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Enhancing Electric Power Reliability, Security, and Resiliency

Jeff Dagle, PE
Chief Electrical Engineer
Electricity Infrastructure Resilience
Pacific Northwest National Laboratory
Richland, WA
+1 (509) 375-3629
jeff@pnnl.gov

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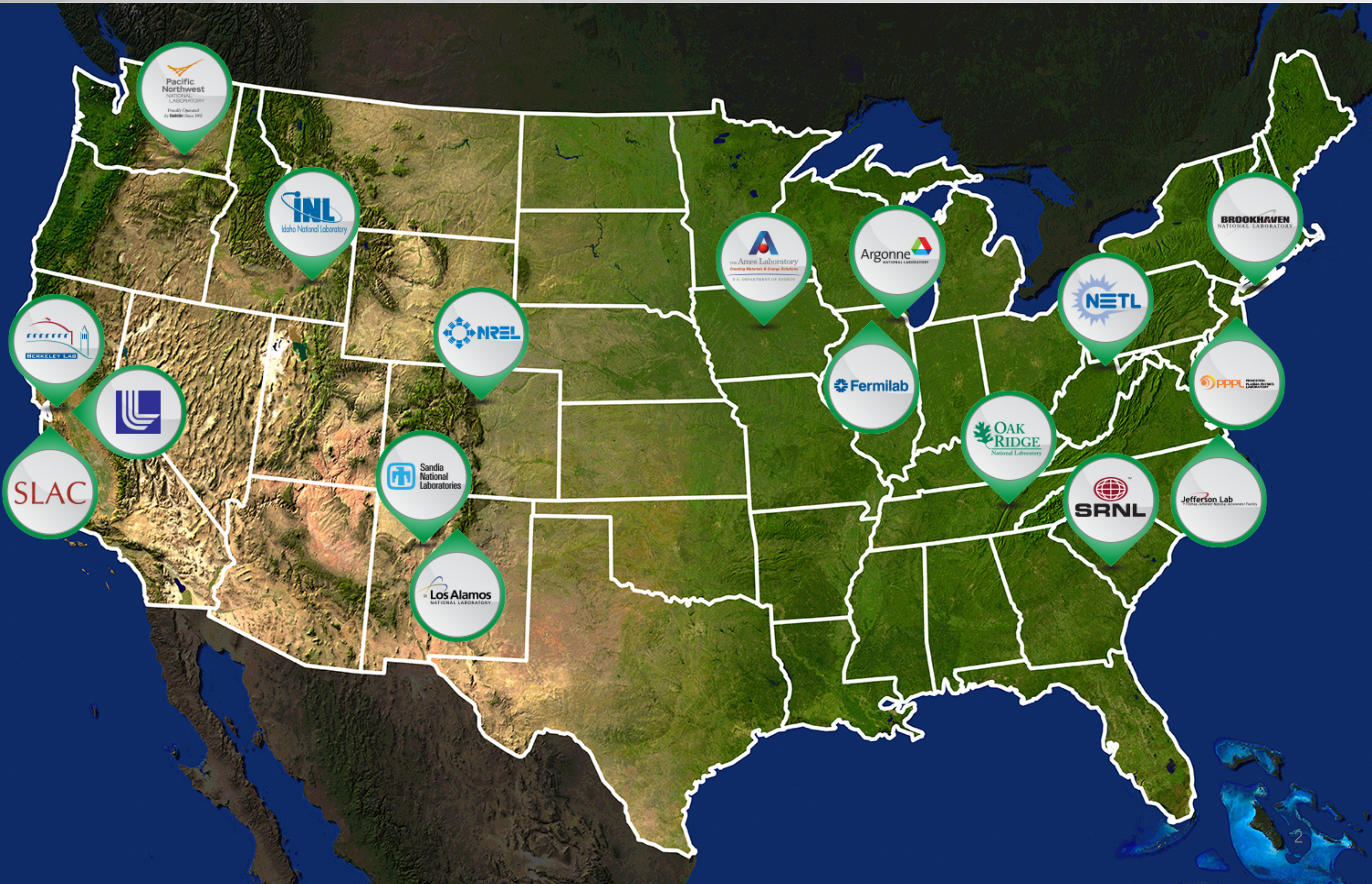

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Outline

- Power grid reliability
  - Basic reliability approach
  - Lessons learned from prior blackouts
    - Case study #1: August 10, 1996
    - Case study #2: August 14, 2003
- Resilience
- Some examples of R&D conducted by PNNL to address some of these issues
- U.S. Department of Energy (DOE) Grid Modernization Initiative
- Findings and recommendations from the National Academy committee report “Analytic Research Foundations for the Next-Generation Electric Grid”
  - Report available for download: http://www.nap.edu/21919

Basic Reliability Approach

- "The interconnected power system shall be operated at all times so that general system instability, uncontrolled separation, cascading outages, or voltage collapse will not occur as a result of any single contingency or multiple contingencies of sufficiently high likelihood."
  WECC Minimum Operating Reliability Criteria
- Systematically consider the impact of ***credible contingencies*** on the stable operation of the power system
  - Shorthand notation: "N-1" (removing one of N components)
  - In reality, there are different categories of contingencies considered
- Achieved by:
  - Generation having sufficient operating reserve, spinning reserve
  - Strict adherence to transfer capacity limits on the transmission grid
    - Determined through comprehensive planning studies
  - Operations discipline, detailed procedures, coordination
  - When all else fails, rely on emergency controls to limit cascading failure (e.g., under frequency load shedding)
- Operational Priorities
  1. Safety (public, workers)
  2. Protect equipment from damage
  3. Reliability of the bulk interconnected system
  4. Optimize the economical operation of the system

Restoration

- Black start restoration
  - A significant fraction of grid generation assets require offsite power in order to function
    - Operating auxiliaries associated with the power plant itself
    - Providing reference for frequency and/or voltage regulation
  - “Black start” generators can begin operating without any offsite power
  - Black start restoration plans give priority to restarting as many generating assets as possible within the shortest amount of time
    - Requires transmission paths between the black start units and the other generators that are available
- Load restoration priority
  - Depending on the nature of the physical damage, restoration is prioritized associated with the criticality of the facilities
    - Taking into account any on-site generation that might already be available and operating effectively
    - For large-scale events, priority is given to assets that are critical in providing support to the overall restoration process
  - Goal is to restore as many customers as quickly as possible

Examples of Major North American Blackouts: Uncontrolled Cascading Failures

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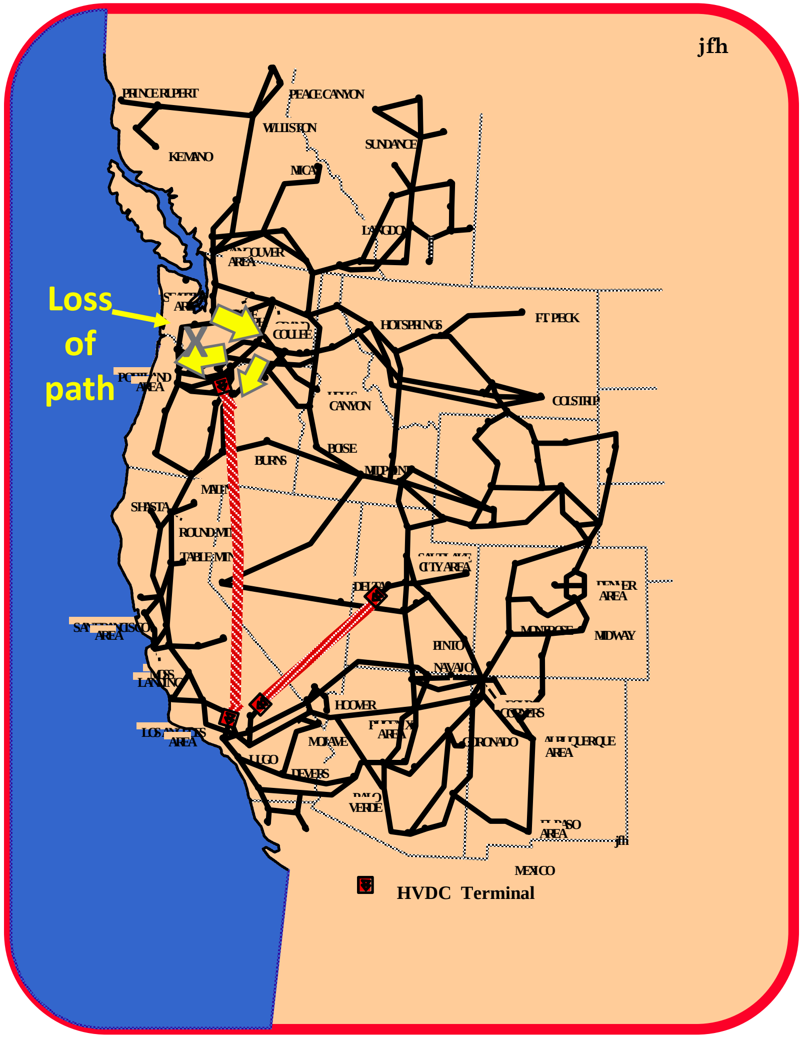
Date	Location	Load Interrupted
November 9, 1965	Northeast	20,000 MW
July 13, 1977	New York	6,000 MW
December 22, 1982	West Coast	12,350 MW
March 13, 1989	Quebec	21,350 MW
January 17, 1994	California	7,500 MW
December 14, 1994	Wyoming, Idaho	9,336 MW
July 2, 1996	Wyoming, Idaho	11,743 MW
August 10, 1996	Western Interconnection	30,489 MW
June 25, 1998	Midwest	950 MW
August 14, 2003	Northeast	61,800 MW
September 8, 2011	San Diego	7,835 MW

August 10, 1996: At the time, the largest blackout in the history of the North American power grid. (Current ranking: #2)

Conditions prior to the blackout:

- Above average water year
  - Extensive hydro generation available in Canada
- Lower Columbia generation not available
  - Water bypass for salmon migration
- Key transmission assets out of service for maintenance in Seattle-Portland area
- Temperatures above 100°F in California
- Transmission system experiencing abnormally high transfers, operating in unusual pattern that hadn't been studied



Sequence of Events

- 14:01 500 kV Big Eddy – Ostrander line, ground fault (tree)
  - Returned to service 14:03
- 14:06 A-phase opened on the Big Eddy-Ostrander line, reclosed, then all three phases opened and remained out of service
  - PGE's Big Eddy-McLoughlin line opened and reclosed
- BPA dispatchers began to receive low voltage alarms, corrected by switching out shunt reactors and switching in shunt capacitors
- 14:52 500kV John Day—Marion line opened and locked out when the line flashed and grounded to a tree near Marion.
  - Because a Marion 500 kV circuit breaker was out of service, the 500 kV Marion – Lane line was forced out of service
  - At 14:56 the John Day – Marion line opened when it was tested
- 15:42 500kV Keeler-Allston line tripped after flashing to a tree near Keeler

Source: NERC

Sequence of Events (cont.)

- At this point, five 500kV line segments were out of service, removing several hundred MVAR of reactive support from the system while simultaneously increasing the reactive requirement as other lines picked up the electricity flow previously carried out by the out of service lines. BPA dispatchers requested maximum reactive power boost from John Day and The Dalles within one minute of the Keeler—Alston opening.
- While the BPA system voltage was being assessed, the Keeler—Allston line was tested from Allston and opened on test at 15:44.
- Prior to the Keller-Allston trip, the 13 McNary hydro generating units were producing 860 MW and 260 MVAR. After the line trip, they were producing 475 MVAR which was over their maximum sustained output.

Source: NERC

Sequence of Events (cont.)

- 15:47 230 kV Ross—Lexington line opened (flashed to a tree)
- This relay operation resulted in system protection removing Swift generating unit (207 MW)
- The reactive output of the McNary units was boosted to 494 MVAR. The units held at this level for a short time, then system protection began removing them from service. Between 15:47 and 15:49 all 13 units were removed from service as a result of erroneous operations of a phase unbalance relay in the generator exciters.
- During the removal of the McNary units, a 0.224 Hz system oscillation became negatively damped.
- Additional capacitors were switched in at Malin 500 kV and Walla Walla 115 kV
- The PDCI began to fluctuate in response to the AC voltage.
- 15:48 Voltage collapsed, tie lines opening due to out-of-step and low voltage conditions

Source: NERC

Wide Area Measurements Captured System Events – Useful to Support Investigation

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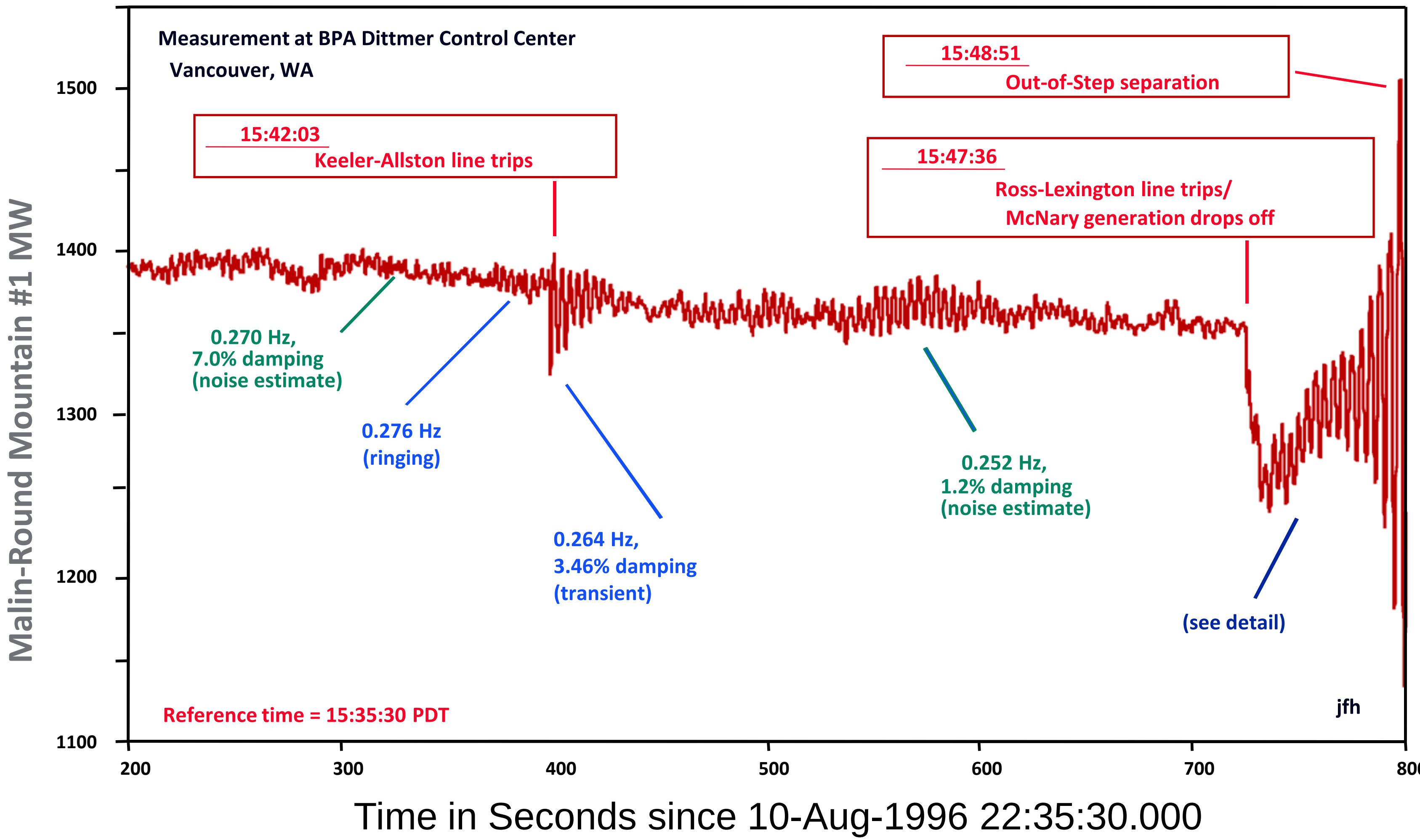

