Improving Power System Reliability and Resiliency through Enhanced Modeling and Advanced Software Tools

Marianna Vaiman, V&R Energy
IEEE PES Policy Technical Support Task Force
marvaiman@vrenergy.com

FERC Technical Conference
Washington, D.C. • June 26 – 28, 2017

IEEE PES Power & Energy Society®

IEEE

Contents

1. Improving Reliability through Enhanced Power System Modeling
2. Improving Resiliency of the Grid through Advanced Software Tools
3. Related IEEE Activities
4. Future Work
5. Conclusions

1. Improving Reliability through Enhanced Power System Modeling

Improving Reliability through Enhanced Power System Modeling

- Enhanced State Estimation (SE)
  - Importance of minimizing/removing the pseudoloads
  - Creating a back-up State Estimator platform using synchrophasors
  - Dynamic state estimation
- Bridging real-time and planning power system models by using a node-breaker model

Power System State Estimator

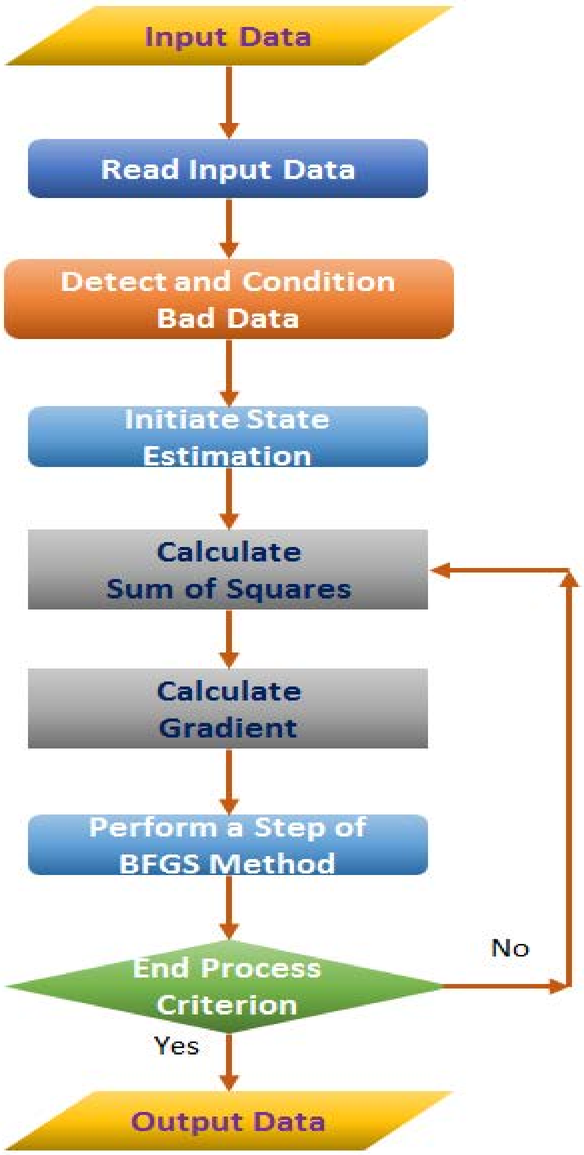
- Main tool to assess reliability and stability of a power system in real-time environment at a utility/ISO:
  - Basis for all advanced applications and market applications
- Designed to produce a system state based on the "best estimate" of the system voltages and phase angles:
  - Provided that there are errors in the measured quantities; and
  - That there is a redundancy in measurements
- Minimizes the sum of the squares of the differences between the measured and estimated values of variables:
  - Voltage magnitude
  - Real and reactive power flows on the branches

BFGS Method

- Real and imaginary parts of voltages at all buses in a power system network are considered as variables of the objective function
- An optimization algorithm – an effective quasi-Newton BFGS (**B**royden, **F**letcher, **G**oldfarb, **S**hanno) Method
  - Unlike the commonly used Newton method, BFGS method does not require a time-consuming calculation of the Hessian matrix of second derivatives of the function to be minimized
  - Instead, the Hessian matrix is approximated using an expression that is based on the difference of gradients at the end and at the beginning of each minimization step

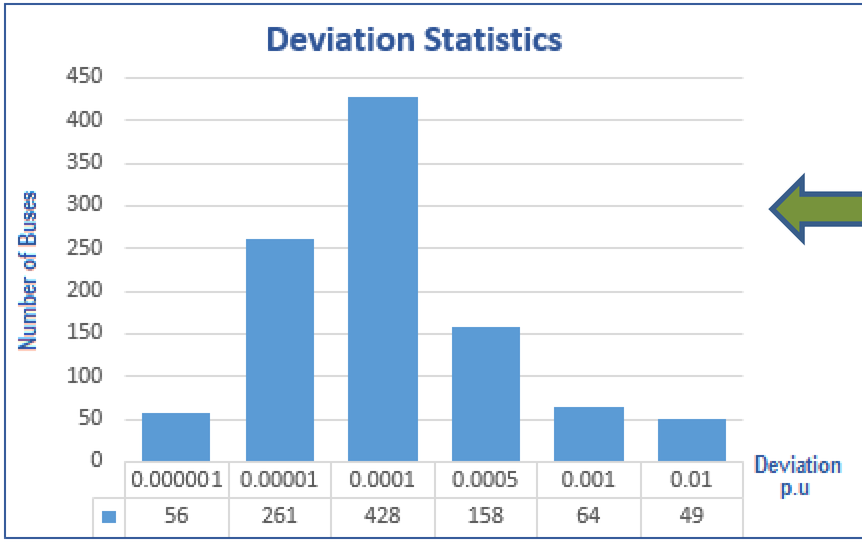
Use of BFGS Method for State Estimation[1]

- Optimization steps are performed in a cycle:
  - To control accuracy and duration of state estimation process
  - At each optimization step, objective function and its gradient are computed multiple times
- Results in faster and more accurate state estimation
  - Important for market applications



[1] NYSERDA Project: "Advanced State Estimation to Improve Reliability of Con Edison's Network"

Advantages of Using BFGS Method



- Distribution of the difference between measured and estimated values of voltage magnitude
  - Small, ranges from –0.0095 p.u. to 0.0087 p.u., which is **less than 1%.**

- Major advantage is creating an SE case with negligibly small pseudo-loads

Bus From Number	Bus To Number	Real Power Flow, p.u.	Reactive Power Flow, p.u.
12xxx9	12xxx9	0.297342	0.202057
12xxx9	12xxx5	-0.29935	-0.18745
Pseudo-Load, p.u.		-0.002	0.014605

- When converted to MW and MVAr, pseudo-loads = 0.2 MW and 1.46 MVAr
- **Such small pseudo-loads may be neglected when an SE case is created**

Linear State Estimator

- Linear State Estimator (LSE) is based on PMU measurements of voltage and current:
  - Voltage and current vectors are considered as the state variable
- Advantages of LSE:
  - Improves quality of PMU data
  - Speed of state estimation due to using a direct non-iterative solution
  - A comparison check for the conventional state estimator
  - A backup to the conventional SE solution if it fails (for example, experiences convergence issues)

Functionalities of LSE

- Bad data detection, including:
  - Bad PMU data;
  - Bad SCADA data;
  - Bad system parameters;
  - Errors in the process of conventional state estimation.
- Topology estimation, if breaker status is not available
- Separating bad data with an onset of an event

Framework for Real-Time Situational Awareness

Linear State Estimation

Observability Analysis	Bad Data Detection/Conditioning

↓

Advanced Applications

Contingency Analysis	Voltage Stability Analysis	Automatic Corrective Actions	Phase Angle Limit Computation	Analysis of Cascading Outages

