What every power system engineer needs to know about August 10, 1996 and August 14, 2003: Sequence of events, root causes, and lessons learned

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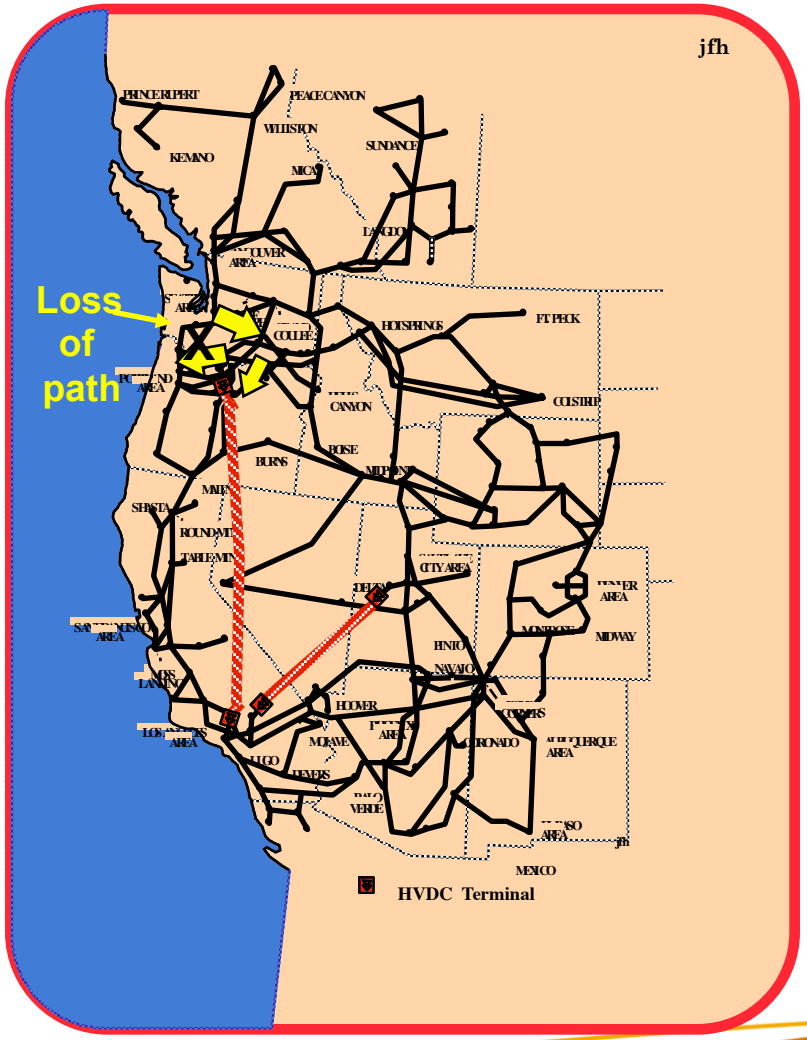
Major North American Blackouts