Generator Response: Loss of McNary units critical factor

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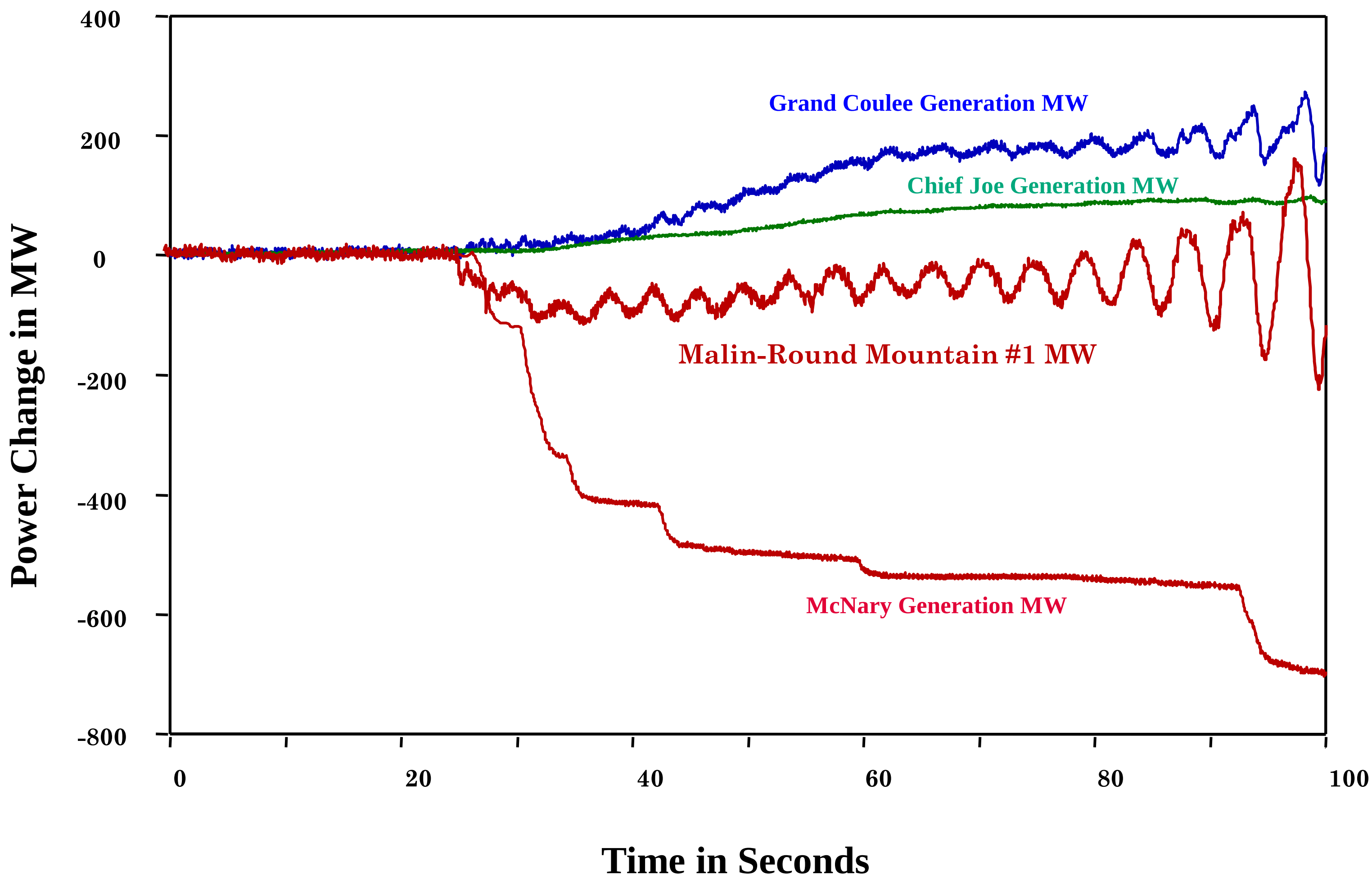
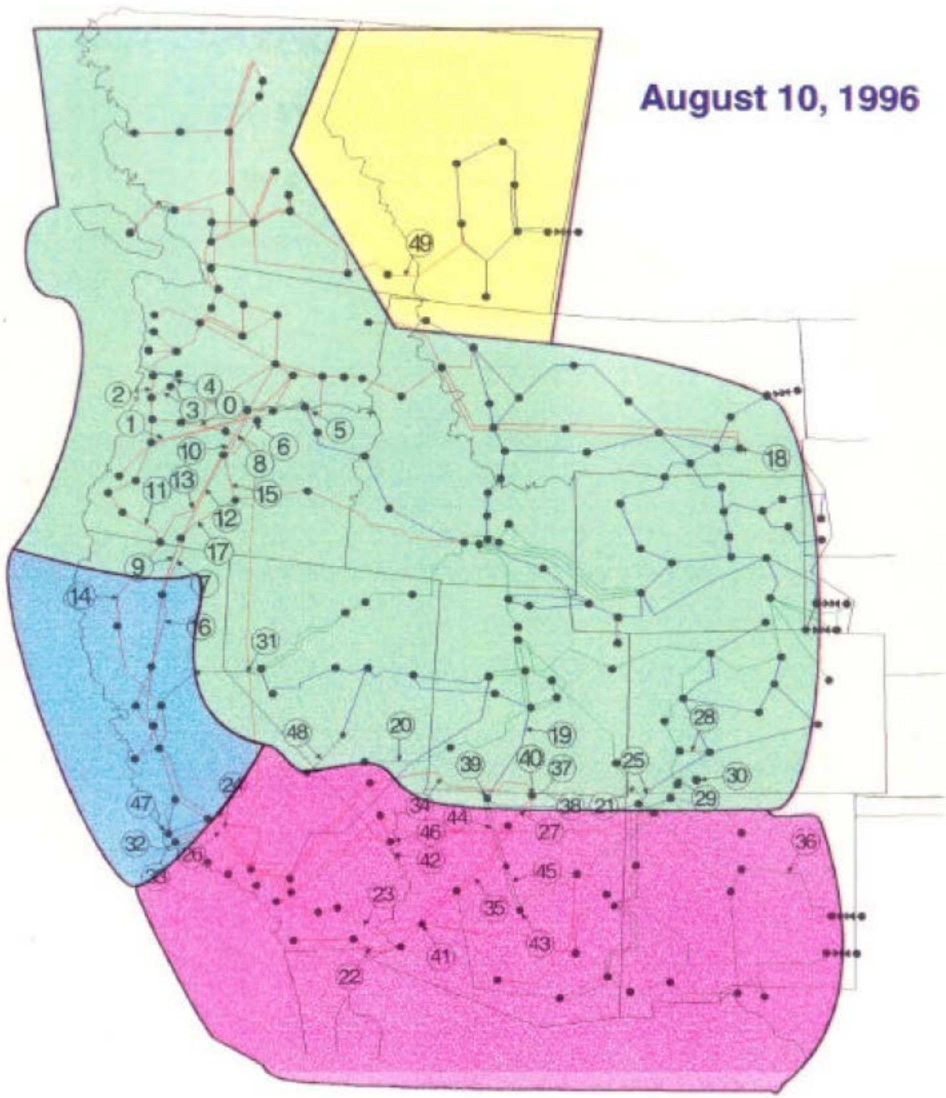


Four Electrical Islands Formed

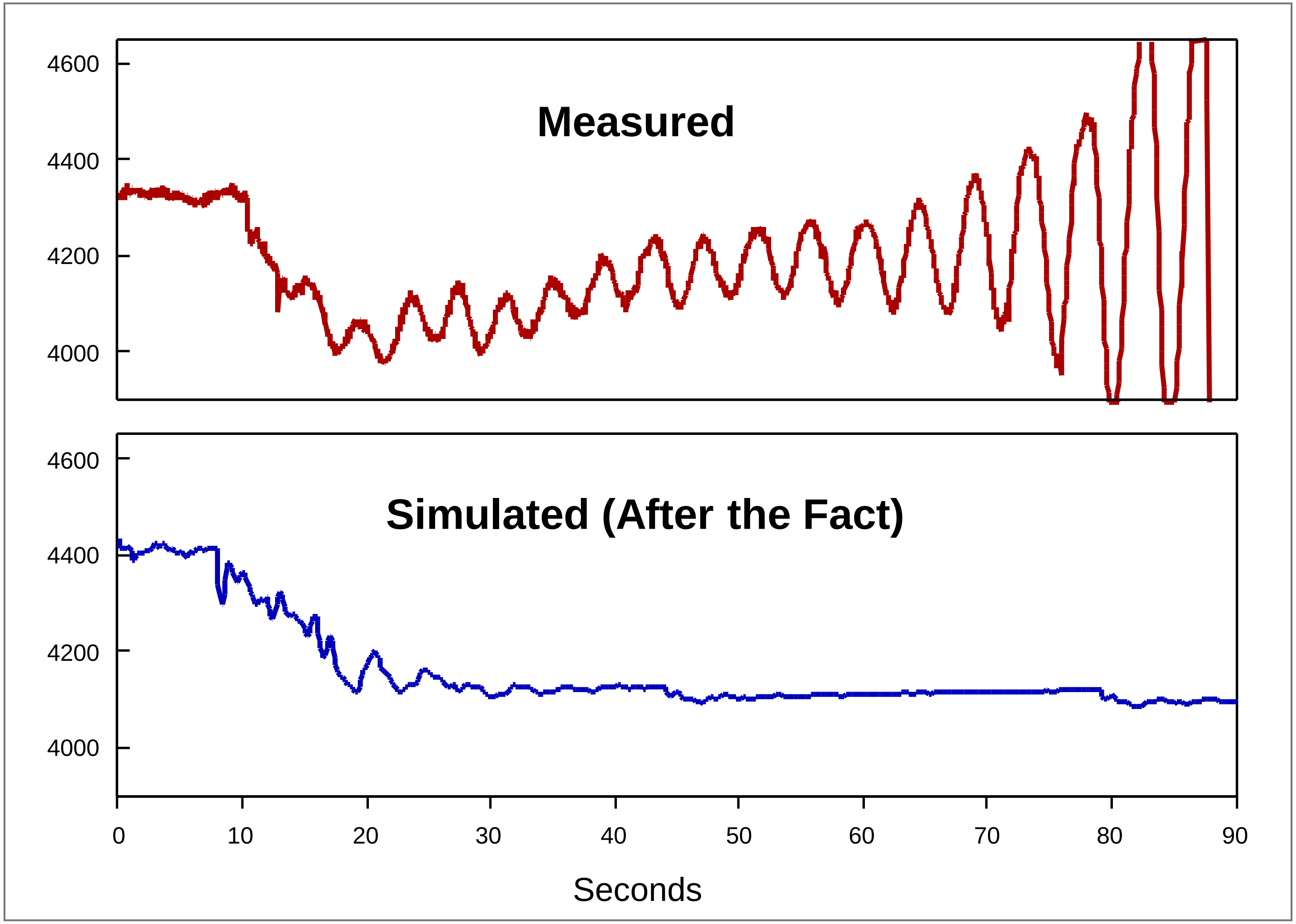


Source: NERC

Blackout Investigation Findings

- Right-of-way maintenance (tree trimming) was inadequate
- The system was being operated in a condition in which a single contingency outage would overload parallel transmission lines
  - Because adequate operating studies had not been conducted
- Outages in the hours leading up to the blackout were not fully communicated to other utilities
  - Each deemed insignificant at the time
  - With this information, other utilities might have reduced loadings on lines or adjusted local generation as precautionary measures to protect against the weakened state of the system
- McNary units tripped due to exciter protection error
  - These units were responding to reduced voltage
  - Other generators in the area did not respond to the extent assumed in previous planning studies
- System break-up caused significant generation loss

Lesson Learned: Modeling Errors



Case Study #2:
August 14, 2003

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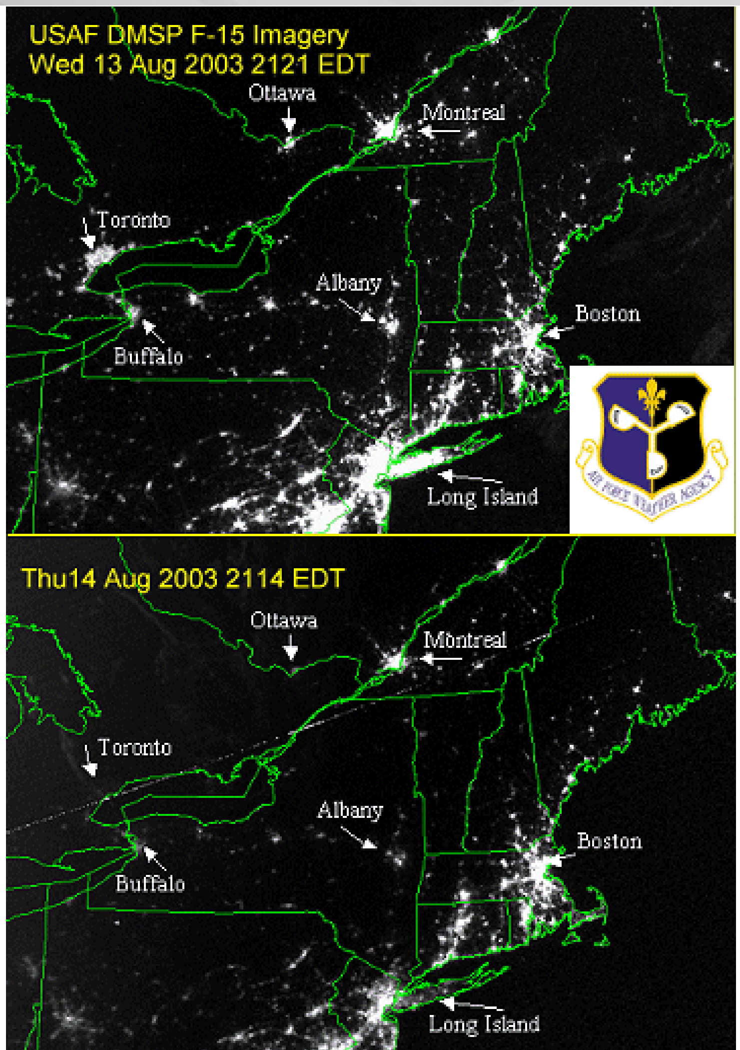


www.usatoday.com THE NATION'S NEWSPAPER 50 CENTS

LATE SPORTS

NFL preseason

What's next for Mr. Vick?

