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Achieving Electricity Resilience

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PNNL is operated by Battelle for the U.S. Department of Energy

Outline

- Measures taken to achieve reliability
- Lessons learned from prior North American blackouts
  - Case study #1: August 10, 1996
  - Case study #2: August 14, 2003
- What is resilience, and how is that different than reliability?
- Concluding remarks

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

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

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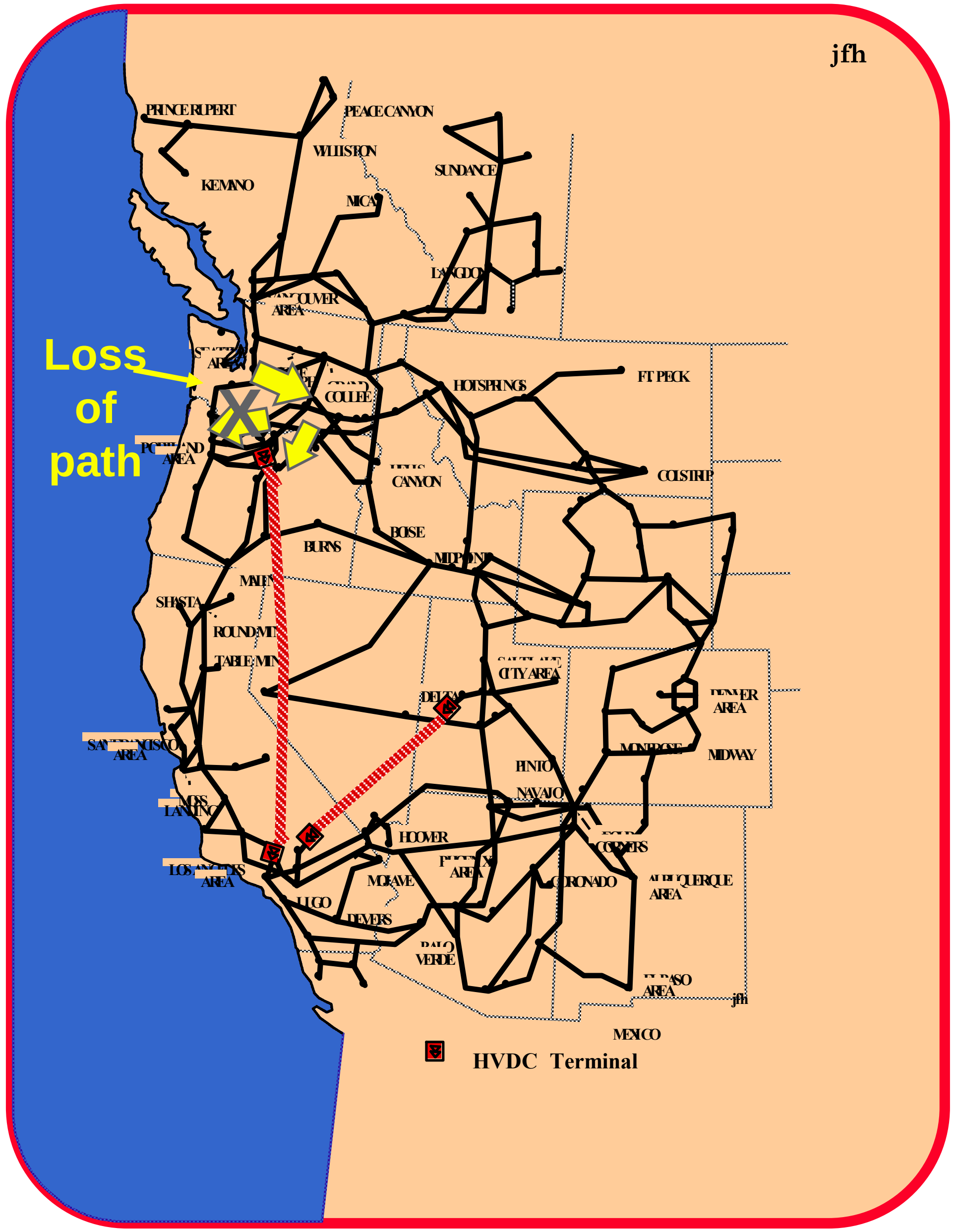
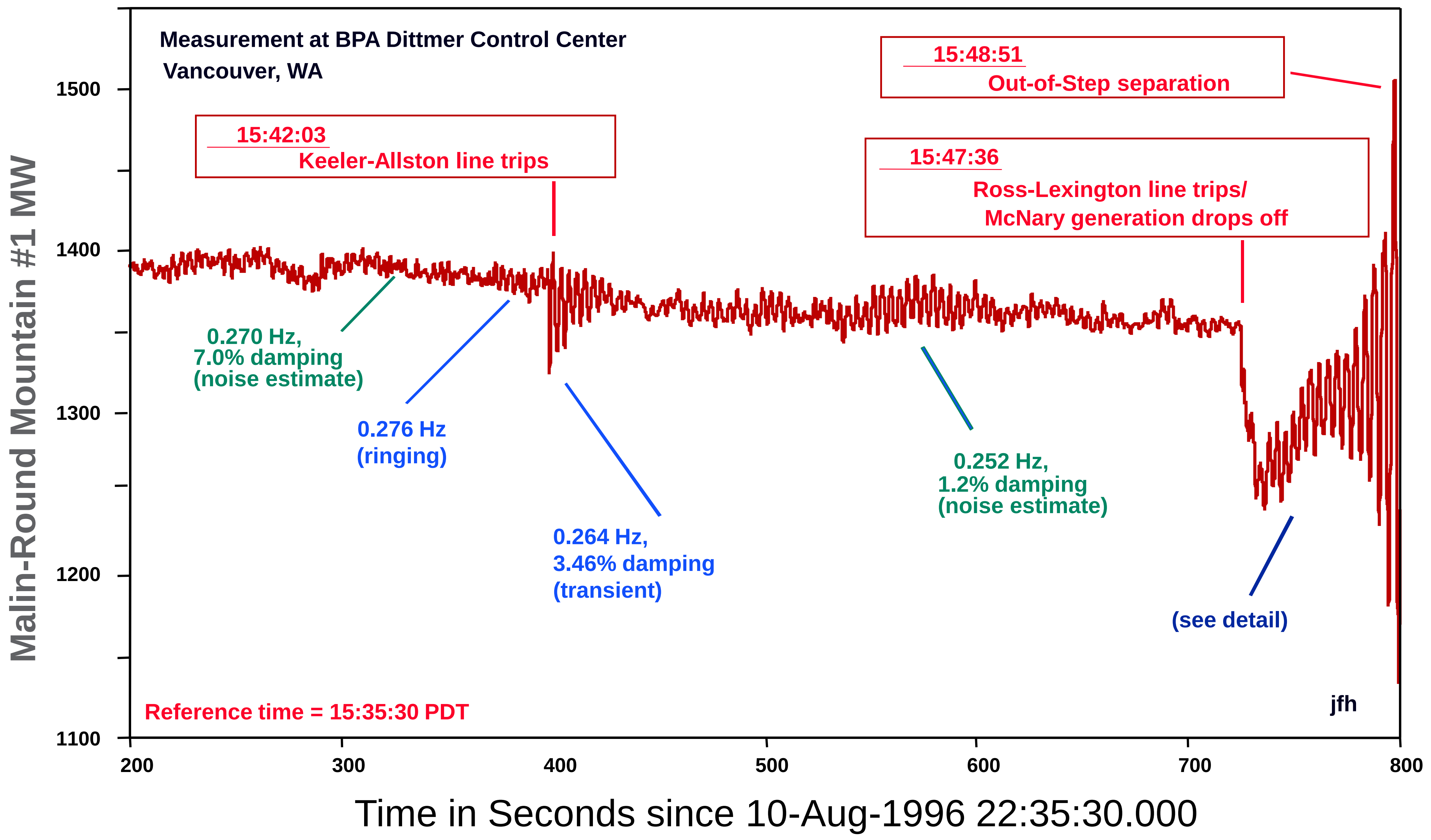
August 10, 1996: At the time, the largest blackout in the history of the North American power grid. (Current ranking: #2)

Conditions prior to the blackout:

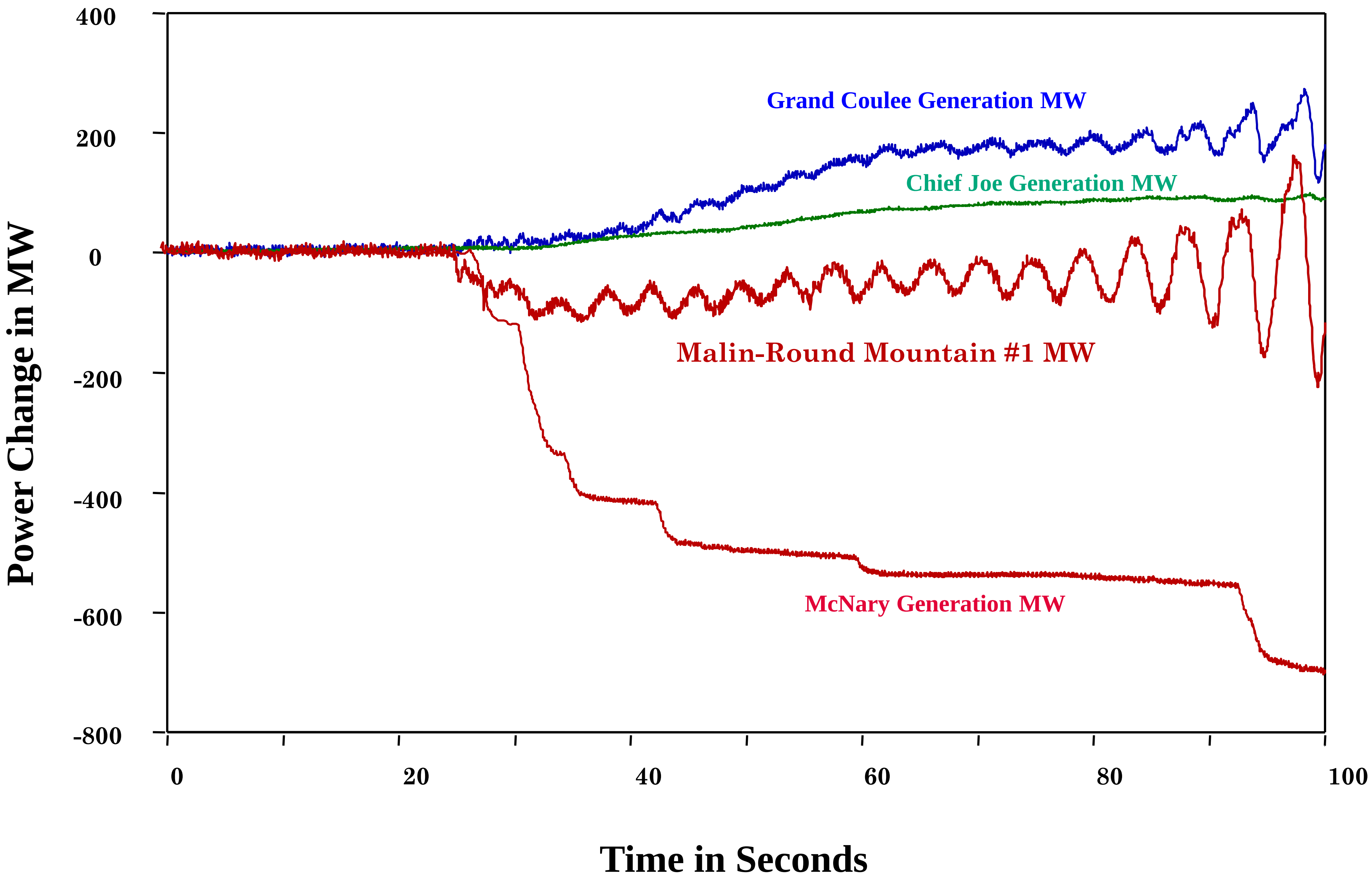
- Above average water year
  - Extensive hydro generation available in Canada
- Lower Columbia generation not available
  - Water bypass for salmon migration
- Key transmission assets out of service for maintenance in Seattle-Portland area
- Temperatures above 100°F in California
- Transmission system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



