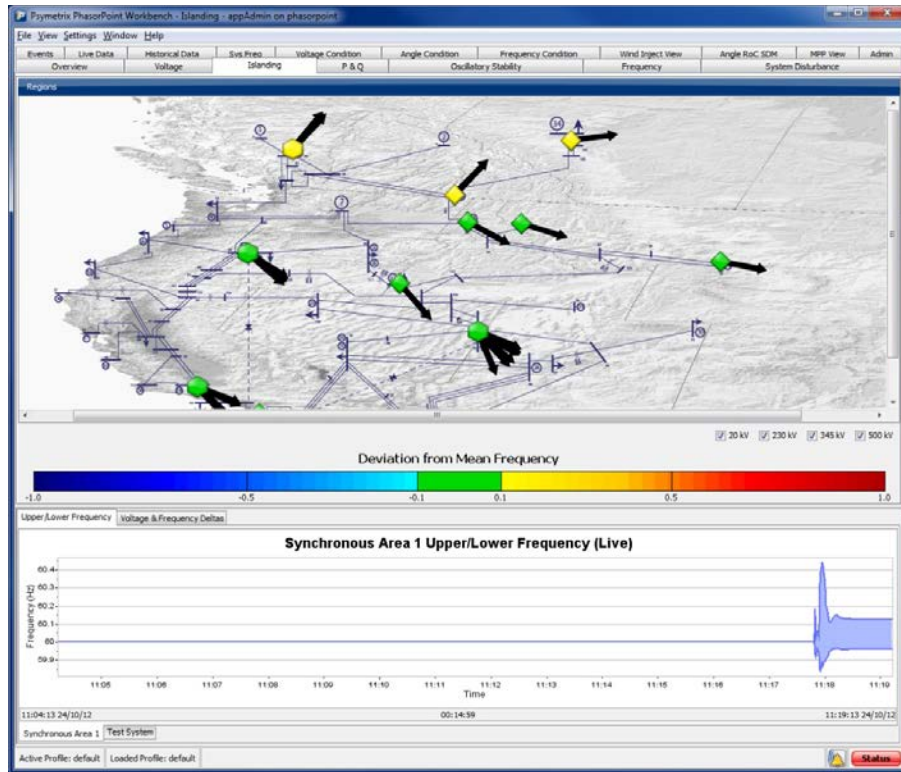
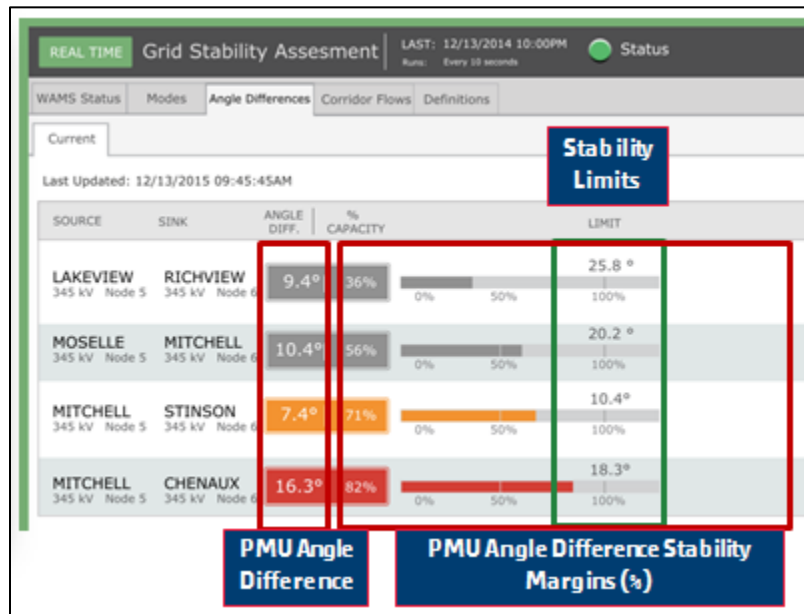Figure 10: Relative phase angle visualization (under islanding conditions) monitoring in ALSTOM Grid Tool

Figure 11: Angle Difference monitoring/alarming with respect to stability limits ALSTOM Grid Tool

5.13 ELECTRIC POWER GROUP

Application name: EPG RTDMS.

Objective of the application:
- Calculate phase angle difference
- Trigger alarms and events based on user configured limits
- Visualization of phase angle differences values and alarms results for operators and engineers

Application requirements (hardware, software, visualization telecommunications, etc.): This application will be part of the RTDMS Server. Typical hardware and software configuration for production servers are:

Server 1 Hardware Requirements Will run EPG's RTDMS Server software	
Operating System	Microsoft Windows 2008 R2
Processor Speed	2.5GHz
Processors-Cores/CPU	2 Physical Processors
Memory	8 Gigabytes Minimum
I/O ports	1 Network Interface Card (NIC) supporting 1GbPS
Hard Disk Storage	100 Gigabytes

Server 2 Hardware Requirements - Real Time Data Storage Will run EPG's RTDMS Database hosted in Microsoft SQL Server	
Operating System	Microsoft Windows 2008 R2
Database System	Microsoft SQL Server 2008 R2
Processor Speed	2.5GHz
Processors-Cores/CPU	2 Physical Processors (each with quad-core)
Memory	24 Gigabytes Minimum
I/O ports	1 Network Interface Card (NIC) supporting 1GbPS
Hard Disk Storage	2.5 TB Disk Storage (200 PMUs for 30 Days RAW phasor data, calculated data, alarms, and events)