↓

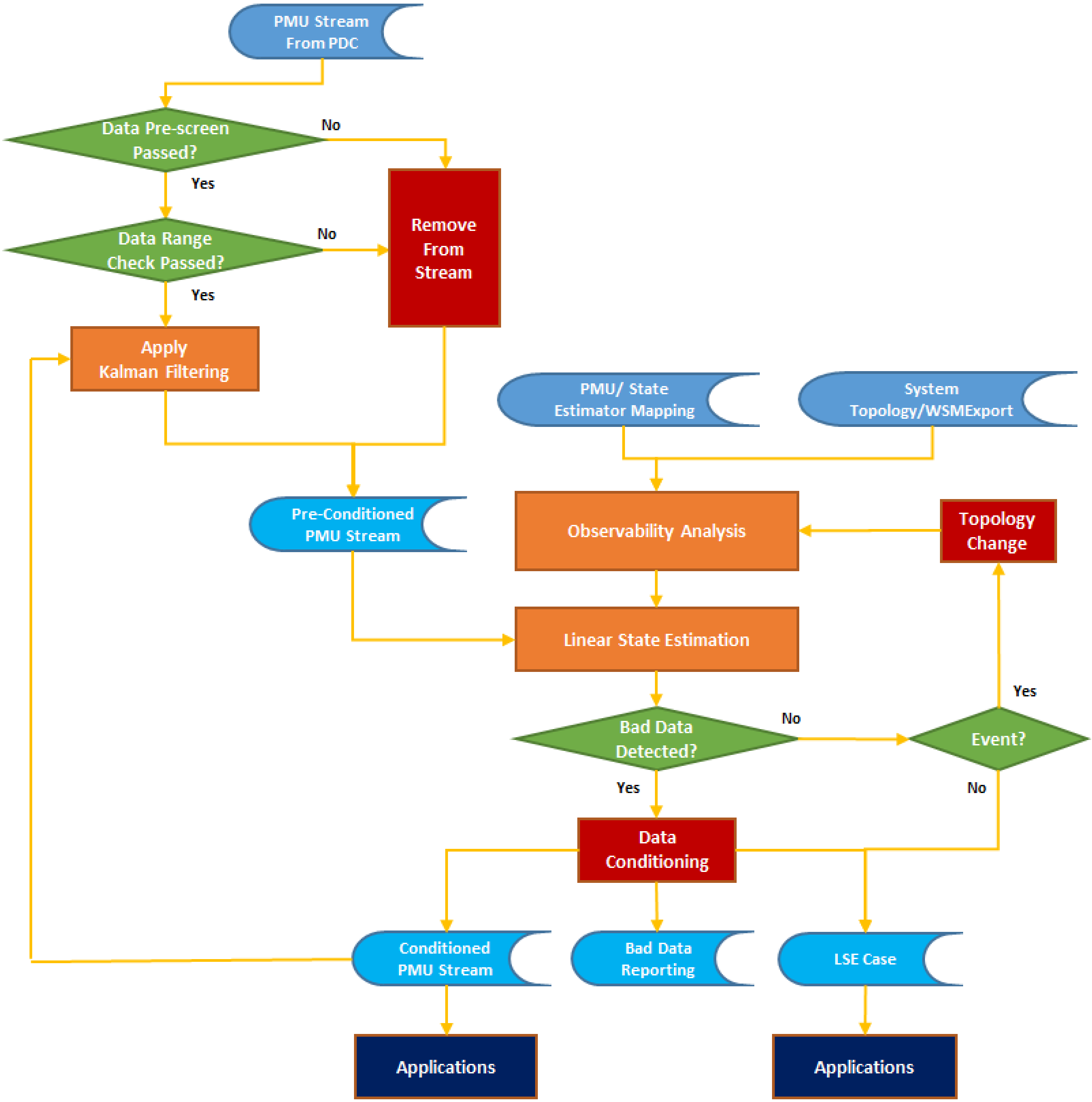
Visualization/Alarming

Visualization of:	Alarming on:
Limits	Voltage/Transient Stability Limits
Critical Contingencies/Cascades	Phase Angle Limit
Trending	Critical Contingencies/Cascades

IEEE PES Power & Energy Society® IEEE

Components of LSE Framework[2]

- Multi-step process:
  1. Several pre-screening techniques
  2. Data range checks
  3. Combination of filtering and smoothing techniques based on Kalman filter
  4. Linear state estimation
  5. End-to-end machine learning



[2] DOE Peak Reliability Synchrophasor Project (PRSP) with CAISO, IPC, Peak, SCE, SDGE, and V&R Energy

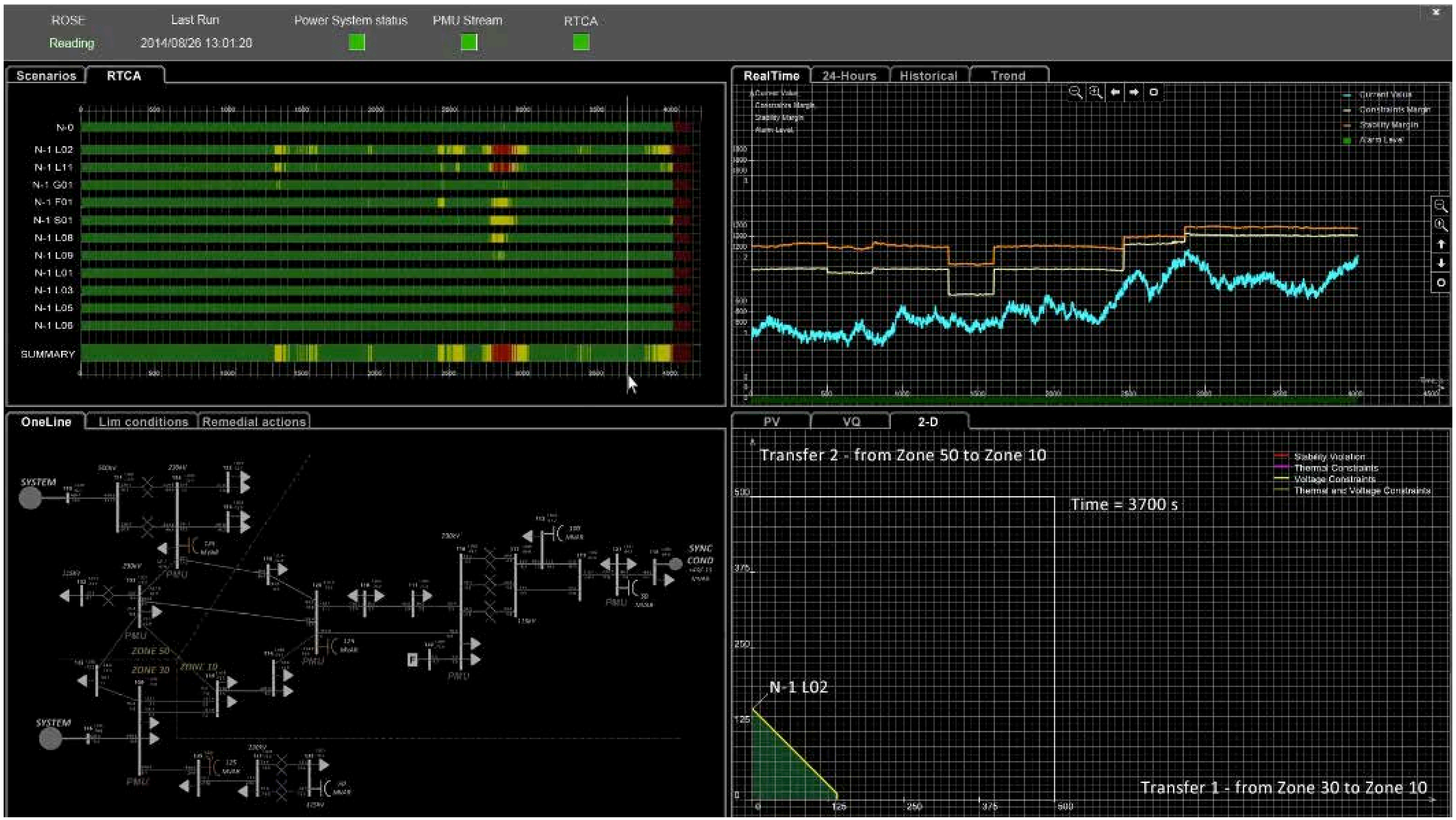
Results of Observability Analysis

- To perform observability analysis, the following data is used:
  - PMU data
  - State Estimator (SE) data
  - PMU/SE mapping
- The results change when topology changes or PMU signal is lost

	Number of Buses in SE Case	Observable Buses		Observable Branches	Number of Observable Islands	Number of PMU Signals Used for Observability
		Number of Buses	% of Buses in SE Case			
Company 1	23628	600	2.5	811	27	951
Company 2	6250	209	3.3	293	10	306
Company 3	1693	62	3.6	115	2	126
Company 4	495	58	11.7	75	4	81
Company 5	525	54	10.3	78	2	146

Measurement – Based VSA

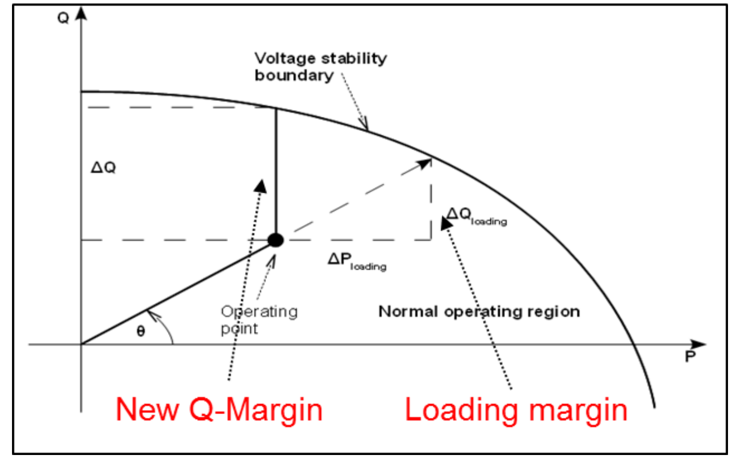
- Based on cases created by Linear State Estimator



Source - V&R Energy. 2017 ISGT Panel Session: "Industry Best Practices in Using Synchrophasor Technology"

Comprehensive Voltage Management

- **Hybrid solution would work best** – each method offers benefits
- **Model-free** methods
  - Good for dynamic voltage instability detection and trend monitoring
  - Able to distinguish FIDVR from voltage instability even if voltage is very low



- **VSA** methods: accurate margins if accurate models and good scenarios
- **Hybrid** - Nothing "falls between the cracks":
  - If VSA model not accurate, model-free will detect instability; converse also true
  - Could automatically trigger "out of sequence" SE/VSA on instability