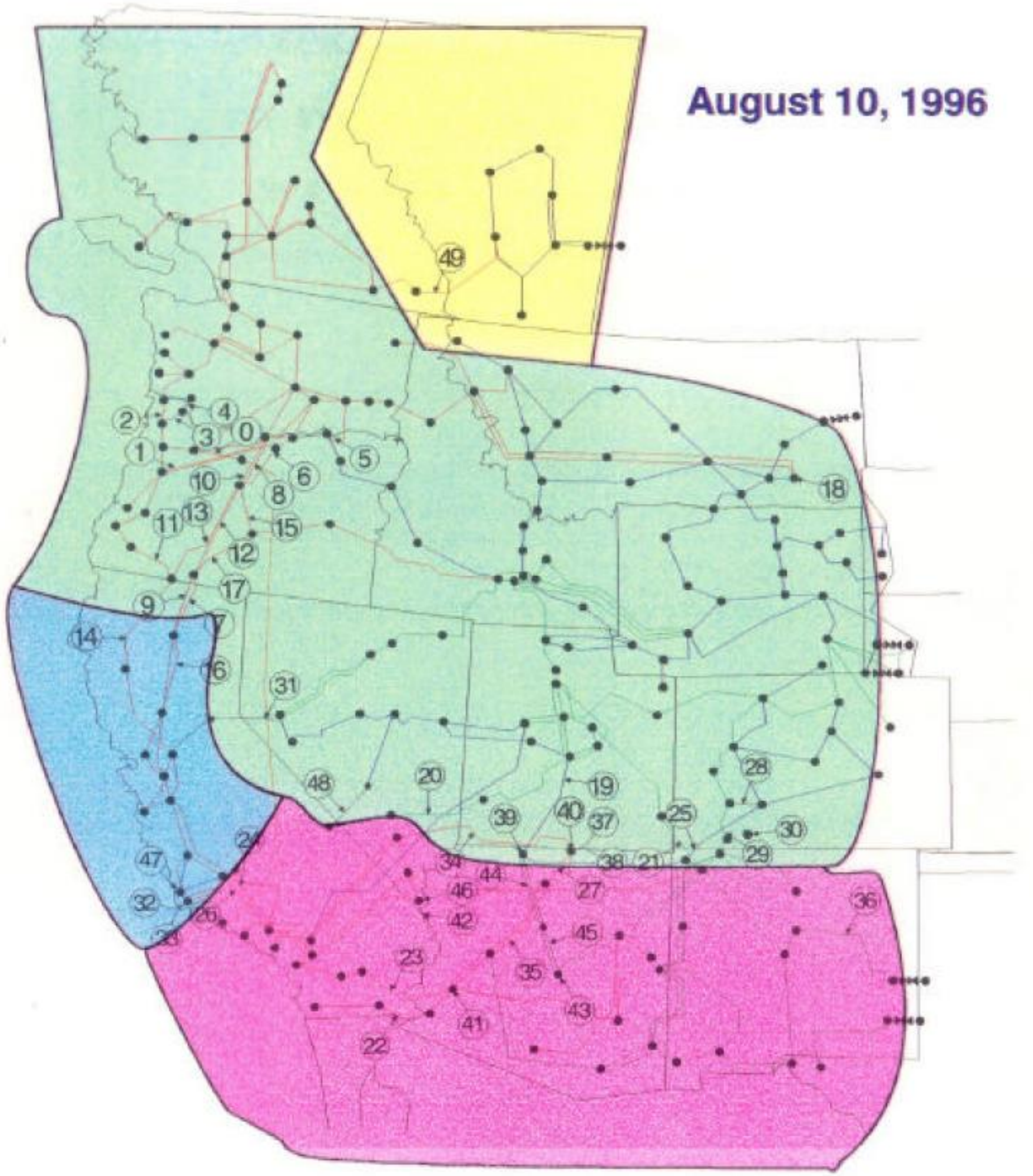
Wide Area Measurements Captured System Events – Useful to Support Investigation