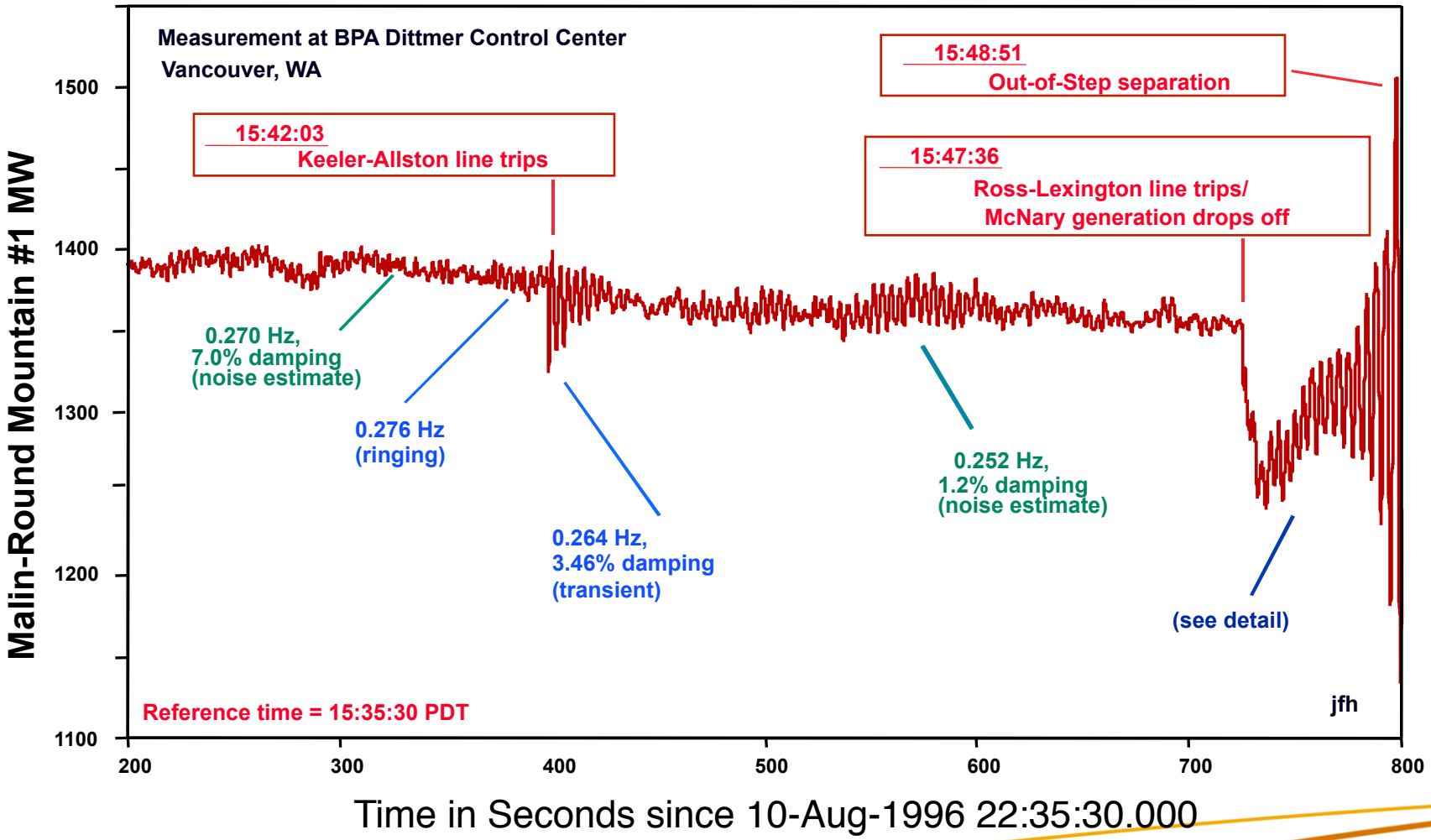
Date	Location	Load Interrupted
November 9, 1965	Northeast	20,000 MW
July 13, 1977	New York	6,000 MW
December 22, 1982	West Coast	12,350 MW
January 17, 1994	California	7,500 MW
December 14, 1994	Wyoming, Idaho	9,336 MW
July 2, 1996	Wyoming, Idaho	11,743 MW
August 10, 1996	Western Interconnection	30,489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