Source – Quanta Technology. 2017 WECC JSIS Meeting

Situational Awareness and Wide-Area Visualization

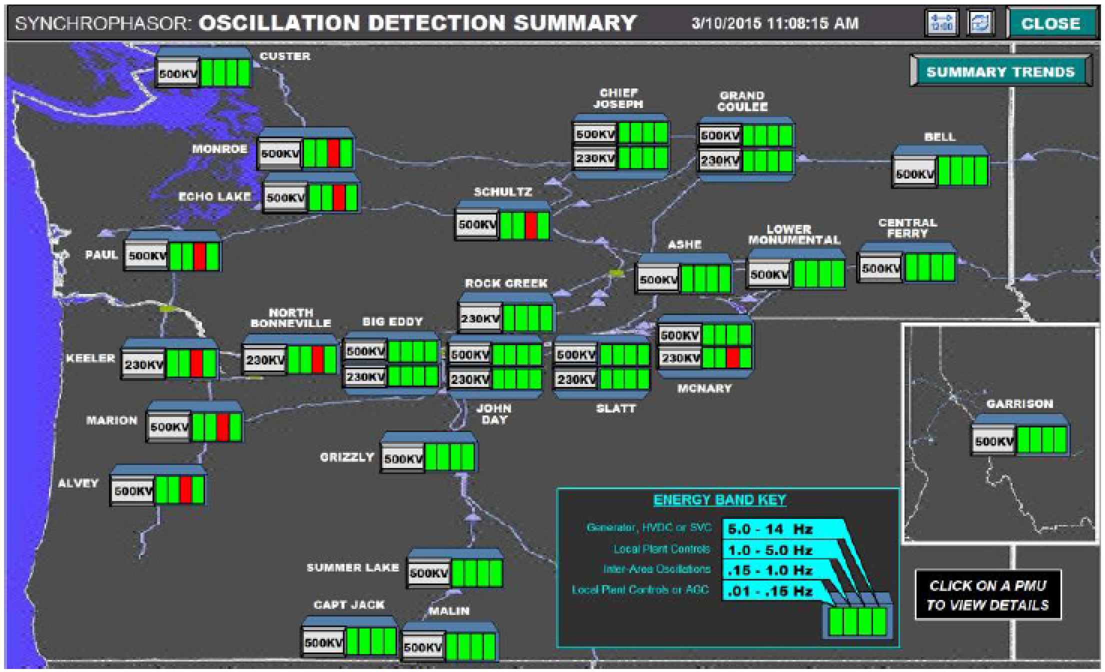
- Currently PMUs are already used for improving situational awareness and wide-area visualization

Source – SEL. 2017 ISGT Panel Session: “Industry Best Practices in Using Synchrophasor Technology”

IEEE PES Power & Energy Society® IEEE

Oscillation Detection at BPA

BPA deployed Oscillation Detection in its control room in October 2013



Scans 140 signals for signs of growing or sustained low frequency oscillations

Alarms dispatchers when an oscillation is detected

Dispatcher training sessions were performed

Operating instructions are under development

Most detected oscillations are due to generator control issues, bad operating point, or local instabilities

Source – BPA. 2017 ISGT Panel Session: “Industry Best Practices in Using Synchrophasor Technology”

Dynamic State Estimation (DSE)

- The objective of Dynamic State Estimator (DSE) is to predict dynamic behavior of a power system for:
  - (1) preserving transient stability of the system, and
  - (2) guaranteeing quality of transient processes
- Inputs for DSE are:
  - Electrical parameters (voltage, current, etc.) directly measured by PMUs in vector form
  - Scalar parameters (rotor angle, frequency, frequency derivative, mechanical power, excitation voltage and current, etc.), which may be measured by PMUs or estimated, if PMU data is not available
- For some types of generators, PMUs may directly measure rotor angles

Capabilities of DSE

- Predictive capability
- Estimation of dynamic parameters using Kalman filters:
  - Rotor angle, rotor slip
  - System inertia
  - Damping
- Identify in real-time dynamic disturbances in the system, faults, switching, etc.
- Real-time control capabilities;
- Analysis and prediction of both electromechanical and those electromagnetic processes which are relatively slow:
  - Important for control purposes, maintaining transient stability, and guaranteeing quality of transient processes
- Identifying non-synchronous behavior of generators
- Use for development of protection schemes

Use of a Node-Breaker Model

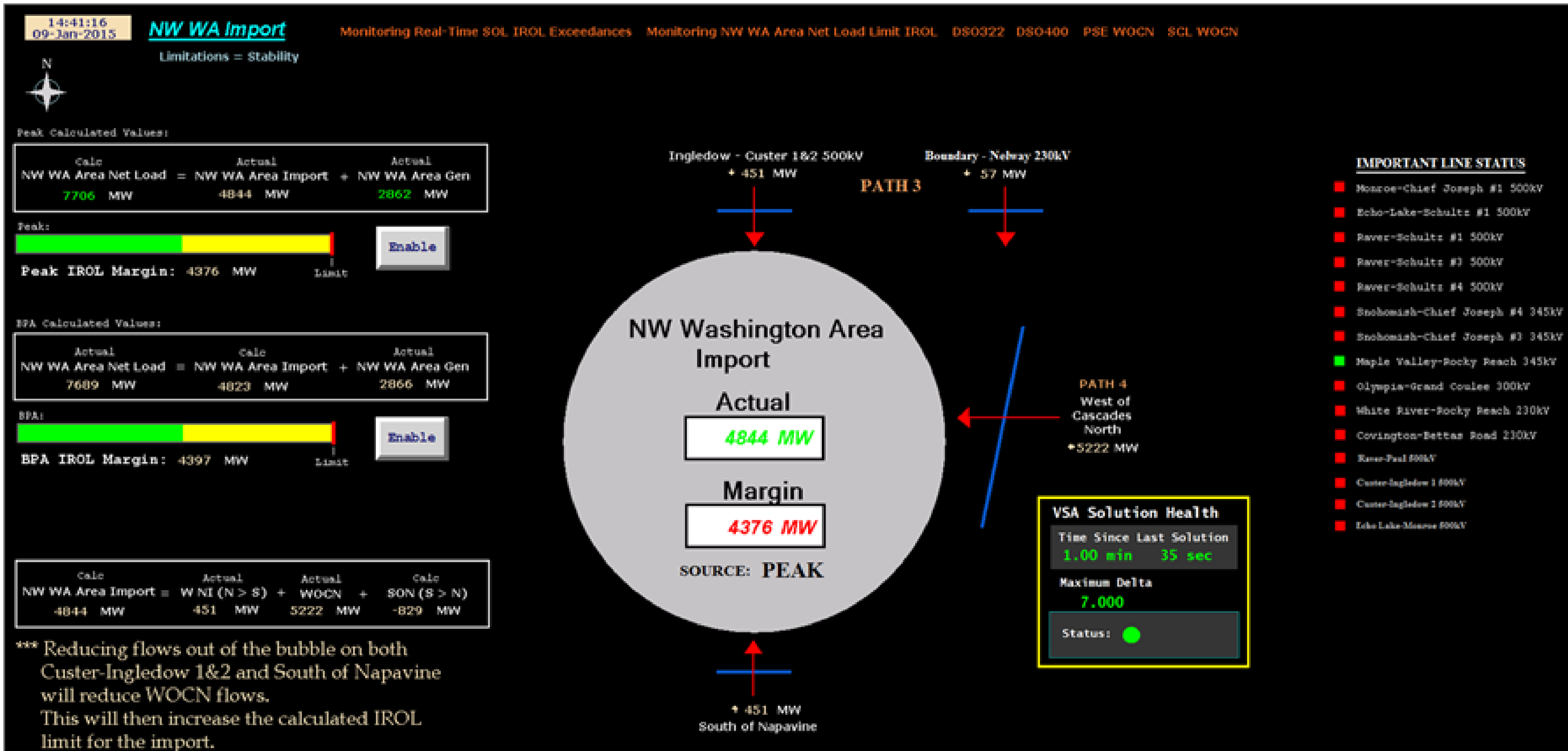
- Bridges real-time and off-line analyses
- Includes three different frameworks for using node-breaker model:
  - Using node-breaker State Estimator case for both real-time and off-line analyses:
    - Case can be saved as a node-breaker or bus-branch model
  - Creating a "hybrid" model based on the planning case such that a part of the model is node-breaker and a part is in bus-branch model
  - Inserting real-time data into planning model:
    - Inserting State Estimator case into a planning case
    - Inserting historical real-time measurements into a planning case

Use of Node-Breaker Model for Voltage Stability Analysis

- Voltage stability analysis (VSA):
  - Runs multiple user-defined scenarios
  - Computations performed for each scenario are:
    - Determining interface limits
    - Performing PV-curve analysis
    - Performing VQ-curve analysis
- Automatic AC contingency analysis
- Reading of existing real-time RAS
- Topology processing
- Satisfies Cyber Security requirements