Generator Response:
Loss of McNary units critical factor



Four Electrical Islands Formed

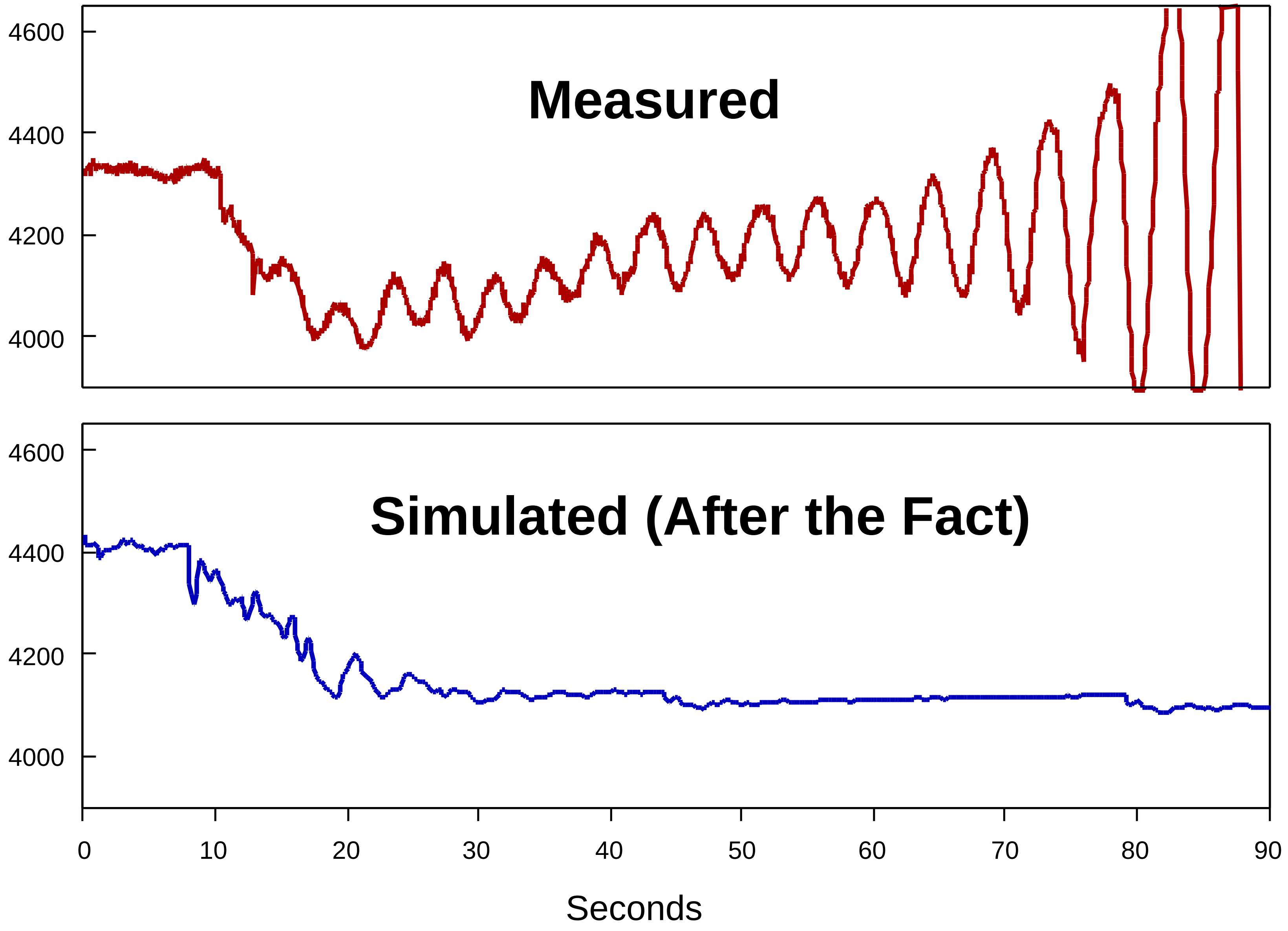


Source: NERC

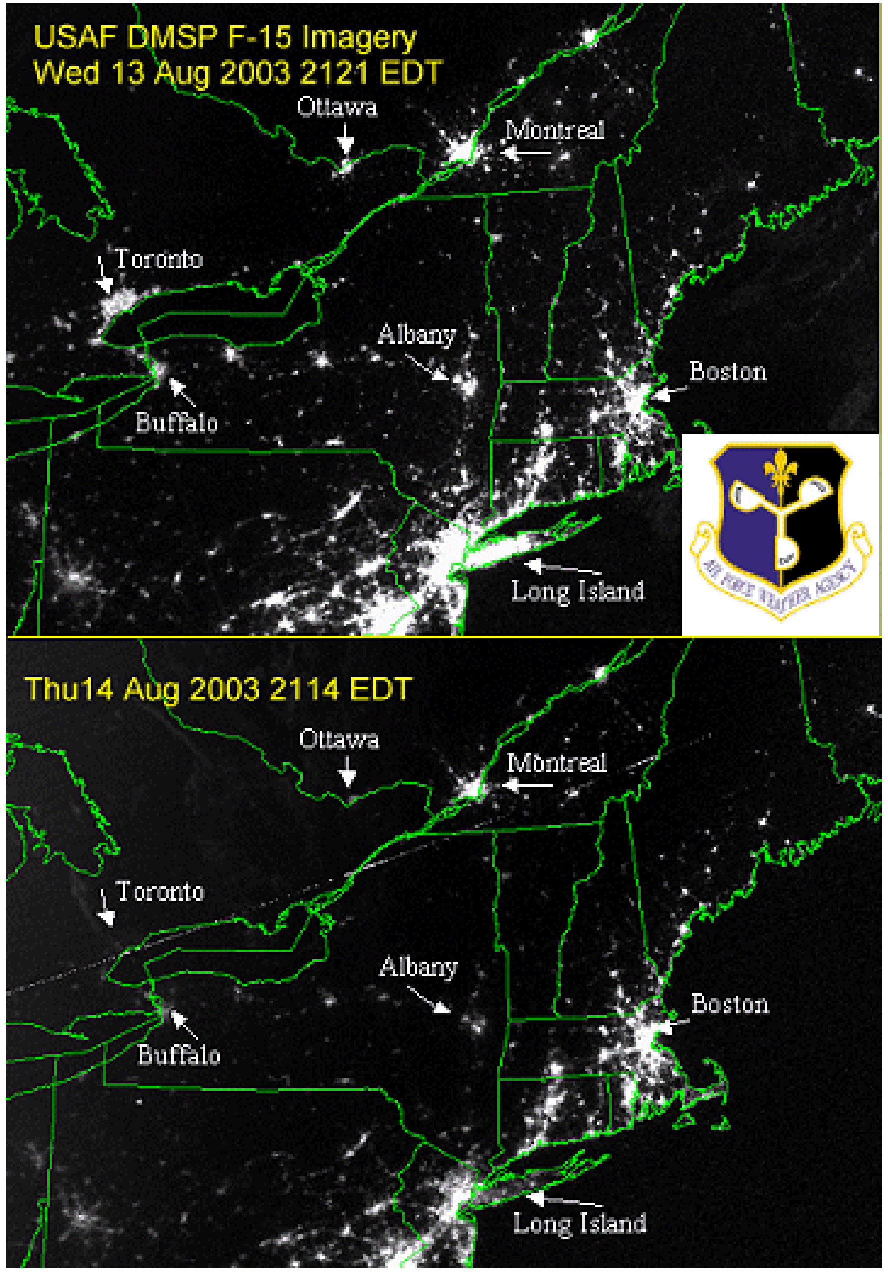
Blackout Investigation Findings

- 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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LATE SPORTS

NFL preseason

'One good day' at the PGA
Mickelson 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

Reality TV: Jessica Simpson with husband Nick Lachey of 98 Degrees.

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

What's next for Mr. Vick?
A Super Bowl isn't far-fetched for Atlanta. Not with him at QB ■ 1C

Fri/Sat/Sun, August 15–17, 2003

Newsline

California ballot is a field of dreamers
Voters have never heard of most of the 135 people running for governor. Georgy Russell, 26, is only one of those seeking their 15 minutes of electoral fame ■ 6A

U.S. captures suspect in Bali, Jakarta bombings
'Hambali,' an Indonesian man believed to be the mastermind behind the deadly attacks, is being interrogated at an undisclosed location, Bush administration official says ■ 8A

LifeSavers changing flavors
With hard-candy market slumping, the classic roll undergoes first change since 1935 launch ■ 3B

France threatens to block Libya deal

Money: Refinancing is still an option

Sports: NCAA keeps eye on finances

Life: 'American Splendor' a treat

USA TODAY Snapshots
Biggest ratio in the big house

Brooklyn Bridge: Thousands of commuters in New York took to their feet Thursday evening after a major power outage hit the city and much of the Northeast.

Outage spawns rush-hour chaos from Detroit eastward

Cities, states and provinces most affected

More annoyance than angst in NYC, despite early fears

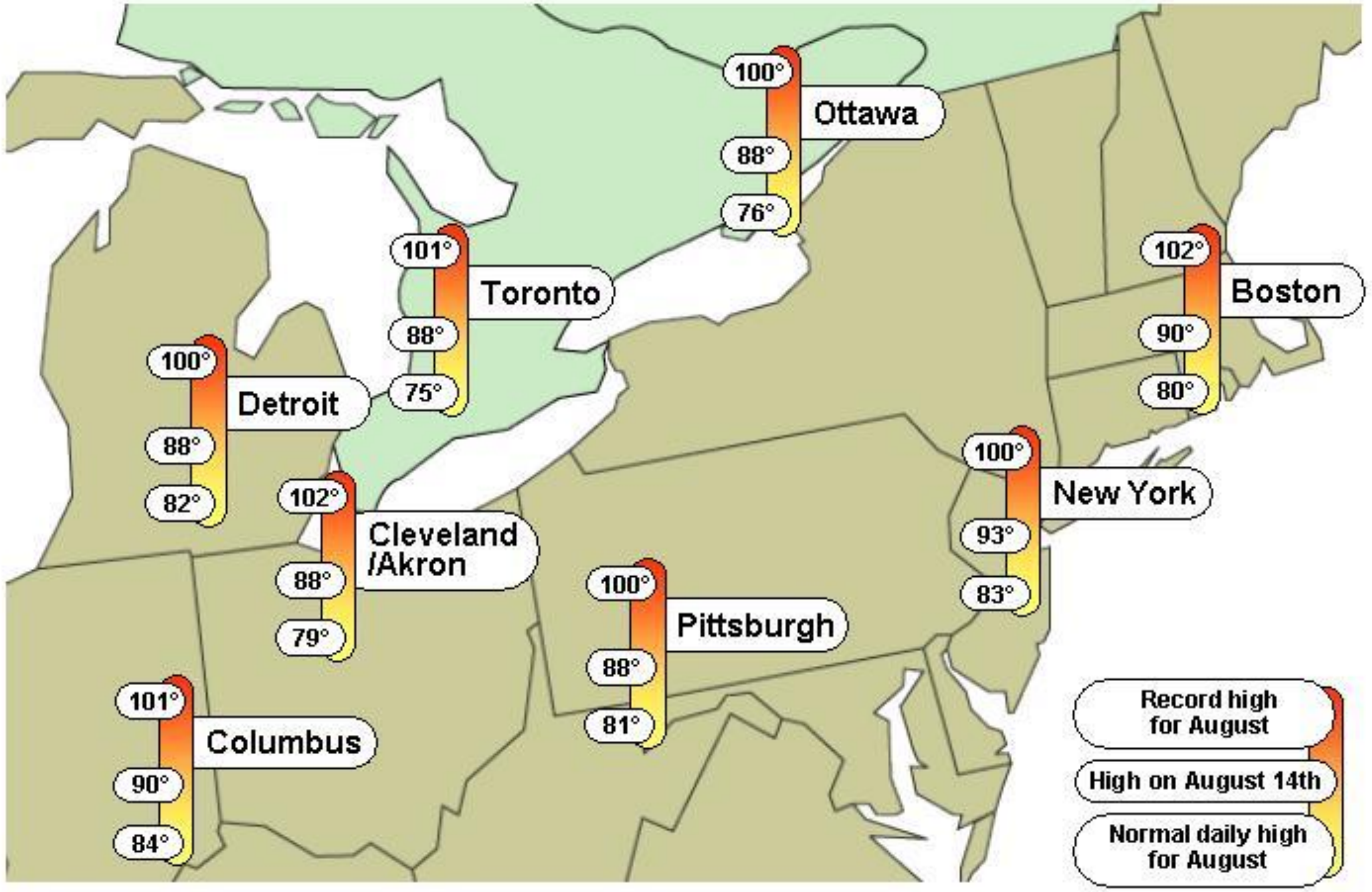
Exodus recalls images of 9/11

Cover story

August 14 Conditions Prior to Blackout

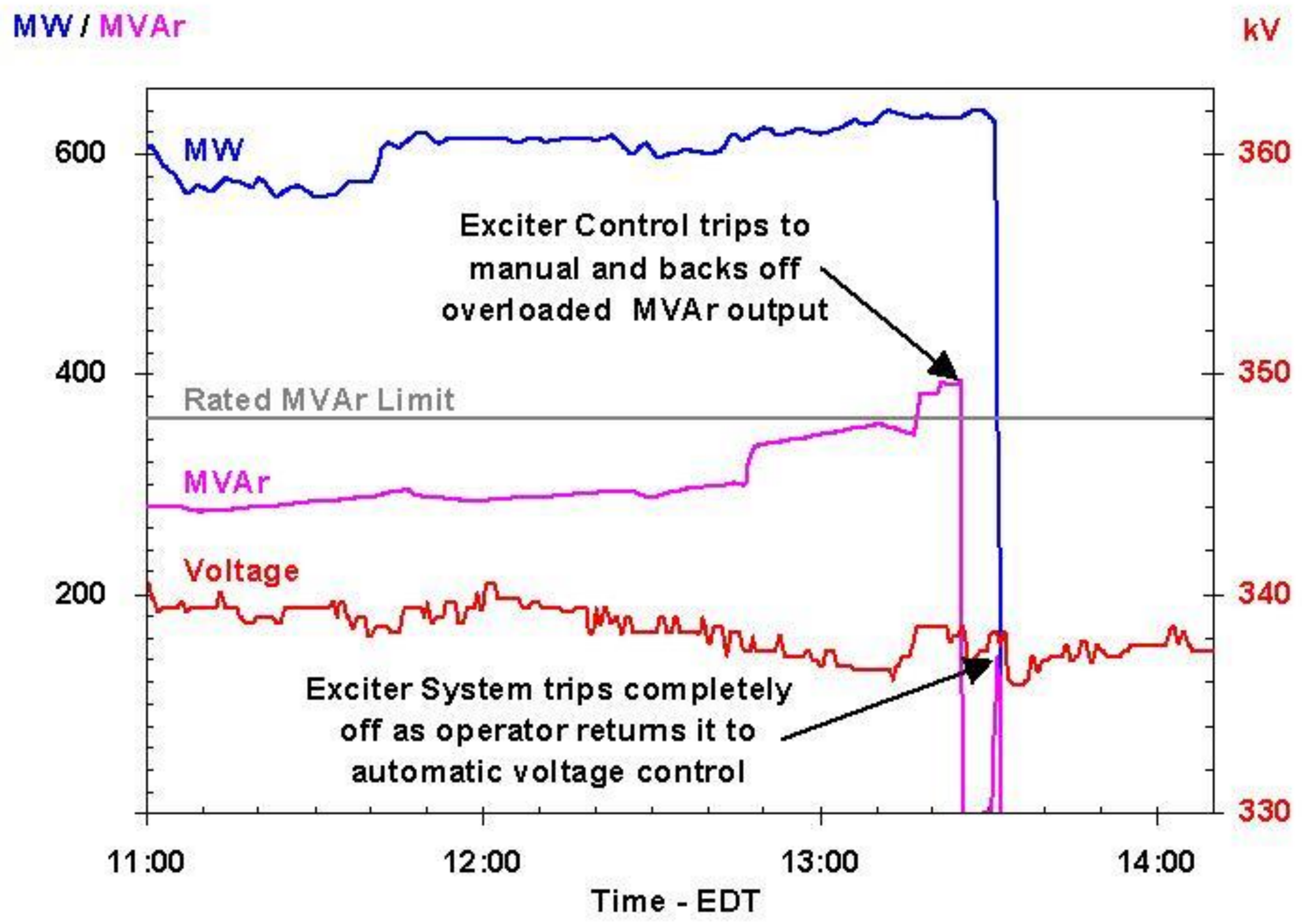
- Planned outages
  - Cook 2, Davis Besse nuclear plants
  - East Lake 4, and Monroe 1
- Transfers high to northeast U.S. + Ontario
  - Not unusually so and not above transfer limits
- Critical voltage day
  - Voltages within limits
  - Operators taking action to boost voltages
- Frequency
  - Typical 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



