Using Synchrophasor Data for Voltage Stability Assessment

NASPI Control Room Solutions Task Team Paper

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Acknowledgments

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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: enhanced state estimation, phase angle monitoring, oscillation detection, system islanding detection and blackstart restoration, determining disturbance locations, and voltage stability assessment. Existing versions of these papers can be found on the CRSTT page of the NASPI website (https://www.naspi.org/crstt).

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1. Introduction

This paper describes certain functional entity roles and responsibilities related to voltage stability monitoring, considers how synchrophasor technology may be used to identify actual or potential voltage stability issues, and describes some of the related commercial applications that are currently available to the industry.

This paper describes applications for which the NASPI CRSTT received information from application users or vendors and may be updated to include additional applications as new information is provided.

Synchrophasor technology provides high resolution and time-synchronized measurements of voltage magnitude and angle along with other power system measurements over the wide-area of the utility system and its interconnection. These measurements are input to applications for determining the voltage stability of the grid. A grid's stability limit varies in real-time as the grid's current operating conditions and constraints change.

2. Functional Entity Responsibilities Related to Voltage Stability Assessment

The Reliability Coordinator (RC) and Transmission Operator (TOP) functional entities have similar roles in ensuring reliable operation of the bulk power system.[1]

- The RC maintains real-time operating reliability of its own RC Area and coordinates with neighboring RCs to provide a wide-area view of the grid. The RC's roles focus on both the transmission and balancing operations. The RC has authority to direct other entities to take action to ensure reliable operation within its RC footprint.
- The TOP is responsible for reliable real-time operation of the transmission assets under its purview and has the authority to take actions to ensure its TOP Area operates reliably.

Though the TOP and RC have similar roles, their scopes with respect to safe and reliable operation of the bulk transmission grid are different. The TOPs focus on their

[1] Refer to the "NERC Functional Model": http://www.nerc.com/pa/Stand/Pages/FunctionalModel.aspx

defined area of operation, while the RCs ensure a wide-area view of their entire RC Area and neighboring RC Areas.

The entities registered to perform these functions must be able to identify and address voltage stability issues that may adversely impact reliability.

2.1 Transmission Operator Responsibilities

Each TOP must establish System Operating Limits (SOL) for its portion of the RC Area that are consistent with the SOL methodology developed by the RC. Examples of SOLs may include, but are not limited to – Facility Ratings, voltage operating limits, voltage stability limits, transient stability limits, Transmission Path limits or any other operating limit established to ensure acceptable system performance in pre- and post-contingency states.

Each TOP, either individually or jointly with other TOPs, must develop, maintain and implement formal policies and procedures to provide for transmission reliability. These policies and procedures must address the execution and coordination of activities that impact inter- and intra-regional reliability, including responding to Interconnection Reliability Operating Limit (IROL) and SOL violations. The *Glossary of Terms Used in NERC Reliability Standards* defines IROL as, "A System Operating Limit that, if violated, could lead to instability, uncontrolled separation, or Cascading outages that adversely impact the reliability of the Bulk Electric System (BES)."

TOPs must perform seasonal, next-day and current day studies to determine SOLs and must have sufficient information and analysis tools to determine the cause(s) of SOL violations. These analyses must be conducted in all operating timeframes and the results used to immediately mitigate SOL violations.

Upon occurrence of an IROL exceedance, TOPs must take all appropriate actions up to and including shedding of firm load, or directing the shedding of firm load, to return the transmission system within the IROL as soon as possible but no longer than 30 minutes. TOPs experiencing or contributing to an IROL or SOL violation must take immediate steps to relieve the condition, which may include shedding of firm load.

2.2 Reliability Coordinator Responsibilities

The RC is required to monitor elements of the BES within its RC Area that could result in an SOL or IROL violation and must know the status of all critical facilities whose failure, degradation, or disconnection could result in an SOL or IROL violation. The RC must also monitor current pre- and post-contingency element conditions (voltage, thermal, or stability), including any applicable mitigation plans to alleviate SOL or IROL violations and identify actual or potential SOL and IROL violations in real-time.

When an assessment of actual or expected system conditions predicts that an IROL in its RC Area will be exceeded, the RC must implement one or more Operating Processes, Procedures or Plans to prevent exceedance of that IROL. When actual system conditions show that there is an instance of exceeding an IROL in its RC Area, the RC shall, without delay, act or direct others to act to mitigate the magnitude and duration of the instance of exceeding that IROL within the IROL's Tv (the maximum amount of time the system operator has to return to a state that is at or below the limit before being subjected to compliance sanctions). The RC shall evaluate actions taken to address an IROL or SOL violation and, if the actions being taken are not appropriate or sufficient, direct specific actions required to return the system to within limits.

3. Using Synchrophasor Data to Detect Voltage Stability Issues

Before exploring how synchrophasor data can be used to detect voltage stability issues, it's important to understand how synchrophasor technology works.

3.1. Overview of Synchrophasor Technology

A synchrophasor is a time-synchronized measurement of a quantity described by a phasor.[2] Like a vector, a phasor has magnitude and phase information. Devices called Phasor Measurement Units (PMU) measure voltage and current and with these measurements calculate parameters such as frequency and phase angle.[3] Data reporting rates are typically 30 to 60 records per second, and may be higher. 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 an accuracy of a microsecond, synchronized using the universal clock 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 determined as 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.[2]

[2] NASPI, "Synchrophasor Technology Fact Sheet", 2014. Available at https://www.naspi.org/File.aspx?fileID=1326.

[3] Phadke, A.G.; Thorp, J.S. *Synchronized Phasor Measurements and Their Applications*, New York, Springer, 2008.

3.2. How Synchrophasor Data Can Be Used for Voltage Stability Assessment

Voltage stability is one of the fundamental concepts in power system stability analysis, and is essential for maintaining normal operation of today's power systems. Most grid oscillations and voltage stability challenges were not observable before PMU deployment enabled high-speed grid monitoring across much of the grid. Both local and interconnection-wide oscillations have the potential to harm grid assets and could set off wide-scale blackouts. Similarly, local voltage stability issues can cause power quality problems and could cascade into major grid disruptions.

There are multiple definitions of voltage stability, including:

- "Voltage stability is the capability of the system to supply the load with reactive power for a given real power demand", V. Venikov.
- "Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition", IEEE/CIGRE Joint Task Force on Stability Terms and Definitions (P. Kundur et al), "Definitions and Classification of Power System Stability," IEEE Trans. on Power Systems, vol. 19, no. 2, August 2004, pp. 1387-1401.

System dynamics influencing voltage stability are usually slow, therefore steady-state (power flow) analysis offers an effective way to perform Voltage Stability Assessment (VSA). Power – voltage (PV) and voltage – reactive power (VQ) curves are the most frequently used steady-state techniques for voltage stability assessment. Prior to synchrophasor data, on-line VSA was performed in the operator's State Estimator (SE) at its operational rate, which usually occurs every three to ten minutes. This is more than 1000 times slower than synchrophasor data.