A Super Bowl isn't far-fetched for Atlanta. Not with him at QB 1C

'One good day' at the PGA

Micklelson shares lead, takes aim at his 1st major 1, 8-9C

USA TODAY

NO. 1 IN THE USA

Married – with cameras

MTV moves in with pop newlyweds Simpson & Lachey 1-2E

Blackout misery

50 million affected in Northeast and beyond as power grid fails

Transportation Many 'wait it out,' by air and land 4A | Scenes Moms in labor, cars stuck in car washes 5A | Impact Offices close, ATMs idle, cellphones jam 1B

Fri/Sat/Sun, August 15-17, 2003

Newsline

California ballot is a field of dreamers

U.S. captures suspect in Bali, Jakarta bombings

LifeSavers changing flavors

France threatens to block Libya deal

Outage spawns rush-hour chaos from Detroit eastward

More annoyance than angst in NYC, despite early fears

Exodus recalls images of 9/11

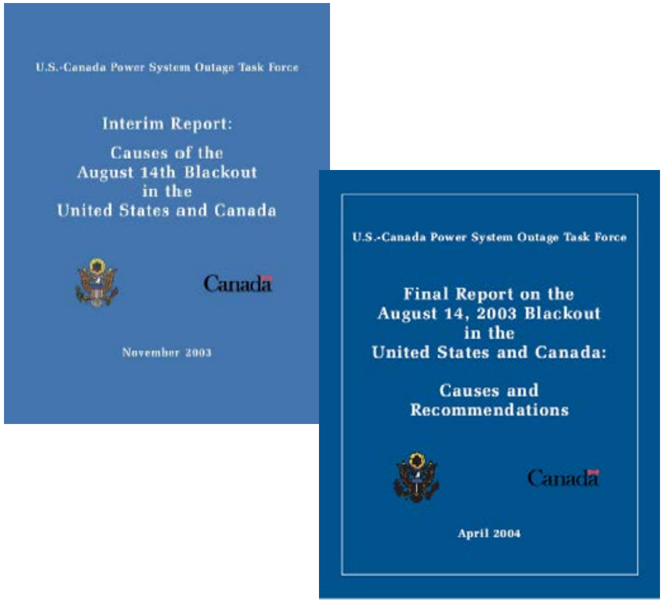
Cover story

August 14, 2003 Blackout Investigation

Joint U.S. - Canada Power System Outage Task Force

Electric System Working Group	Nuclear Working Group	Security Working Group
Investigate the cascading electrical failure.	Review performance of plants and assess possibility of damage.	Determine if failures were caused with malicious intent.

- Phase I
  - Investigate the outage to determine its causes and why it was not contained
  - Interim report released November 19, 2003
- Phase II
  - Develop recommendations to reduce the possibility of future outages and minimize the scope of any that occur
  - Final report released April 5, 2004



Control Areas and Reliability Coordinators at the Epicenter of the August 14 Blackout

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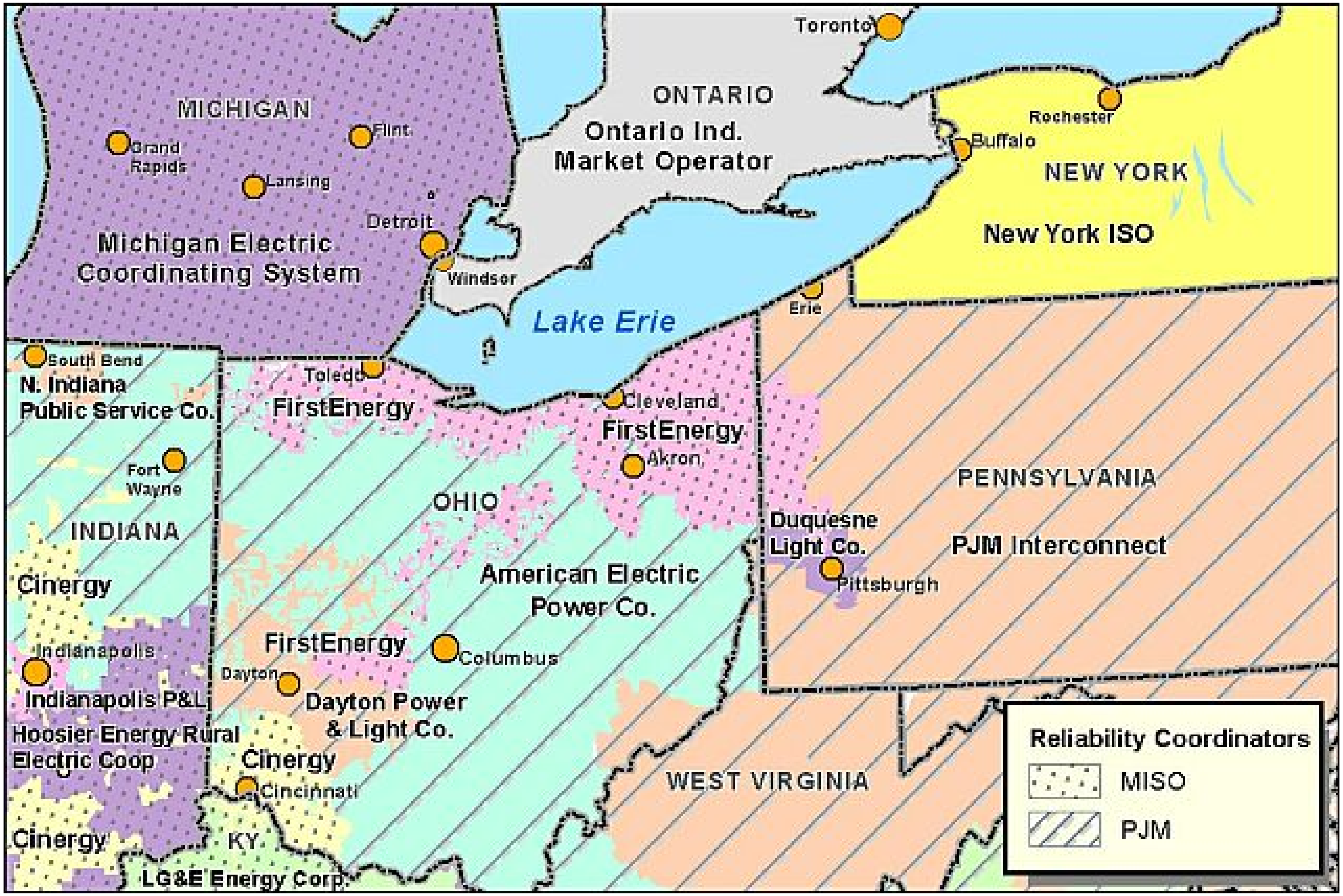
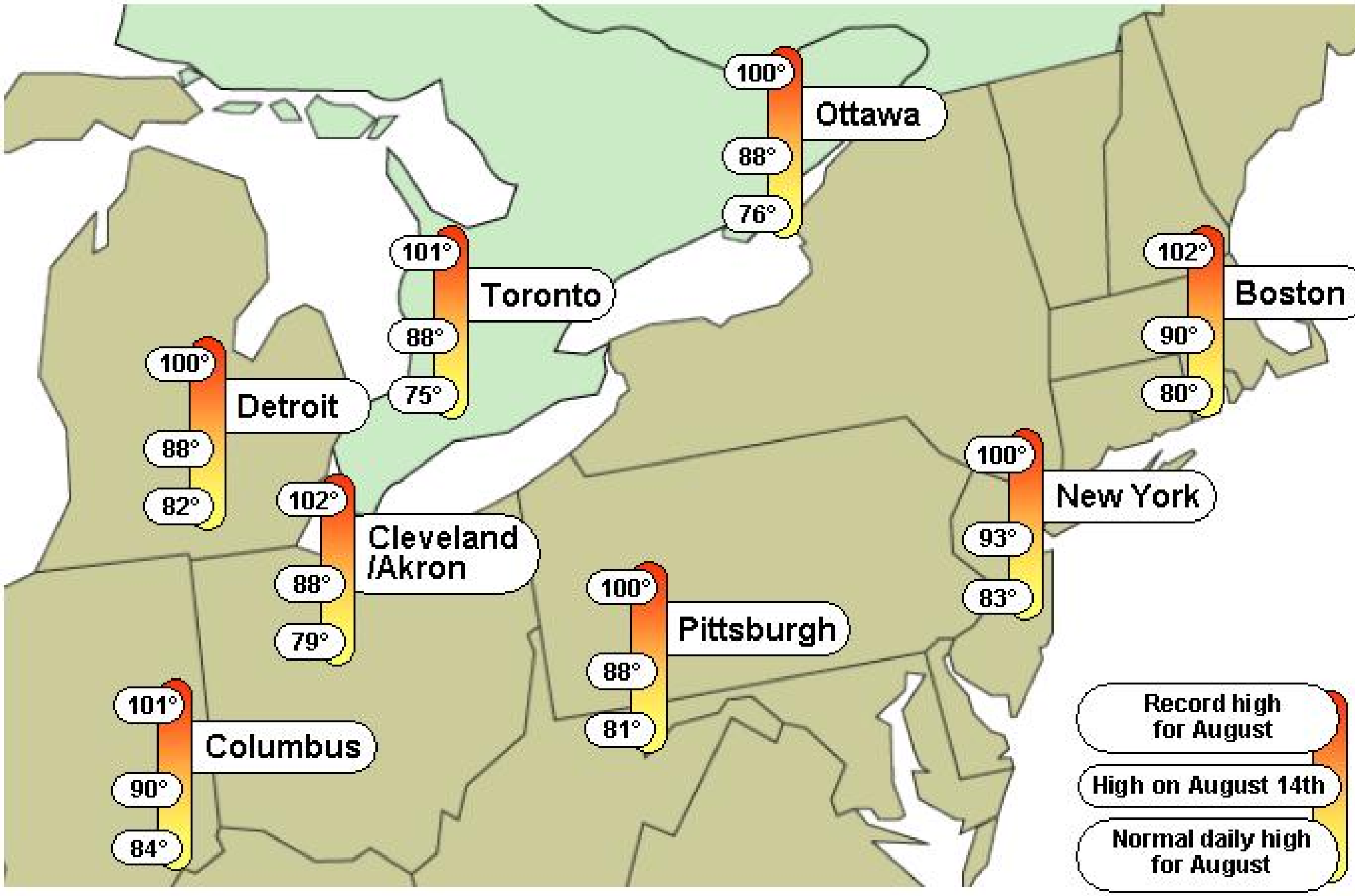


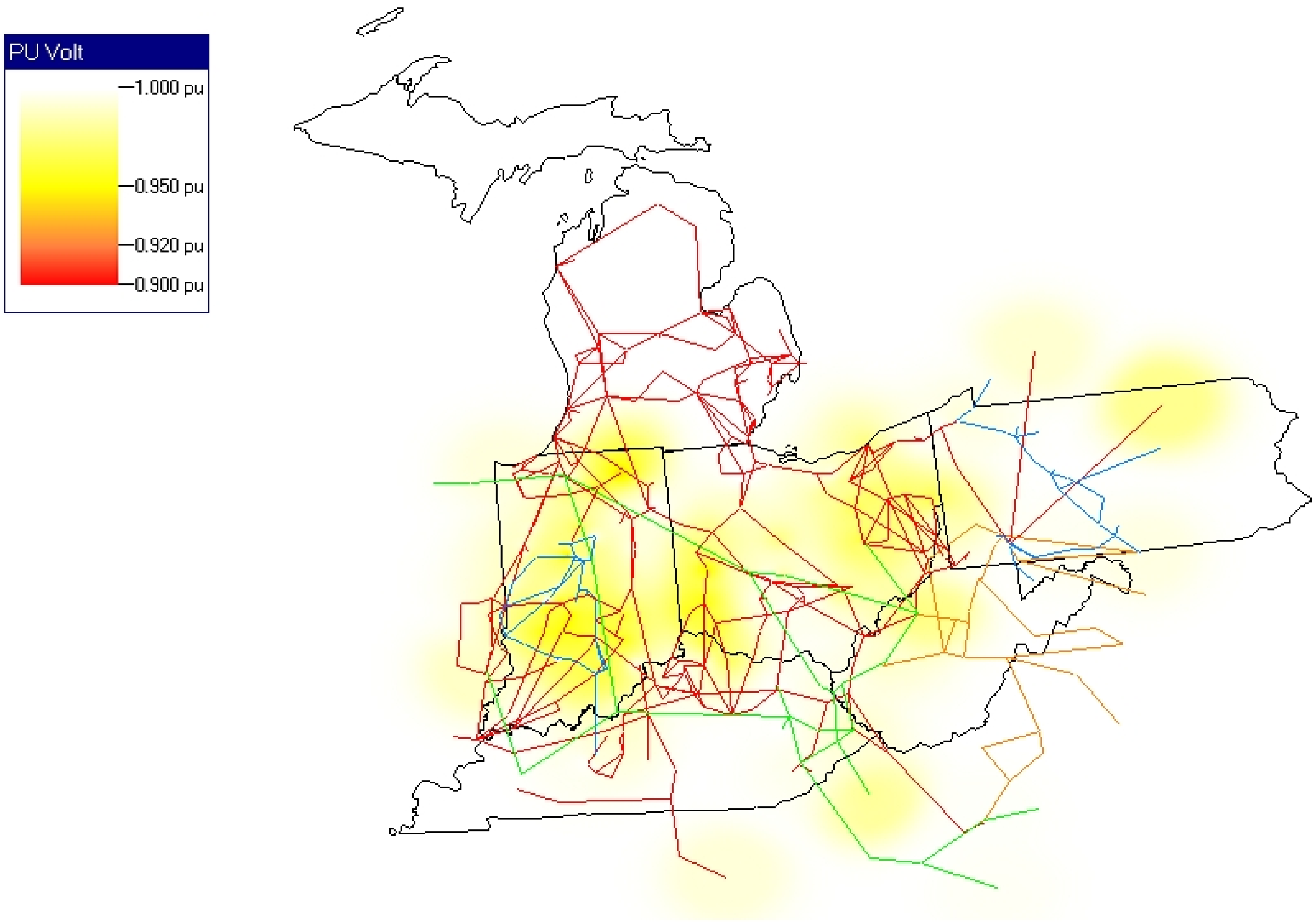
August 14 Conditions Prior to Blackout

- Planned outages
  - Cook 2, Davis Besse nuclear plants
  - East Lake 4, and Monroe 1
- Transfers high to northeast U.S. + Ontario
  - Not unusually so and not above transfer limits
- Critical voltage day
  - Voltages within limits
  - Operators taking action to boost voltages
- Frequency
  - Typical for a summer day
- System was within limits prior to 3:05 pm, on both actual and contingency basis