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

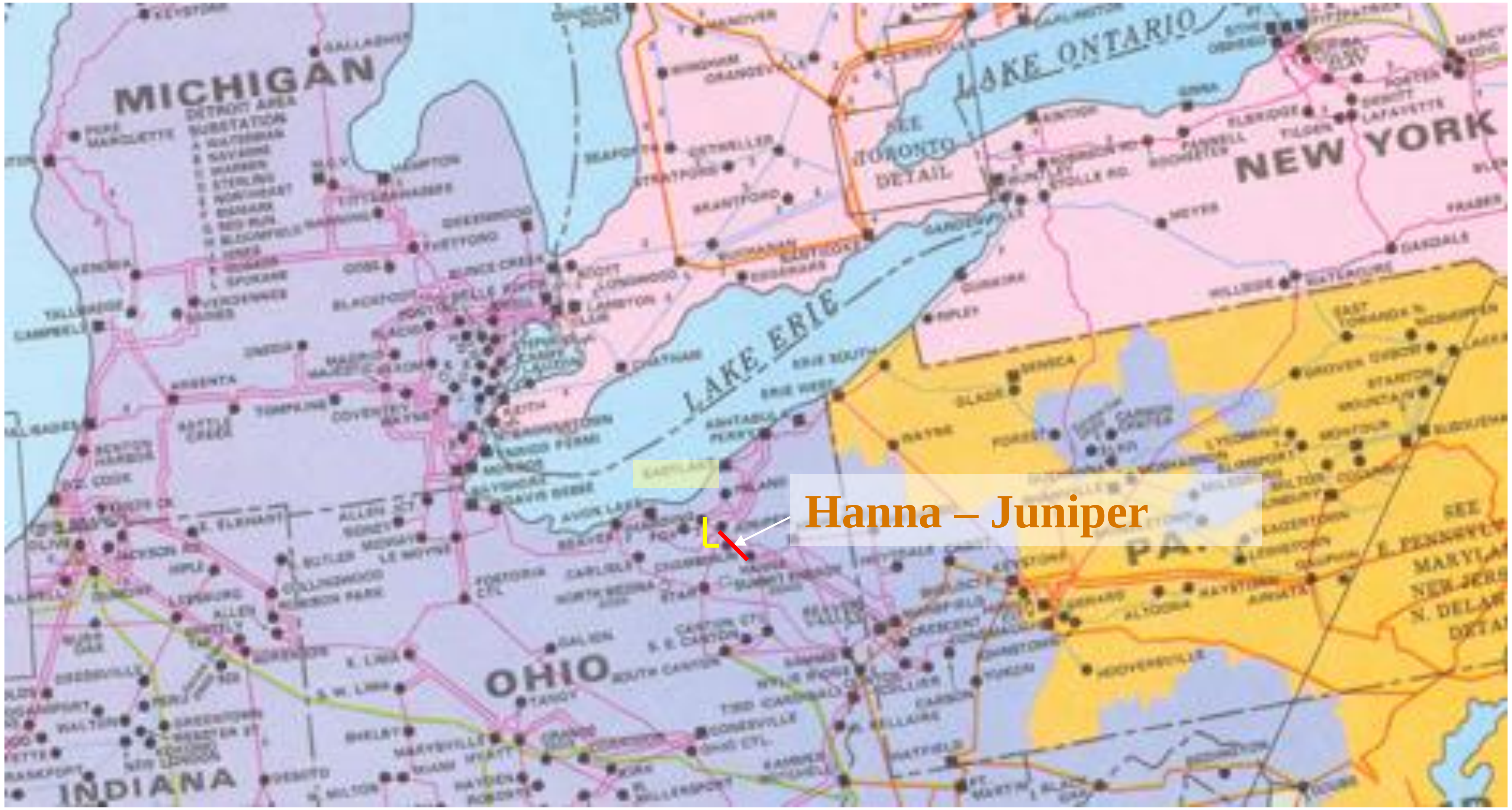
Significance: Contingency analysis system at the Midcontinent Independent System Operator failed due to incomplete topology information (software glitch)

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

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



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

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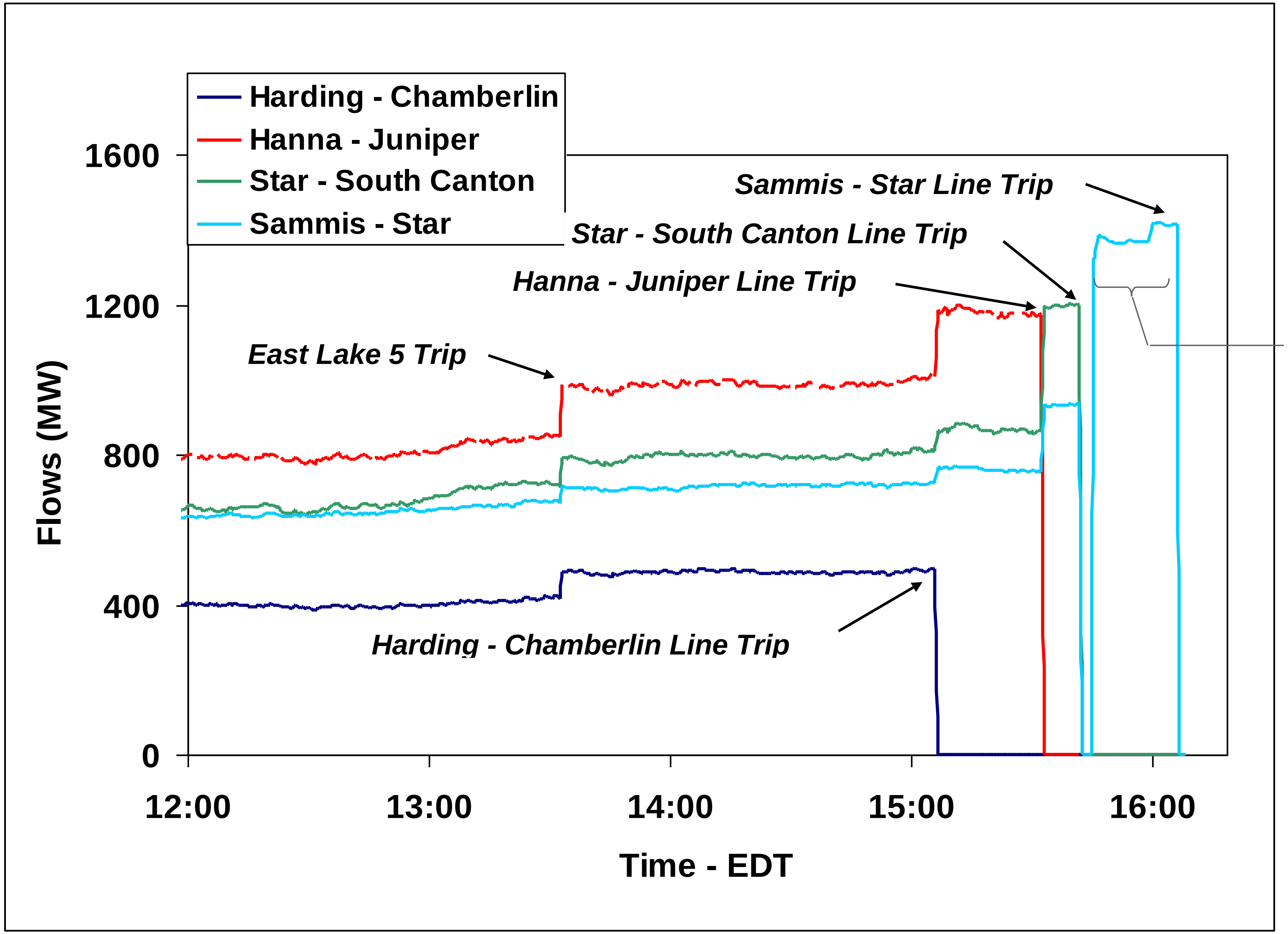
3:41:35pm – Star – South Canton 345 kV line opens
Note: Previously tripped and reclosed twice