Peak's Visualization of VSA Results Using Node-Breaker Model

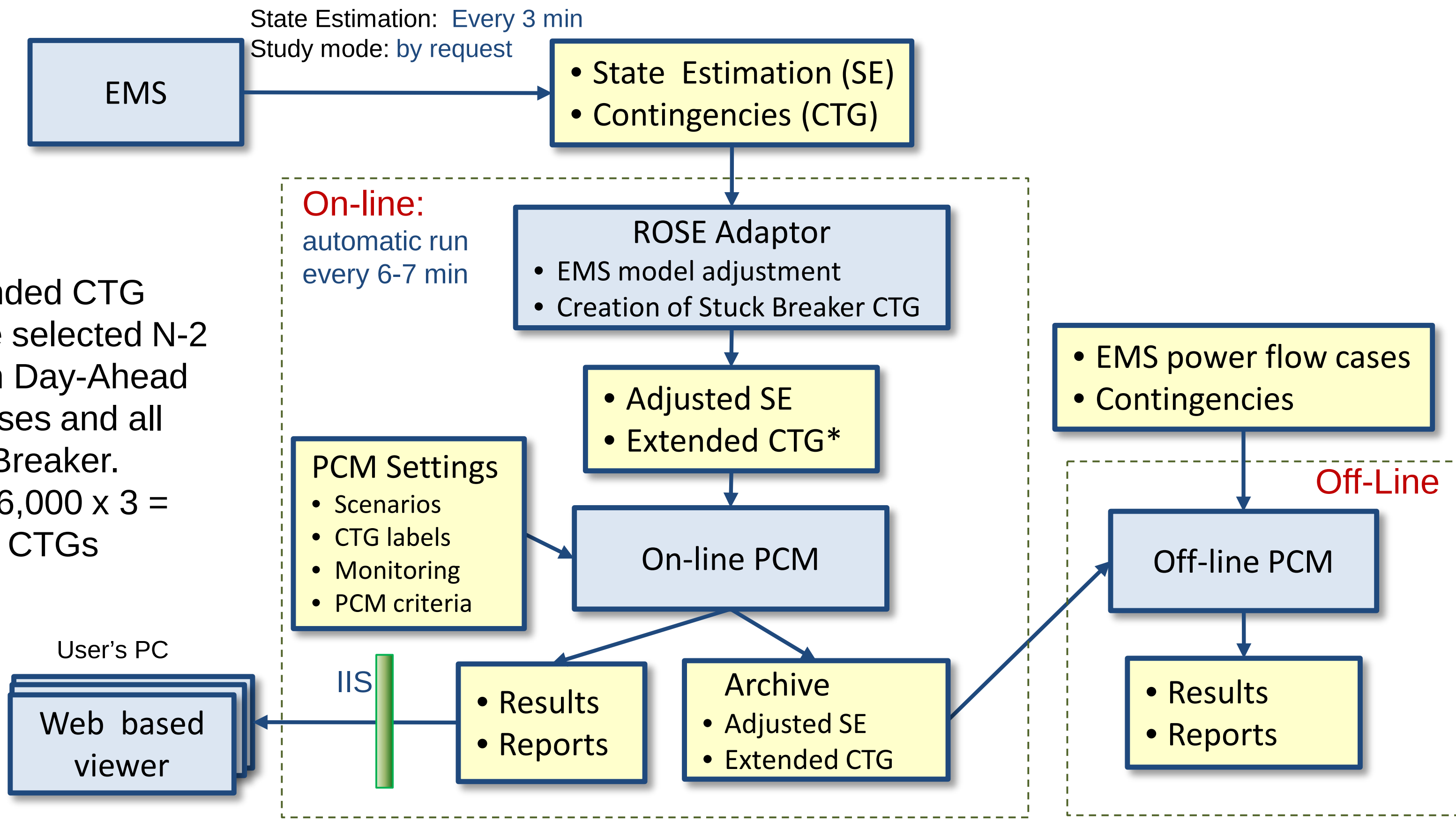
- Visualization for NW Wash Net Load IROL Margin



Source – Peak Reliability. 2015 WECC JSIS Meeting

Use of Node-Breaker Model for Online Cascading Analysis at ISONE[3]

* Extended CTG include selected N-2 used in Day-Ahead processes and all Stuck Breaker. Total ~6,000 x 3 = 18,000 CTGs



[3] 2016 FERC Technical Conference, "Use of Online Cascading Analysis for Reducing the Risk of Blackouts", presentation by ISO NE

2. Improving Resiliency of the Grid through Advanced Software Tools

Improving Resiliency of the Grid

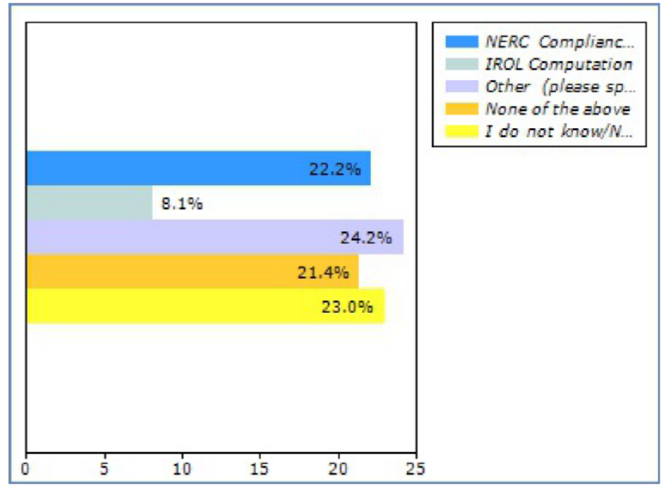
- NERC CIP-014 standard
  - Protect critical stations - if inoperable/damaged as a result of a physical attack could result in "widespread instability, uncontrolled separation, or cascading"
- Automated cascading analysis:
  - Steady-state stability perspective
  - Transient stability perspective
- On-line cascading analysis
- Use of synchrophasors to predict cascades

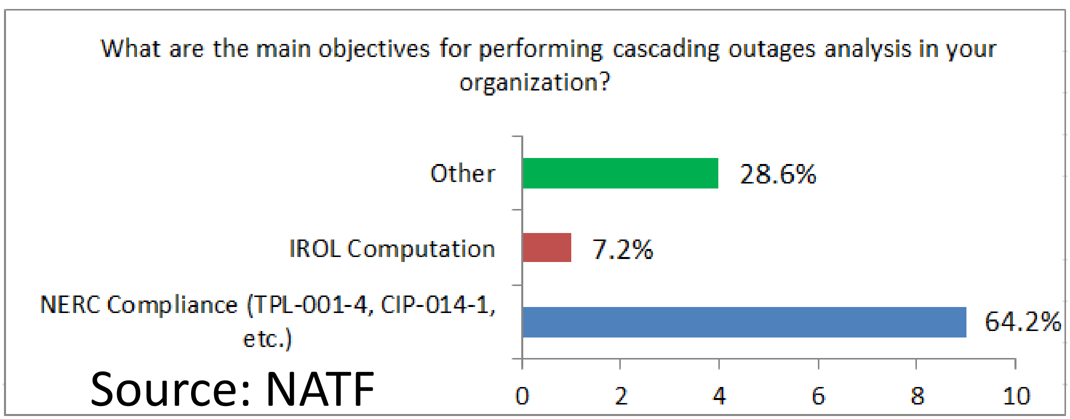
2015 CFWG Survey: What are the main objectives for performing cascading outages analysis?

IEEE Advancing Technology for Humanity

What are the main objectives for performing cascading outages analysis in your organization?

NERC Compliance (TPL-001-4, CIP-014-1, etc.)	55	22.2%
IROL Computation	20	8.1%
Other (please specify)	60	24.2%
None of the above	53	21.4%
I do not know/Not applicable	57	23.0%
Total	**248**	**100.0%**





Source: NATF

NERC Standards Related to Cascading

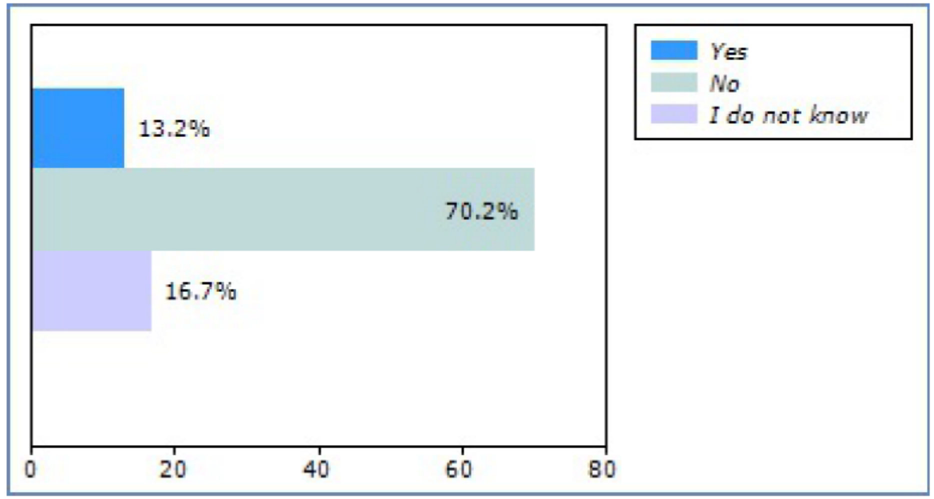
- PRC-002-2 — Disturbance Monitoring and Reporting Requirements
- TPL-001-4 — Transmission System Planning Performance Requirements
- CIP-014-2 — Physical Security
- CIP-002-5.1 — Cyber Security — BES Cyber System Categorization
- PRC-023-2 — Transmission Relay Loadability
- PRC-024-1 — Generator Frequency and Voltage Protective Relay Settings
- EOP-002-3.1 — Capacity and Energy Emergencies
- EOP-003-2— Load Shedding Plans
- TOP-001-2 — Transmission Operations
- TOP-004-2 — Transmission Operations
- FAC-003-3 — Transmission Vegetation Management
- FAC-011-2 — System Operating Limits Methodology for the Operations Horizon
- IRO-008-1 — Reliability Coordinator Operational Analyses and Real-time Assessments
- IRO-010-1a — Reliability Coordinator Data Specification and Collection