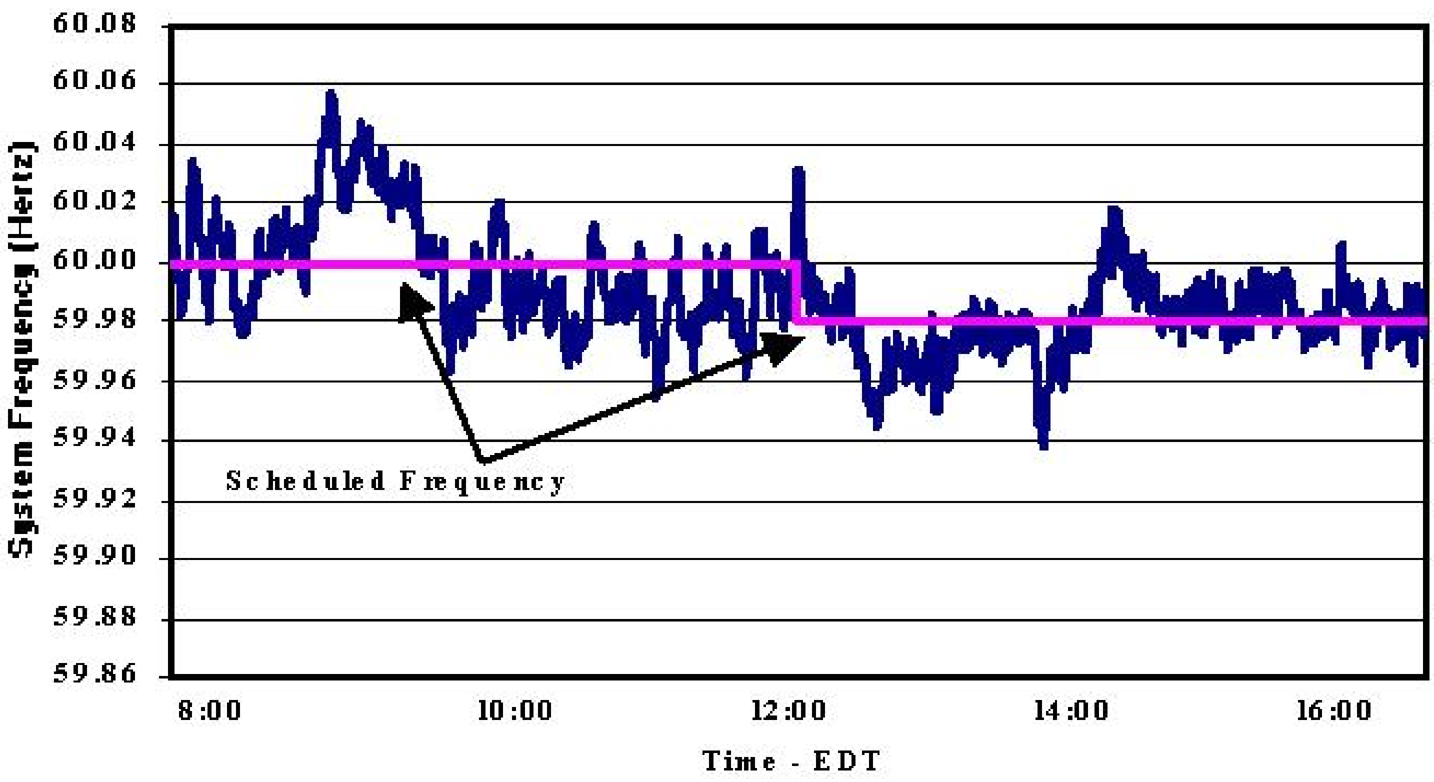
Warm But Not Unusual for August



Voltages Prior to 3:05 pm - Low But Within Limits

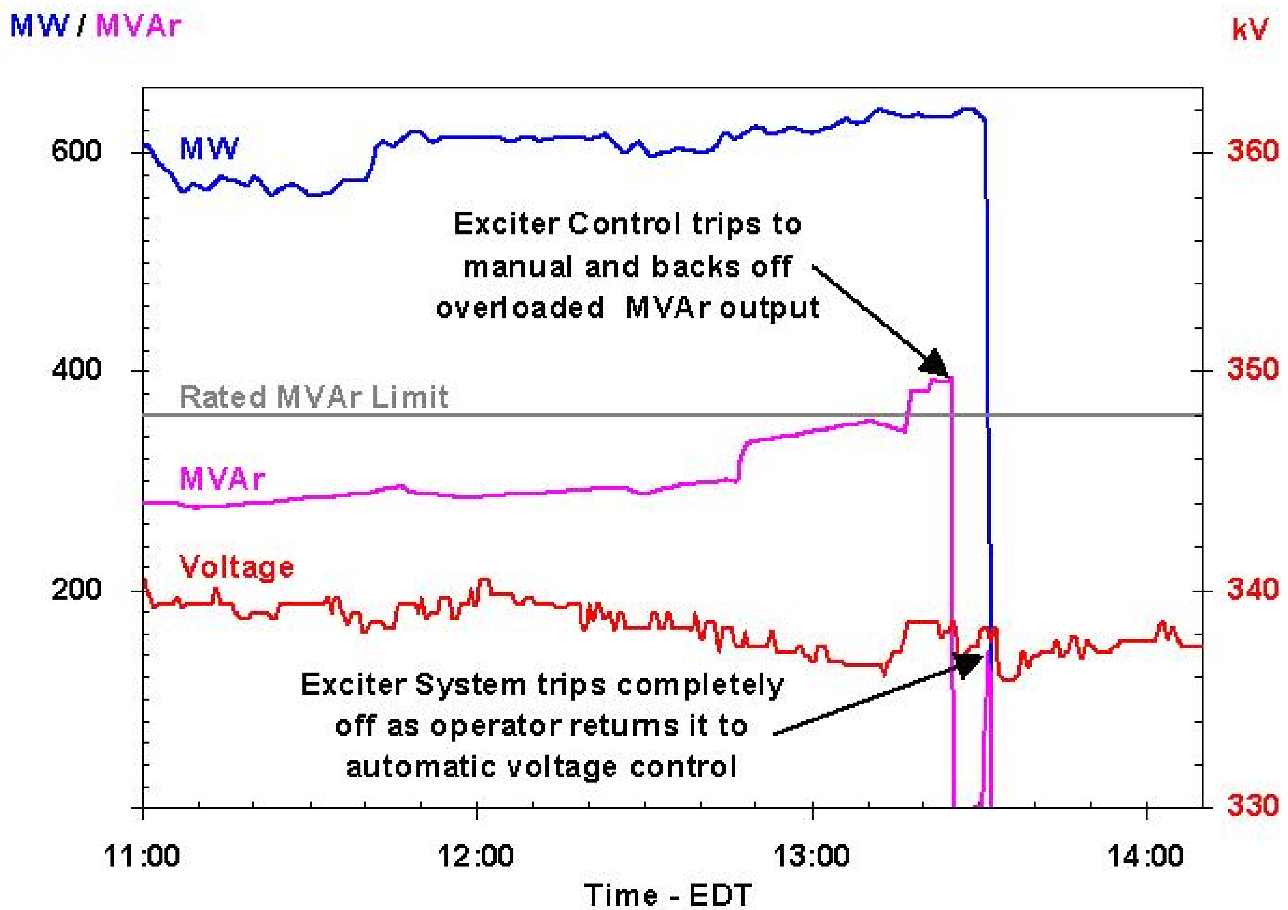


Frequency – Nothing Unusual



1:31:34pm – Eastlake Unit 5 Trips

East Lake 5 Exciter Failure Causes Trip



2:02pm – Transmission line trips in southwestern Ohio

Cause: Brush Fire

Significance: Contingency analysis system at the Midwest Independent System Operator failed due to incomplete topology information (software glitch)

FirstEnergy (FE) Computer Failures

- 2:14 pm Alarm logger fails and operators are not aware
  - No further alarms to FE operators
- 2:20 pm Several remote consoles fail
- 2:41 pm Energy Management System (EMS) server hosting alarm processor and other functions fails to backup
- 2:54 pm Backup server fails
  - EMS continues to function but with very degraded performance
  - FE system data passed normally to others: MISO and AEP
  - Automatic Generator Control (AGC) function degraded and strip charts flat-lined
- 3:08 pm Reboot of EMS appears to work, but alarm process not tested and still in failed condition
- No contingency analysis of events during the day including loss of East Lake 5 and subsequent line trips
- FE received calls from MISO, AEP, and PJM indicating problems on the FE system but did not recognize evolving emergency

3:05:41pm – Harding – Chamberlain 345kV line trip

Chamberlain-Harding Ground Fault due to Tree Contact as Measured by Digital Fault Recorder

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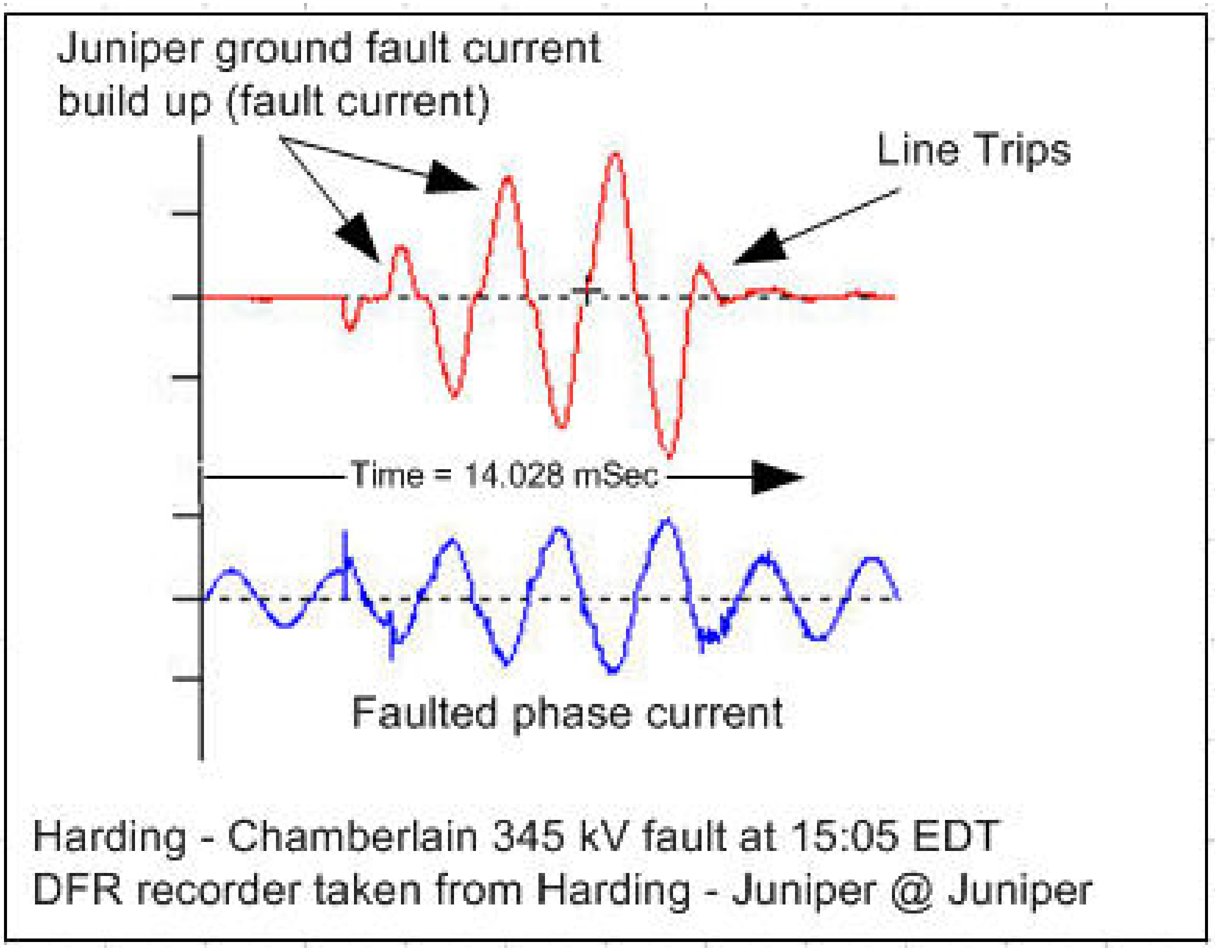

3:32:03pm – Hanna – Juniper 345kV line trip

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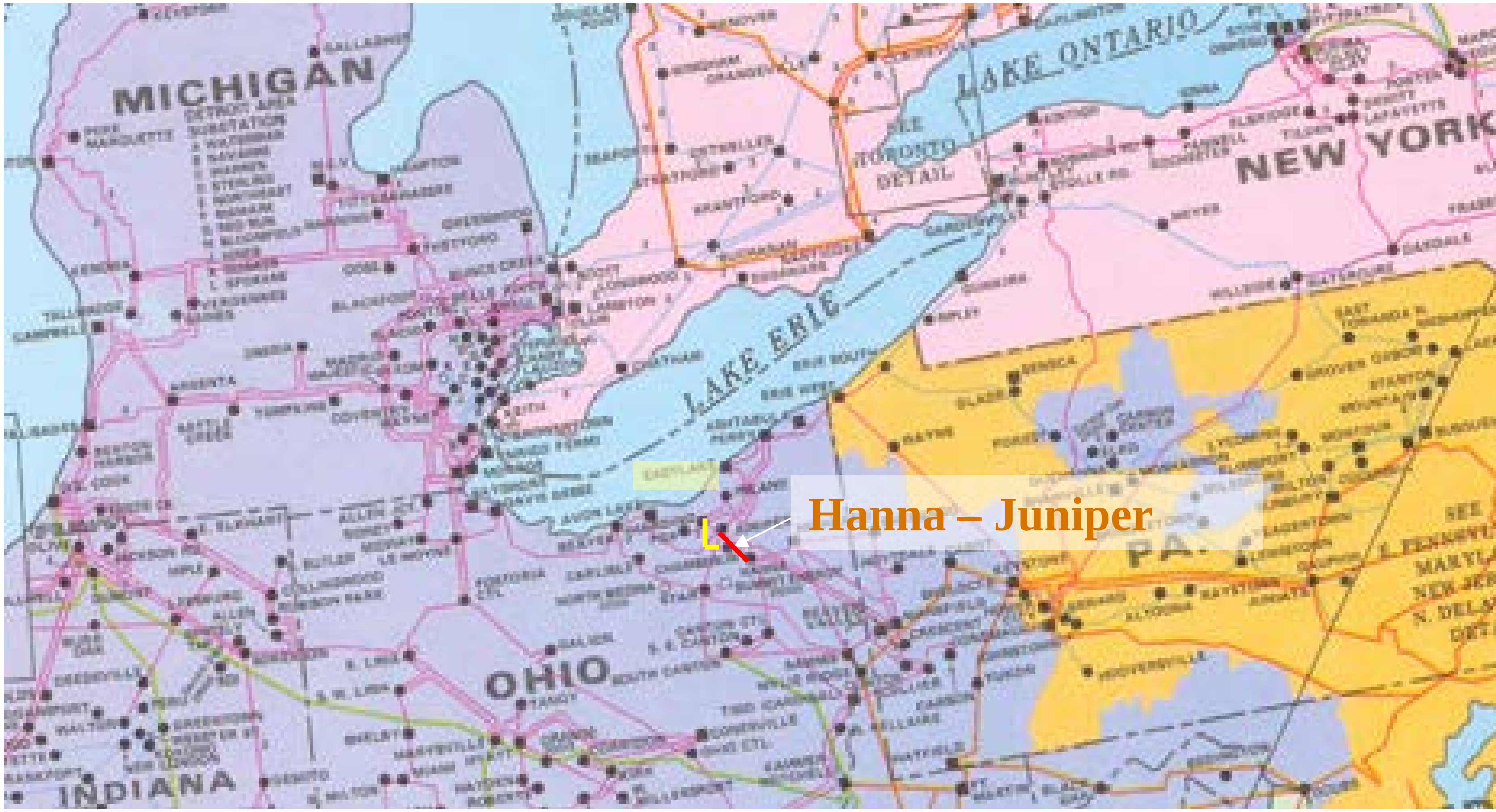


