IEEE PES Cascading Failures Working Group (CFWG): Analysis and Recommendations

Working Group: Understanding, Prediction, Mitigation and Restoration of Cascading Failures

IEEE PES Computer and Analytical Methods Subcommittee (CAMS)

Milorad Papic, Idaho Power Co.

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NASPI/ISGAN International Synchrophasor Symposium

March 22 – 24, 2016 · Atlanta, GA

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1. IEEE PES Cascading Failure Working Group (CFWG) Activities

hubpages.com

http://www.wikihow.com/Not-Get-Bored-when-the-Power-Goes-Out

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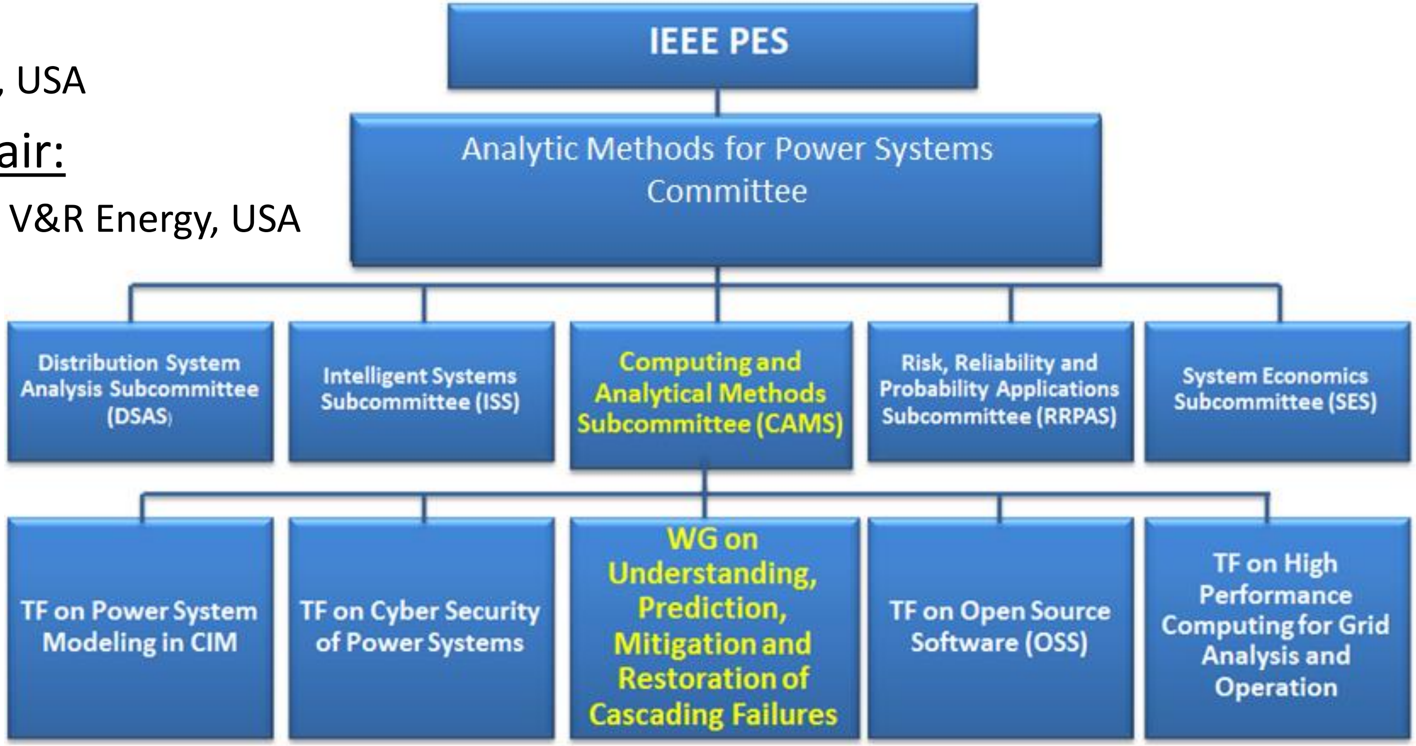
IEEE CAMS WG on Cascading Failures

- Initiated during 2007 IEEE PES GM:
  - *"To investigate new methods, technologies and tools in order to better understand, predict, mitigate and restore cascading failures. Sponsor technical sessions, tutorial courses, workshops, conferences for effective exchange of information on the state-of-the art, best practices, procedures and strategies."*
- WG Chair:
  - Milorad Papic, IPC, USA
- PMU Subgroup Chair:
  - Marianna Vaiman, V&R Energy, USA
- Drivers:
  - Blackouts
  - NERC Standards
  - Limited commercially available Tools

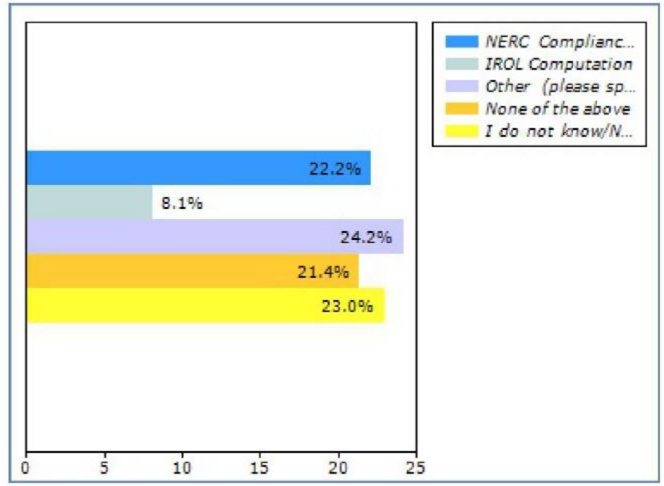


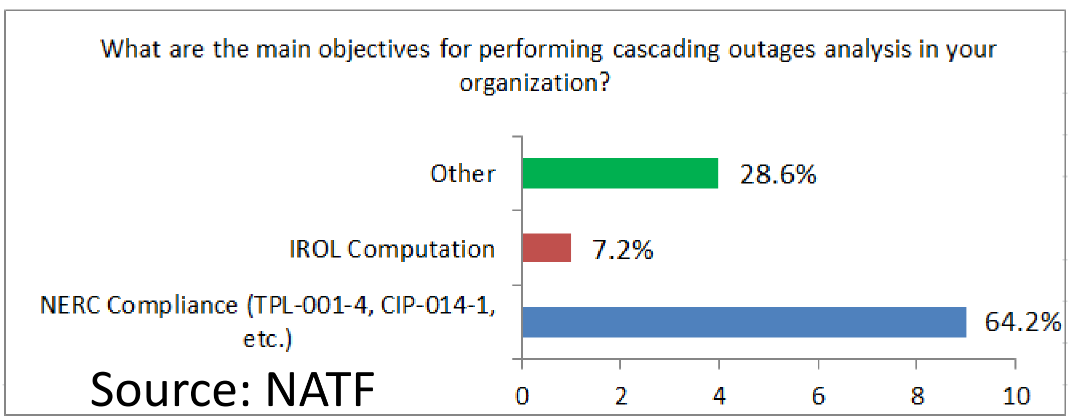
2015 CFWG Survey: What are the main objectives for performing cascading outages analysis?