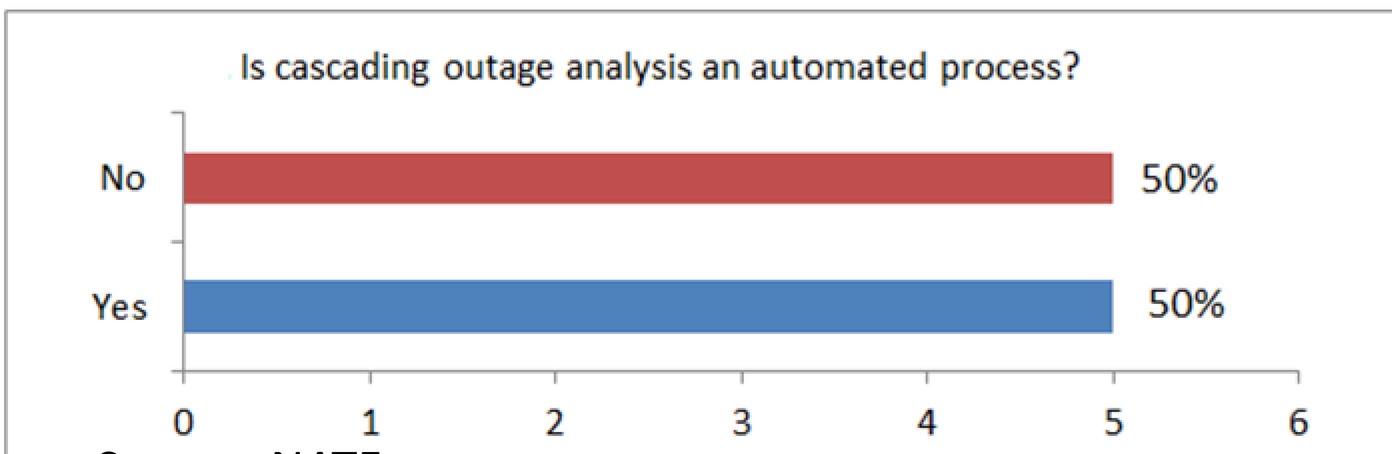
2015 CFWG Survey: Is cascading outage analysis an automated process?

IEEE Advancing Technology for Humanity

Is cascading outage analysis an automated process?

Yes	30	13.2%
No	160	70.2%
I do not know	38	16.7%
Total	**228**	**100.0%**





Source: NATF

IEEE PES Power & Energy Society®

IEEE

What is a Cascading Outage?

Various Definitions:

- IEEE PES Cascading Failure Working Group (CFWG) definition: Cascading Failure is a Sequence of Dependent Failures of Individual Components that successively Weakness the Power System

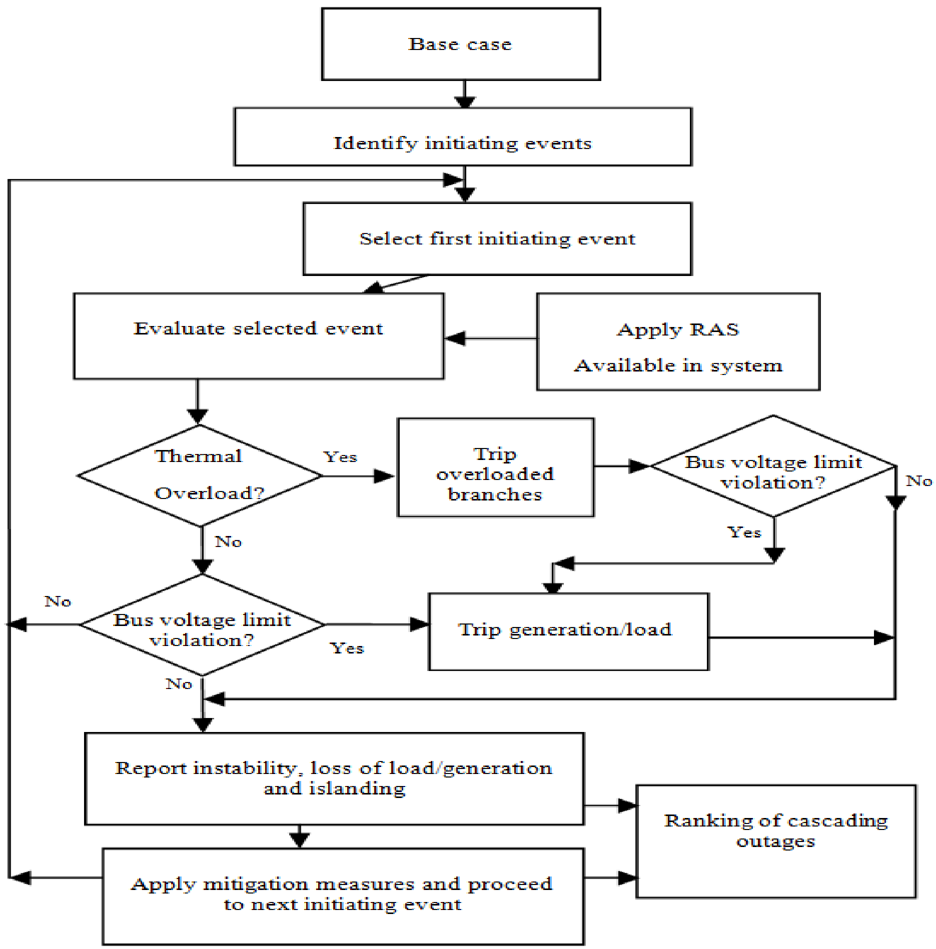
Initiating Events:

- Natural disasters
- High winds
- Contact between conductors and vegetation,
- Human error,
- Etc.

Propagation Mechanisms:

- Equipment failures
- Protection Failures
- Control actions failure
- Tree Contact
- Operator error
- Thermal overloads
- Voltage violations
- Voltage instability
- Computer or software errors /failures
- Stalled motors triggered by low voltages or off-nominal frequency
- Generator rotor dynamic instability
- Insufficient reactive power resources
- Etc.

Idaho Power Automated Analysis of Cascading Outages: Steady-State Analysis[4]



- Fast sequential contingency simulation is used to identify potential cascading modes.
- Outages are consecutively applied until:
  - System fails to solve due to voltage instability;
  - Thermal/voltage violations are alleviated or drop below the thresholds.
- Loss of load and generation is monitored and reported
- Probabilities of initiating events and consequences may be added

[4] 2017 IEEE PES General Meeting Tutorial: "Industry Best Practices, Needs, and Challenges in Cascading Analysis"

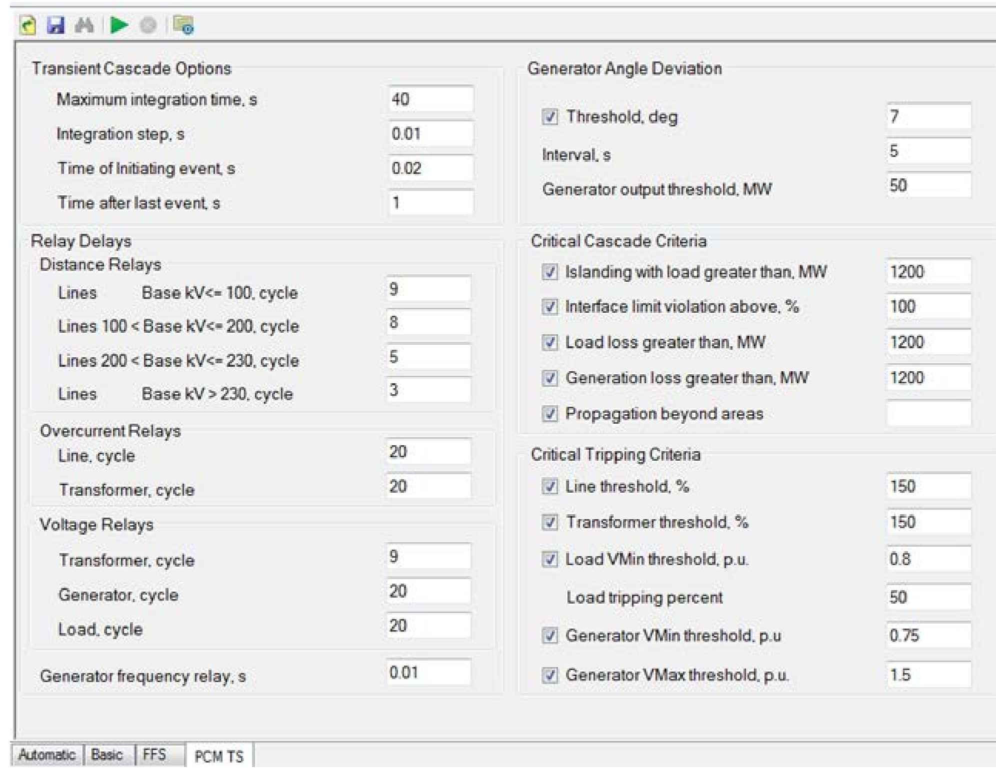
Cascading Analysis at IPC

- Simultaneous outage of two stations is an initiating event
- Cascading results for CIP-014 using PCM