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

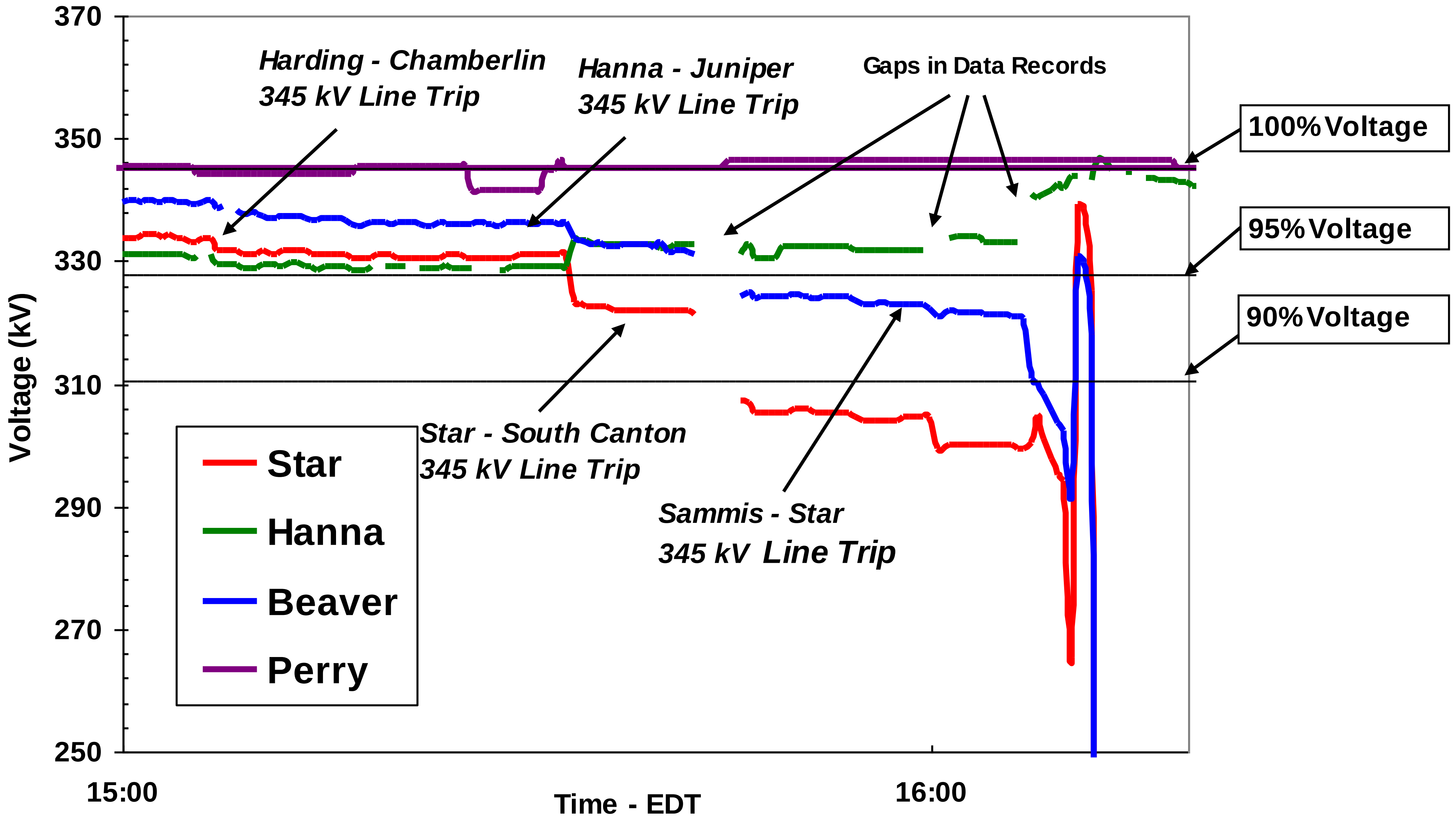
4:05:57.5pm – Sammis – Star 345 kV line trip

Loading on Critical Lines

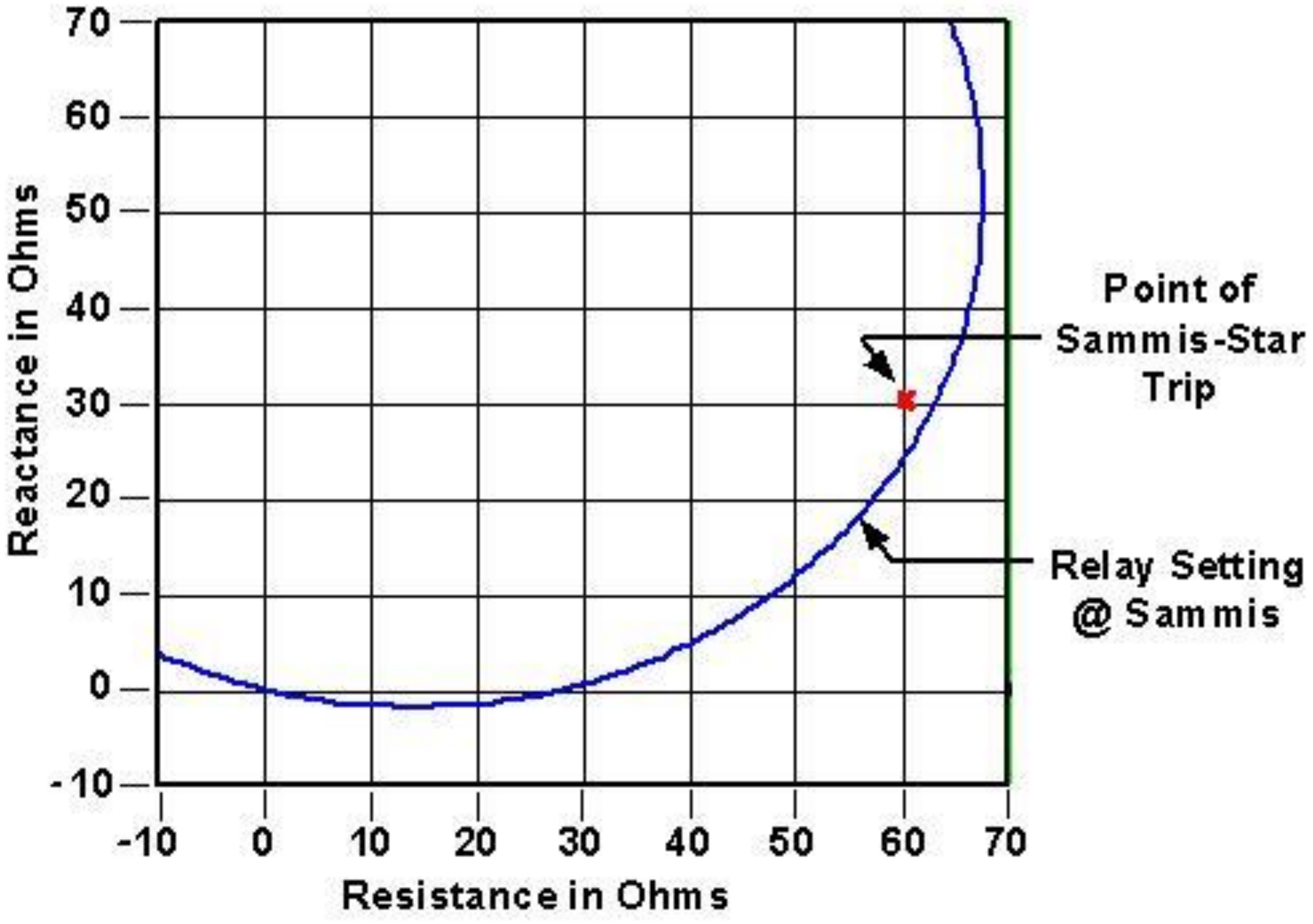


Several 138 kV lines in the vicinity trip during this time.

Key Voltages



Sammis-Star "Zone 3" Relay Operates on Steady State Overload



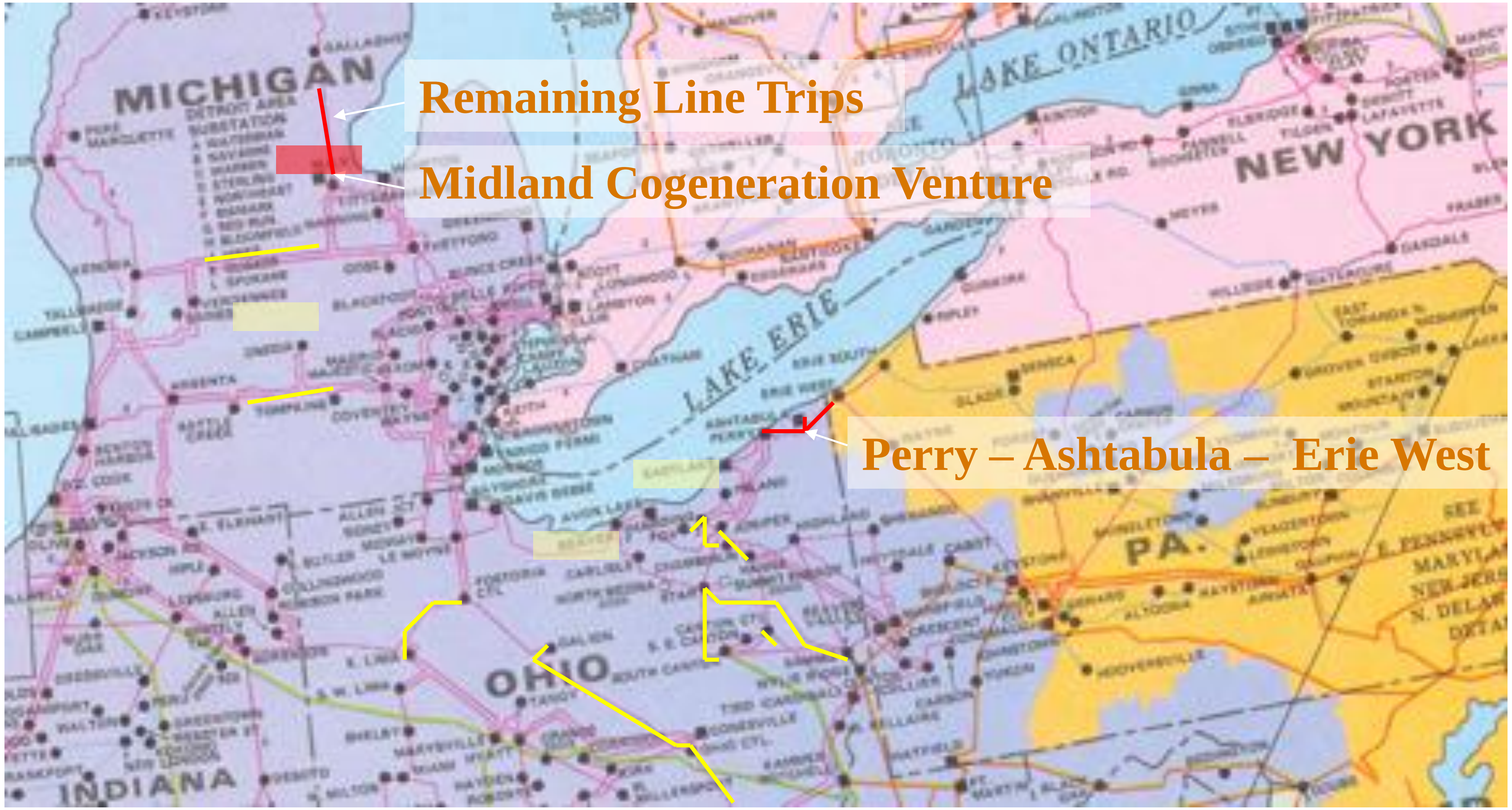
4:08:58pm Galion – Muskingum – Ohio Central 345 kV line trip

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.