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

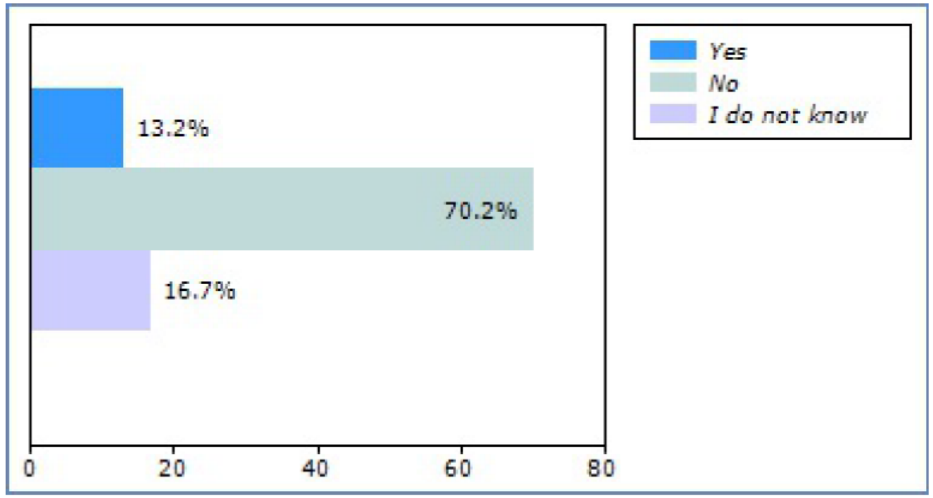
- PRC-002-2 — Disturbance Monitoring and Reporting Requirements
- TPL-001-4 — Transmission System Planning Performance Requirements
- CIP-014-2 — Physical Security
- CIP-002-5.1 — Cyber Security — BES Cyber System Categorization
- PRC-023-2 — Transmission Relay Loadability
- PRC-024-1 — Generator Frequency 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

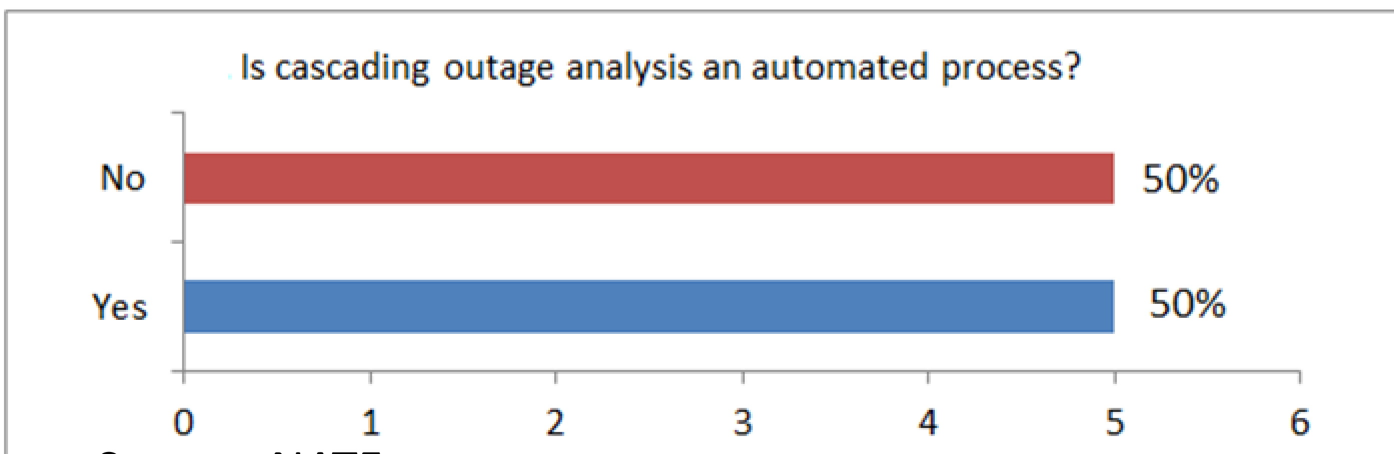
2015 CFWG Survey: Is cascading outage analysis an automated process?

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%**





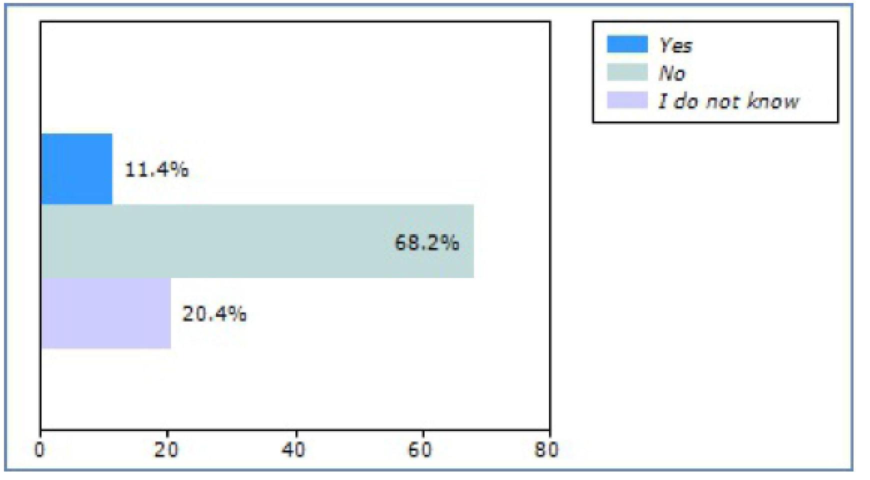
Source: NATF

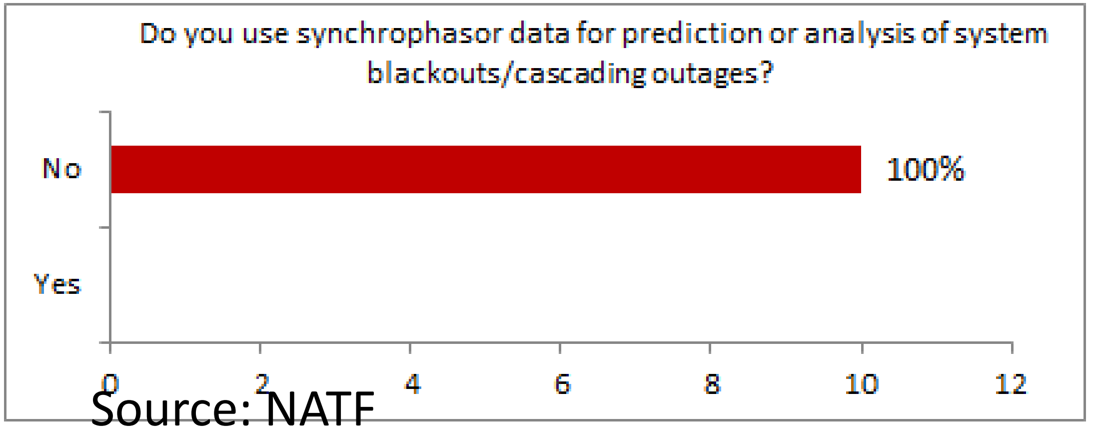
2015 CFWG Survey: Does your company use synchrophasor data for prediction or analysis of system blackouts/ cascading outages?

IEEE Advancing Technology for Humanity

Does your company use synchrophasor data for prediction or analysis of system blackouts/cascading outages?