Individual PC Hardware Requirements Will run EPG's RTDMS Client Application	
Operating System	Microsoft Windows 7, 32 or 64-bit.
Processor Speed	2.5GHz
Processor Type	Intel Core2 Quad or i7 processor
Memory	8 Gigabytes Minimum
I/O ports	1 Network Interface Card (NIC) 1 GBPS
Video Card	AMD Radeon 7500 series or better, or HD 6500 or better, or FirePro V7900 or better, with 2GB RAM or more

Figure 12: Typical hardware requirements for EPG's RTDMS Tool

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.):

- Phasor data at the rate available at the entity using the application, usually 30 samples/second.
- Voltage phasor and current phasor measurements for locations of interest

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: The phase angle separation between different locations is an indicator of the grid stress. A sudden rise in angle difference implies an impedance increase mostly caused by change of system topology, or an increase in power transfer between the monitored two locations. Either of the above causes will result in increased grid stress.

Monitoring angle separation can increase transmission system reliability by indicating and identifying excessive stress if the safe limits are approached or exceeded. With topology changes, power flows across an interface may remain unchanged leading an operator to believe conditions are satisfactory, while for the same topology change, phase angle separation changes point to increased grid stress and potential vulnerabilities that require operator attention. RTDMS monitors key phase angle separations in real-time, and the application alarms on abnormal conditions based on predefined thresholds.

Current status of the application (in development, testing, in operation):
If in operation, where? RTDMS was deployed at NYISO, ConEd, PJM, Dominion, Duke Energy, ERCOT, Oncor, LCRA, AEP, Southern Co., California Independent System Operator (CAISO), Salt River Project (SRP) and Los Angeles Department of Water and Power (LADWP).

Application software (open source, proprietary): The software is proprietary.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): RTDMS can integrate with historical data systems and EMS/SCADA systems using DNP3, OPC. It can also integrate with OSI Soft PI systems. ICCP adapter is under development.

Describe how the application could be operationalized (i.e. used in real-time): Please see #5 above.

Type of application GUI: Typical RTDMS Displays with phase angle difference monitoring:
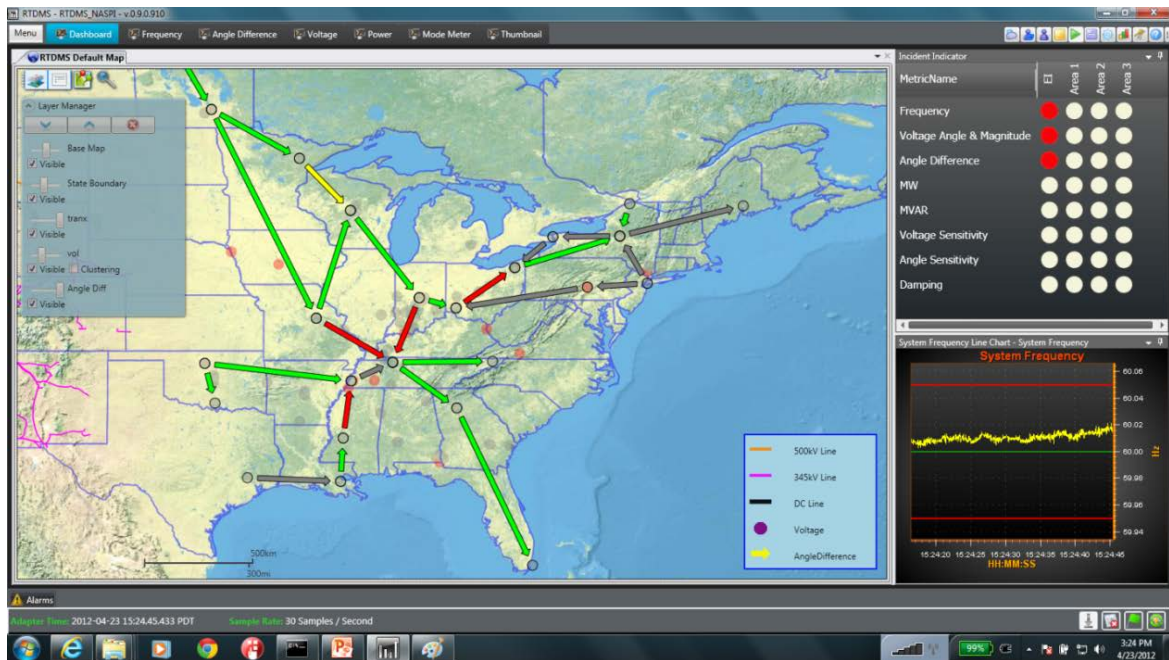
Figure 13: Typical dashboard with phase angle difference layer in map in EPG's RTDMS Tool. Corresponding alarm shows in alarm panel on the right.