Case	Type of Extreme Contingency	Number of Initiating Events	Number of Occurrences of Voltage Instability	Number of Occurrences of Cascading
15HS	Sub + Sub	36046	24	41
15LW	Sub + Sub	39060	11	18
20HW	Sub + Sub	38503	13	28

Cascading - Transient Stability

- An event is classified as a cascading outage if one of the following conditions are met:
  - Sharp drop in transient voltages in a large part of the network
  - Sharp drop in frequency followed by system separation
  - Islands are formed as a result of protection operation, with significant amount of load/generation within the island
  - Disconnection of large amount of generation
  - Disconnection of large amount of load



SPP's Method: Cascading Analysis from Transient Stability Perspective[4]

- "Category P1 and Extreme contingency events (NERC TPL -001-4) that produced the more severe system impacts were evaluated for cascading. A loss of synchronism as a result of an outaged element is the initiating mechanism for purposes of this assessment. A cascading analysis was performed on all cases shown in Table 2.1 using Fast Fault Scan (FFS) and Potential Cascading Modes (PCM) tools. This analysis determined possible cascading due to transient instability within the SPP System.
- The FFS tool was first used to determine the most severe category P1 fault locations (fault is placed near the bus on each branch to be outaged) within the system. The identified fault locations were ranked in order of decreasing severity (1 being the most severe) using a ranking index. The bus fault and associated outaged branch were then used as the initiating event in the PCM tool to determine possible cascading, meaning a criteria violation (loss of 1,768 MW) had occurred. A criteria violation would merit further analysis.
- Second, Category Extreme events were evaluated for potential cascading, as well. Any loss of MW due to generator instabilities for these events was evaluated against the 1,768 MW criteria. A criteria violation would merit further analysis.

[4] 2017 IEEE PES General Meeting Tutorial: "Industry Best Practices, Needs, and Challenges in Cascading Analysis"

Analysis of Potential Cascading Modes (PCM) – Transient Stability

- Distance relays are modeled to simulate using zone 1 protection of 55% of the line impedance for each transmission line
  - Delays for lines are as follows: <100kV (9cy); 100–200kV (8cy); 200-230kV(5cy);<230kV(3cy);
  - Delays for transformers is 4cy
- Over-current relays are modeled to simulate a 50% overcurrent with a 2000 MW maximum load loss.
- Under-Voltage relays are modeled to simulate using a voltage threshold of 0.1 p.u. for transient voltage responses.
- Under-Frequency relays are simulated using an angle threshold of 180 degrees for rotor angle changes
- Gen angle – initial gen angle > angle threshold

PCM Results (P1) at SPP

Bus	Time (s)	Event	Flow (MW)
1	0.02	1-1a faulted	279
	0.08	1-1a line tripped due to fault	
	0.08	1-1b line tripped due to fault	
	.01	1-1c XFMR tripped due to fault	
2	0.02	2-2a faulted	397
	0.08	2-2a line tripped due to fault	
	0.08	15-2a line tripped due to fault	
	0.08	remote line tripped due to overload	
	0.27	remote transformer tripped due to fault	
	0.35	remote transformer tripped due to fault	
	0.35	remote transformer tripped due to fault	
	0.51	Generator tripped (1261MW) due to loss of synchronism	

<u>PCM Results for Fault Buses 1 and 2</u>

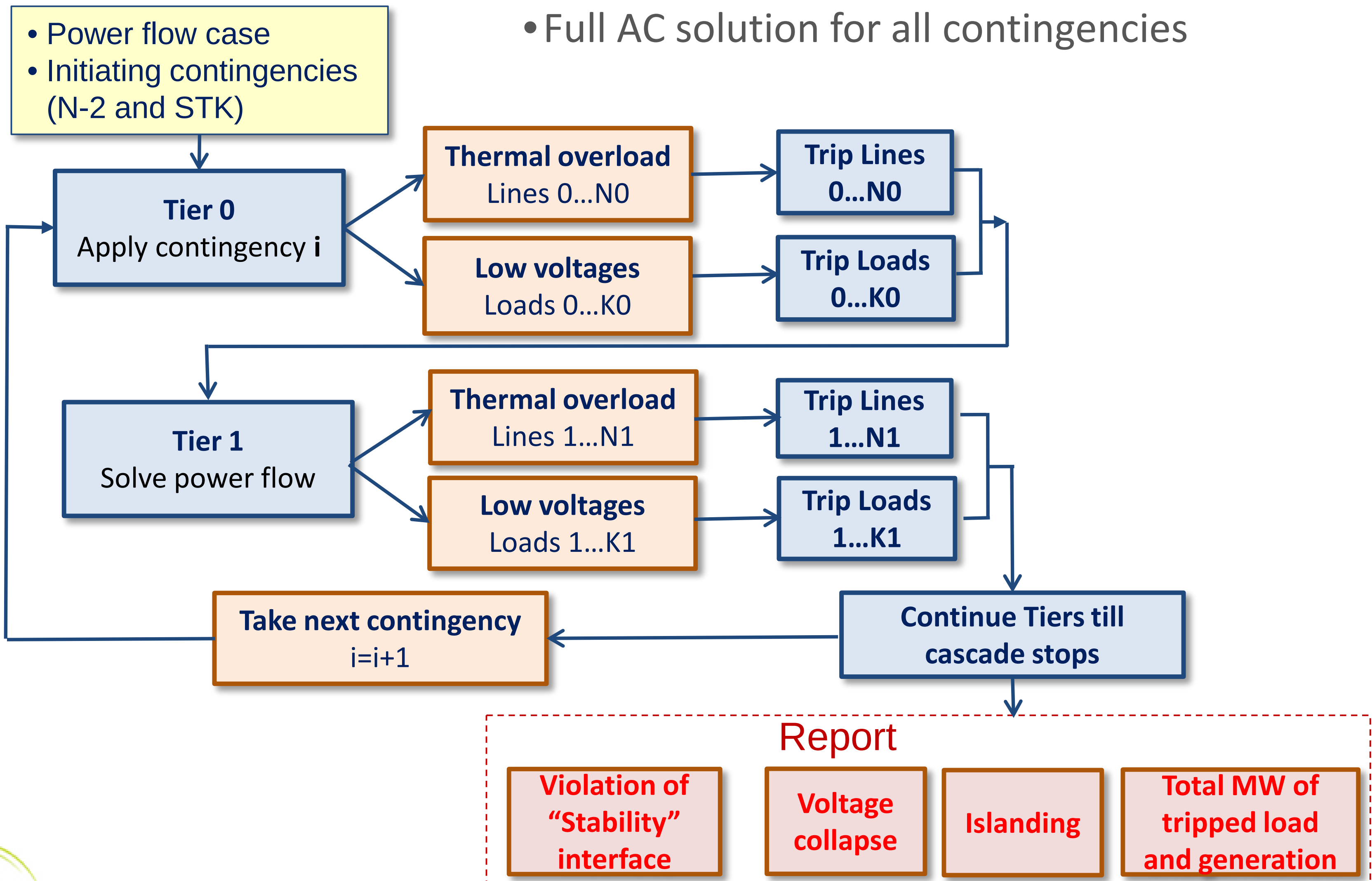
On-Line Cascading Analysis at ISONE[3]

- Can be used as a basis for IROL (Inter-Regional Operational Limit) violation analysis and compliance
- Can be a basis of consistent, quantifiable and auditable process of IROL violation analysis
- Is a practical instrument to satisfy generic NERC requirements of IROL compliance
- Current industry practice based on classification of IROL interfaces can be dramatically improved by using cascading analysis
- ISO-NE is targeting two goals by creating online Cascading Analysis
  - Preventing the risk of uncontrolled outages and blackouts
  - Dramatically improve IROL compliance

[3] 2016 FERC Technical Conference, "Use of Online Cascading Analysis for Reducing the Risk of Blackouts", presentation by ISO New England