Yes	23	11.4%
No	137	68.2%
I do not know	41	20.4%
Total	**201**	**100.0%**



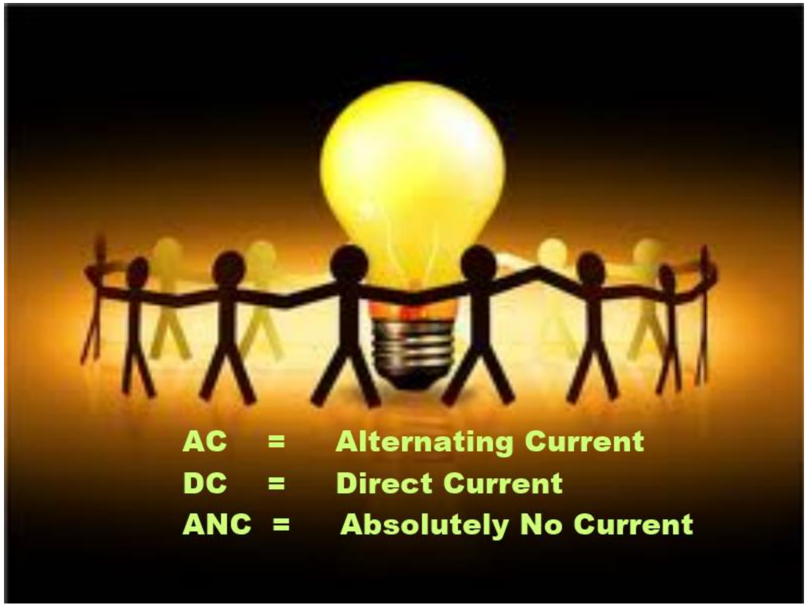


Source: NATF

PMU Subgroup

- PMU Subgroup focuses on the uses of synchrophasors for analysis of cascades:
  - Create a repository of standards associated with PMUs and their uses, as related to cascading analysis;
  - Create a repository of major industry implementations (projects, practices), R&D activities, and references on using synchrophasors for cascading analysis;
  - Collaborate with NASPI, NERC SMS (Synchronized Measurement Subcommittee), DOE, CIGRE;
  - Invite speakers from industry, academia, vendor community to present on this subject at CFWG monthly conference calls.

2. What is a Cascading Outage?



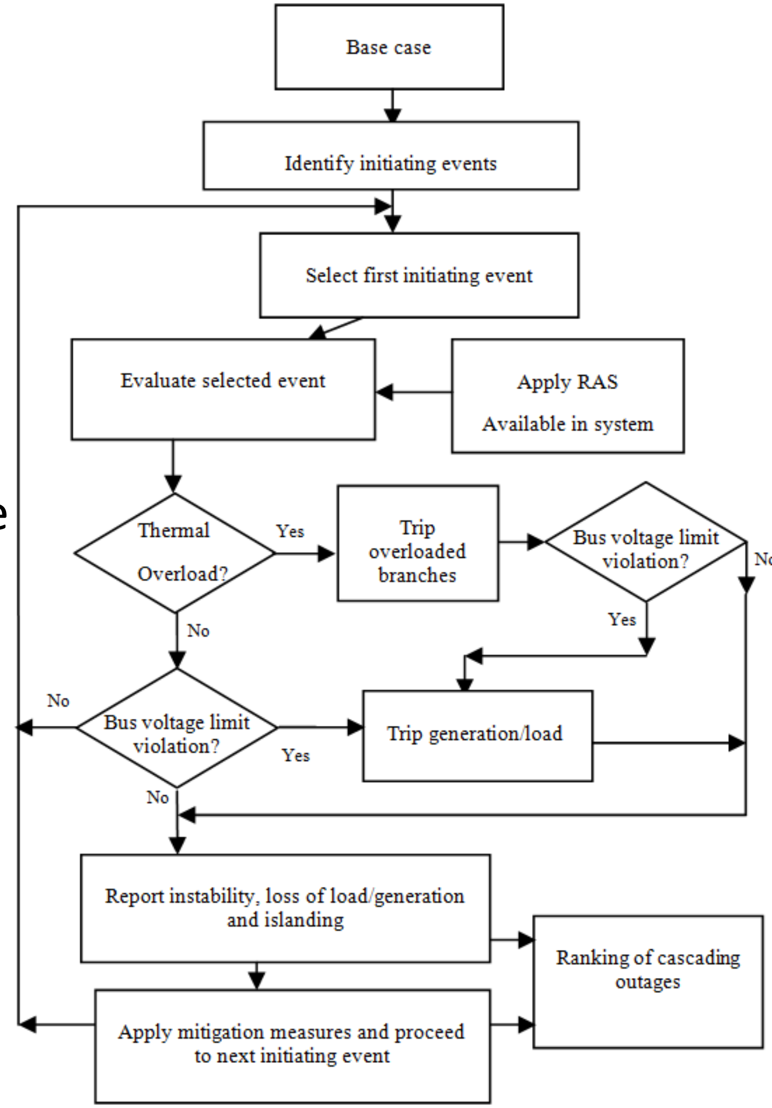
newsforyoulove.blogspot.com

We had a power outage today ... and my PC, TV, and DVD were all shut down. Then I discovered that my phone battery was flat and I couldn't charge it. To top it off it was snowing outside. So I couldn't play golf and I couldn't fish. So I talked with my wife for a few hours. She seems like such a nice person.

https://www.reddit.com/r/Jokes/comments/20o7y8/

Definition of a Cascading Outage

- Many definitions of cascading outages
- CFWG defines a cascading outage as a sequence of events in which an initial disturbance, or a set of disturbances, triggers a sequence of one or more dependent component outages:
  - In some cases they halt before the sequence results in the interruption of electricity service
  - In many case, cascading outages have resulted in massive disruptions to electricity service:
    - Northeast blackouts in 1965 and 2003, New York City blackout in 1977, two WECC blackouts in 1996, Brazil blackout in 2009, WECC blackout in 2011, etc.



Initiating Events Leading to Cascading Outages

- Initiating events for cascading outages may include a wide variety of disturbances such as: high winds, natural disasters, contact between conductors and vegetation, human error, etc.
- Many mechanisms by which subsequent outages can propagate beyond the initial outages: overloaded transmission lines that subsequently contact vegetation; hidden failures or inappropriate settings in protection devices; voltage collapse; stalled motors triggered by low voltages or off-nominal frequency; over /under excitation in generators; generator rotor dynamic instability; computer or software errors /failures, etc.

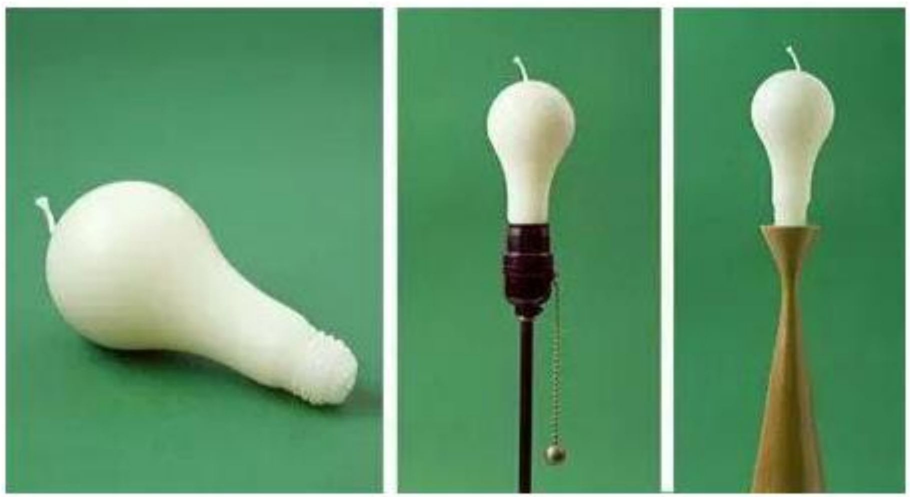
Contribution of Cascading Outages to Blackout Risk