Figure 14: Hover over angle difference layer on map showing detailed info with alarm threshold, signal value, data quality, etc. in EPG's RTDMS Tool
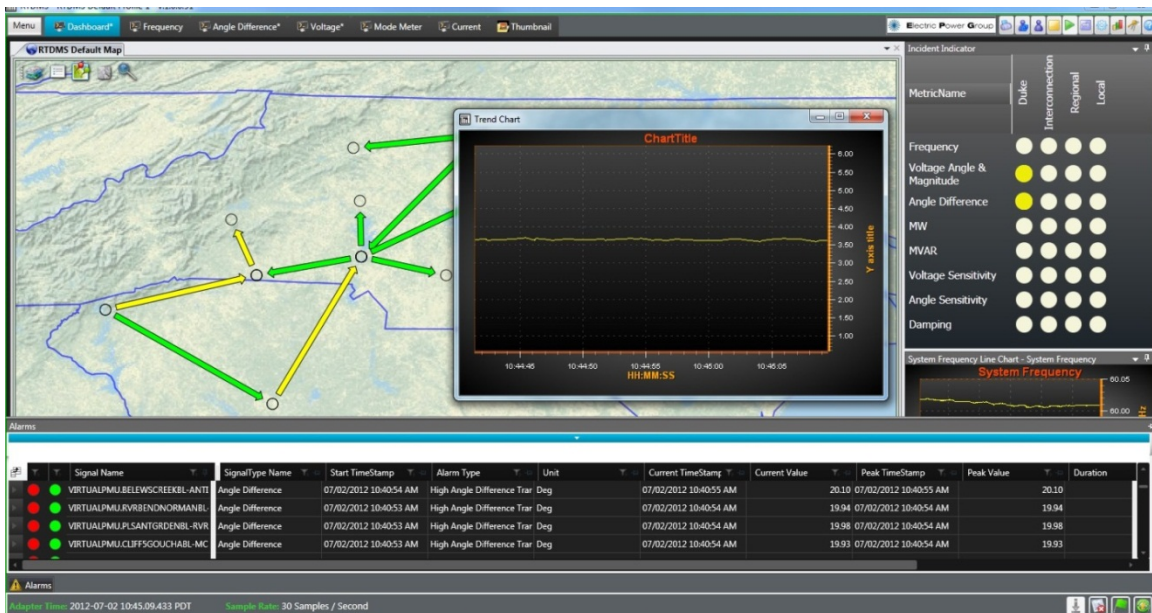
Figure 15: From alarm view to locate alarm on map and to pop up angle difference signal in trend chart in EPG's RTDMS Tool

The phase angle display can be configured in any way that fits the user's need, using various view templates in RTDMS.

Identify operating entities that are using the application: This application is used at NYISO, PJM, Dominion, Duke Energy, ERCOT, Oncor, LCRA, AEP, Southern Co., CAISO and SRP.

5.14 EPRI AND POWERTECH LABS

Application name: VOB – Visualization of Operating Boundaries

Objective of the application:
- Visualize the relation between angle separation and system stability
- Visualize transfer limits
- Drill-down/root cause analysis
- Consolidation of multiple data sources in one display: PMU, VSA results, TSA results (VSA/TSA: Voltage/Transient Stability Assessment)

Application requirements (hardware, software, visualization telecommunications, etc.):
- Web application in an intranet environment
- Host server computer for the intranet environment
- Client workstation, can be laptop or desktop connected to intranet

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.):

- Transient and voltage stability assessment results provided by real-time DSA analysis in a universal XML format specified in VOB's manual
- PMU data in IEEE C37.118 format streamed through a TCP port

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment:
- Visualize the relationship between angle separation and system stability
- Consolidation of PMU results super-imposed on a traditional transfer analysis display

Current status of the application (in development, testing, in operation):

- PMU enhancement to VOB is under development/testing
- The VOB project in general has gone through several iterations since 2012

If in operation, where?

- Under development/testing

Application provider or developer:
Provider: EPRI
Developer: Powertech Labs Inc

Application software (open source, proprietary):
Proprietary. Available to EPRI members

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI):
- Integrates with PMUs/PDCs/other application that streams PMU data in IEEE C37.118 format
- Integrates with online/offline security assessment results (both VSA and TSA)
- Can connect with any software so long as it outputs/converts output to the universal XML format described in VOB's manual
- Currently Powertech Lab's VSAT and TSAT already outputs this format

Describe how the application could be operationalized (i.e. used in real-time):
It requires the followings:
- Visualize a consolidated transfer limit display of VSA, TSA and PMU data on one merged display in real-time as soon as results become available

Type of application GUI
- Web-based intranet application
- GUI accessed from an internet browser (Internet Explorer, Firefox, Chrome)

Identify operating entities that are using the application:
- The PMU portion of VOB is still under development/testing. Case studies have been performed by a couple utilities such as Southern Company and ISO-NE.

Any other relevant information
- Visualization of Operating Boundaries (VOB) 2.0. EPRI, Palo Alto, CA: 2013. 3002001161
- Visualization of Operating Boundaries (VOB) 3.0. EPRI, Palo Alto, CA: 2014. 3002002874
- Visualization of Operating Boundaries: Case Study for ISO-NE. EPRI, Palo Alto, CA: 2014. 3002004872
- Visualization of Operating Boundaries: Case Study for Southern Company. EPRI, Palo Alto, CA: 2013. 3002002496.
- "Real-time Visualization of Security Boundary" Presentation at WECC JSIS Meeting, March 2015

5.15 QUANTA TECHNOLOGY

Application name: (Voltage) Phase Angle (Difference Monitoring and) Alarming

Note: This application is limited to voltage phase angle difference monitoring and alarming between a pair of nodes of a grid for angle stability monitoring purpose. The "phase angle difference" and "phase angle" may be used to mean the same "voltage phase angle difference" in this document.