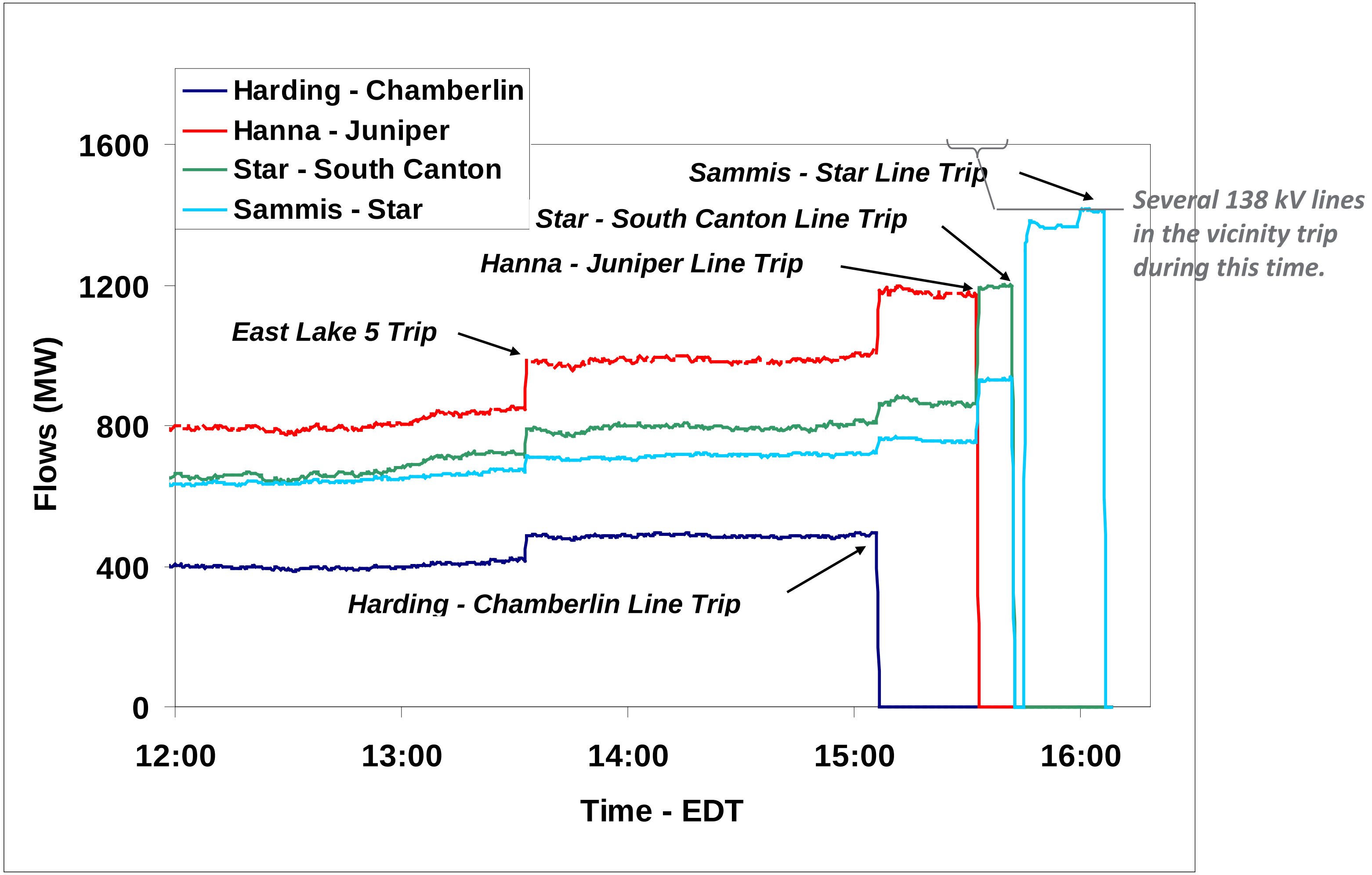
Hanna - Juniper confirmed as tree contact at less than the emergency ratings of the line

3:41:35pm – Star – South Canton 345 kV line opens
Note: Previously tripped and reclosed twice

3:45:41pm – Canton Central – Tidd 345 kV line trip
Line recloses 58 seconds later, but 345/138 kV transformers at Canton Central remain open

4:05:57.5pm – Sammis – Star 345 kV line trip

Loading on Critical Lines



Key Voltages

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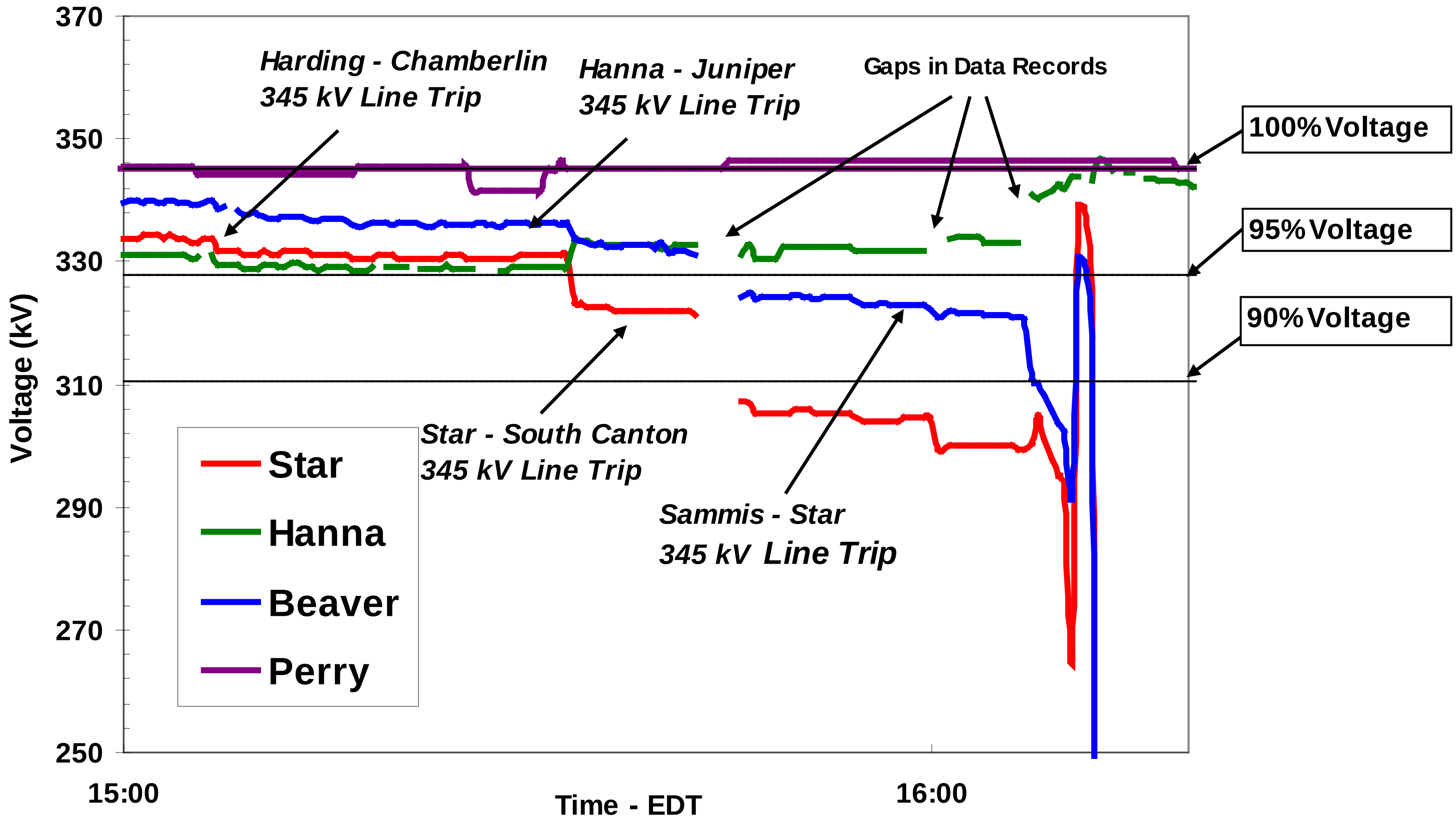
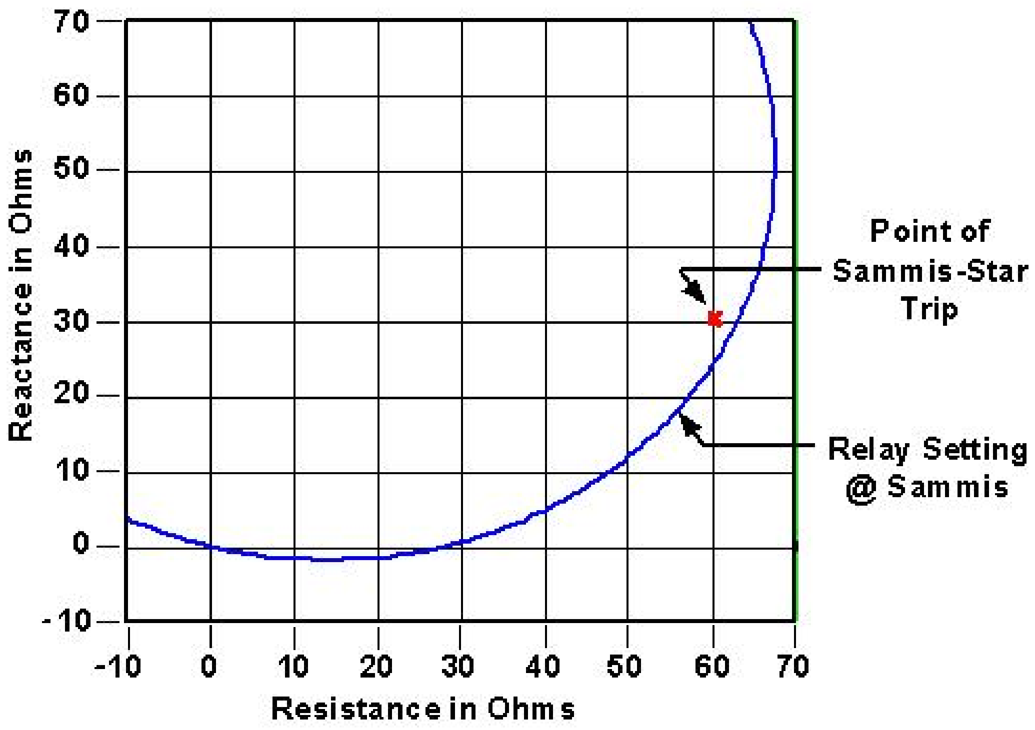


Sammis-Star “Zone 3” Relay Operates on Steady State Overload



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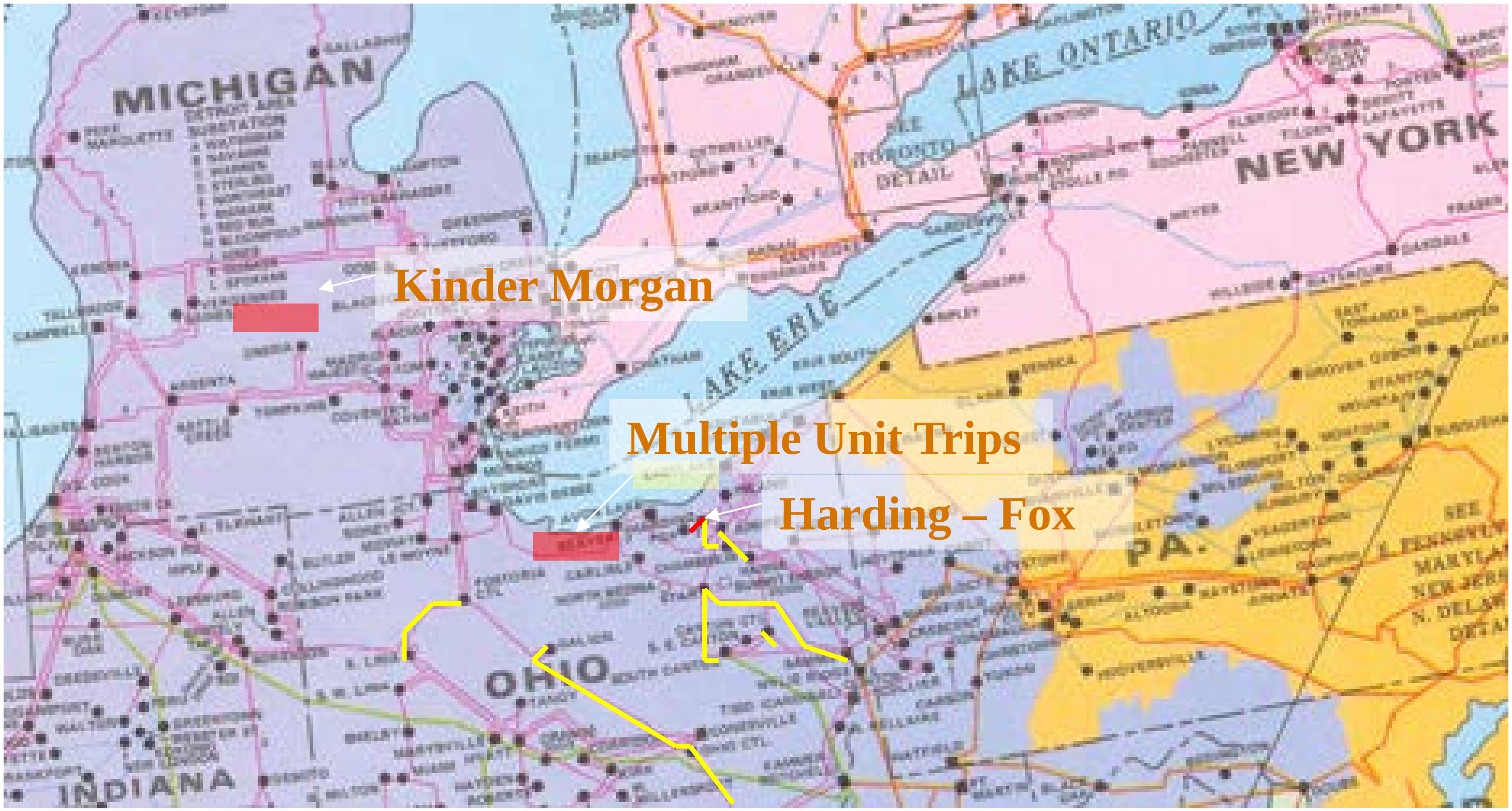
4:08:58pm Galion – Muskingum – Ohio Central 345 kV line trip