The advantage of synchrophasor data is that it allows for continuous monitoring of the power system and observation of actual voltage conditions, with computation of operating margins at much higher resolution rates than what has been available with VSA using SCADA and SE data. Synchrophasor data also provides advanced real-time visualization of current operating conditions and voltage stability limits to better assess the power system's proximity to system collapse. Calculation of voltage stability conditions and forecasting of future conditions using synchrophasor data uses more precise and up-to-date grid condition information, enabling better VSA and predictions. Therefore, PMU-based alarming on when the power system has low voltage stability margins and is approaching system collapse reflects real-time information about the power system state, rather than minutes-old, SE-based information.

A voltage stability assessment tool that offers value for a reliability coordinator or transmission operator should be able to perform the following functions:

- Accurately determine real and reactive power margins in real-time across a wide area and in local detail;
- Identify, alert and alarm operators to locations and conditions where voltage is not presently within appropriate limits;
- Using sensitivity analysis for PV, QV, dV/dP, dV/dQ, or other factors, estimate, alert and alarm to conditions where, based on current trends or contingencies, voltage may soon violate appropriate limits;
- Identify limiting contingency(ies);
- Display all of the above visually;
- Suggest actions that can be taken to address and mitigate identified voltage instability problems.

4. NASPI Voltage Stability Workshop

NASPI held an Oscillation Detection and Voltage Stability Tools Technical Workshop in Houston, Texas on October 22, 2014. All participating vendors were given identical datasets for each test case in order to perform synchrophasor-based analysis. Data included a power system steady-state model, all operating assumptions, PMU measurement locations, and PMU data.

The goal of the Workshop was to test several vendors' applications against a known dataset to compare the various computational methods, algorithms, and visualization techniques used by each vendor tool. The participating vendors submitted videos describing their methodology, tools, and test case results prior to the Workshop. The results of the analysis were not known to the participants ahead of time and were only announced on the day of the workshop.

NASPI representatives prepared two test cases for the voltage stability portion of the workshop. Case 1 was a relatively simple case where synchrophasor-based voltage stability analysis was performed for N-0 conditions (i.e., contingency analysis not performed). Case 2 was a more complex case where synchrophasor-based voltage stability analysis was performed for N-0 and N-1 contingency conditions.

Since voltage instability is a relatively rare phenomenon, it is hard to use actual data sources for recreating test cases for voltage stability analysis. Therefore, NASPI created test cases using power flow solutions using a Time Step Simulation (TSS) power flow methodology. The TSS generated a set of power flow base cases with input data such as generator outputs and load changes and discrete switching actions such as transmission line opening operations and other automatic operations (i.e., shunt capacitor switching, generation operation modes, etc.). The datasets included PMU output data for the PMU locations, but not the entire set of power flow solutions. The data provided allowed the VSA tools to detect all automatic operations and system states.

The test cases developed by NASPI and the results of measurement-based voltage stability analysis submitted by workshop participants are described below, and are posted on the NASPI website.

4.1. NASPI VSA Test Case 1

Test Case 1 is a 10-bus model (see Fig. 1) that represents a wind generation hub consisting of three independent wind farms and one shunt capacitor connected to a long 230kV transmission line. PMUs were located at all major transmission-level buses; note that all other buses represented either mid-line taps, system equivalents, or generation equivalents.

The event dataset for this test case included:

- The system model (10-bus power flow base case) at time t=0 s;
- 600-seconds of synchrophasor data from the PMUs indicated in Fig. 1 at the sampling rate of 30 samples/sec;
- System modeling and operating assumptions necessary to perform voltage stability assessment.

The test simulation consists of a large ramp in wind, with the system remaining stable throughout the ramp. However, variability of the renewable generation resources demands better visualization tools and analytics for understanding how “close to the edge” the system is from voltage collapse. Therefore, the goal of this test case was simply to showcase the tools available for visualizing the boundary of voltage instability and the current operating state.

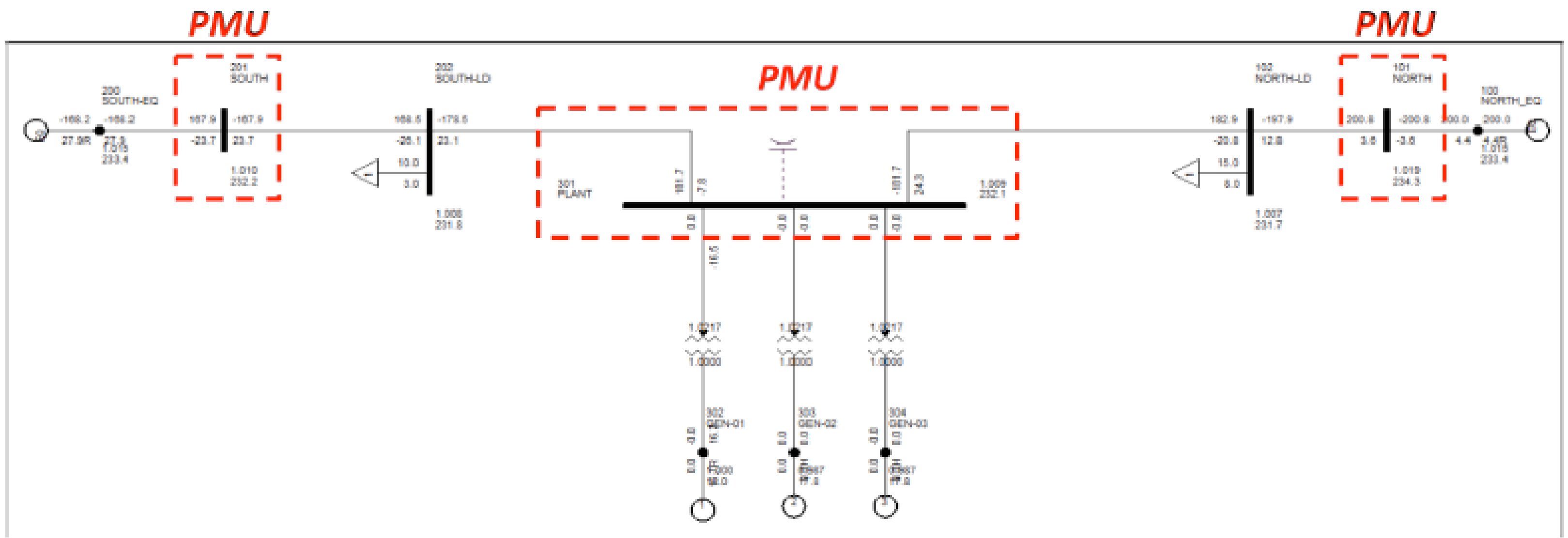

Fig. 1. NASPI VSA Test Case 1

4.2. NASPI VSA Test Case 2

Test Case 2 is a 26-bus model (see Fig. 2) that represents a “radial” load pocket consisting of various voltage transformations, reactive resources, and a transmission network. PMUs were located throughout the network at six buses (for additional details refer to the NASPI website), such that the majority of the network was observable. Two equivalent generators, identified as “SYSTEM”, represented this smaller network’s connection to the larger bulk power system. The system was also separated into three Zones (10, 30, and 50) to help illustrate the issue of a cohesive load zone. This enabled identification of cut planes, load zones, and generation pockets necessary to perform stability assessment, as shown in Fig. 2.