- Cascading failures continue to contribute significantly to blackout risk
- The number of blackouts that result in a loss of over 1000 MW of demand doubles every 10 years
- Over 50% of blackouts involved many cascading elements and were “slow” in progression
- **PMUs can help to detect “fast” cascading and (in combination with models) help predict the path of “slow” cascades**

Some Findings and Recommendations after Blackouts

- Arizona – Southern California Outages on September 8, 2011: Causes and Recommendations: **Finding 12 Inadequate Real-Time Tools**:
  - Affected TOPs' real-time tools are not adequate or, in one case, operational to provide the situational awareness necessary to identify contingencies and reliably operate their systems.
- NERC Disturbance Reports indicate that **~70% of major disturbances involve protective relays or special protection schemes**.
  - In these cases, post-disturbance misoperation of the protection system fails to prevent the spread of a major blackout
- The August 14, 2003 Blackout Task Force recommends:
  - "**improvements may be needed in under-frequency load shedding and its coordination with generator under- and over-frequency protection and controls**"
- **PMUs CAN HELP!**

3. State-of-the Art in Cascading Analysis



www.sapeople.com

Pioneers in Cascading Analysis

- Southwest Power Pool (SPP)
  - Pioneered massive automated analysis of cascading outages from transient stability perspective while considering protection system at the end of 2015 using PCM-TS tool
- ISO New England
  - Pioneered massive on-line cascading analysis and introduced a concept of the "Critical Cascade" using ROSE-PCM tool in 2014
- Peak Reliability
  - Pioneering multiple measurement-based applications, including Linear State Estimator for the entire WECC footprint, measurement-based voltage stability and control actions application as a part of DOE PRSP project
- Idaho Power Co.
  - One of the first utilities to run automated massive cascading analysis using PCM tool since 2011
- BPA
  - Installed synchrophasor-based RAS in 2015
- SCE
  - Implementing synchrophasor Voltage/VAR controller
- NYPA, SDG&E, Dominion, PJM, CAISO, ERCOT and many other utilities are currently implementing multiple measurement-based apps to improve reliability of the grid
- <u>If your utility is doing innovative work and we missed you, please let us know, so that we can add your organization!</u>

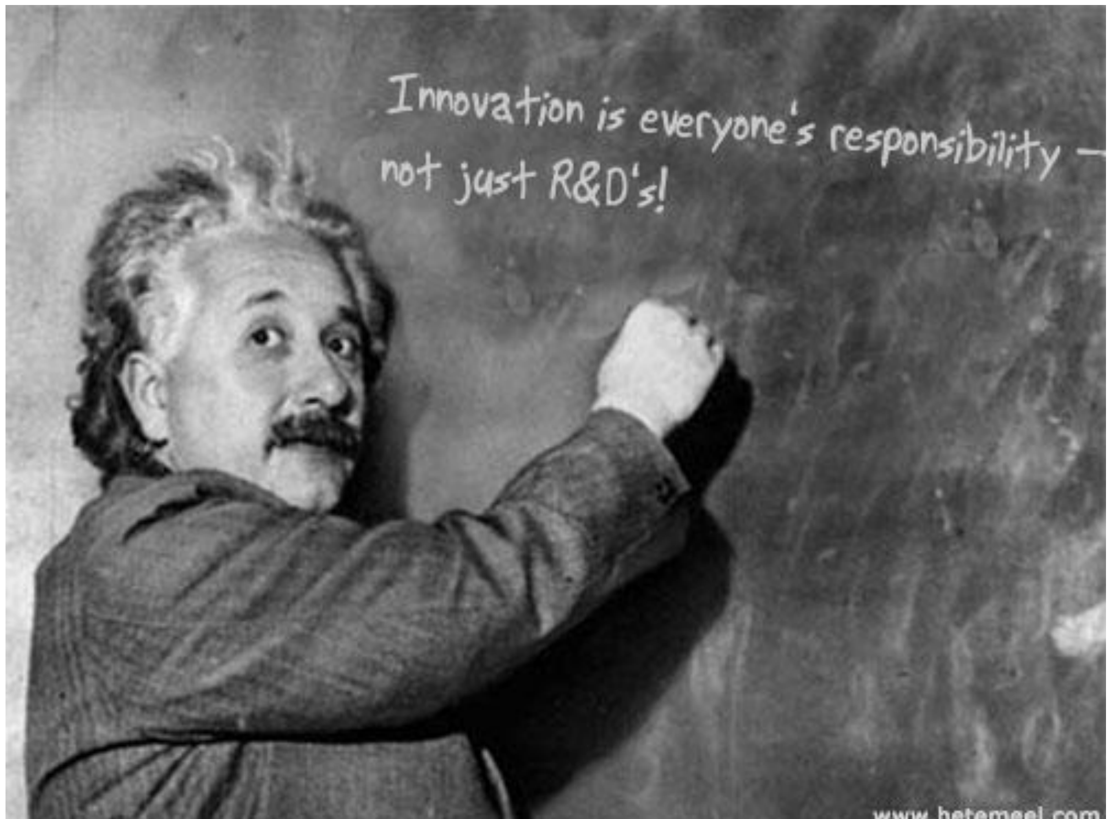
Utility Experience

- Today's panel includes three industry presentations on current utility practice for analysis of cascading outages from:
  - Peak Reliability
  - XM Colombia
  - ISO New England

  and

- Two research presentations on the state-of-the-art in cascading analysis from:
  - Quanta Technology
  - Iowa State University