ISONE Modeling of Cascading Process

- Full AC solution for all contingencies



IEEE PES Power & Energy Society® IEEE

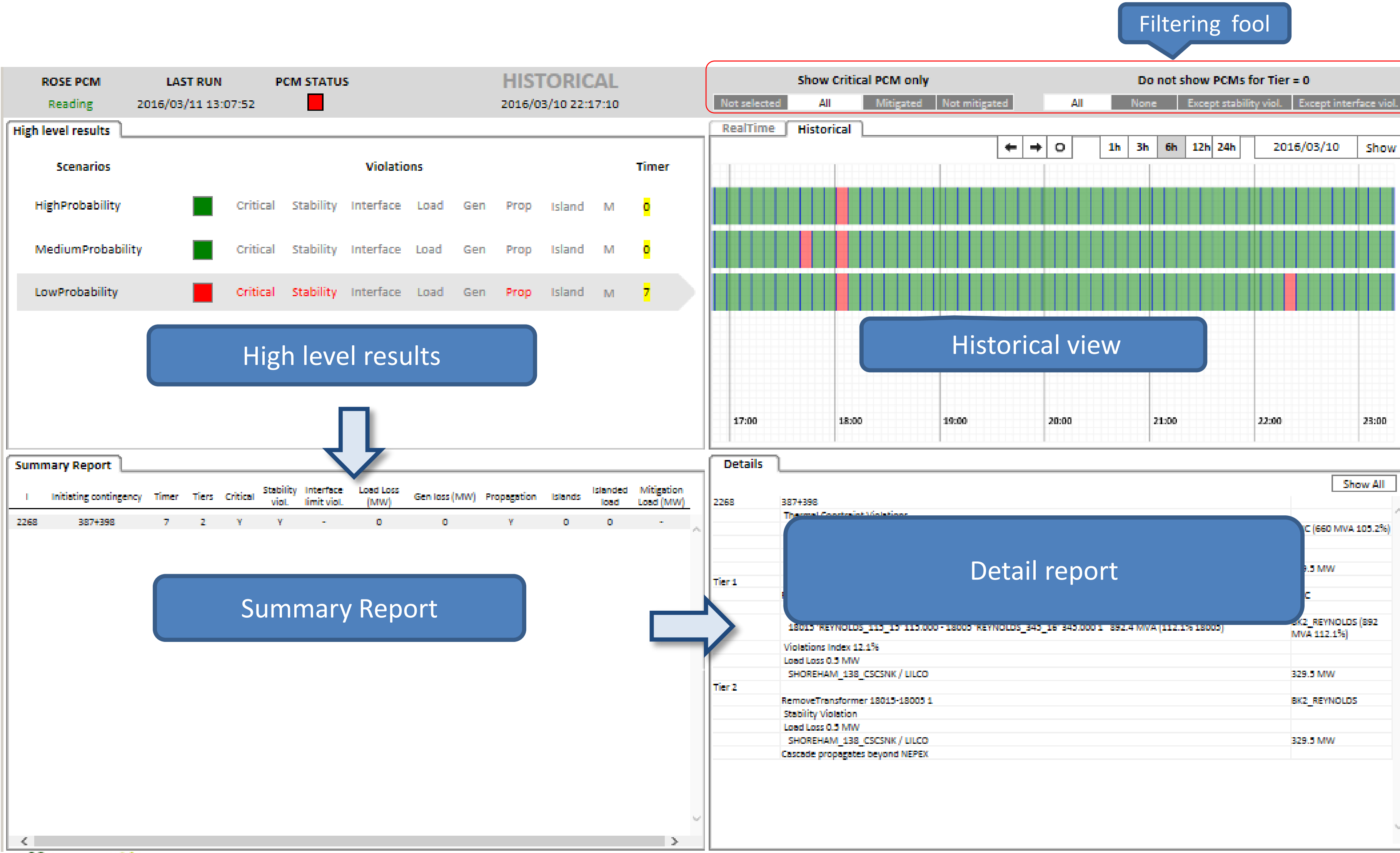
Scenarios in Cascading Analysis

- Cascading study is deterministic per defined tripping criteria
- Tripping criteria can be defined only approximately due to lack of information on relay settings, load composition, operator actions
- Risk of cascading can be evaluated by running several cascading Scenarios for the same initiating contingencies with different tripping criteria

Tripping criteria for Scenarios

Scenario	Line % of rate C	Transformer % of rate C	Load voltage p.u.	Load % tripped
HighProbability	130%	130%	0.85	50%
MediumProbability	115%	115%	0.85	40%
LowProbability	101%	101%	0.85	30%

ISONE On-line GUI to View Results



PMUs for Predicting Cascading Outages

- Functionalities to predict/prevent cascading outages:
  - Situational awareness and wide-area visualization
  - Early detection of events
    - Variations of reactive/active injections
    - Complements the information coming from breaker status signals
  - Voltage stability analysis
    - Used to compute voltage stability margins
    - PMU-based alarms are issued when voltage stability margin is small/decreasing
  - Phase Angle Monitoring
    - Monitors high angle displacements to detect highly loaded lines
    - Importance of phase angle limit computation in real time
  - Oscillatory analysis
    - Predicts unstable oscillations which may trigger line trippings

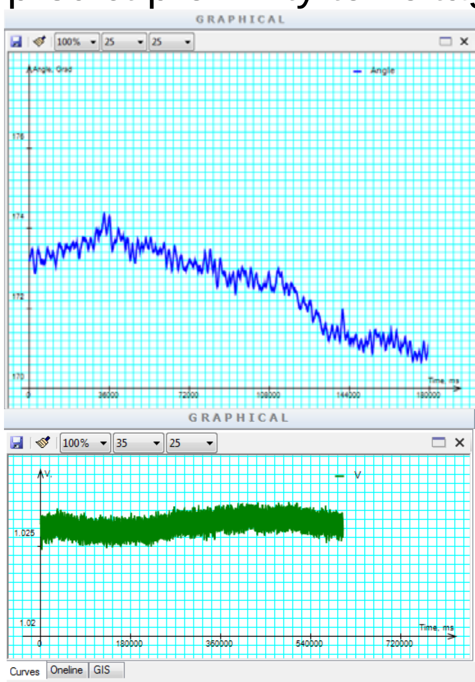
PMUs for Mitigation/Restoration from Cascading Outages

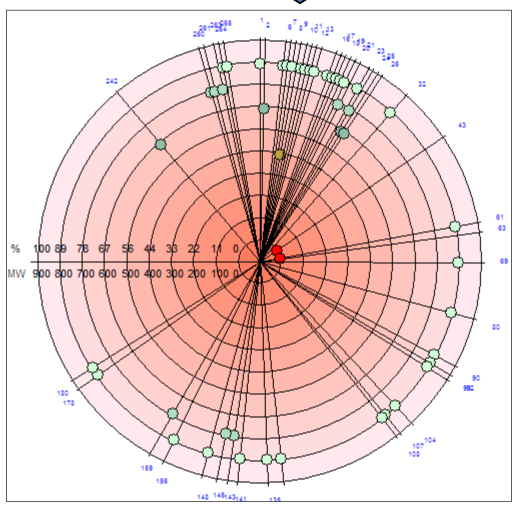
- PMU measurements allow for faster and more accurate relay operation and enabling *RAS*
- Wide area oscillation *damping control*
- Advanced defense functions, like *coordinated* wide area *load shedding* actions, *controlled islanding*, etc.

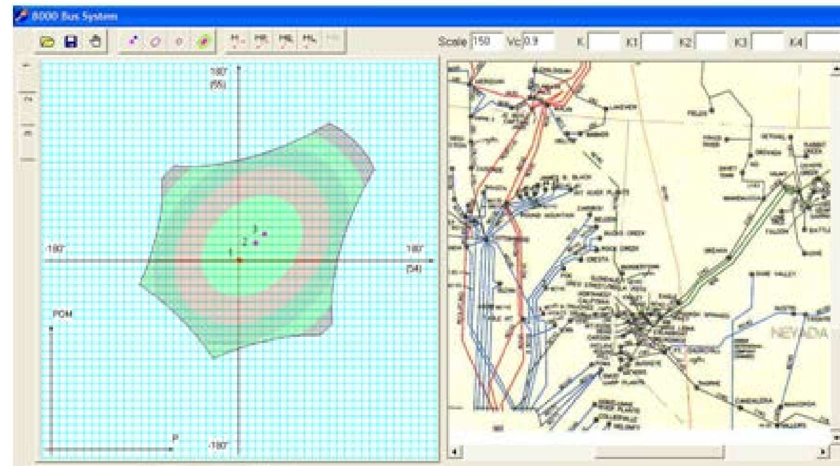
PMU Applications for Cascading Analysis

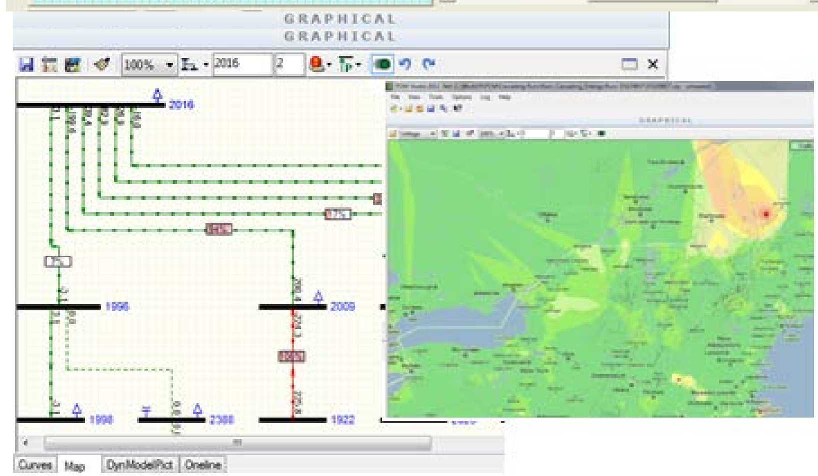
Phase angle and voltage monitoring

Using PMU measurements to compute system steady-state stability limits and predict proximity to voltage collapse