The event dataset included the following information:

- The system model (26-bus power flow base case) at time t=0 s;
- Over 6000-seconds of synchrophasor data from 6 PMUs at 2-second down-sampled rate;
- Contingency list that contained 40 contingencies;
- System modeling and operating assumptions necessary to perform voltage stability assessment.

NASPI also provided a detailed set of system modeling and assessment assumptions so they could recreate the sequence of events either using PMU data or using models derived from the t=0 base case and the PMU data.

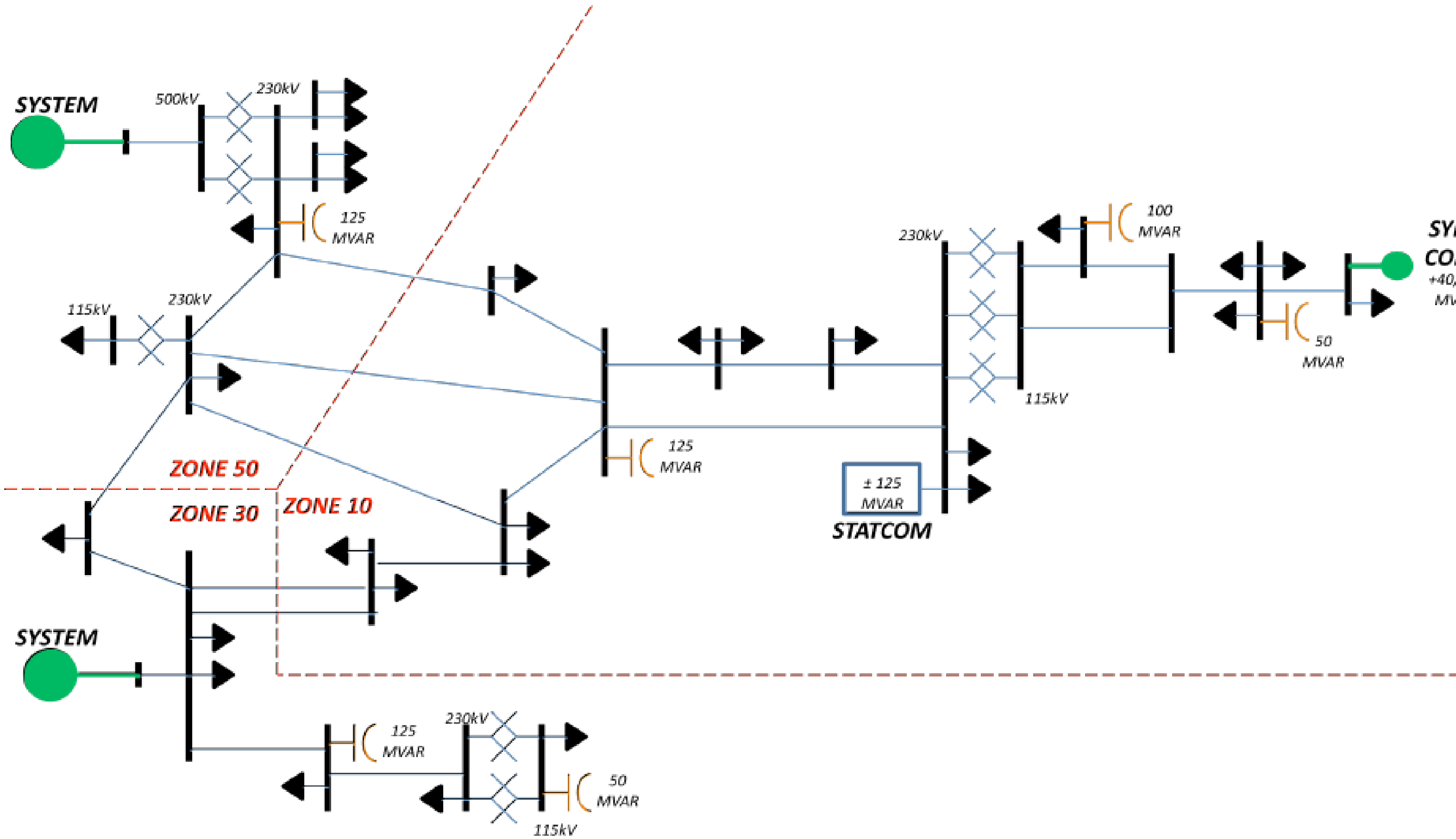

Fig. 2. NASPI VSA Test Case 2

This test case was significantly more challenging than Test Case 1, requiring assessment of voltage insecurity and voltage instability for high transfer levels into the load area (Zone 10). Generation retirements in the area resulted in higher required imports and therefore increased the risk of voltage insecurity and collapse. System operators need awareness of Real and Reactive Power margins for pre- and post-contingency operating conditions to manage imports reliably.

The NASPI event sought to test the accuracy of voltage stability analytics and demonstrate how the region of voltage stability can be monitored and identified in real-time. The workshop asked the vendors for Case 2 to report the following information for their analyses of the Case 2 dataset:

1. Time at which the system moved into an insecure operating region (insecurity defined using N-1 contingency analysis for contingency list provided);
2. Time at which the system loses stability;
3. Real and reactive power stability margins for transfers into Zone 10;
4. Visual alarming of system conditions using software capabilities; and
5. Any other useful information system operators would like to have available.

4.3. NASPI Workshop Results for VSA Test Case 1

For NASPI VSA Test Case 1, participants were requested to demonstrate their tools by visually displaying any of the following information:

- Voltage profile trends;
- One-line diagrams of the system network;
- Real and reactive power margins;
- Voltage alarms or indicators;
- Sensitivity analyses – PV or QV analysis, dV/dP, dV/dQ analytics, etc.
- Any other useful information to the system operator.

The VSA tool results for Test Case 1 are shown in Table 1. Margins were identified using PV and QV analysis at each TSS power flow base case developed. Unacceptable operating conditions were defined by a set of operating criteria provided to the vendors ahead of time.