4. Bringing Cascading Analysis to the Next Level: Applications and Benefits of Synchrophasors



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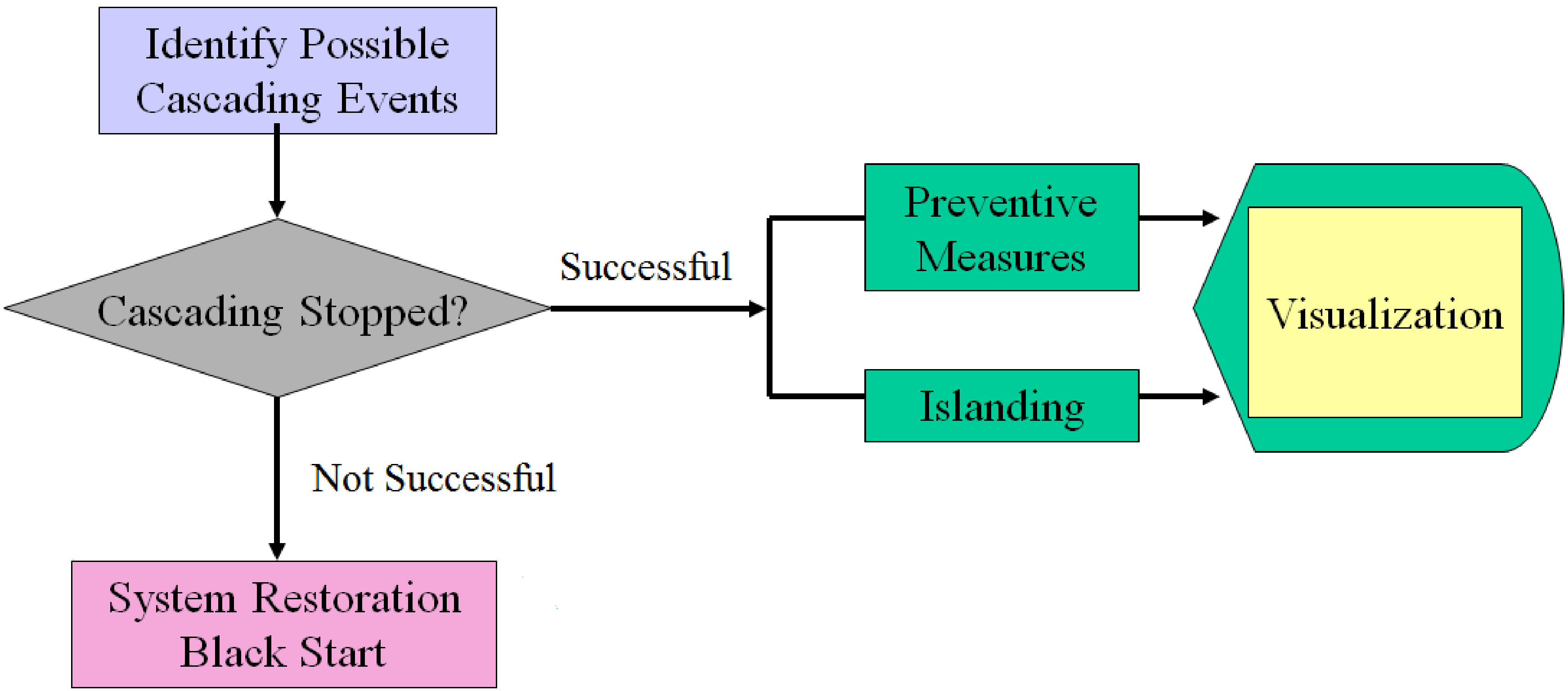
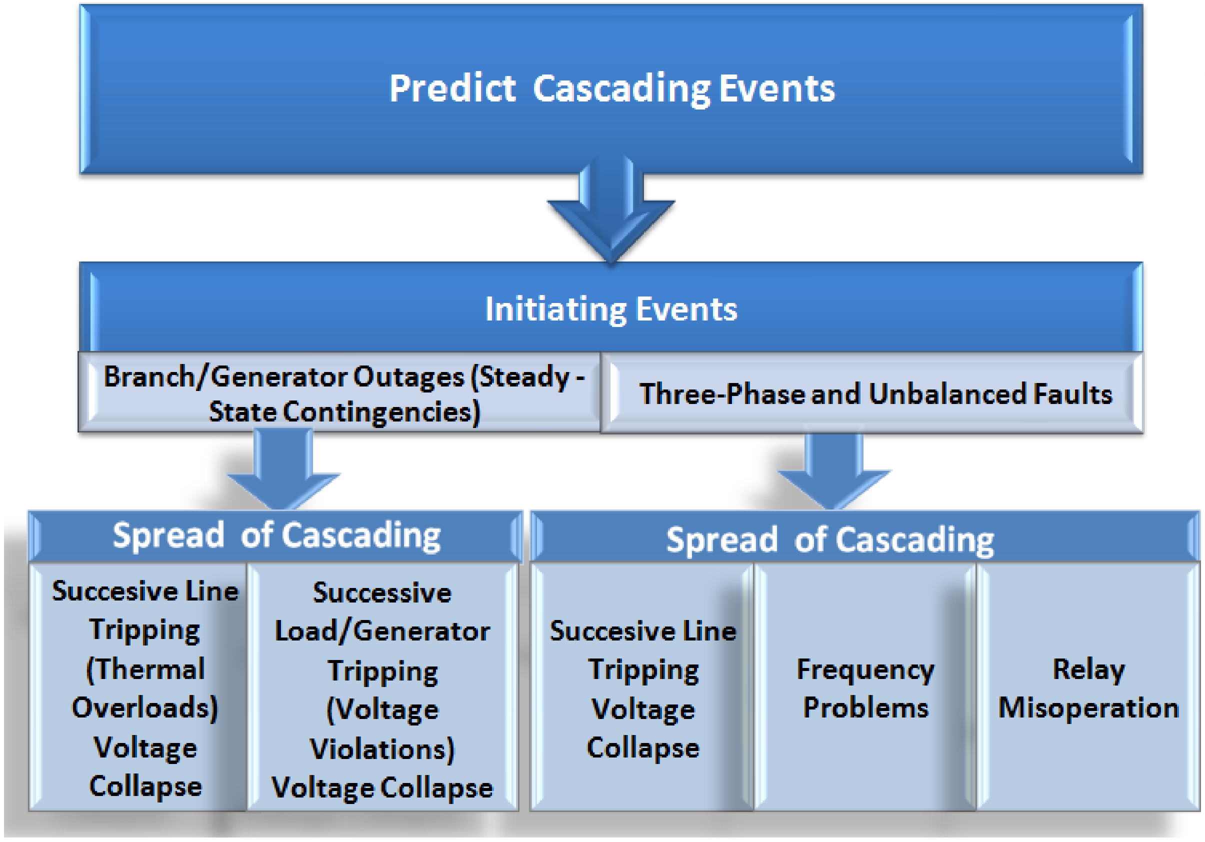
Framework for Cascading Analysis



Identifying Possible Cascading Events

- Cascading analysis framework consists of two components:
  - Identifying initiating events that may lead to cascading (steady state contingencies and faults);
  - Identifying the spread of the cascading outages.



PMUs for Detecting Cascading Outages

- Enhanced power system modeling:
  - Linear State Estimation
  - Hybrid State Estimation
- Model validation (power plant model validation)
- Situational awareness and wide-area visualization
- Early detection of events
  - Variations of reactive/active injections
  - Complements the information coming from breaker status signals

Situational Awareness and Wide-Area Visualization

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

SEL Synchrowave Central Application

Framework for Measurement-Based Analysis

Linear State Estimation

Observability Analysis	Bad Data Detection/Conditioning

↓

Advanced Applications

Contingency Analysis	Voltage/Transient /Small Signal 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

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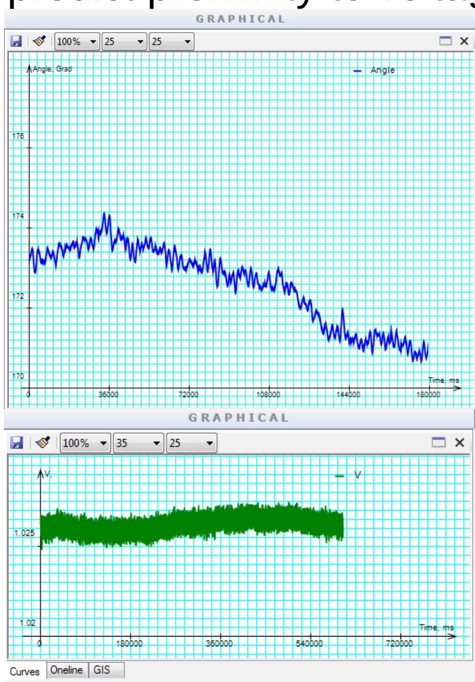
PMUs for Analysis of Cascading Outages