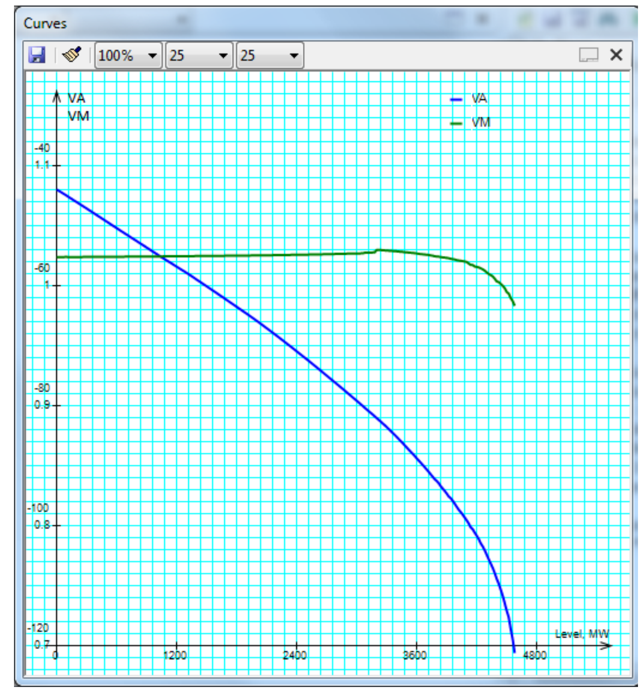




Source: M.Ya. Vaiman, M.M. Vaiman, S. Maslennikov, E. Litvinov, X. Luo, "Calculation and Visualization of a Power System Stability Margin Based on the PMU Measurements", 2010 IEEE SmartGridComm:31 - 36

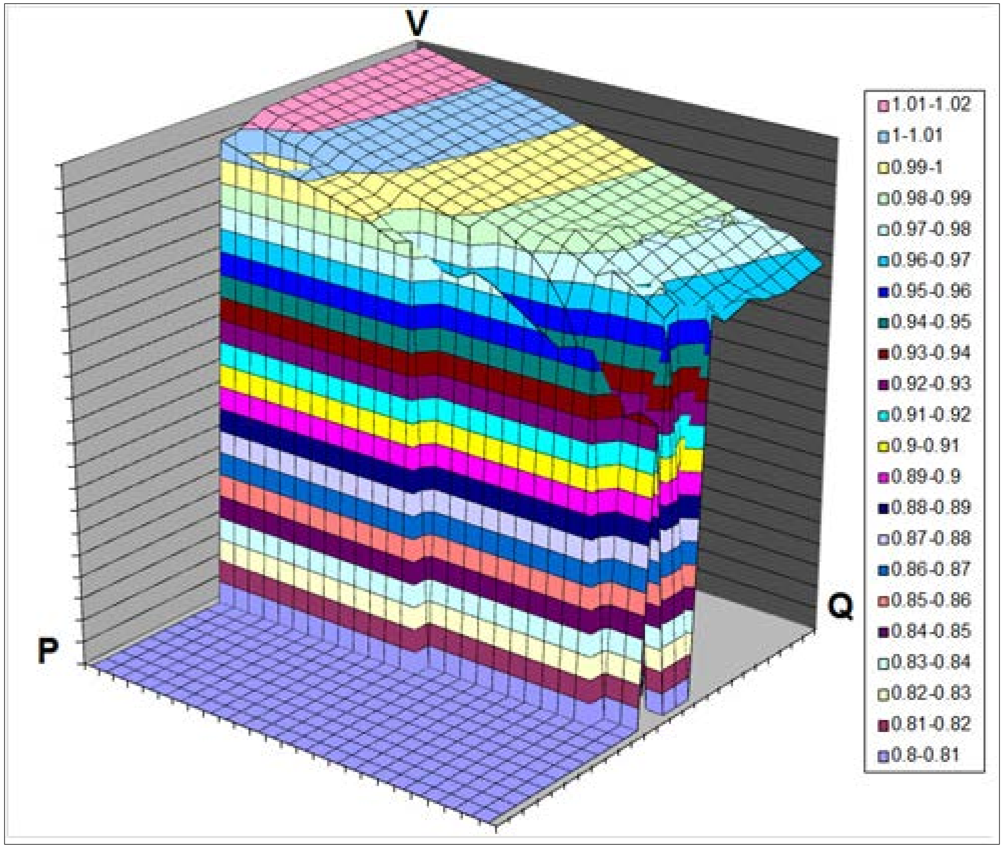
Phase Angle for Steady-State Voltage Stability Analysis[5]

- **Voltage magnitude and phase angle are equal indicators of voltage collapse because**
  - Voltage collapses and angle experiences uncontrollable change at the same level of stressing
- In many cases, it's more effective to monitor **Pδ-curve** than PV-curve
  - Voltage remains almost constant over a wide range of stressing, while angle significantly changes

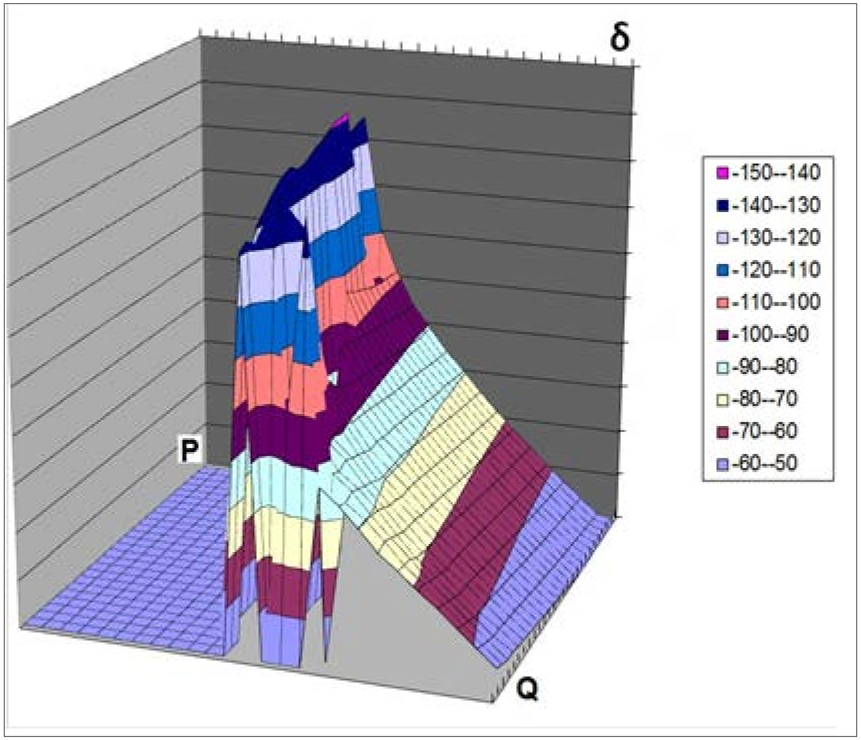


[5] Source: V&R Energy, Patent Pending

Angle: An Indicator of Voltage Collapse[5]



$V(P,Q)$



$\delta(P,Q)$

[5] Source: V&R Energy, Patent Pending

3. Related IEEE Activities

IEEE PES Resource Center

- Tutorials, webinars, technical publications
- Online training platform - Next GenEEI

- Tutorials include:
  - Synchrophasors Estimation and Control of Power System Dynamics
  - Smart Grid 308 – Distributed Energy Resources
  - IEEE 1547 Standard for Interconnecting Distributed Energy Resources with Electric Power Systems
  - Industry Best Practices, Needs, and Challenges in Cascading Analysis: Tutorial and Training
  - Managing Uncertainties in the Future Grid: Evolution of EMS Control Centers - Synchrophasor Solution
  - Cybersecurity of the Electric Power Transmission and Distribution System

2017 IEEE ISGT Conference

- 2017 ISGT – Washington, D.C. April, 2017
- Panel Sessions Included:
  - Industry Best Practices in Using Synchrophasor Technology
  - Opportunities and Challenges for PMU Implementation in Distribution Systems and Microgrids
  - Cloud Computing and Cybersecurity Issues for Power Grid Applications
- Tutorials included:
  - Managing Uncertainties in the Future Grid: Evolution of EMS Control Centers - Synchrophasor Solutions
  - DER Integration Course - Impacts on T&D
  - Introduction to Smart Grid Data and Analytics

4. Future Work

Future Work – Industry Needs

- Computing phase angle limit in real-time:
  - Wide-area and for line reclosing
- Determining the most dangerous direction of system stressing in real-time:
  - What is the combination of flows on all interfaces such that the system margin to collapse is the smallest?
- Real-time voltage stability analysis:
  - Separating local vs. global voltage collapse and quantifying voltage collapse
  - Separating numerical vs. physical voltage stability
- Accessing system health in real-time, simultaneous AGC/AVC systems' control, and many more challenges!

5. Conclusion

Conclusion

- IEEE PES offers expertise and technical resources to facilitate development, adoption, and sharing of new methodologies, and provide training on new technologies

PES

STANDING COMMITTEES
- Awards
- Organization & Procedures
- Power and Energy Education
- Standards Coordination
- Technical Sessions

PES TECHNICAL COUNCIL

COORDINATING COMMITTEES
- Intelligent Grid and Emerging Technologies
- Marine Systems
- Wind and Solar Power

TECHNICAL COMMITTEES
- Analytics Methods for Power Systems
- Electric Machinery
- Energy Development and Power Generation
- Energy Storage and Stationary Battery
- Insulated Conductors
- Nuclear Power Engineering
- Power System Communications and Cybersecurity
- Power System Dynamic Performance
- Power System Instrumentation and Measurements
- Power System Operations, Planning and Economics
- Power System Relaying and Control
- Smart Buildings, Loads and Customer Systems
- Substations
- Surge Protective Devices
- Switchgear
- Transformers
- Transmission and Distribution