Case Study #1: August 10, 1996

- 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



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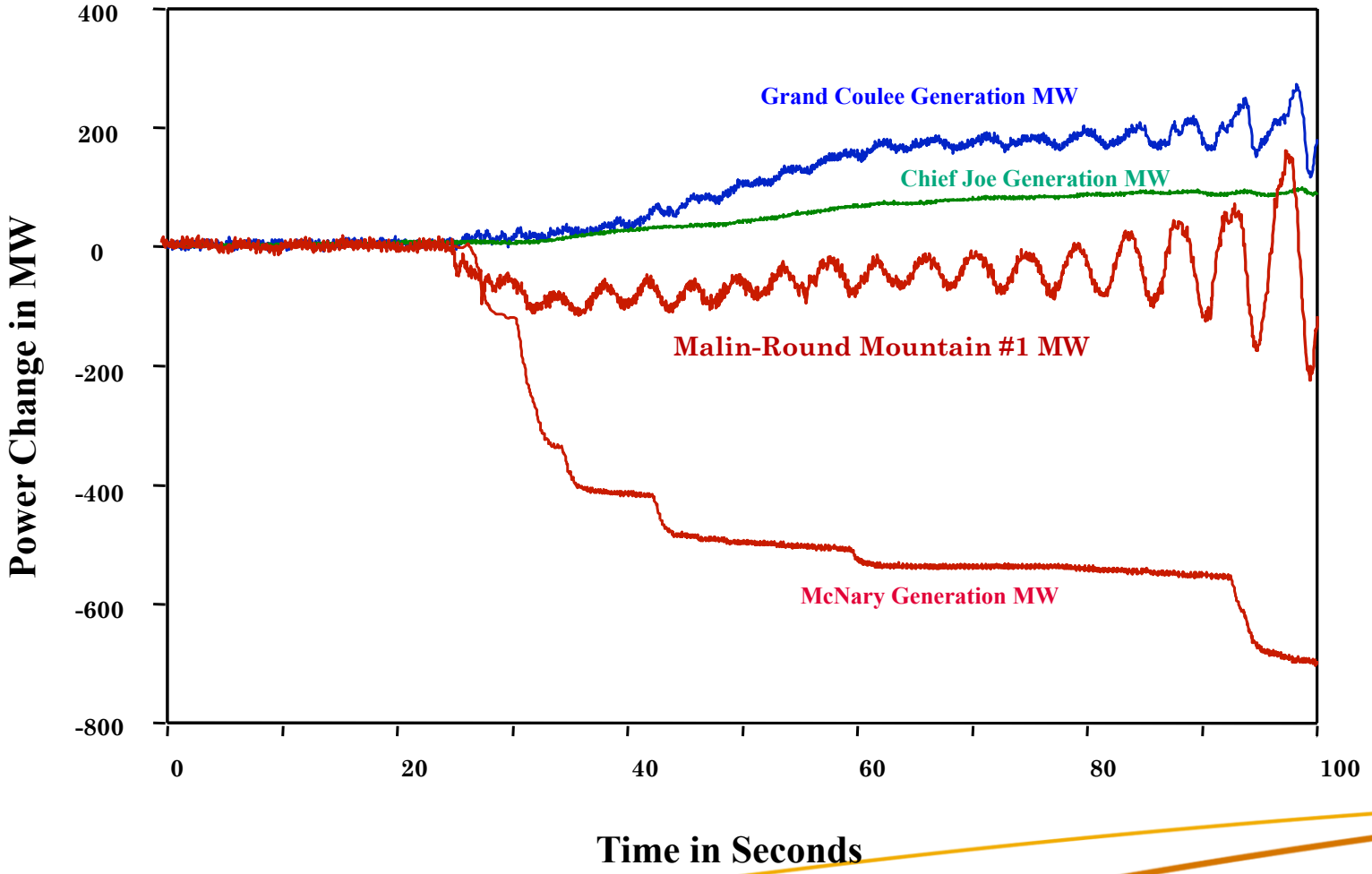
Generator Response:
Loss of McNary units critical factor



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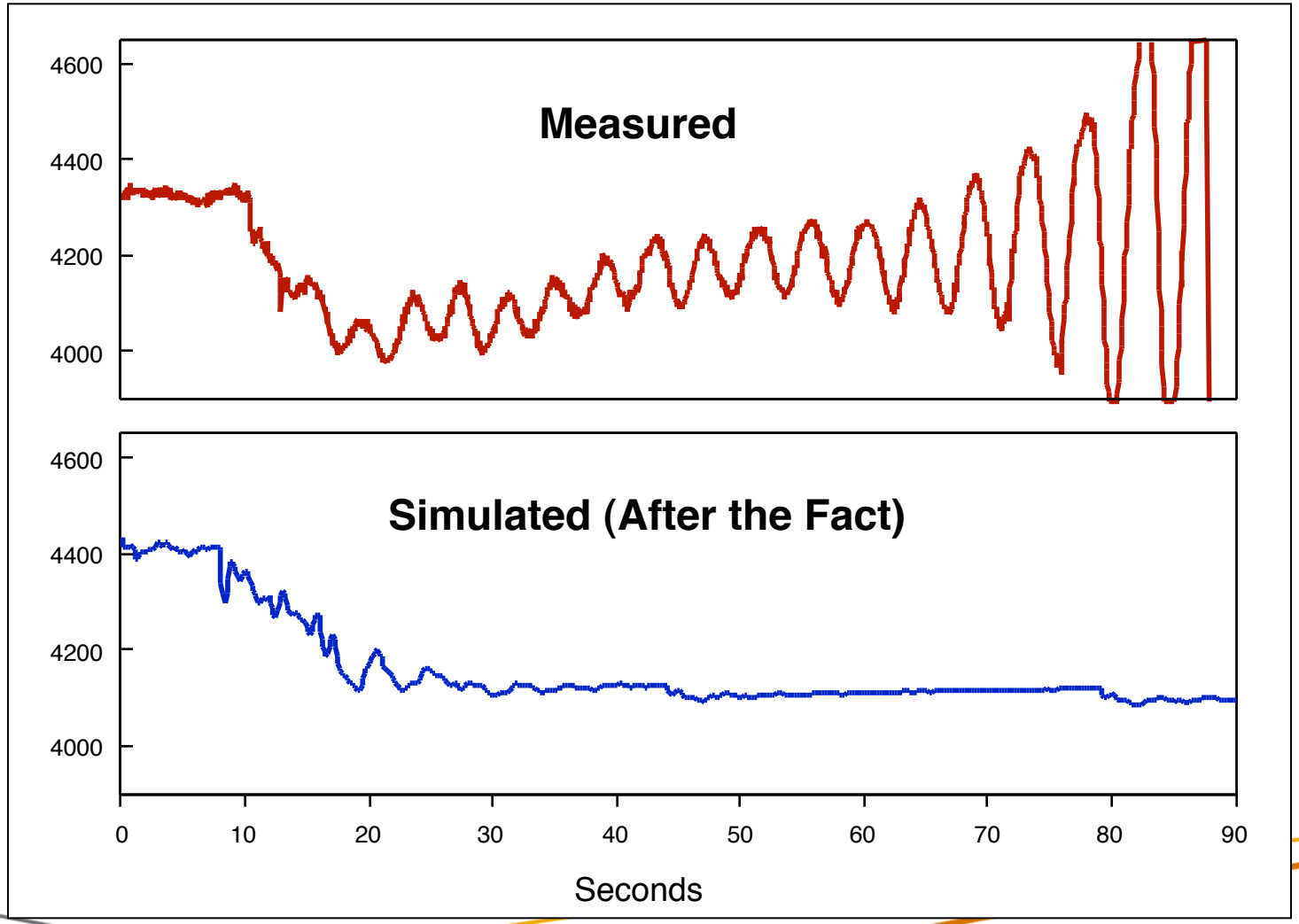
Blackout Investigation Findings