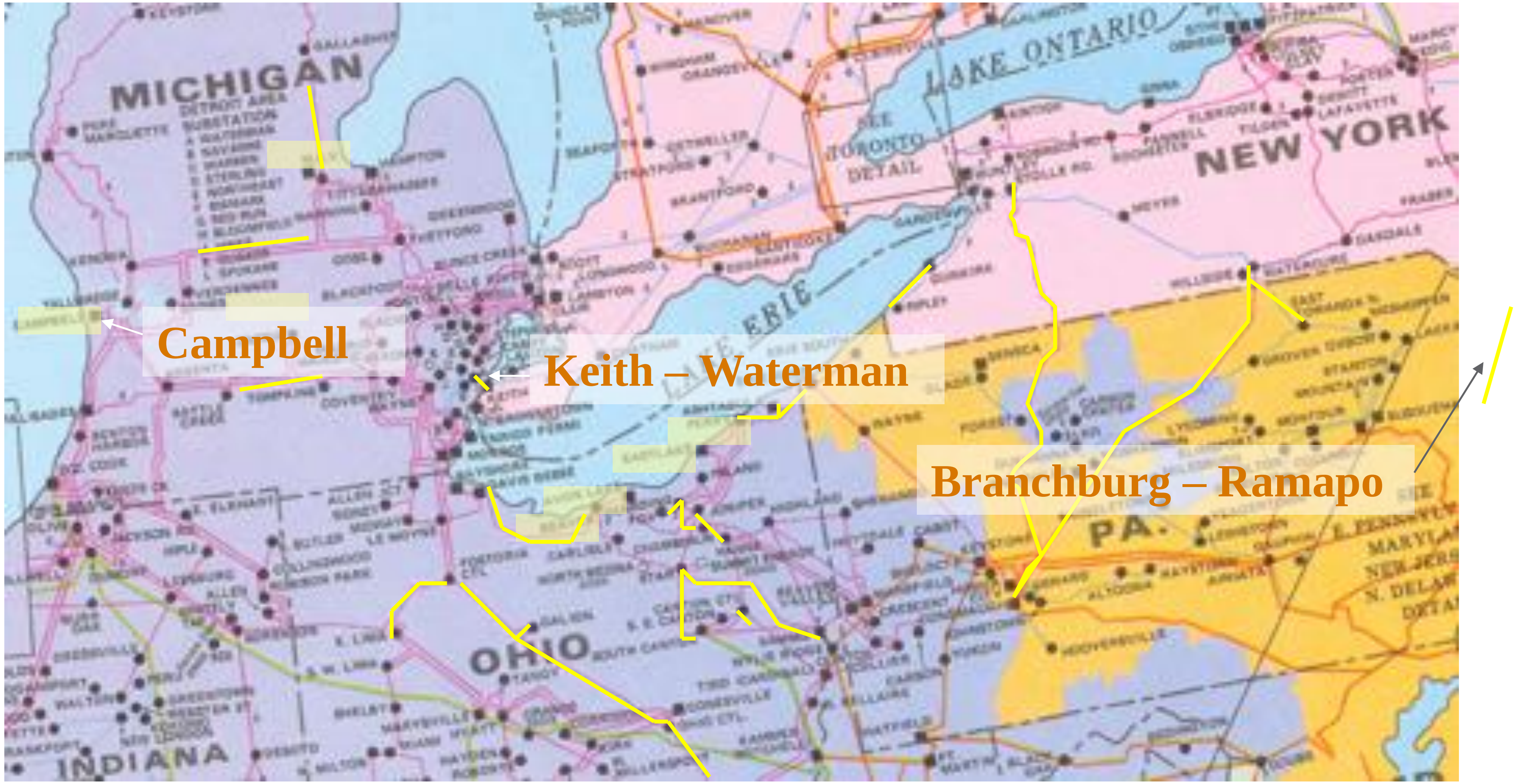
Pennsylvania – New York Separation

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

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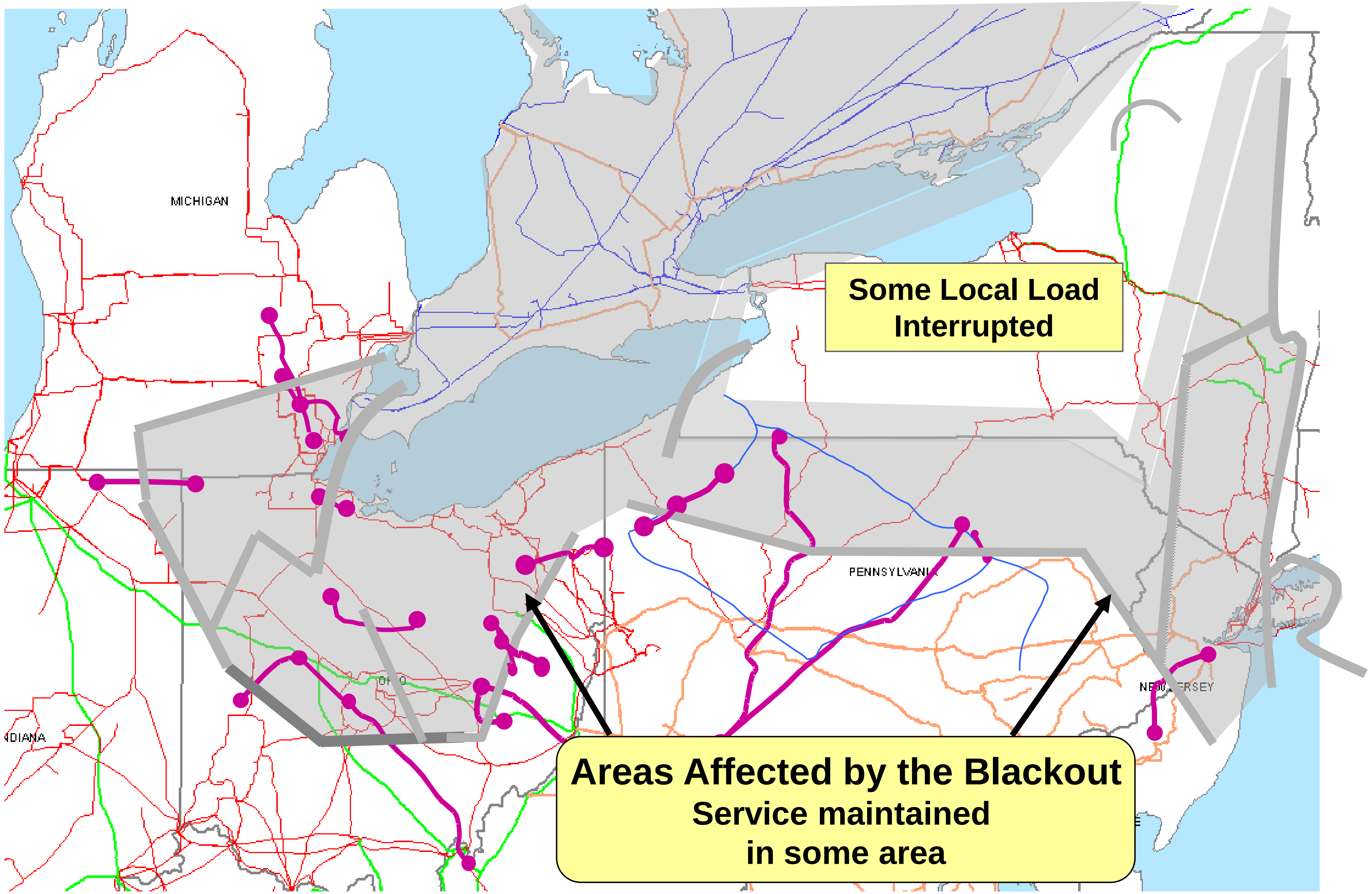
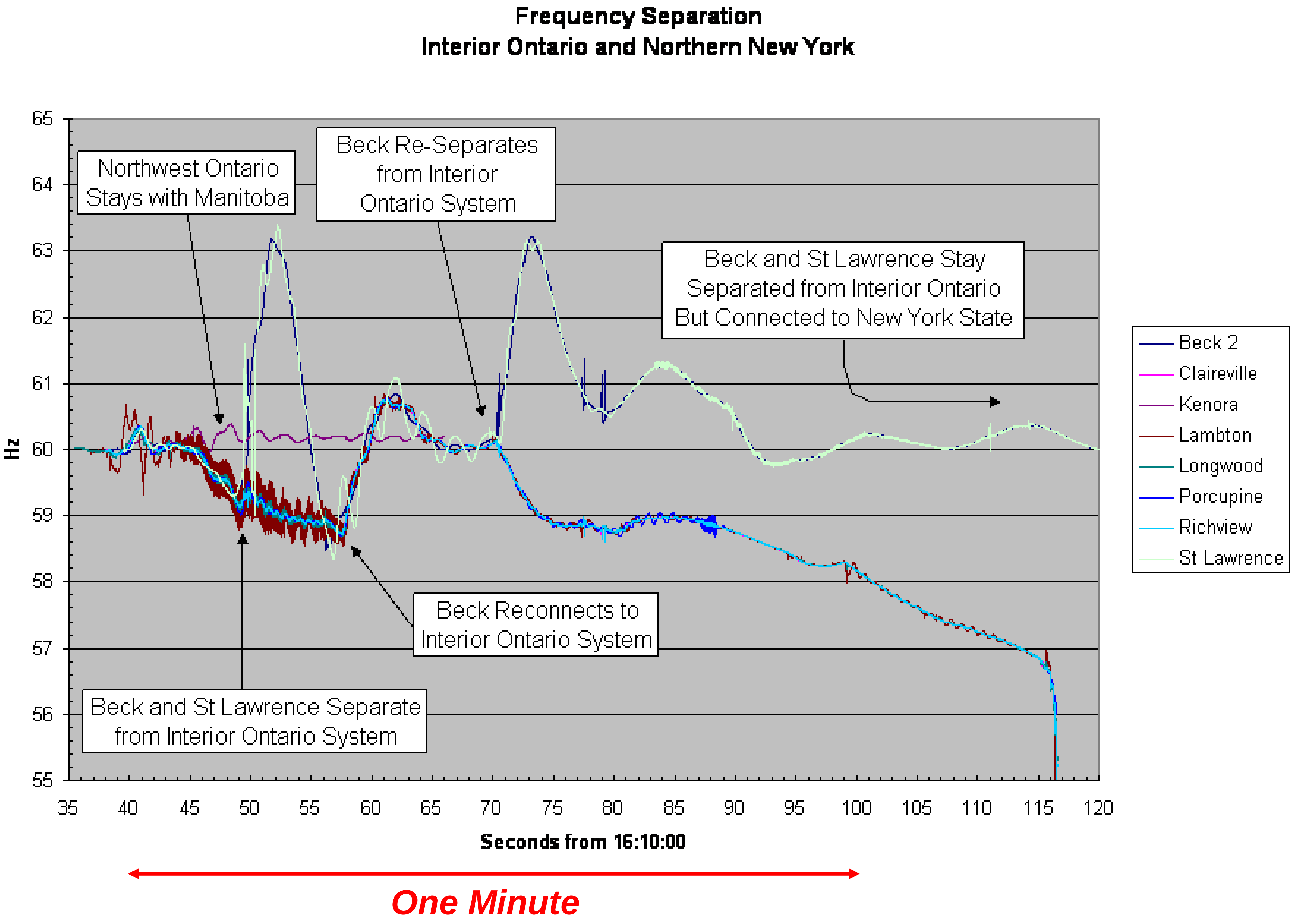
After the Branchburg – Ramapo 500 kV line trips, the underlying 230 kV and 138 kV ties in New Jersey trip, leaving northern New Jersey connected with New York, and southern New Jersey and Pennsylvania remain connected with the remainder of the eastern Interconnection.