Table 1. Correct VSA Test Case 1 Results Announced by NASPI at the Workshop

First Time of Unacceptable Operating Conditions	303.4 sec
Shunt Cap Switching Time	247.8 sec
Pre-Switching Real Power Margin	343.75 MW
Post-Switching Real Power Margin	400.00 MW
Real Power Margin @ 0 sec	618.75 MW
Real Power Margin @ 150 sec	506.25 MW
Real Power Margin @ 305 sec	112.50 MW
Real Power Margin @ 445 sec	400.00 MW
Description of Method	PV Analysis

Five vendors participated in the Test Case 1 showcase. Results (submitted by the five participants to NASPI a week prior to the workshop) are shown in Table 2. The following overall observations are made regarding the results:

1. All participants were able to detect changes in discrete capacitor switching, which was fully observable in the dataset provided.
2. Two of the five participants were able to detect unacceptable operating conditions, with only one participant accurately detecting this time using a Linear State Estimation (LSE) – based approach. This unacceptable state was not directly measured by the PMUs themselves, but could be derived from the data provided in conjunction with the model.
3. The findings of each method are described below:
    a. The LSE- based approach provided stability results that were very accurate when compared with the actual results obtained from the sequence of power flow models.
    b. Voltage sensitivity method is not able to provide any indication of real power margin to system voltage collapse, only change in voltage for a given change in real power transfer.
    c. The Real-Time Voltage Instability Identifier (RVII) and equivalencing methods both significantly underestimated the Real Power margins greatly, identifying a boundary but one that limits transfers.
    d. The AQ Bus Method identified a boundary that was past the point of instability; however, results were fairly close to the actual results obtained from the model.

Table 2. VSA Test Case 1 Results Submitted by Five Vendor Participants Prior to the Workshop

VOLTAGE STABILITY CASE 1
RESULTS AND COMMENT SHEET

	Electric Power Group	RPI	V&R	Alstom Grid	ABB
First Time of Unacceptable Operating Conditions	170	None	303.5	None	None
Shunt Cap Switching Time	247	247.8	245	247.8	248
Pre-Switching Real Power Margin	23.53 kV/100 MW	411	335	29	92
Post-Switching Real Power Margin	7.5 kV/100 MW	461	391	86	92
Real Power Margin @ 0 sec	0.38 kV/100 MW	645	617	Not Available	196
Real Power Margin @ 150 sec	3.1 kV/100 MW	520	515	76	193
Real Power Margin @ 305 sec	6 kV/100 MW	190	111	46	32
Real Power Margin @ 445 sec	2.9 kV/100 MW	388	385	69	107
Description of Method	Voltage Sensitivity to Change in Real Power	AQ Bus Method	Linear State Estimation, PV/QV Analysis	RVII – local voltage instability detector	Equivalencing, PV analysis

4.4. NASPI Workshop Results for VSA Test Case 2

For NASPI VSA Test Case 2, participants were requested to identify and represent a region of stability and the respective stability margins at specific times. This included identification of security and stability limits, unacceptable system conditions, and other useful information for visualization. The correct results obtained from the sequence of power flow solutions created by the TSS are given in Table 3.

Table 3. Correct VS Test Case 2 Results Announced by NASPI at the Workshop

NASPI North American SynchroPhasor Initiative

Voltage Stability Case 2

First Time of Insecure (N-1) Operating Condition	1312 seconds
Reason(s) for Insecurity	Voltage Violation in Zone 10 – N-1 Outages
First Time of Unacceptable N-0 Operating Condition	None
Reason for Unacceptable Condition	N/A
Time of Instability	4012 seconds
Security Margin (Transfer into Zone 10) @ 1500 sec	50.0 MW
Stability Margin (Transfer into Zone 10) @ 1500 sec	250.0 MW
Security Margin (Transfer into Zone 10) @ 4000 sec	0.0 (-) – Insecure
Stability Margin (Transfer into Zone 10) @ 4000 sec	0.0 (-) – N-1 Unstable
Assumptions Used	50/50 Pickup
Noticeable System Changes	1. Line 115-130 Trips 2. Line 115-130 Returned to Service 3. Bus 122 STATCOM Trips 4. Bus 122 STATCOM Switched Back In 5. Bus 112 Shunt Cap Switches In 6. Line 116-120 Trips - Unstable
Description of Method	PV, Contingency Analysis

Two vendors participated in the Case 2 showcase. Results submitted by the two vendors prior to the NASPI workshop are given in Table 4. The following overall observations are made regarding the results:

1. Both methods identified insecure operating conditions; however, the LSE-based method was able to accurate identify the times and reasons for insecurity.
2. The findings of each method are described below
    a. The measurement-based approach detected an unacceptable operating condition that actually occurred after the point of system collapse. It identified the point of instability 58 seconds after the point of collapse. The margins

identified by the measurement-based approach were significantly incorrect when compared with the actual results.

b. The LSE-based approach correctly identified the time of system collapse. ; The margins identified by the LSE-based approach were very close when compared with the actual results.

3. Both vendor tools correctly identified line switching and shunt capacitor switching; however, the model-based LSE approach also correctly identified the failure and return to service of the dynamic reactive resources in the load center. The STATCOM tripping offline has a significant impact on the reactive margin calculations.

Table 4. VSA Test Case 2 Results Submitted by Two Vendor Participants Prior to the Workshop

NASPI North American SynchroPhasor Initiative

VOLTAGE STABILITY CASE 2
RESULTS AND COMMENT SHEET

	Alstom Grid	V&R Energy
First Time of Insecure (N-1) Operating Condition	2410	1312
Reason(s) for Insecurity	Line L02	Contingency L02 Contingency L11
First Time of Unacceptable N-0 Operating Condition	4064	None
Reason for Unacceptable Condition	Voltage Violation @ Bus 113	N/A
Time of Instability	4070	4012
Security Margin (Transfer into Zone 10) @ 1500 sec	730	40
Stability Margin (Transfer into Zone 10) @ 1500 sec	760	250
Security Margin (Transfer into Zone 10) @ 4000 sec	170	Negative
Stability Margin (Transfer into Zone 10) @ 4000 sec	200	Negative
Assumptions Used	-Total generation is the sum of three branches: • Bus 151 to Bus 156 CKT 1 • Bus 151 to Bus 156 CKT 2 • Bus 136 to Bus 130 CKT 1 -Upper bound voltage limit criteria was relaxed -Bus 136 generator Pmax increased from 1000MW to 1070MW for transfer analysis	Ignored 500kV equivalents & their voltages
Noticeable System Changes	At t=502s, line 130-115 circuit 1 tripped and reconnected at t=800s At t=2246s, first shunt cap (100 MVAR at bus 112) gets switched in at load in zone 10=912MW At t=2868s, Second shunt cap (125 MVAR at bus 120) gets switched in at load in zone 10=1152MW	Event 1 - 502 s. Switching off line 130-115 "1". Event 2 - 802 s. Line 130-115 "1" switched back. Event 3 - 1302 s. Switching off FACTS at bus 122. Event 4 - 1602 s. Switching in FACTS at bus 122. Event 5 - 2462 s. Shunt cap switching at bus 112. Event 6 - 2868 s. ("non-switching"). Increase in transformer 116-117 flow. FACTS reaches reactive limit, loses control of bus 116 voltage. Event 7 - 4012 s. Contingency 116-120 which causes system collapse at 4012 s. There is no State Estimator solution after this N-1 contingency occurs.
Description of Method	PV Analysis	Linear State Estimation, AC Contingency Analysis, VS assessment (PV/QV, Sensitivity)

5. Commercial Applications that Use Synchrophasor Data for Voltage Stability Assessment

This section of the paper describes some of the related commercial applications that are currently available to the power system industry. These descriptions are based on information provided by the vendors and application developers and do not reflect CRSTT or NASPI positions or endorsements. This information may be updated in the future to include additional applications or updates on existing applications as new information becomes available.