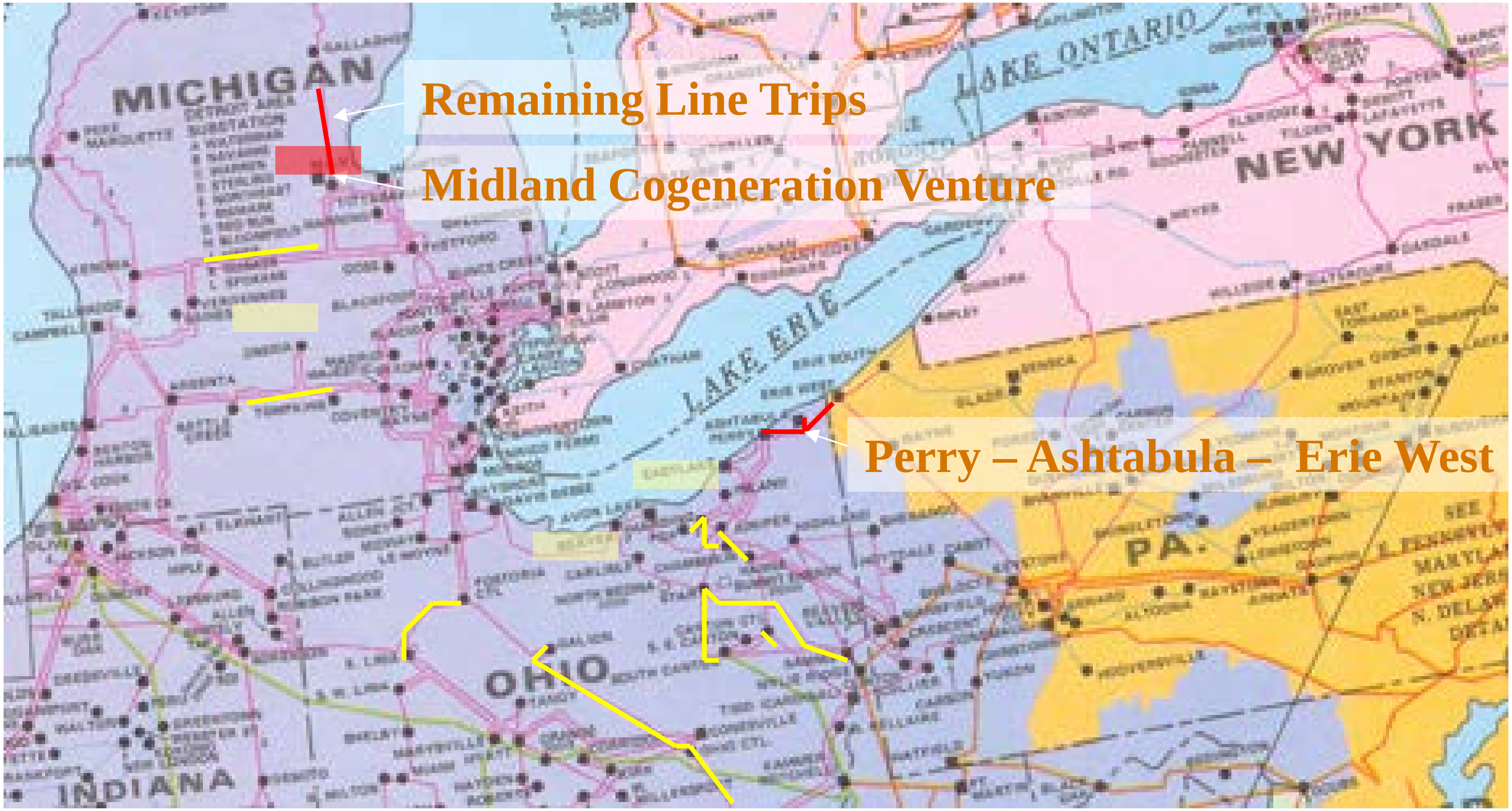
4:09:06pm – E. Lima – Fostoria Central 345 kV line trip

4:10pm Harding – Fox 345 kV line, Kinder Morgan unit trips, 20 generating units (2174 MW) trip in Northern Ohio



4:10:37pm 345 kV transmission lines trip between western and eastern Michigan

4:10:38pm - Midland Cogeneration Venture unit trip (loaded to 1265 MW), Transmission system separates northwest of Detroit, Perry-Ashtabula-Erie West 345 kV line trip



4:10:38pm Situational Assessment:

Northern Ohio & eastern Michigan collapsing, many units tripped, only connection remaining is with Ontario.

When last tie between Pennsylvania and Ohio trips, power drawn into the affected region suddenly reverses direction around Lake Erie.

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Pennsylvania – New York Separation

4:10:40pm – Homer City-Watercure Road 345 kV
4:10:40pm – Homer City-Stolle Road 345 kV
4:10:41pm – South Ripley-Dunkirk 230 kV
4:10:44pm – East Towanda-Hillside 230 kV

4:10:41pm
Fostoria Central-Galion 345 kV line trip
Perry 1 nuclear unit trip (rated 1252 MW)
Avon Lake 9 unit trip (rated 616 MW)
Beaver-Davis Besse 345 kV line trip

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Northeast portion of the grid separates from the interconnection

4:10:42pm – Campbell unit 3 (rated 820 MW) trips
4:10:43pm – Keith-Waterman 230 kV line trip
4:10:45pm – Wawa-Marathon 230 kV line trip (above Lake Superior)
4:10:45pm – Branchburg-Ramapo 500 kV line trip

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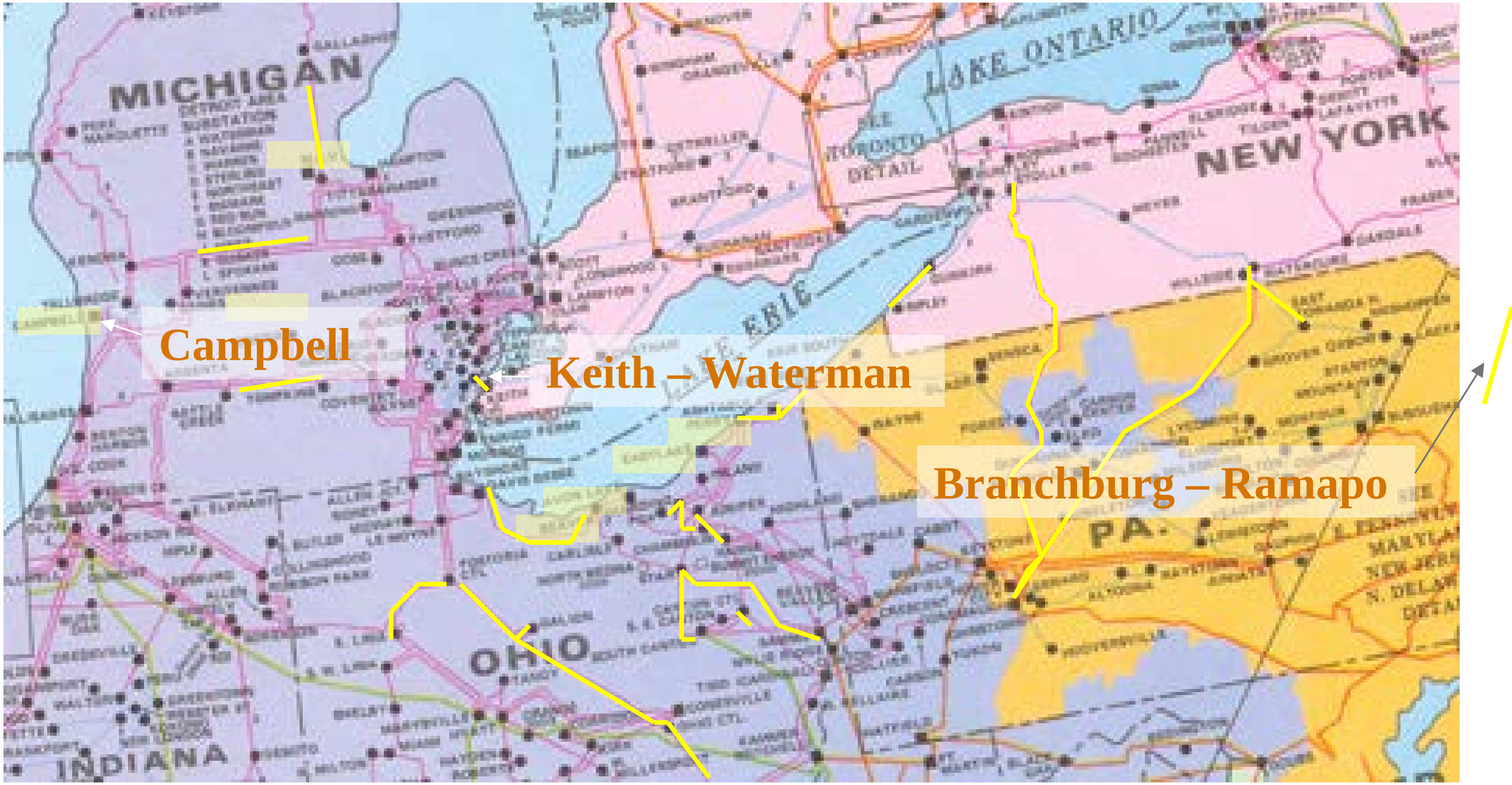

After the Branchburg – Ramapo 500 kV line trips, the underlying 230 kV and 138 kV ties in New Jersey trip, leaving northern New Jersey connected with New York, and southern New Jersey and Pennsylvania remain connected with the remainder of the eastern Interconnection.

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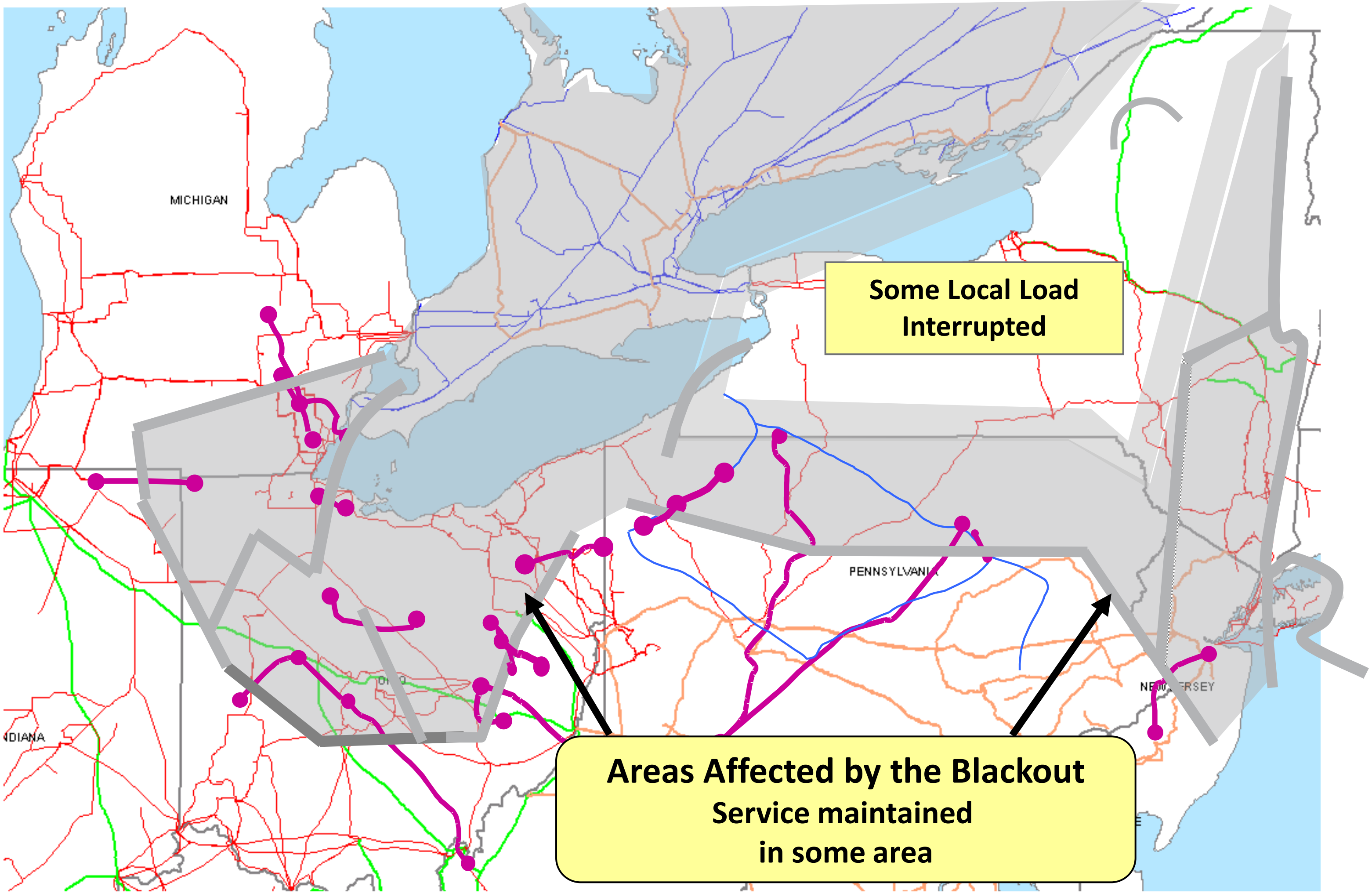
End of the Cascade



Frequency in Ontario and New York during Breakup
Niagara Generation Stays with Western NY