Objective of the application: Provide grid operators with a new real-time dynamic grid stress level monitoring and alarming tool to assist operators in
- Visualizing system stress levels correlated to monitored phase angles
- Generating alarms to alert grid operators to any approaching and occurring conditions that may lead to major system disturbances

Application requirements (hardware, software, visualization telecommunications, etc.):
- PMUs installed at required locations
- A system including at minimum communication networks to transfer measurement data from PMUs to grid control centers, software system for data collection and validation, phase angle difference visualization (on geospatial / one-line, dial chart, trending chart, etc.), alarm generation, display / sounding, logging and management

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): For all intended uses of the application as described in 2
- 30 frames/s or higher synchrophasor data rates

- sub-second latency

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment: Phase angle alarming is important when certain phase angles directly linked to the angel stability of part of the system (e.g. phase angle difference between a remote generation station and main grid)
- Generate an audible / visual alarm when a phase angle exceeds a predetermined threshold frees operator from constantly monitor the phase angle while still can respond to the situation quickly
- Generate an audible / visual alarm when a phase angle and the change of the phase angle indicate that it is moving towards to exceeds a predetermined threshold – this will provide an early warning to operators for an developing condition, which will provide operator time to take corrective actions to prevent it developing into a major disturbance

The visibility of stress level provided by high resolution and low latency phase angle difference visualization is extremely useful in assisting operators in assessing various grid operating conditions where phase angle difference will determine the actions needed
- Generation / load control – adjust dispatching to make the angle difference within a pre-determined threshold
- Assist operators in adjusting generation and load to bring the phase angle to be within the limit – used to be done based on past experience or trial & error

Current status of the application (in development, testing, in operation):
Phase angle monitoring and alarming application is available in off-the-shelf products from several suppliers (see 8 below). It is generally available as part of their products which have been installed at a number of utilities. The specific features, functionalities and performance may vary from product to product though (e.g. not all use rate of change of phase angle for alarming)

If in operation, where? If this means the product has been installed, then YES, a number of DOE SGIG recipients and a few utilities have installed various products that included this application.

If this means it has been used in the daily operation, then it is still a NO for many users. Enhanced data validation tool, baseline studies, new operation procedures, and proper operator training are needed for the application to be operational use ready. Many users are still in the process to work these out.

Application provider or developer: Here is an incomplete list of suppliers: ABB, Alstom, EPG, GE, SEL, Space-Time Insight (STI) and Siemens. There are many oversea suppliers not listed here.

Application software (open source, proprietary): Proprietary for those suppliers listed above

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): In general, there is no major technical barrier for such integration. Alarms generated by the application can be sent to EMS/SCADA for display and data archiving by data historians. The major challenge is on EMS/SCADA side as getting such data to a particular EMS/SCADA system is supplier dependent and not the same for all EMS/SCADA systems.

Describe how the application could be operationalized (i.e. used in real-time):
It requires the followings:
- Validated synchrophasor data at phasor data rate as input to the application
- Operational use related studies to establish various threshold settings for angle stability monitoring and alarming for selected angles
- Operation procedure for its uses (e.g. breaker reclosing, what operator should do when an alarm is generated)
- Operator training in a realistic operation environment – e.g. operator must be trained to simultaneously use both EMS system and the synchrophasor system to handle various operation situations if both systems are used in a control center

Type of application GUI
The followings should be included for angle and angle changes:
- Angle real-time visualization GUI
  - System view (either geospatial or one-line system view) that show the angle difference being monitored and the alarms
  - Angle visualization in dial chart
  - Angle difference trending chart
- Alarm view and management GUI
  - Real-time visualization – could be part of a dashboard view or other customized view
  - Alarming log view – generally is part of an alarm log view for all alarms
- Configuration GUI – for defining angle pairs to monitor, setting alarm thresholds

5.16 SCHWEITZER ENGINEERING LABORATORIES (SEL)

Application name: SEL SynchroWAVe Central

Objective of the application: SynchroWAVe Central provides situational awareness to operators and engineers through real-time visualization and post event analysis.

Application requirements (hardware, software, visualization telecommunications, etc.): SEL SynchroWAVe Central requires a C37.118 data stream from each location where phase angle visibility and alarming is desired.

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.): SEL SynchroWAVe Central can display and alarm at any C37.118 data stream message rate.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment:
SEL SynchroWAVe Central phase angle alarming and visualization provides awareness of system stress conditions and provides the information necessary to take action.

Current status of the application (in development, testing, in operation): SEL SynchroWAVe Central
- Real-time and historic synchrophasor visualization application with an installed base world-wide.
- Applications range in size from local generation monitoring with a signal PMU to wide-area monitoring with more than 100 PMUs.

If in operation, where? Please reach out to SEL for more information on application installations.

Application software (open source, proprietary): SEL SynchroWAVe Central code is proprietary.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): SEL SynchroWAVe Central supports multiple C37.118 data stream inputs.

Describe how the application could be operationalized (i.e. used in real-time):
SynchroWAVe Central provides phase angle alarms to operators from the dynamic dashboard. Phase angle alarm threshold information is provide upon selection of the alarm. Angle differences between locations can be displayed via geospatial displays, chart trends and phasor diagrams for real-time visualization.

Type of application GUI: SEL SynchroWAVe Central Server\Web-client application for easy access and sharing of customizable displays.

Identify operating entities that are using the application: Please reach out to SEL for more information on application installations.