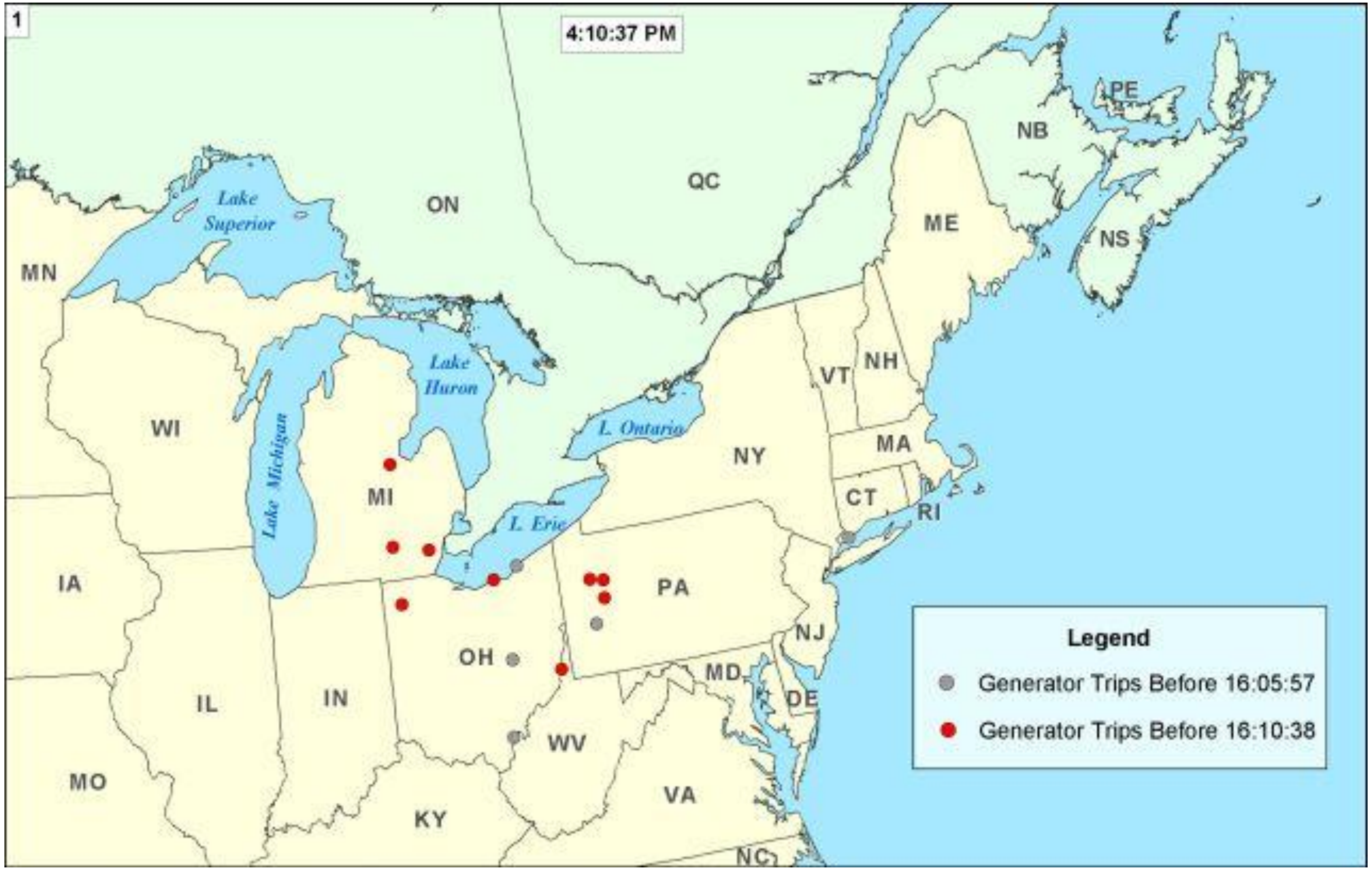
End of the Cascade



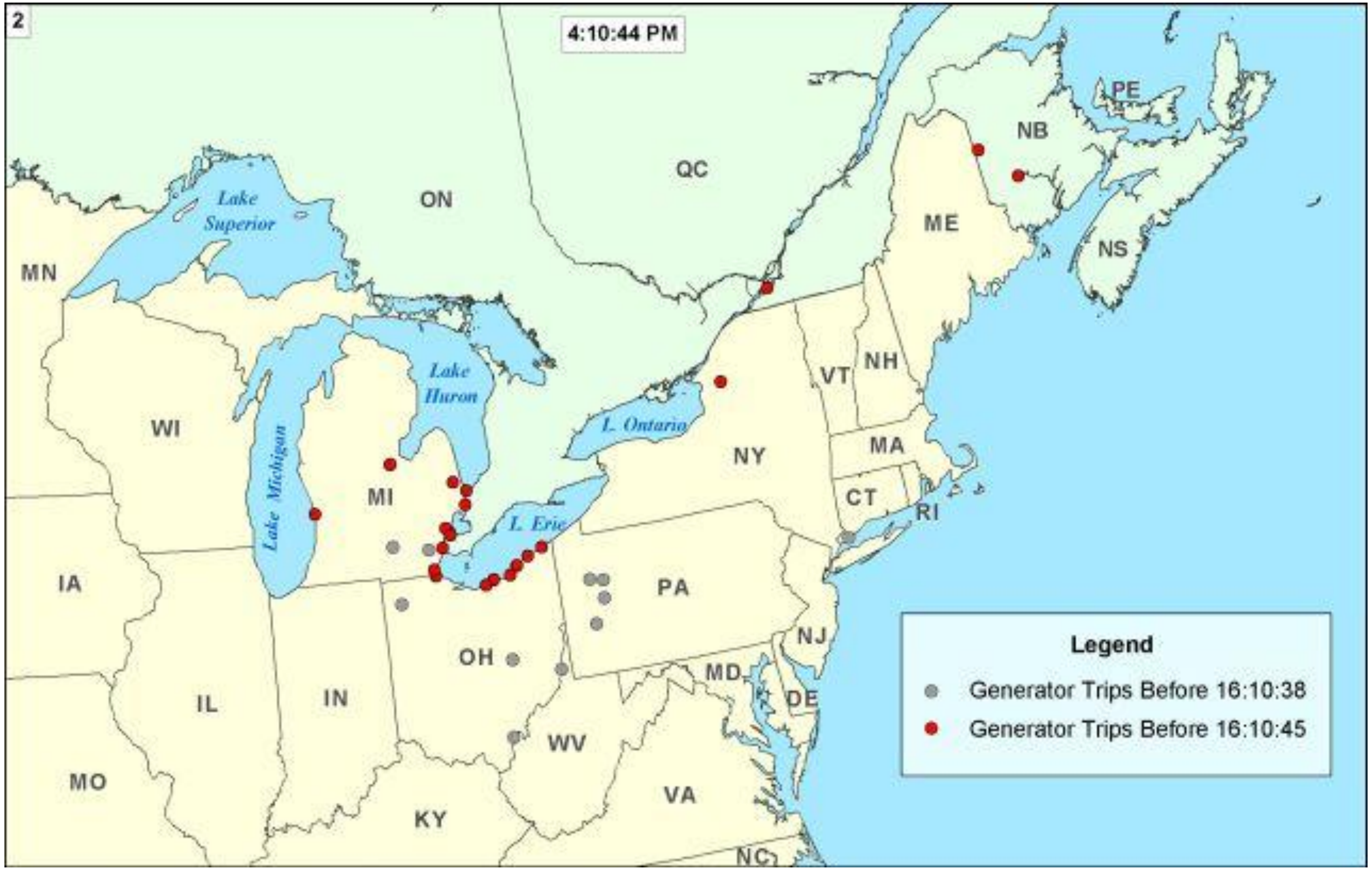
Frequency in Ontario and New York during Breakup Niagara Generation Stays with Western NY