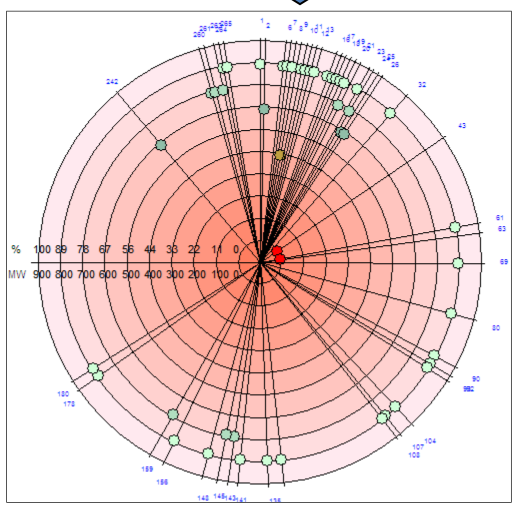
- Voltage stability analysis
  - Used to compute voltage stability margins
  - PMU-based alarms are issued when voltage stability margin is small/decreasing
- Oscillatory analysis
  - Detect oscillations which may trigger line trippings
- Transient Stability analysis
  - Dynamic simulations of cascading events while considering protection system
- Phase Angle Monitoring
  - Monitors high angle displacements to detect highly loaded lines
  - Importance of phase angle limit computation in real time

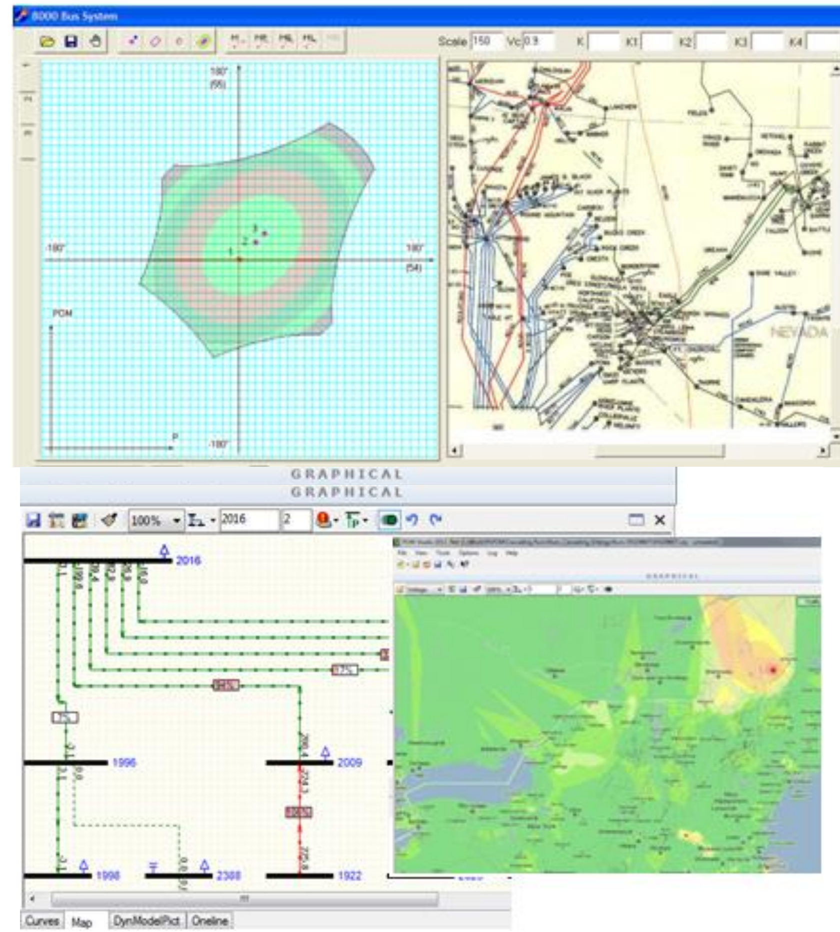
PMU Applications for Cascading Analysis

Phase angle and voltage monitoring

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







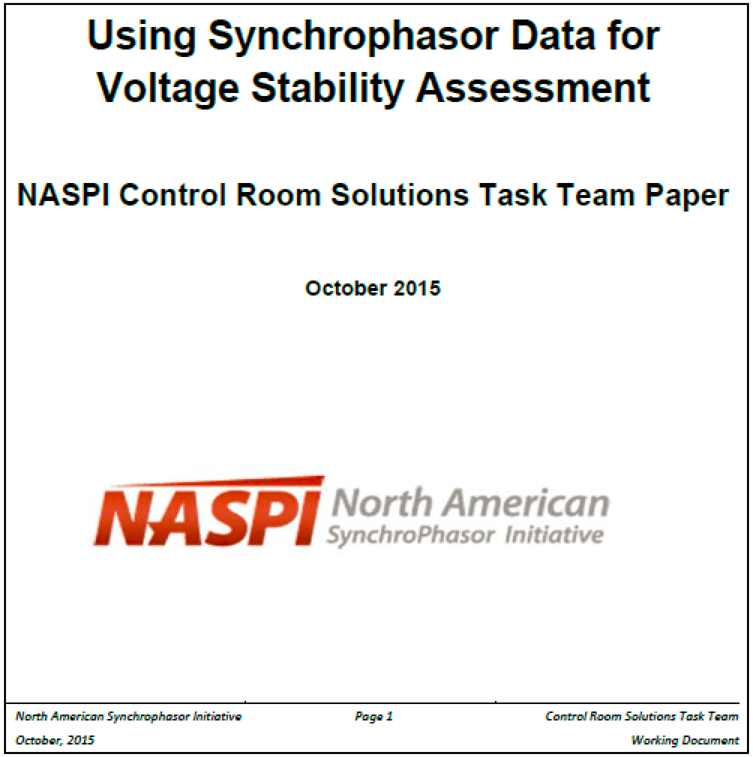
Source: M.Ya. Vaiman, M.M. Vaiman, S. Maslennikov, E. Litvinov, X. Luo, "Calculation and Visualization of a Power System Stability Margin Based on the PMU Measurements", 2010 IEEE SmartGridComm:31 - 36

Phase Angle Limit Computation

- Important to compute phase angle difference limit in real time during cascading analysis:
  - Not based on historical data
- Phase angle limit depends on:
  - System topology and conditions;
  - How the system is stressed;
- The limit changes with system conditions

Voltage Stability Analysis (VSA)

- The advantage of synchrophasor data:
  - 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 using SCADA and SE data.
  - 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.