Any other relevant information:

Example: Can you provide a sample video clip demonstrating the capabilities of the tool

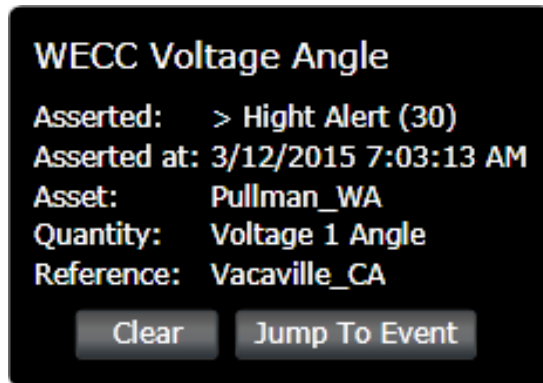Figure 16: Alarm Panel Display in SEL's SynchroWAVe Tool

Figure 17: Alarm Overview Display in SEL's SynchroWAVe Tool

Figure 18: Customized Phase Angle Display in SEL's SynchroWAVe Tool

Figure 19: Geospatial Angle Difference Display in SEL's SynchroWAVe Tool

5.17 V & R ENERGY

Application name: Region of Stability Existence (ROSE)

Objective of the application: Objectives of the application include:
- State Estimation:
  - Traditional – uses SCADA data;
  - Linear – uses synchrophasor measurements;
  - "Hybrid" – uses both SCADA data and synchrophasor measurements.
- Power flow;
- Real-time AC contingency analysis:
  - N-1, N-1-1, and N-2 AC contingency analysis while modeling complex real-time RAS actions.
- Voltage stability analysis:
  - Computes voltage stability margins under N-k contingency conditions.
  - Computes transfer (interface) limits. Simultaneously monitors and enforces voltage stability, voltage constraints and thermal overloads during computations
  - Performs PV-curve, QV-curve analyses.
- Phase Angle Limit Computation;
- Automatic remedial actions:
  - Automatic corrective actions to alleviate voltage, thermal, and voltage stability violations;
  - Automatic actions to increase voltage stability margins.
- Boundary-based solution;
- Analysis of cascading outages.

Application requirements (hardware, software, visualization telecommunications, etc.):

Typical hardware configuration for production servers are:

- 4X XEON E7-4870 @ 2.4 GHz with 32 GB RAM.
- 500 GB to 1 TB hard drive is sufficient. However, this depends on the amount of archived data that will be kept on the server.
- No specific requirements for other hardware components (video card, network card, etc.)

Software requirements for production servers are:

- Microsoft® Windows® Server 2008
- Microsoft® Internet Explorer 9
- IIS v.7
- .Net Framework 4.0

Typical hardware configuration for desktop computers are:

- Core i7-3930K, 16GB, 1TB
- Application is optimized for screen resolution 1920 x 1200

Software requirements for desktop computers are:

- Microsoft® Windows® 7
- Microsoft® Internet Explorer 9
- IIS v.7
- .Net Framework 4.0

Definition of data requirements (e.g. phasor, SCADA, resolution, etc.)

For "hybrid" – based ROSE, phasor and State Estimator data sets are required:

- Phasor data at the rate available at the entity using the application, usually 30 samples/second.
- State Estimator data at the rate available at the entity using the application, usually 3 to 5 minutes.

For measurement – based ROSE, phasor data is required:

- Phasor data at the rate available at the entity using the application, usually 30 samples/second.

Identify the incremental improvement or benefit to be derived by using this application in the real-time operating environment

The application provides continuous real-time determination of exact system limits:

- o Voltage stability limits, including:
    - Computing interface limits;
    - Performing PV-curve and QV-curve analyses;
    - Determining the region of secure system operation and its boundary.
- o Phase angle limit:
    - Across any user-defined bus pairs;

- Across locations, automatically identified by ROSE.

Depending on the implementation computations are based on:

- Combination of model and measurement data for "hybrid"-based ROSE:
In this implementation, the limit is computed using State Estimator data at State Estimator sampling rate, and current operating point is computed using synchrophasor data at synchrophasor sampling rate.

    OR

- Linear state estimation for measurement-based ROSE:

    In this implementation, both the limit and the current operating point are computed using synchrophasor data at synchrophasor sampling rate.
- The application computes <u>the EXACT ACCURATE VALUE, NOT APPROXIMATION, of the voltage system limits, including voltage stability margin, and phase angle limit</u>.

Current status of the application (in development, testing, in operation).

If in operation, where?
- ROSE was deployed at Peak Reliability, and is designed to become part of suite of applications used by Peak Reliability in its operations.
- ROSE application has been successfully deployed at ISO-NE and demonstrated the efficiency for on-line power system security estimation and monitoring. Application is used by engineers today and ISO-NE has developed synchrophasor technology roadmap to migrate the technology into control room.
- As a result of new DOE project, ROSE will be also deployed at Bonneville Power Administration (BPA), CAISO, Idaho Power Company (IPC), San Diego Gas & Electric (SDGE) and SCE.

Application software (open source, proprietary): The software is proprietary. Code for customization, interfacing, and visualization that is developed for a particular entity is transferred to that entity.

Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI): ROSE has been already integrated with EMS systems and data historians. State Estimator cases and RAS status points (when applicable) are read by ROSE Real-Time on a schedule basis 24/7; alarms (both State Estimator and PMU) are sent back from ROSE to the EMS. ROSE Off-Line performs the same analysis as ROSE Real-Time when initiated by a user.

Describe how the application could be operationalized (i.e. used in real-time): See item 6.

Type of application GUI: "Hybrid"-ROSE utilizes both State Estimator and PMU data to compute voltage stability limit and phase angle limit and margin. Values of phase angles at given buses are computed at the base case and at Voltage Stability Limit. The difference between the phase angle values at the voltage stability limit and base case is phase angle margin. ROSE computes phase angle margins, and triggers alerts/alarms when phase angle margin violates user-defined threshold.