5.1. EPG – Real-Time Dynamics Monitoring System

1. ***Application name:***

   Voltage Sensitivity and Angle Sensitivity in Real-Time Dynamics Monitoring System (RTDMS)

2. ***Objective of the application:***

   Objectives of the application include:
   - Calculate voltage and angle sensitivity
   - Trigger event on high sensitivity
   - Visualization of sensitivity results for operators and engineers
   - Populate results in Automatic Event Analyzer

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

   This application will be part of the Advanced Calculation Engine in RTDMS. 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

4. *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 sensitivity locations of interest

5. *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 analysis of user-defined sensitivity. The voltage sensitivity application calculates the impact of change in power flow on voltage at a bus. It is the real-time assessment of the slope of the P-V or Q-V curve at that operating point. Typically, the voltage sensitivity at a bus increases as the operating point moves towards the voltage collapse point, thus, it is an indicator of the proximity to voltage instability.

Similarly, angle sensitivity is a measure of how much the voltage angle difference varies for a change in amount of power flow. Sensitivity analysis is important because for the operation of large power systems, proper voltage support should be available at substations along the transmission corridors so that system stability is maintained. Additionally, a system disturbance such as a transient fault may be accompanied by sharp fluctuations in voltage magnitudes and voltage angles. Sensitivity analysis helps in determining the impact of such a disturbance on the system.

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

   RTDMS was deployed at NYISO, ConEd, PJM, Dominion, Duke Energy, ERCOT, Oncor, LCRA, AEP, Southern Co., CAISO, SRP and LADWP. The application vendor is Electric Power Group: www.electricpowergroup.com

7. ***Application software (open source, proprietary):***

   The software is proprietary.

8. ***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. It can also integrate with OSI Soft PI systems.

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

   Please see #5 above.

10. ***Type of application GUI***

    Typical Sensitivity Display (see Fig. 3and Fig. 4):

Fig. 3. Top: Sensitivity scatter chart for different locations being monitored; Bottom: Sensitivity trend chart showing history with alarm threshold

Fig. 4. Left two charts: Voltage and power flow line charts of monitored locations; Top right: Sensitivity trend chart showing history with alarm threshold; Bottom right: Sensitivity gauge showing current sensitivity value with alarm threshold

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

*11. **Identify operating entities that are using the application***

This application is used at PJM, CAISO, SRP and ERCOT.

5.2. EPRI – Measurement-Based Voltage Stability Assessment

*1. **Application name:***

Measurement-Based Voltage Stability Assessment (MBVSA)

*2. **Objective of the application:***

To assess maximum power transfer capability into a load area constrained by voltage stability using synchrophasor measurements

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

- A PC that performs MBVSA calculations at the sampling rate of synchrophasor measurements received
- MBVSA engine software loaded on the PC
- Synchrophasor voltage and current measurements at the boundary substations of the load area of interest (These measurements are fed into the MBVSA engine)
- Synchrophasor infrastructure (PMUs at boundary substations; communication channels from boundary substations to the PC location; a PDC to collect and feed the synchrophasor measurements into the PC's MBVSA engine)
- MBVSA can be interfaced with synchrophasor application visualization platforms for visualization of the MBVSA results.

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

Positive-sequence voltage phasors at boundary substations. Positive-sequence current phasors into the boundary substations (or active and reactive power flows into the boundary substations)

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

Continuous calculation of Pmax at high sampling rate (e.g. 30 times per second) by the MBVSA provides continuous situational awareness of voltage stability performance at the current operating point (N).

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

   - *If in operation, where*: In test mode at Entergy
   - *Application provider or developer:* EPRI

7. ***Application software (open source, proprietary):***

   Proprietary (but may be made open source in the future)

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

   To be tested (not yet implemented in real-time operations EMS environment)

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

   A combination of MBVSA results and traditional simulation-based voltage stability assessment results during real-time operational environment can help the operator in providing a warning of an impending voltage stability problem, especially during the time when real-time contingency analysis studies are in progress and the results are yet not available.

10. ***Type of application GUI:***

    Presently it is a standalone application. Work is planned to integrate it into OpenPDC environment

11. ***Identify operating entities that are using the application:***

    Test mode at Entergy

5.3. Quanta Technology – Real Time Voltage Instability Indicator

1. ***Application name:***

   Real Time Voltage Instability Indicator (RVII)

2. ***Objective of the application:***

   Detect voltage instability at a bus, corridor, or a compact load area, and estimate active and reactive power margins to collapse in real time.

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

   It can be deployed on a standalone system that has access to synchrophasors, or integrated within a synchrophasor management system.

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

   The analytical engine requires synchrophasor data consisting of local bus voltage phasors, adjacent branch flows, and in some versions status of the adjacent branches.

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

   It can detect FIDVR (fault induced delayed voltage recovery); can detect voltage instability (at the phasor rate) and without requiring a state estimator solution.

6. ***Current status of the application (in development, testing, in operation):***
   - *If in operation, where?*
     PG&E, within Alstom e-terra platform; SCE, in Advanced Technology Laboratory (standalone); Tenaga Nasional Berhad (Malaysia) - within OpalRT platform.

   - *Application provider or developer:*
     Quanta Technology; also bundled by Alstom at PG&E

7. ***Application software (open source, proprietary):***

   Proprietary

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

The primary host platform is a synchrophasor system, where visualization and archiving can be performed by the platform's standard functionality.

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

Early real-time applications already deployed. Full productization in progress.

10. ***Type of application GUI:***

Leverages the GUI of the host platform. Displays can be customized to present results of interest. Figures below show illustration of power margins (see Fig. 5Fig. 6) as well as propagation of the ratio of load and Thevenin equivalents, as indicator of voltage instability (see Fig. 6).