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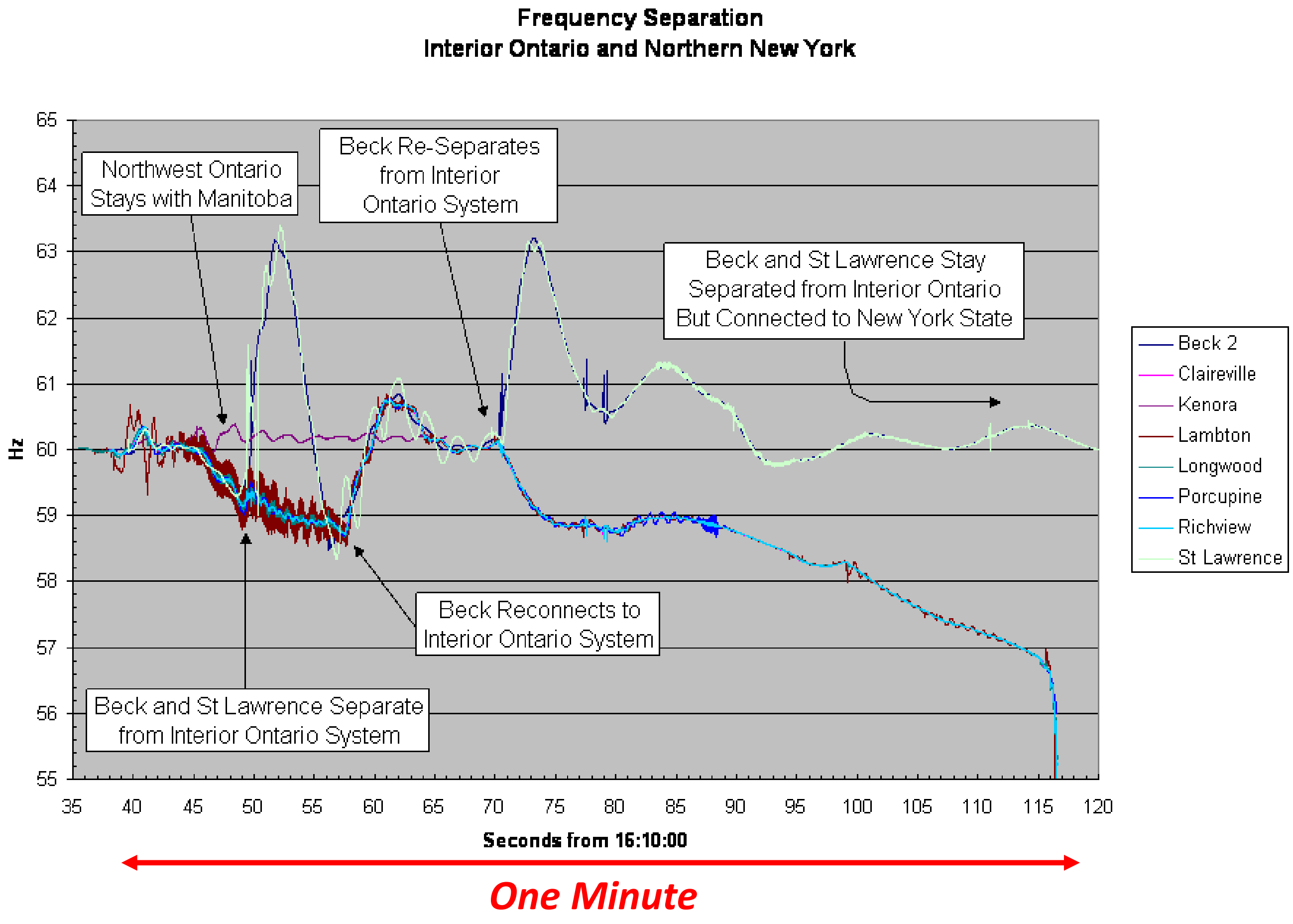
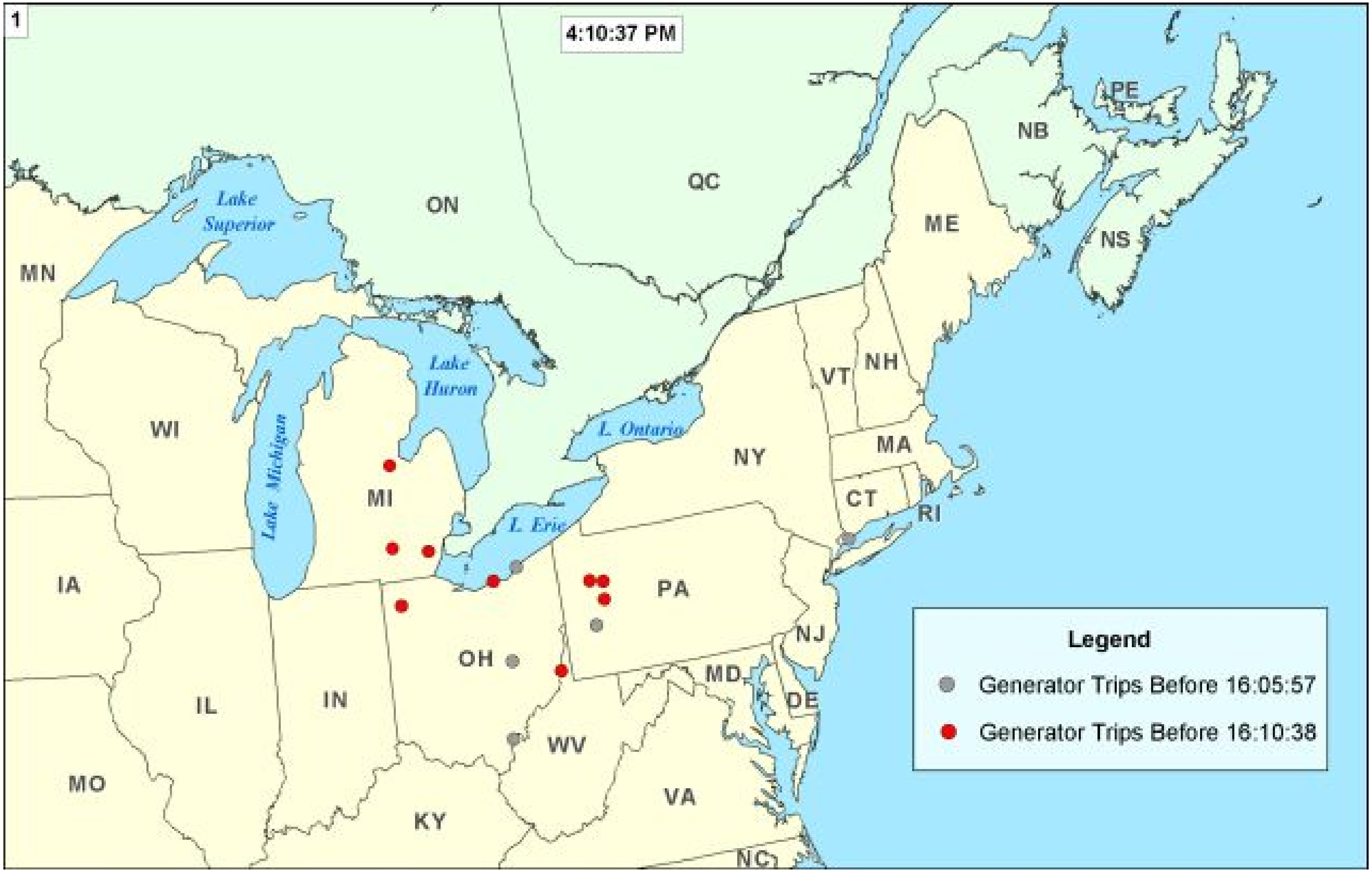
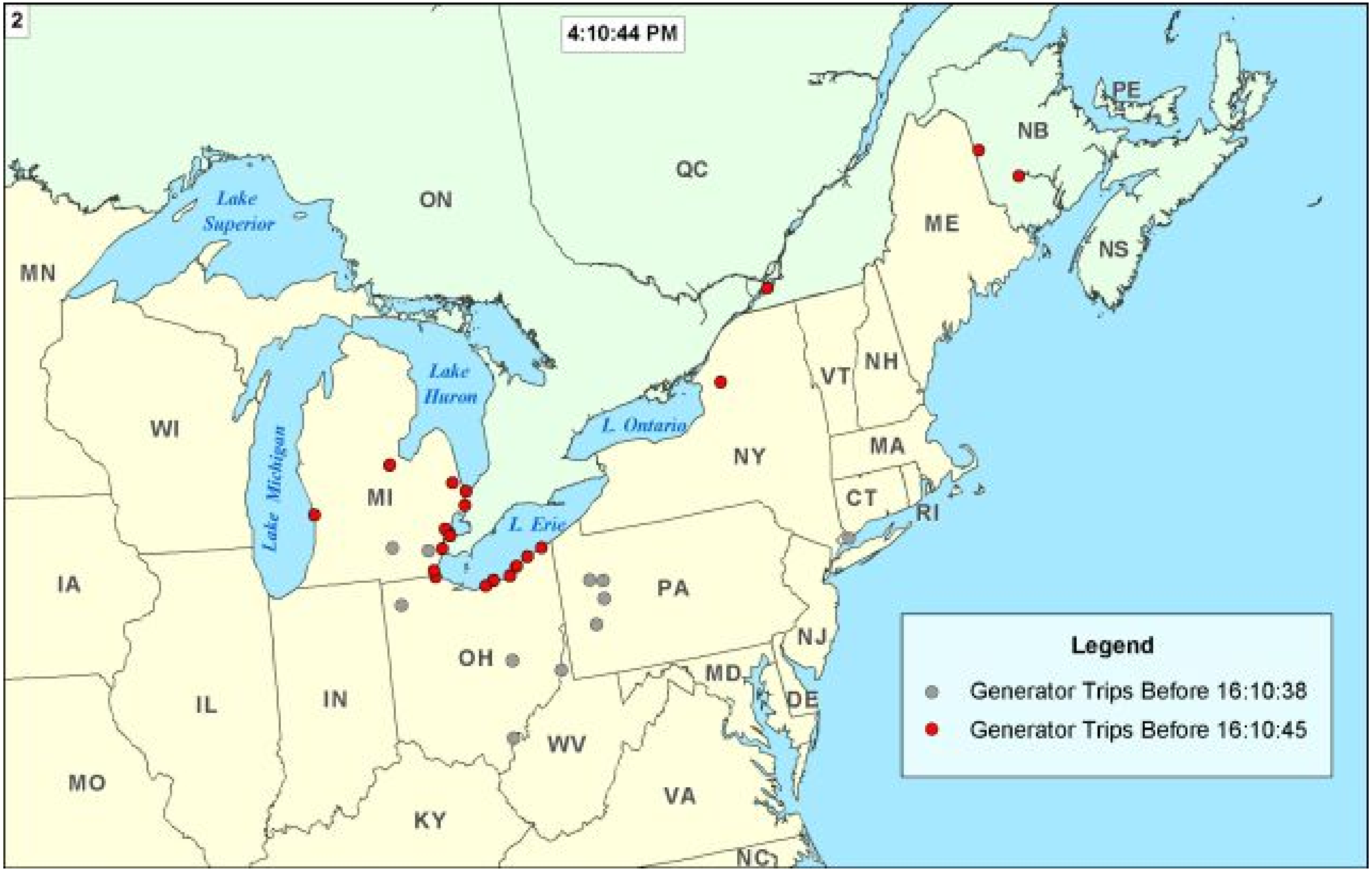


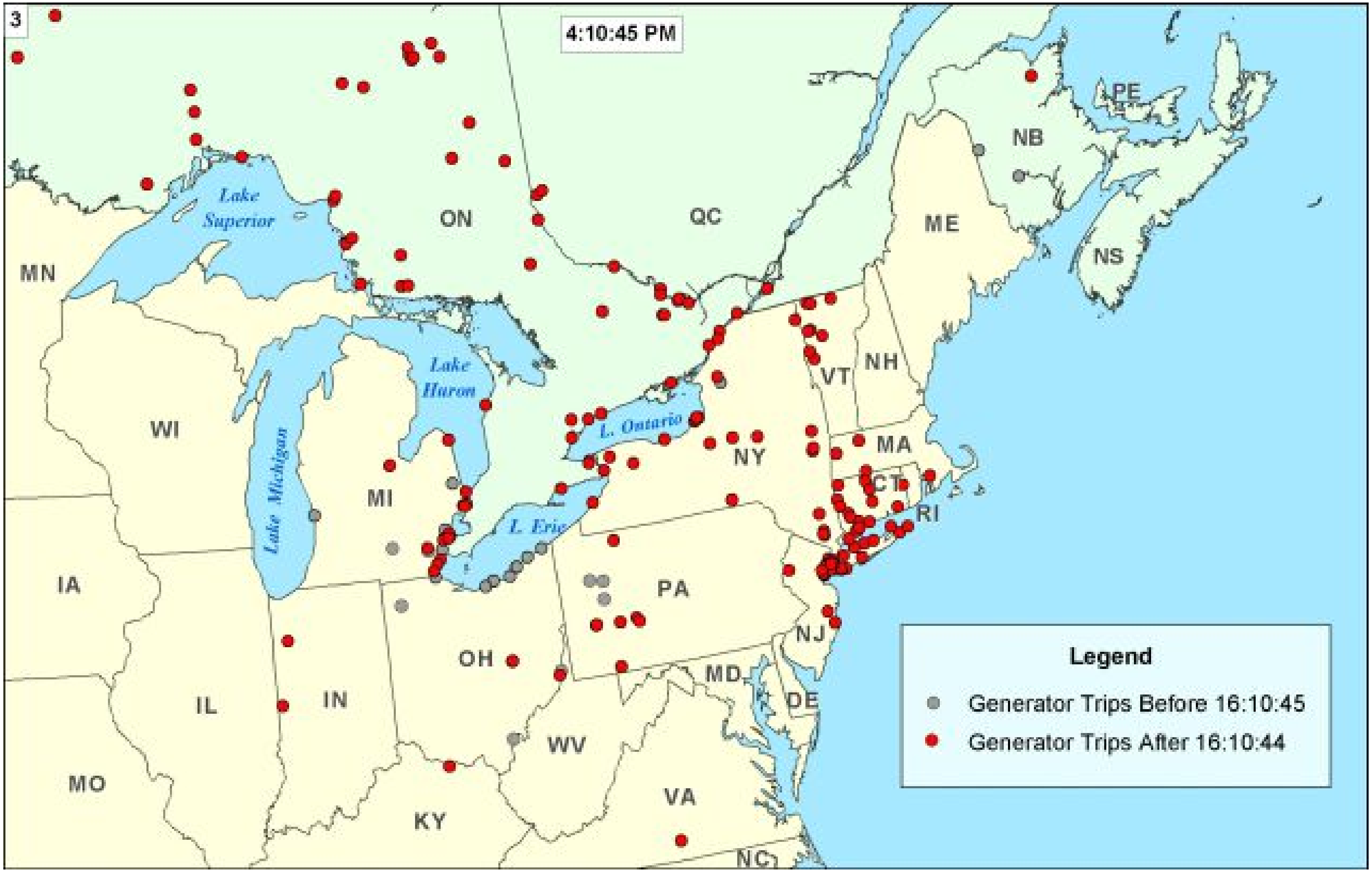
Generator Trips to 4:10:38pm



Generator Trips – Next 7 Seconds



Generator Trips – After 4:10:44pm



Blackout Root Cause Finding #1 Failure by FirstEnergy and ECAR to Understand Inadequacies of the System