Peak-ROSE GUI is shown in Fig. 20. This is a "hybrid"-ROSE implementation, which utilizes both State Estimator and PMU data.
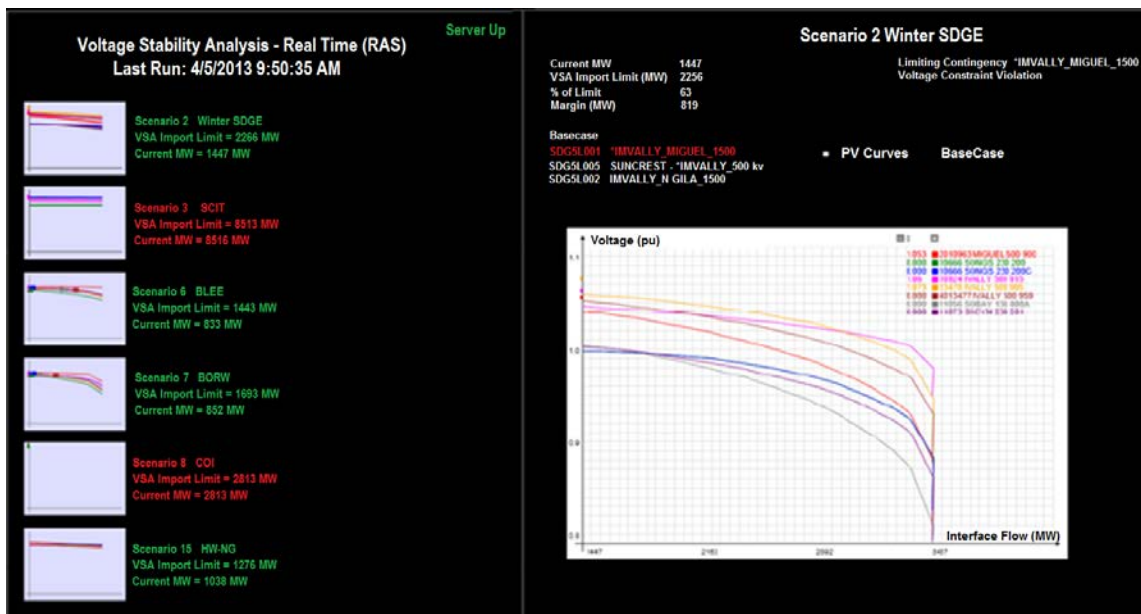

Figure 20: GUI of V&R Energy's ROSE tool at Peak

ISONE-ROSE GUI is shown in Fig. 21. This is a "hybrid"-ROSE implementation, which utilizes both State Estimator and PMU data.
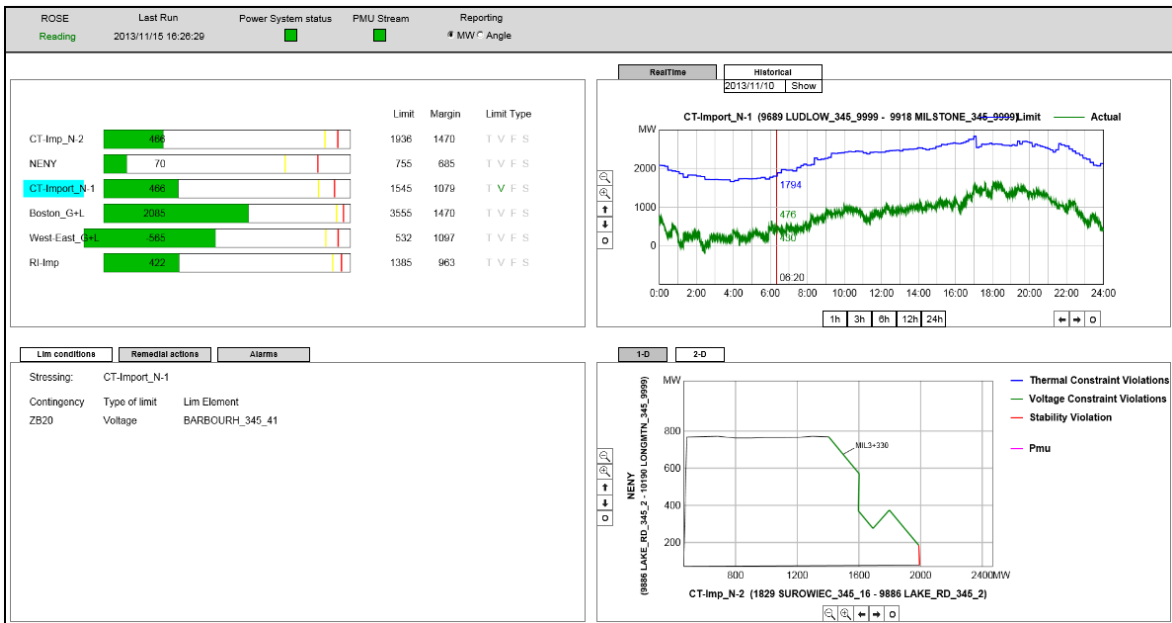
Figure 21: GUI of V&R Energy's ROSE tool at ISO New England