Using Synchrophasor Data for Voltage Stability Assessment

NASPI Control Room Solutions Task Team Paper

October 2015

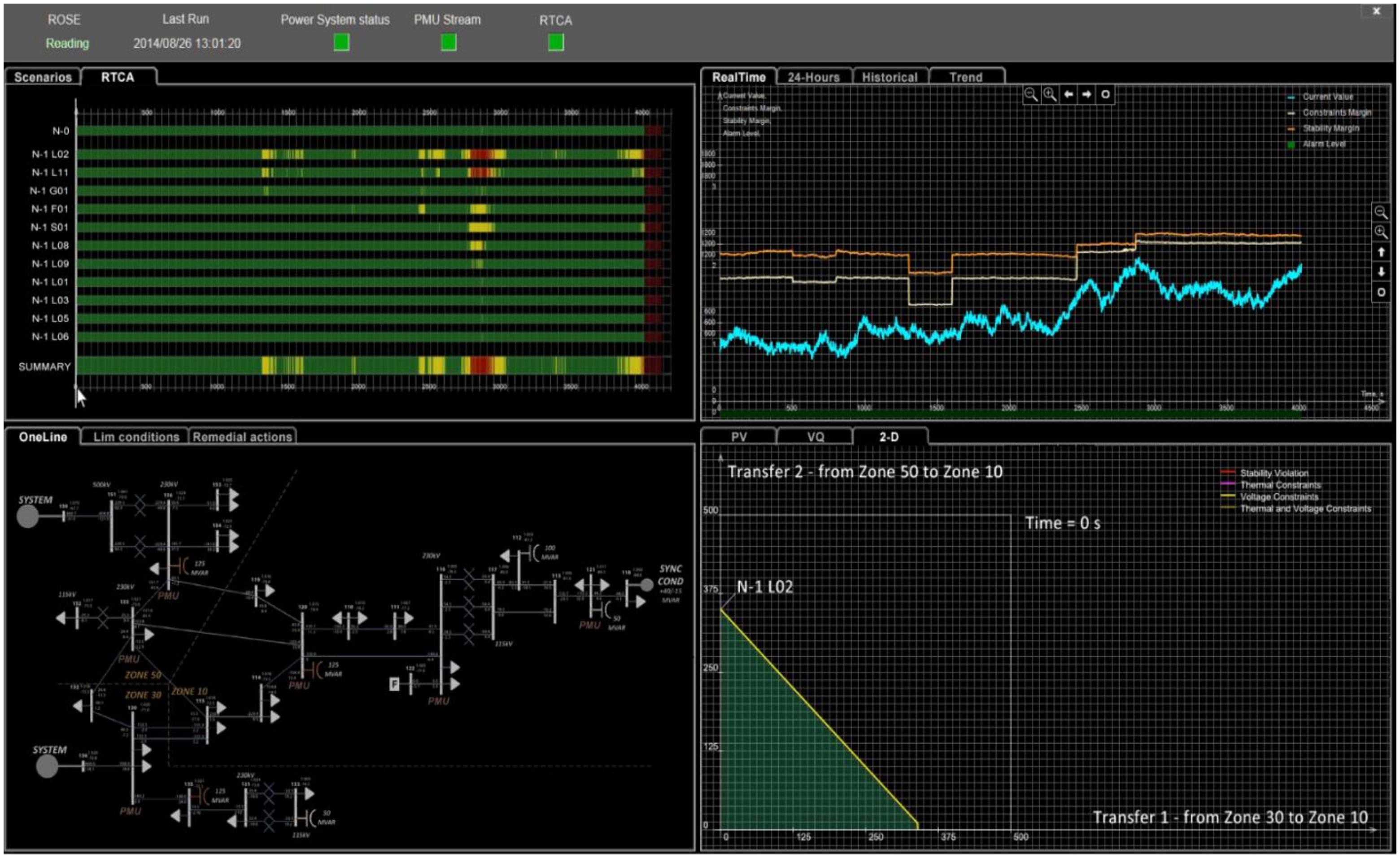
NASPI North American SynchroPhasor Initiative

North American Synchrophasor Initiative | Page 1 | Control Room Solutions Task Team
October, 2015 | | Working Document

- NASPI Voltage Stability Workshop at https://www.naspi.org/site/Module/Meeting/Forms/General.aspx?m___ID=MEETING&meetingid=347

Measurement – Based VSA

- Based on cases created by Linear State Estimator



V&R Energy ROSE Application

Cascading Analysis from Transient Stability Perspective

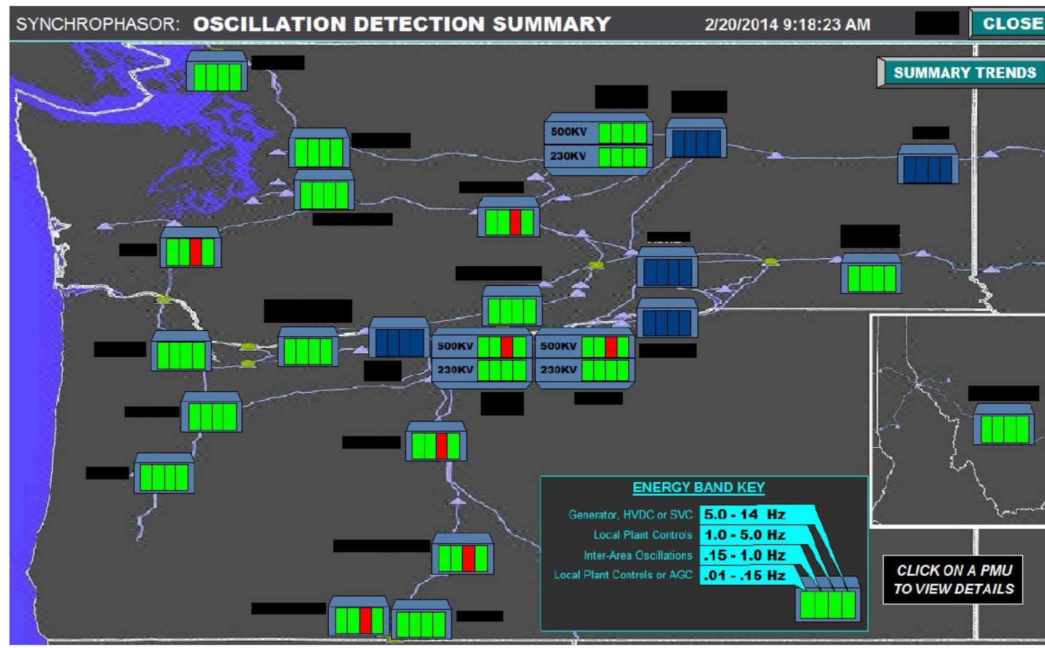
- 2015 CFWG survey indicated that the most needed computation is dynamic simulation of cascading outages which includes protection system modeling
- A screening methodology, such as Fast Fault Screening, may be used to identify potential most severe faults in the system:
  - These are initiating events for cascading analysis, processed through dynamic simulations;
- Protection system modeled during cascading analysis includes:
  - Distance relays;
  - Overcurrent relays;
  - Under-voltage relays;
  - Under-frequency relays.

Cascading Analysis from Transient Stability Perspective

- An event is classified as a cascading outage if it leads to at least one of following conditions being met:
  - Loss of transient (angular) stability,
  - 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.

Oscillatory Analysis

- Large scale integration of non-synchronous generation (such as, wind and solar) may have impact on the modes of power oscillations
- PMU-based applications for analysis of oscillations include:
  - Oscillation detection to identify growing or sustained high energy oscillations
  - Estimating frequency, damping and shape of inter-area modes of oscillations
  - Used by BPA and others in WECC



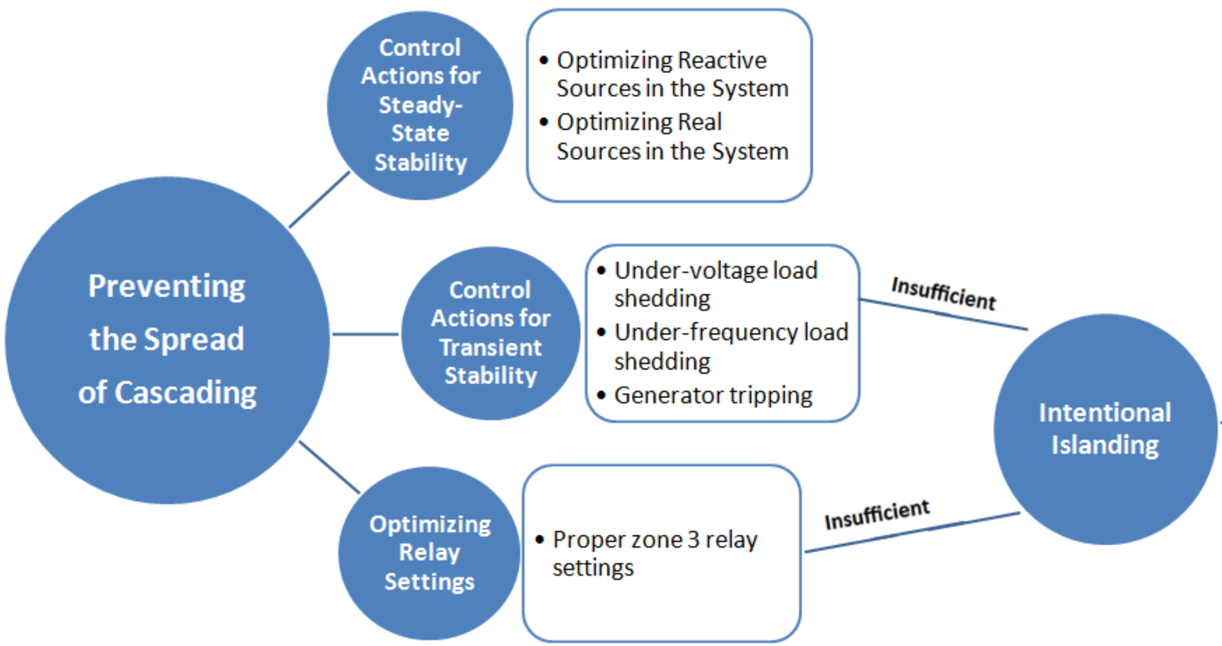
Montana Tech Oscillation Detection Application