- FirstEnergy failed to conduct rigorous long-term planning studies of its system (neglected to conduct multiple contingency assessments)
- FirstEnergy did not conduct sufficient voltage analyses for its Ohio control area and used operational voltage criteria that did not reflect actual voltage stability conditions
- The East Central Area Reliability Coordination Agreement (ECAR) did not conduct an independent review or analysis of FirstEnergy's voltage criteria and operating needs
- Some of NERC's planning and operational requirements and standards were sufficiently ambiguous that FirstEnergy could interpret them to include practices that were inadequate for reliable system operation

Blackout Root Cause Finding #2 Lack of Situational Awareness by FirstEnergy Operators

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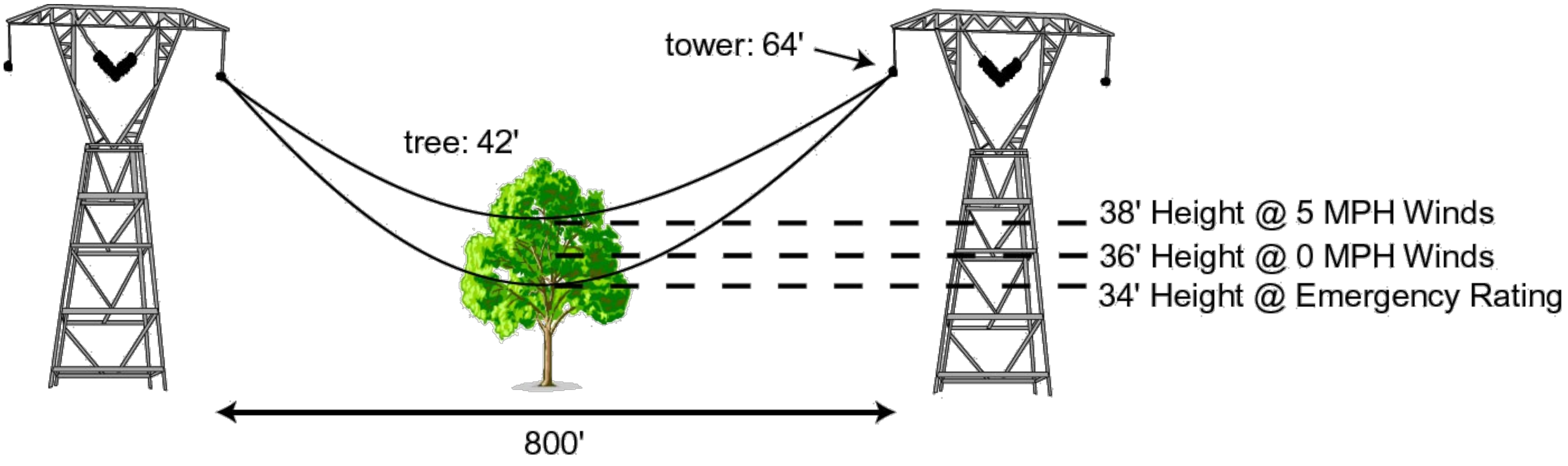
- FirstEnergy did not:
  - ensure a reliable system after contingencies occurred because it did not have an effective contingency analysis capability
  - have effective procedures to ensure operators were aware of the status of critical monitoring tools
  - have effective internal communications procedures
  - have effective procedures to test monitoring tools after repairs
  - have additional high level monitoring tools after alarm system failed

Blackout Root Cause Finding #3
Inadequate Vegetation Management

- FirstEnergy did not adequately manage tree growth in its transmission rights of way
  - Common cause of the outage for three 345 kV transmission lines and one 138 kV line

Effects of Ambient Conditions on Transmission Line Ratings



Another word about vegetation management…

- Sometimes utilities have disputes with landowners preventing necessary work from occurring
- Columbus – Bedford (345kV) Line in Indiana owned by Cinergy
  - 12:08:40.0 Line trips and locks out
  - 18:23:00.0 Line returned to service

August 14, 2003

October 9, 2003

Blackout Root Cause Finding #4
Improper Reliability Coordinator Diagnostics

- Midwest Independent System Operator's (MISO) state estimator failed due to a data error
- MISO's flowgate monitoring tool didn't have real-time line information to detect growing overloads
- MISO operators couldn't easily link breaker status to line status to understand changing conditions.
- PJM and MISO ineffective procedures and wide grid visibility to coordinate problems affecting their common boundaries

Blackout Investigation Task Force Recommendations

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- Address institutional issues related to reliability (14)
- Strengthen initiatives of the electric power industry's North American Electric Reliability Council (NERC) (17)
- Tighten physical and cyber security (13)
- Canadian nuclear power sector (2)

Blackout report and other materials available at:

http://www.oe.energy.gov/information_center/documents.htm

Infrastructure Resilience

- Ability to reduce the magnitude and/or duration of disruptive events
- Resilient infrastructure can anticipate, absorb, adapt to, and/or rapidly recover from a disruptive event
- Best when **all-hazard** "disruptive events" include the unenvisioned
  - All hazards span naturally occurring events, such as storms or earthquakes, and also include malicious human actions
  - A well-designed resilient system will either maintain maximum practicable functionality, or enable rapid restoration with minimum downtime, regardless of whether or not that particular event or scenario had been anticipated in the design and planning phase
    - Example: response-based special protection schemes vs. event-based logic trees

Resilience Framework - Context

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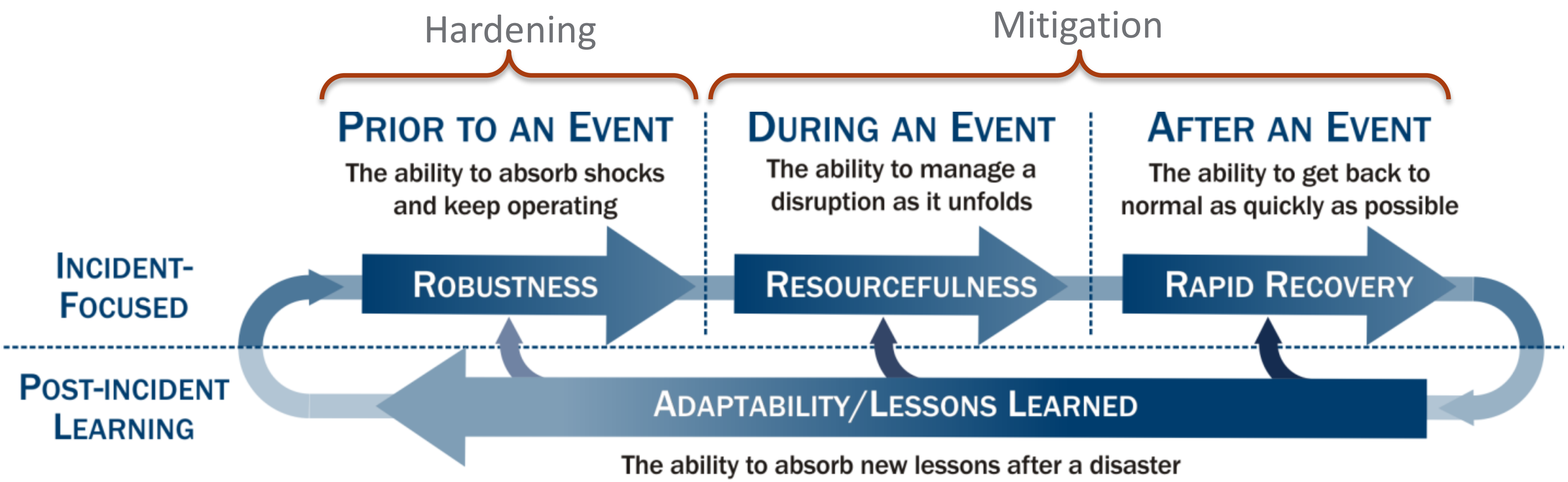
Sequence of the NIAC Resilience Construct



"A Framework for Establishing Critical Infrastructure Resilience Goals,"
National Infrastructure Advisory Council, October 19, 2010

Overview

Electricity Infrastructure Resilience

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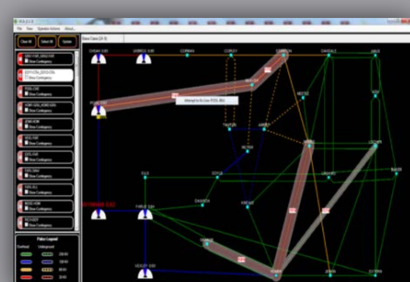
Technology Challenge

Enhance power system reliability, security, and resilience by leveraging new measurement systems to provide wide-area visualization, monitoring and control

Our approach: Improve power system performance and resilience by extracting greater value from grid measurements and data. Key elements include:

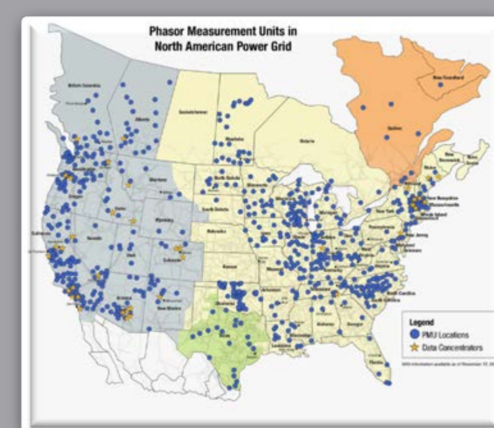
- U.S. DOE's lead for the North American Synchrophasor Initiative (NASPI), a joint effort with NERC, EPRI, and industry to build out phasor measurement units (PMUs) across North America, enabling increased situational awareness and control
- Planning models validation through measurement-based analysis
- Decision support tools for operators
  - Mode meter – uses PMU data to improve detection of grid disturbances, enabling greater asset use and preventative measures; deployed in Western Interconnection Synchrophasor Project
- Electricity Infrastructure Operations Center – providing utilities, vendors and researchers access to real-time grid data for testing in realistic environment with access to operational data and planning tools

Graphical Contingency Analysis



Real-time power flow visualization identifies/prioritizes issues, recommends corrective actions

NASPI



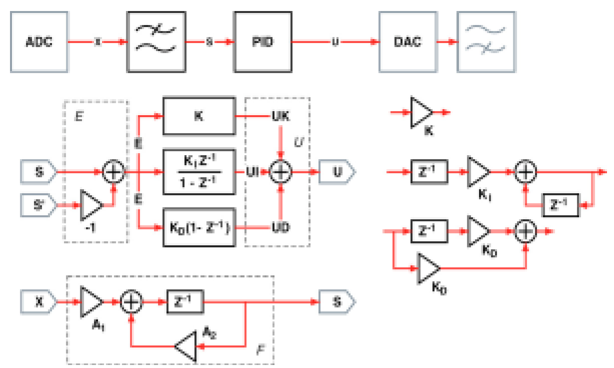
One of the Grid Modernization Focus Areas: System Operations, Power Flow, and Control

Advanced control technologies to enhance reliability and resilience, increase asset utilization, and enable greater flexibility of transmission and distribution

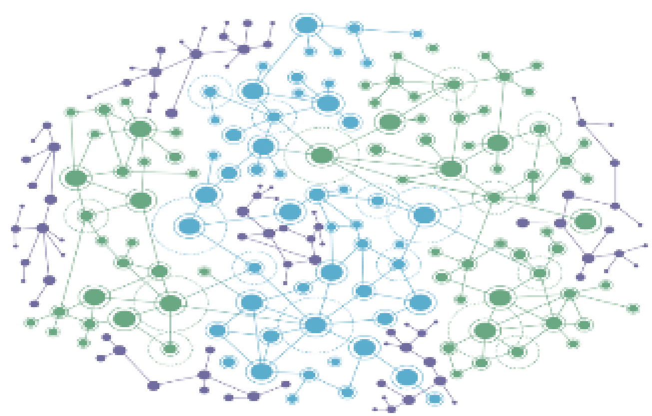
Expected Outcomes

- By 2020 deliver an architecture, framework, and algorithms for controlling a clean, resilient and secure power grid
  - leveraging advanced concepts, high performance computing, and more real-time data than existing control paradigms
  - Involving distributed energy resources as additional control elements
- Develop software platforms for decision support, predictive operations & real-time adaptive control
- Deploy through demonstration projects new classes of power flow control device hardware and concepts
- Advance fundamental knowledge for new control paradigms (e.g., robustness uncompromised by uncertainty)

***Conventional** controls*



***Distributed** controls*



National Academy Committee: Analytic Research Foundations for the Next-Generation Electric Grid

Findings:

- New technologies for measurement and control are becoming available
- Improved models can increase grid efficiency
- Mathematical and computational challenges arise from the integration of more alternative energy sources into the system
- Transmission and distribution are often planned and operated as separate systems
- There need to be better planning models for designing the sustainable deployment and utilization of distributed energy resources
- Modeling and mitigation of high-impact, low-frequency events is especially difficult
  - Fundamental research in mathematics and computer science could yield dividends for predicting the consequences of such events and limiting their damage

National Academy Committee: Analytic Research Foundations for the Next-Generation Electric Grid

Recommendations:

1. Develop and test a full ac optimal power flow model with an optimization algorithm
2. File formats used for the exchange of FERC Form 715 power flow cases be available
3. Descriptions of all models used in system-wide transient stability studies be available
4. Create, validate, and adopt synthetic data and make them freely available to the broader research community
5. Integration of theory and computational methods from machine learning, dynamical systems, and control theory should be a high-priority research area
6. Research dynamical systems theory and associated numerical methods to encompass classes of systems that include electric grids
7. Research data-driven approaches applied to the operations, planning, and maintenance of power systems
8. Conduct fundamental research on nonlinear, nonconvex optimization algorithms
9. Create synthetic data libraries to facilitate studies of, and tool building for, the reliability and control of the future electric grid
10. Develop new open-source software for the grid research community
11. Broaden coordination among researchers
12. Establish a National Electric Power Systems Research Center

Coming Soon!

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Enhancing the Resiliency of the Nation's Electric Power Transmission and Distribution (T&D) System

Concluding Remarks

- The power grid is exceptionally complex, and extraordinarily reliable
  - Most customer outages are due to issues with radial distribution feeders vs. the networked transmission grid
- Hierarchal control strategy provides good tradeoff between reliability and efficiency
- Blackouts provide an opportunity to study and apply lessons learned to further enhance reliability
- As advanced technology is being considered for deployment, need to consider unintended consequences (e.g., cyber security)
- Robustness and resiliency are enhanced by considering all threats to the power system
  - An “all-hazards” approach
- Research is underway to develop technologies that will enhance the reliability, security, and resiliency of the future power grid

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