Bus voltage angle difference is one of the metrics for operating margin in ROSE. PMU data reflects current operating point and trigger alert/alarm if operating margin violates user-defined thresholds, see Fig. 22.
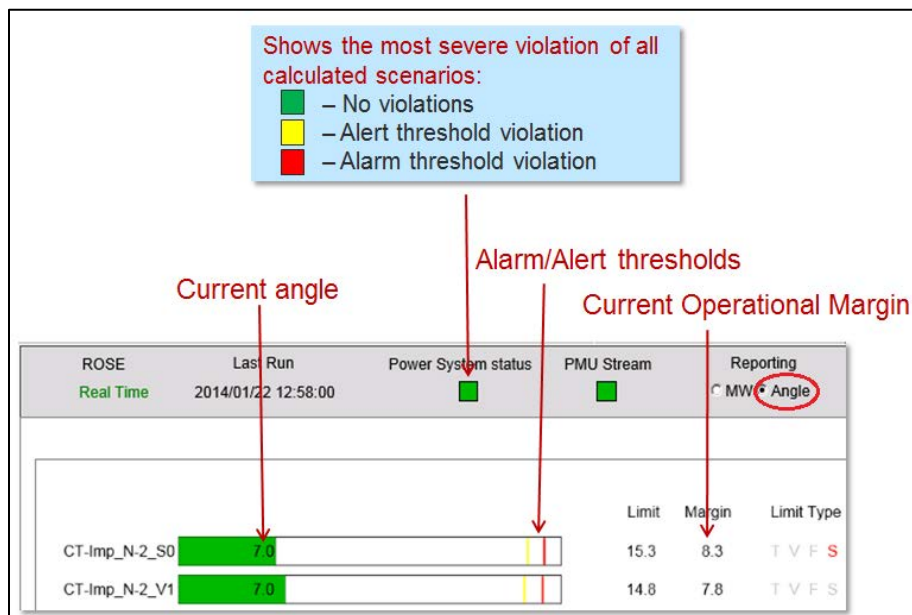

Figure 22: Phase Angle Alarming in V&E Energy's ROSE tool

PMU angles to display the limits and current system state are shown in Fig. 23.
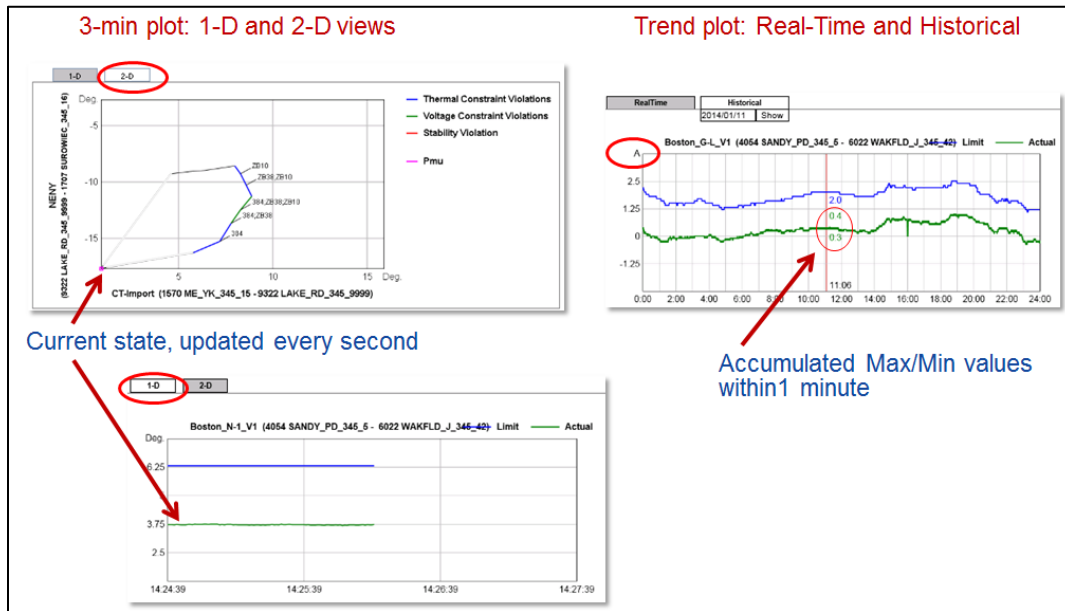

Figure 23: Use of Phase Angles to Compute Current Operating Point and the Limit in V&R Energy's ROSE Tool

A real-time event observed on the plane of phase angle difference across an interface triggered phase angle alarm, when the operating margin dropped below the Alarm threshold, as shown in Fig. 24.
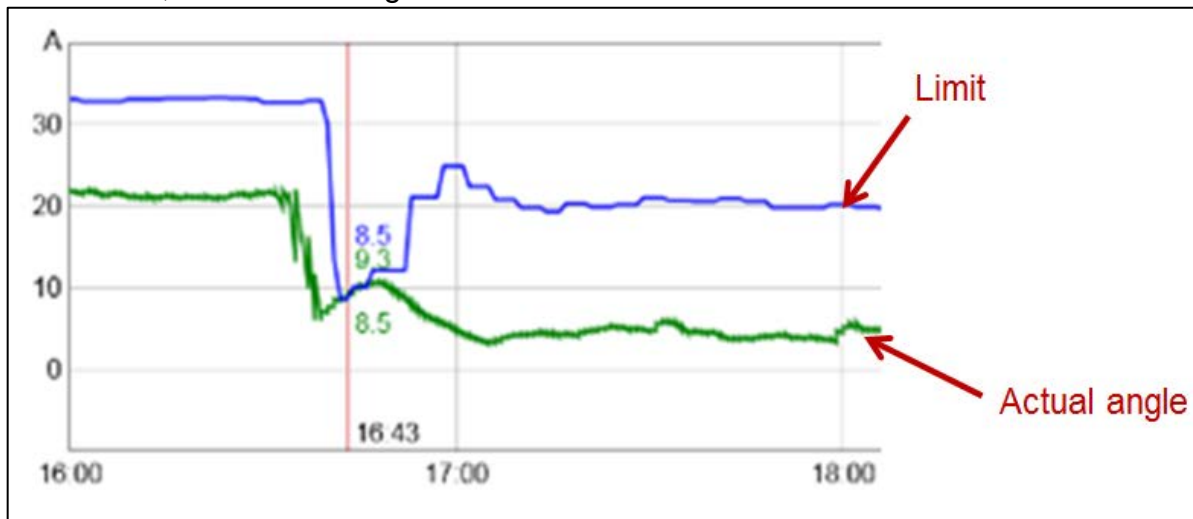