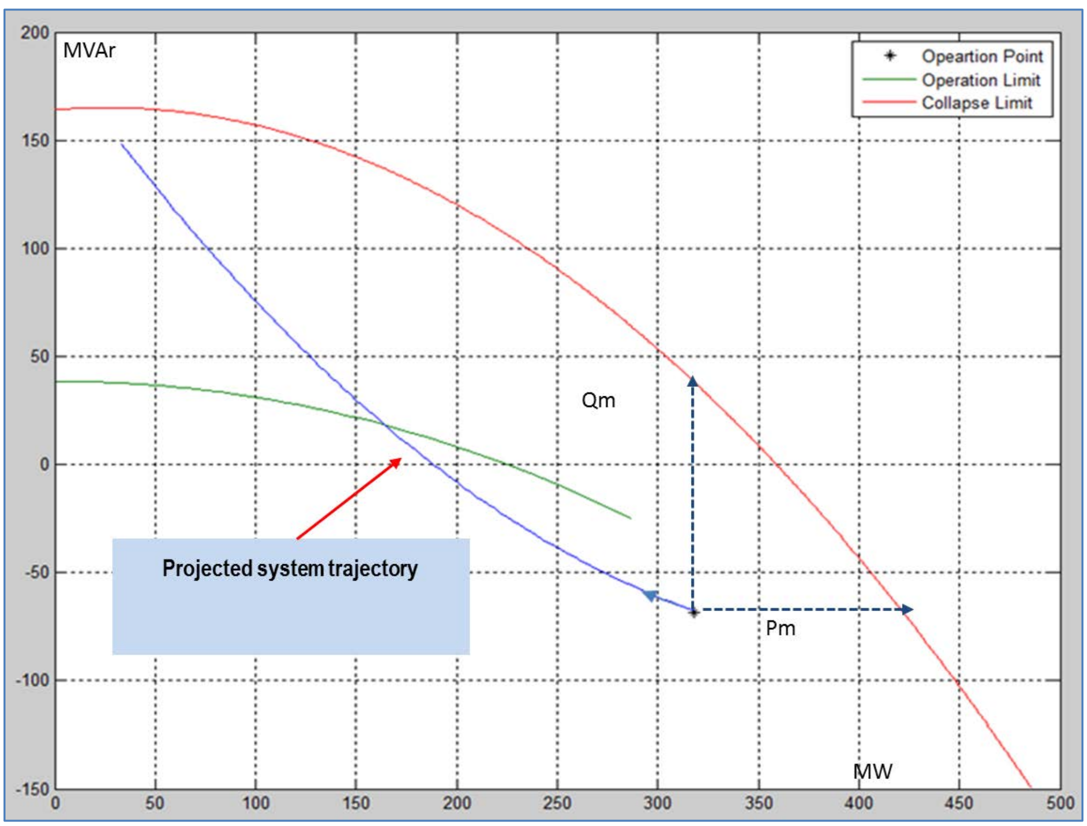

Fig. 5. Power Margins

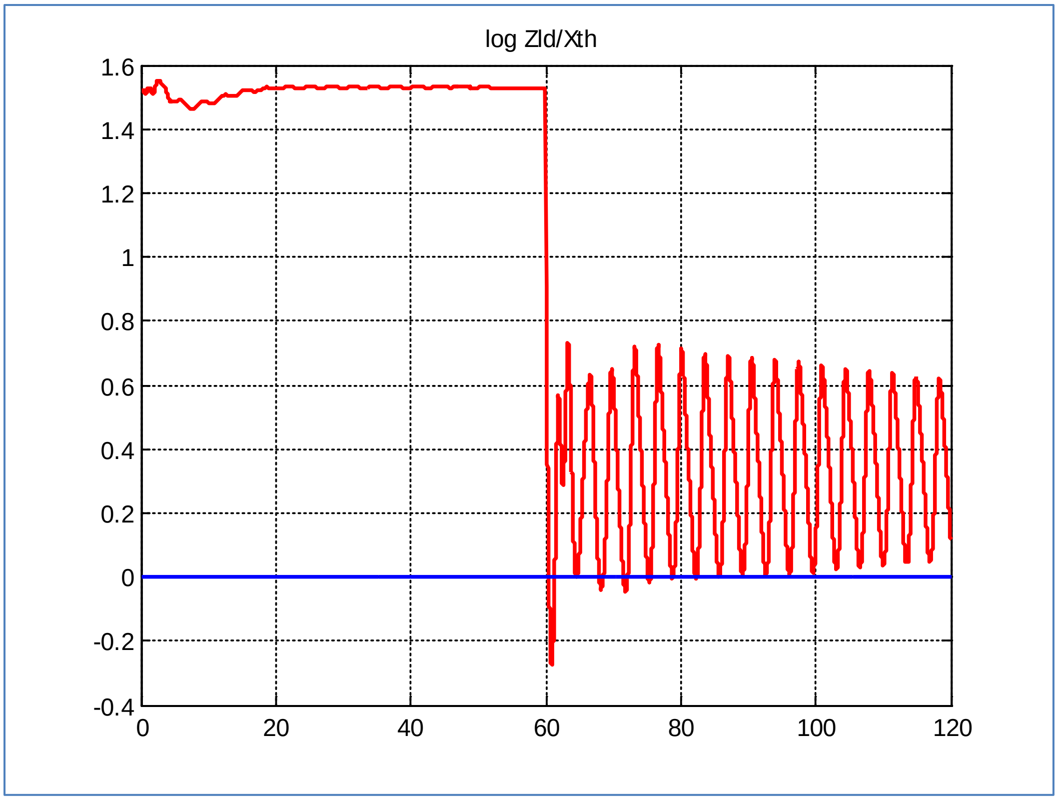

Fig. 6. Propagation of the Ratio of Load and Thevenin Equivalents

11. Identify operating entities that are using the application:

PG&E (Operations Engineering); SCE (AT Laboratory); Tenaga Nasional Berhad.

5.4. V&R Energy – Region Of Stability Existence

1. Application name:

Region Of Stability Existence (ROSE)

2. 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 Phase Angle Limit and Monitoring (PALM):
    - Identifies locations where to monitor phase angle differences in real-time;
    - Identifies locations for monitoring during power transfer analysis, contingency analysis, and cascading analysis;
    - Determines phase angle limit in real-time.
- 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.
- 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.

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

<u>Typical hardware configuration for production servers are:</u>

- Dual Intel Xeon E5-2697 v3 @ 2.60 GHz or similar CPU, 32 GB RAM.
- Typically, 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 R2
- Microsoft® Internet Explorer 11
- IIS v.7
- .Net Framework 4.5

Typical hardware configuration for desktop computers are:

- Intel Core i7-5960X @ 3.00 GHz or similar CPU, 16 GB RAM, 500 GB hard drive
- Application is optimized for screen resolution 1920 x 1200

Software requirements for desktop computers are:

- Microsoft® Windows® 7,8
- Microsoft® Internet Explorer 11
- IIS v.7
- .Net Framework 4.5

4. *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 that is using the application, usually 30 samples/second.

5. *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 voltage stability limits, including:

- o Computing interface limits;
- o Performing PV-curve and QV-curve analyses;
- o Determining the region of secure system operation and its boundary.

Depending on the implementation computations are based on:

- o 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. Simplified computations such as equivalencing to 2-bus model are NOT done.