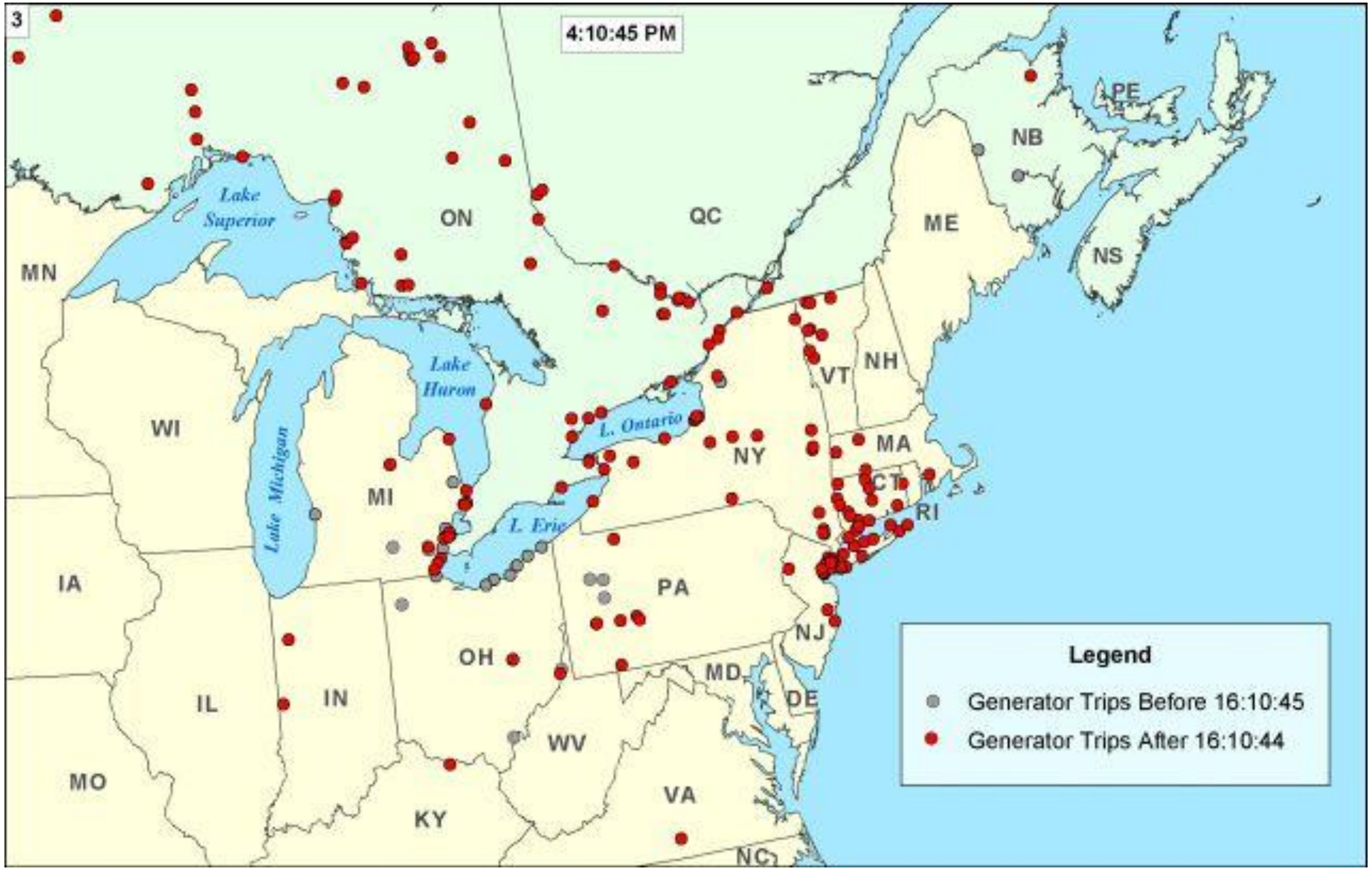
Generator Trips to 4:10:38pm



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

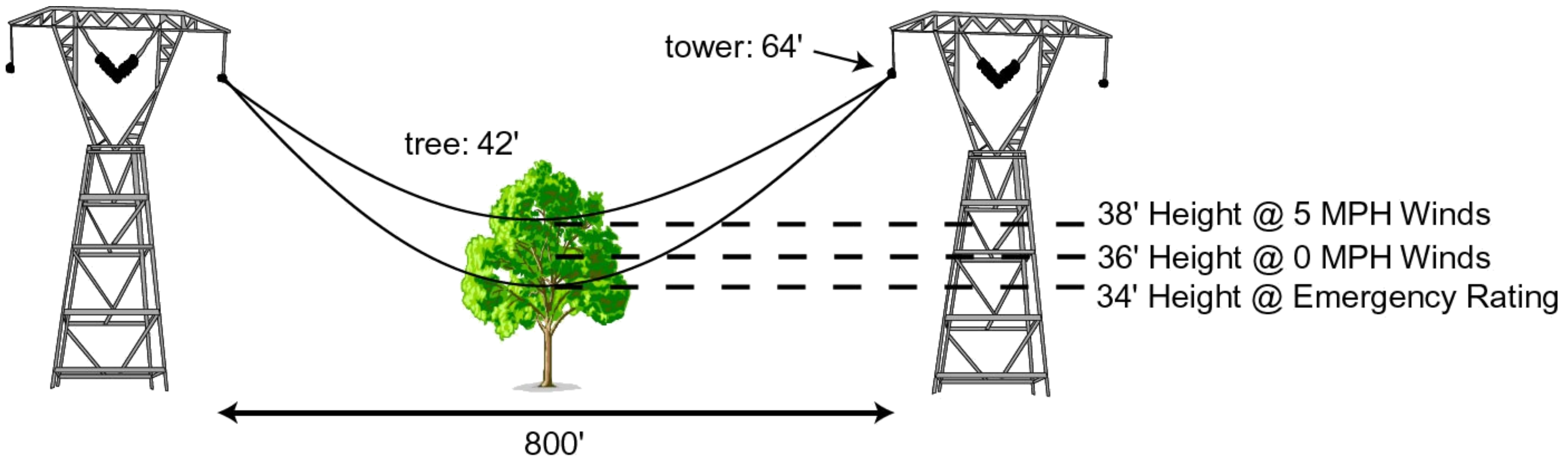
- FirstEnergy failed to conduct rigorous long-term planning studies of its system (neglected to conduct multiple contingency assessments)
- FirstEnergy did not conduct sufficient voltage analyses for its Ohio control area and used operational voltage criteria that did not reflect actual voltage stability 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

- 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

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

- The Midcontinent 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

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National Academies Report Released July 2017

The National Academies of

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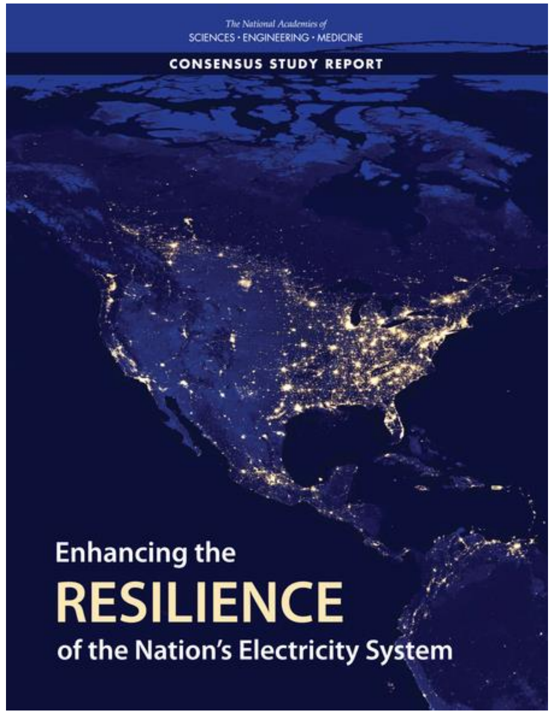
Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

Enhancing the Resilience of the Nation's Electricity System



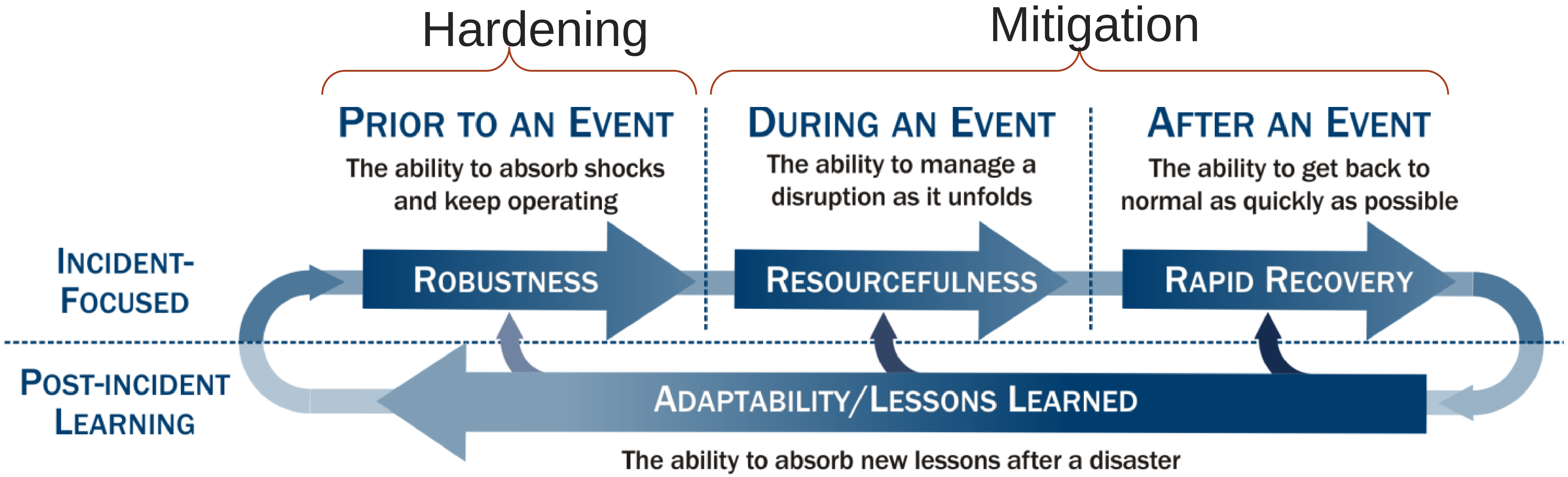
Download the full report and 4-page summary at:
https://www.nap.edu/24836

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
  - These hazards span naturally-occurring events, such as storms or earthquakes, and also include malicious 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

Resilience Framework

Sequence of the NIAC Resilience Construct



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

Resilience Metrics are Challenging

Metrics for reliability are fairly straight forward because they involve looking at the statistics of past outages.

Standard reliability metrics include:

- System Average Interruption Duration Index (SAIDI)
- Customer Average Interruption Duration Index (CAIDI)
- System Average Interruption Frequency Index (SAIFI)

Developing metrics for resilience is extremely challenging because that involves assessing how well we are prepared for, and could deal with, very rare events, some of which have never happened.

The report recommends that DOE work on improved studies to assess the value to customers of full and partial service during long outages as a function of key circumstances.

It also calls for a coordinated assessment of the numerous resilience metrics being proposed.

Technology Opportunities to Enhance System Resilience

- Component hardening and physical security
- Distribution automation
- Better control/coordination of Distributed Energy Resources (DER)
- Enhanced modeling and simulation
- Wide area monitoring and control
- Intelligent load shedding / adaptive islanding
- System architectural considerations to reduce criticality of individual components
- Reducing dependency on supporting infrastructures
- Cyber resiliency

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

Thank you