Figure 24: Expressing an Interface Limit as Angle Difference Across this interface in V&R Energy's ROSE Tool

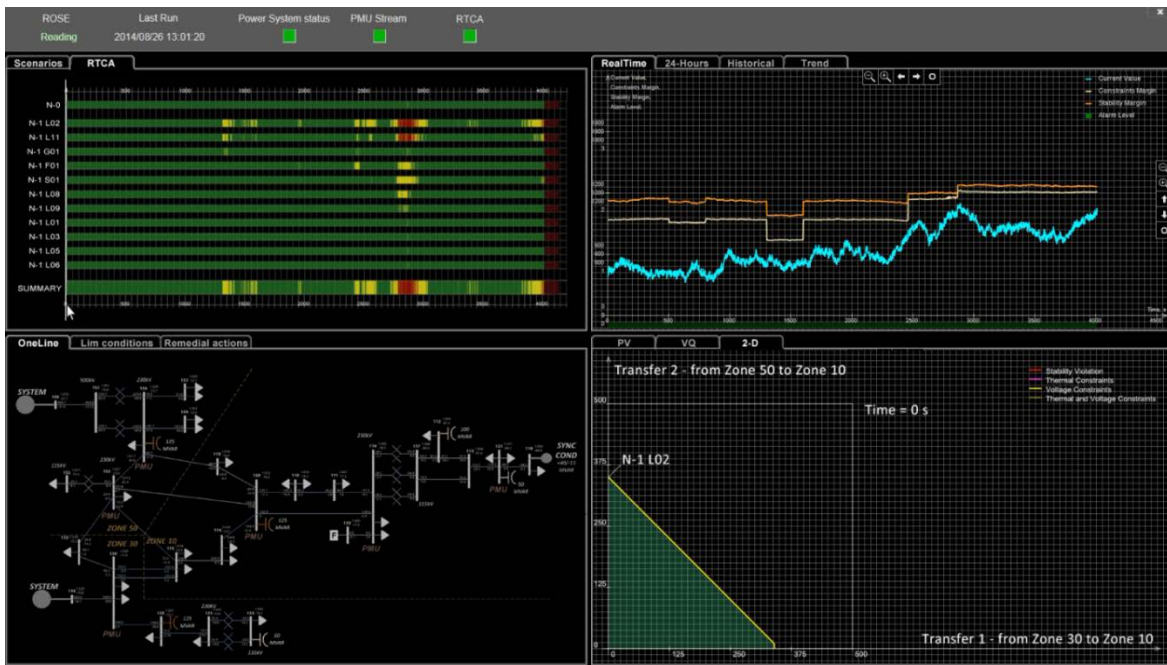Measurement-based ROSE GUI is shown in Fig.25. It utilizes only PMU data.

Figure 25: Measurement -Based GUI in V&R Energy's ROSE Tool

> * *Figures 20- 23 were prepared by ISONE using ISONE-ROSE.*

Identify operating entities that are using the application: ISO New England and Peak Reliability are using the application. Five entities are starting a project to deploy ROSE. They are BPA, CAISO, IPC, SDGE, and SCE.

6   Conclusions

The CRSTT received responses from 17 parties regarding the use of synchrophasor technology for phase angle alarming. From these responses, it is clear that this technology is capable of successfully monitoring phase angles across important locations and alarming for conditions that indicate increased stress across the system. Using this new technology to identify growing angular separation will benefit electric utilities and grid operators by increasing awareness of system conditions that may require corrective action to ensure the grid is operated in a safe and reliable manner.

Glossary of Acronyms

Acronym	Definition
AESO	Alberta Electric System Operator
AC	Alternating Current
APS	Arizona Public Service
ATC	American Transmission Company
BA	Balancing Authority
BES	Bulk Electric System
CAISO	California Independent System Operator
CRSTT	Control Room Solutions Task Team
DNP	Distributed Network Protocol
DP	Distribution Provider
EEA	Energy Emergency Alert
EOP	Emergency Operations and Preparedness
EPG	Electric Power Group
EMS	Energy Management System
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FRCC	Florida Reliability Coordinating Council
GO	Generator Owner
GOP	Generator Operator
GPS	Global Positioning System
IEEE	Institute of Electrical and Electronics Engineers
LADWP	Los Angeles Department of Water and Power
LCRA	Lower Colorado River Authority
MISO	Midcontinent Independent System Operator

Acronym	Definition
MP	Minnesota Power
NASPI	North American Synchrophasor Initiative
NERC	North American Electric Reliability Corporation
NOPR	Notice of Potential Rulemaking
NYISO	New York Independent System Operator
PDC	Phasor Data Concentrator
PJM	PJM Interconnection, LLC
PMU	Phasor Measurement Unit
RC	Reliability Coordinator
RMS	Root Mean Square
ROCOF	Rate-of-Change of Frequency
ROSE	Region of Stability Existence
RTDMS	Real-Time Dynamics Monitoring System
SCADA	Supervisory Control and Data Acquisition
SEL	Schweitzer Engineering Laboratories
SOL	System Operating Limit
SRP	Salt River Project
TO	Transmission Owner
TOP	Transmission Operator
WECC	Western Electricity Coordinating Council