Use of PMUs for Fast Prevention of Cascades

- 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.
- **Coordinated** frequency and voltage control
- No consolidated solutions so far

Preventive Measures during Cascading Outages Analysis

- Use of PMUs during system restoration:
  - Island synchronization
    - Linear State Estimator can be used
    - Synchronized monitoring of islands: voltage magnitude, phase angle, frequency
  - Real-time monitoring of frequency during operator switching actions



5. Recommendations and Future Direction

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Conclusions and Recommendations

- Current uses of PMUs for cascading analysis include:
  - Enhanced situational awareness
  - Early detection of events
  - Improved power system modeling (LSE, parameter estimation, bad data detection, power plant model validation)
  - Analysis of power system oscillations
- Near-future emerging technologies important for cascading analysis:
  - **Real-time phase angle limit computation during cascades**
  - Use of PMUs for voltage stability analysis
  - **Analysis of cascades by combining time-synchronized measurements with transient stability simulations that include protection system models**

Conclusions and Recommendations

- Future emerging technologies important for cascading analysis:
  - Control applications
    - PMU-based RAS
    - Synchronized measurement of generator rotor angle
    - **Coordinated voltage and frequency control**
  - Distribution synchrophasors

References to CWFG Resources

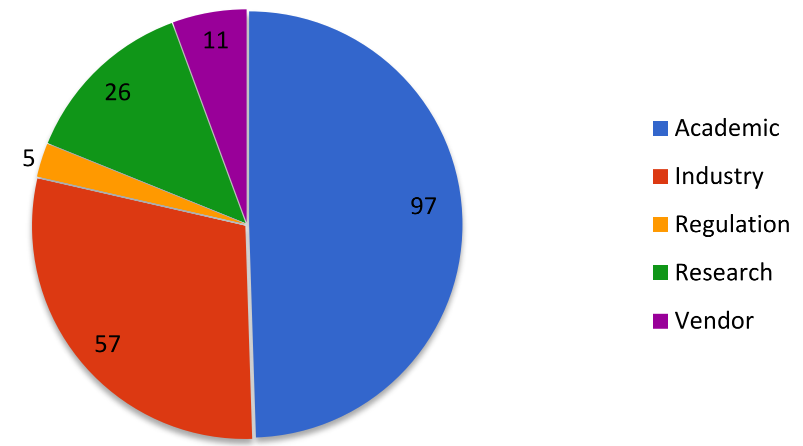
- IEEE PES GM 2015 Tutorial "Understanding Cascading Phenomenon: Methodologies and Industry Practice for Analysis of Cascading Failures", http://sites.ieee.org/pes-camscftf/
- Conference papers:
  - Mitigation and Prevention of Cascading Outages: Methodologies and Practical Applications, 10.1109/PESMG.2013.6672795, PES GM 2013 GM
  - 2011GM0847 Risk Assessment of Cascading Outages: Part I - Overview of Methodologies, PES GM 2011.
  - 2011GM0803 Risk Assessment of Cascading Outages: Part II - Survey of Tools, PES GM 2011.
  - Vulnerability Assessment for Predicting Cascading Failures in Electric Power Transmission Systems, PES PSCE 2009.
  - Initial review of methods for cascading failure analysis in electric power transmission systems, PES GM 2008.
- IEEE Transactions on Power Systems:
  - Risk Assessment of Cascading Outages: Methodologies and Challenges, May 2012, Vol. 27, No. 2 pp. 631-641.
  - Benchmarking and Validation of Cascading Failure Analysis Tools, 10.1109/TPWRS.2016.251866, 2015.

Questions

SUPPLEMENTAL SLIDES

CFWG Membership Profile

Category	Number of Members
Academic	97
Industry	57
Regulation	5
Research	26
Vendor	11
Total	**196**



2015 IEEE CFWG Survey on Cascading Analysis

- To better understand current industry practice, CFWG collaborated on conducting the survey with:
  - IEEE Corporate - Strategic Research;
  - North American Transmission Forum (NATF);
  - North American Electric Reliability Corporation (NERC).
- Three sets of results:
  - 248 usable responses through IEEE
  - 10 usable responses by NATF members
  - NERC coordinated response

Major Blackouts in North America

- The number of blackouts that result in a loss of over 1000 MW of demand doubles every 10 years

Date	Location	Customers Affected	Collapse Time	Nature of Collapse
Nov. 9, 1965	Northeast	30,000,000 people/ over 20,000 MW	13 min	Successive tripping of lines
July 13, 1977	New York City	9,000,000 people/ 6,000 MW	1 hour	Successive tripping of lines and generators
Dec. 22, 1982	West Coast	12,350 MW	Few minutes	Successive line tripping, protection coordination scheme failure
Dec. 14, 1994	Western US	9,336 MW		Transient instability, successive tripping of lines, voltage collapse
July 2, 1996	Western US	2,000,000 (10 % of the customers in the WECC); 11,850 MW	36 sec	Successive tripping of lines, generators and voltage collapse
Aug. 10, 1996	Western US	7,500,000 customers; 28,000 MW of demand shed by under-frequency load-shedding relays	> 1 min	Voltage collapse
June 25, 1998	MAPP, NW Ontario	152,000 customers; 950 MW	>44 min	Successive tripping of lines
August 14, 2003	Northeast	10,000,000 customers in Ontario, 40,000,000 customers in US/61,800 MW	> 1 hour	Successive tripping of lines (400), generators (531), and voltage collapse
Sept. 8, 2011	Western US	2.7 million customers out in AZ, S.CA, MX	11 min	Successive tripping lines, generators, automatic load shedding, and operation of RAS and intertie separation scheme

Major Blackouts in South America, Europe, Asia

Date	Location	Customers Affected	Duration/Collapse Time
December 19, 1978	France	30,000 MW	10 hours/ >30 min
December 27, 1983	Sweden	7,000 MW	5.5 hours/ > 1 minute
April 18, 1984	Brazil	over 15,700 MW	/10 min
March 11, 1999	Brazil	25,000 MW	4 hours/>30 sec
January 2, 2001	India	12,000 MW	13 hours/
January 12, 2003	Croatia	9,000 MW	/Few seconds
September 23, 2003	Sweden/Denmark	Over 6,500 MW	/7 minutes
September 28, 2003	Italy	27,000 MW	19.5 hours/27 min
May 24, 2005	Russia	6,400 MW	>6 hours/

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