- The application computes the EXACT ACCURATE VALUE, NOT APPROXIMATION, of the voltage stability margin.

6. ***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 a new DOE project, ROSE will be also deployed at BPA, CAISO, IPC, SDGE and SCE.

   ➢ *Application provider or developer:*

   Application vendor is V&R Energy: www.vrenergy.com

7. *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.

8. ***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.

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

See item 6 above.

10. Type of application GUI

Peak-ROSE GUI is shown in Fig. 7. Peak-ROSE utilizes both State Estimator and PMU data.

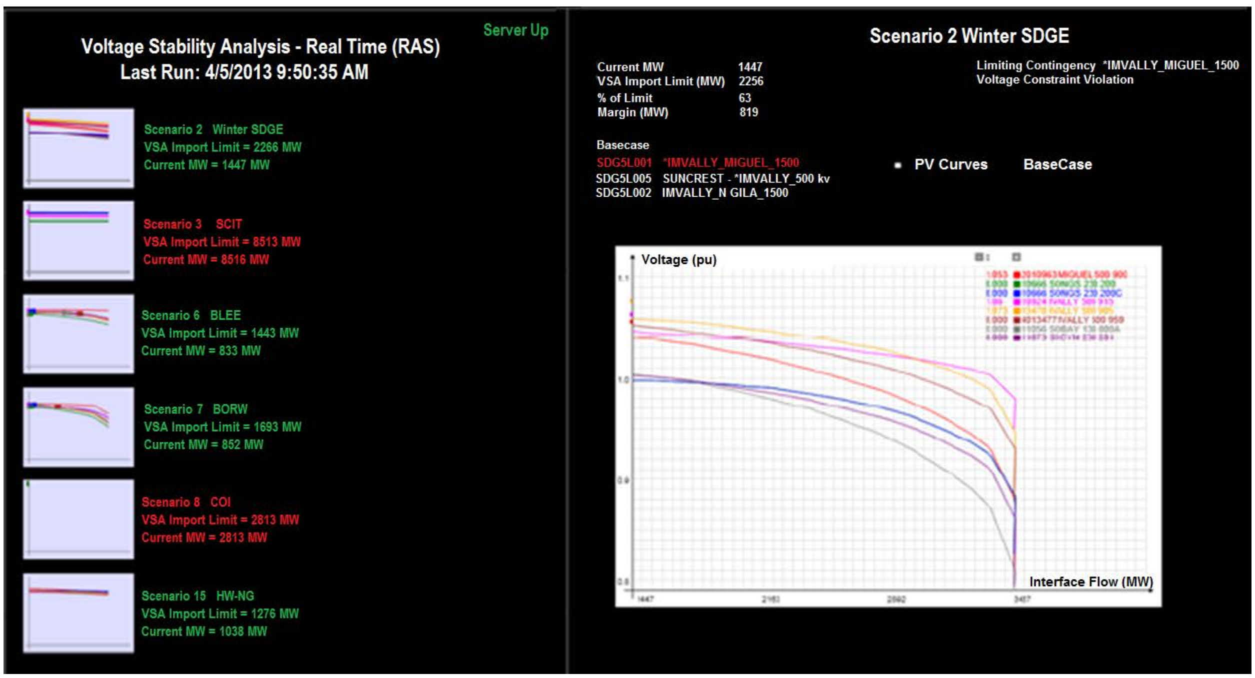

Fig. 7. Peak-ROSE GUI

ISONE-ROSE GUI is shown in Fig. 8. ISONE-ROSE utilizes both State Estimator and PMU data.

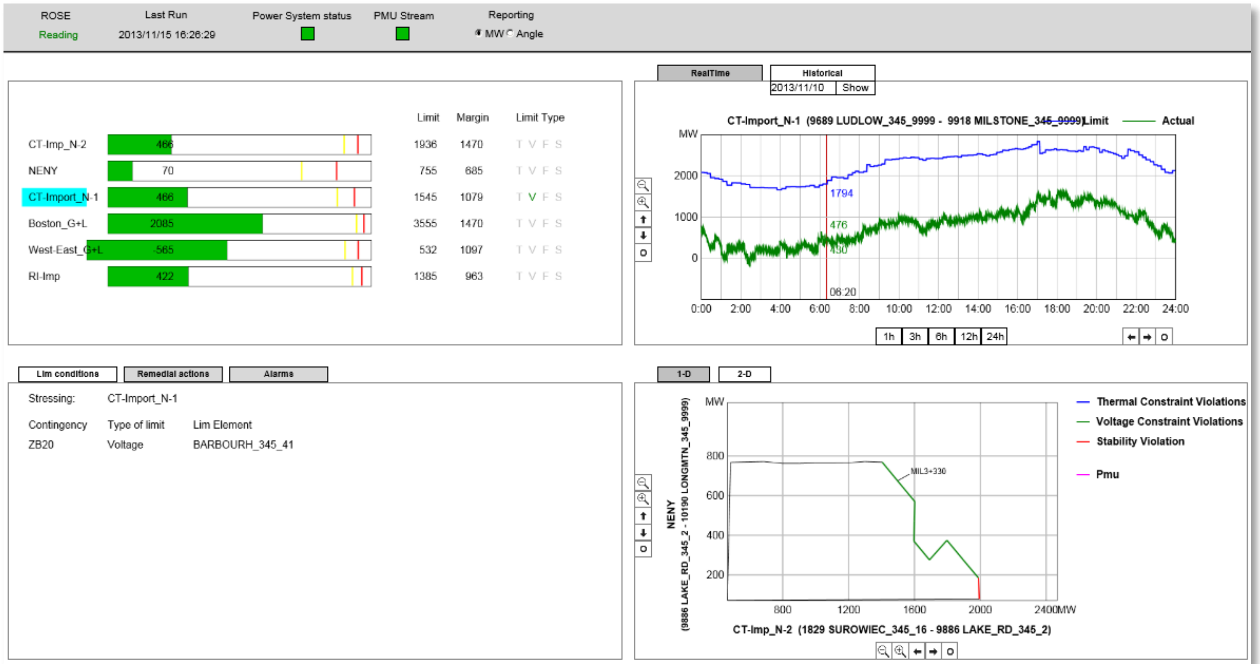

Fig. 8. ISONE-ROSE GUI

Measurement-based ROSE GUI is shown in Fig. 9. It utilizes only PMU data.

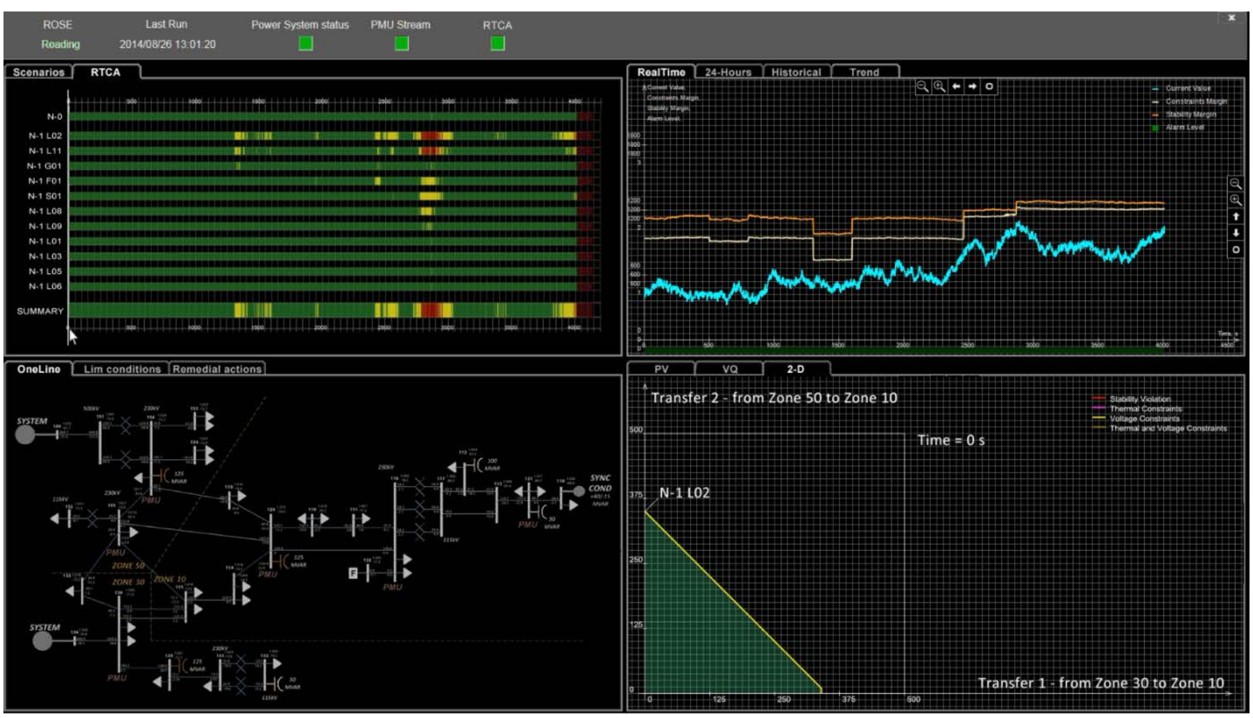

Fig. 9. Measurement-Based ROSE GUI

11. Identify operating entities that are using the application

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

5.5. WSU – Voltage Stability Monitoring System

1. Application name:

Voltage Stability Monitoring System (VSMS)

2. Objective of the application:

- To assess the real-time voltage security of a power system in a distributed fashion using PMUs;
- To provide a voltage security index at any bus in real-time by estimating line QV sensitivities using PMU measurements alone.

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

- Hardware: CPU: 64-bit 1.5G HZ or better; memory: 500MB or better; Graphic card: no specific requirement.
- Software: Windows Server 2008 or advanced versions (e.g. Windows 7). OpenPDC Version 2.0.

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

- PMU Data source: IEEE C37.118 standard data format.
- PMU data stream must be pre-aligned to be processed by VSMS.
- No specific requirements on data resolution.
- NO SCADA data needed.

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

VSMS serves to provide early warning type alarms on voltage insecure portions of a power system using a PMU measurement based platform. This is a model free approach and complements other model based voltage security applications.

VSMS provides security estimates using short windows (less than 30 seconds) of PMU data and therefore can adapt to changing system conditions quickly. VSMS can estimate voltage security strength of any bus and can be used to identify the weak portions of a power system in terms of inadequate reactive power support.

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

   VSMS right now is in testing and validation stage. It has been implemented at Entergy and Idaho Power Company for the past two years and is under operational testing.

   - *If in operation, where?*
     Under testing at Entergy and Idaho Power Company

   - *Application provider or developer*
     Washington State University (WSU), Pullman, WA

7. ***Application software (open source, proprietary):***

   Proprietary owned by WSU.

8. ***Applications ability to integrate with EMS/SCADA systems or data historians (e.g. PI):***
   VSMS results are published as derived measurements from OpenPDC in OpenPDC protocol into OpenPDC historian and can into communication ports. OpenPDC adapters are available to export VSMS results to PI historian.

9. ***Describe how the application could be operationalized (i.e. used in real-time):***
   It could be used in Control Center to provide operators with an overview of voltage security strength at different buses, and to identify vulnerable or weak buses that require operator actions. Since VSMS uses short time window PMU data in estimating the indices, the operators can get quick feedback (within a minute) how the actions affected the security indices.

10. ***Type of application GUI:***
    VSMS is equipped with multiple types of GUI. At Entergy, VSMS results published from OpenPDC are consumed by a visualization application developed by Space-Time Insight. VSMS also comes with WSU developed simpler user interfaces that provide overview of different bus estimates in real-time.

11. ***Identify operating entities that are using the application:***
    Entergy, and Idaho Power Company.

Glossary of Acronyms

ACRONYM	DEFINITION
AC	Alternating Current
AEP	American Electric Power
ATC	American Transmission Company
BES	Bulk Electric System
BPA	Bonneville Power Administration
CAISO	California Independent System Operator
CIGRE	International Council on Large Electric Systems
CRSTT	Control Room Solutions Task Team
EPG	Electric Power Group
EPRI	Electric Power Research Institute
EMS	Energy Management System
ERCOT	Electric Reliability Council of Texas
GPS	Global Positioning System
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineers
IPC	Idaho Power Company
IROL	Interconnection Reliability Operating Limit

ACRONYM	DEFINITION
ISO-NE	Independent System Operator New England
LADWP	Los Angeles Department of Water and Power
LCRA	Lower Colorado River Authority
LSE	Linear State Estimation
MBVSA	Measurement-Based Voltage Stability Assessment
NASPI	North American Synchrophasor Initiative
NERC	North American Electric Reliability Corporation
NIC	Network Interface Card
NYISO	New York Independent System Operator
PDC	Phasor Data Concentrator
PG&E	Pacific Gas & Electric
PJM	Pennsylvania Jersey Maryland
PMU	Phasor Measurement Unit
PV-Curve	Power – Voltage Curve
RC	Reliability Coordinator
ROSE	Region Of Stability Existence
RTDMS	Real-Time Dynamics Monitoring System
RVII	Real-Time Voltage Instability Indicator

ACRONYM	DEFINITION
SCADA	Supervisory Control and Data Acquisition
SCE	Southern California Edison
SDGE	San Diego Gas and Electric
SOL	System Operating Limit
SRP	Salt River Project
TOP	Transmission Operator
TSS	Time Step Simulation
VQ-Curve	Voltage – Reactive Power Curve
VSA	Voltage Stability Assessment
VSMS	Voltage Stability Monitoring System
WSU	Washington State University