- 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
- Breakup caused significant generation loss

Lesson Learned: Modeling Errors



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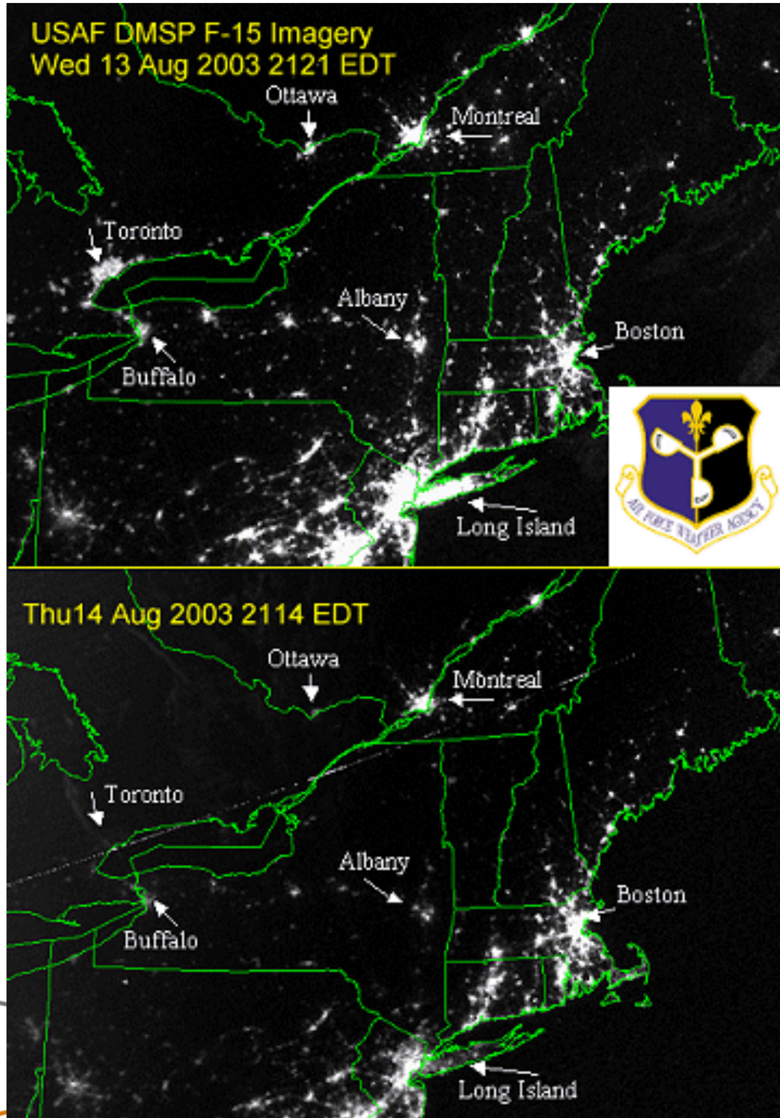
Case Study #2: August 14, 2003

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LATE SPORTS

NFL preseason

'One good day' at the PGA

Mickelson shares lead, takes aim at his 1st major

USA TODAY

NO. 1 IN THE USA

Married – with cameras

MTV moves in with pop newlyweds Simpson & Lachey

What's next for Mr. Vick?

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

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

USA TODAY Snapshots

Outage spawns rush-hour chaos from Detroit eastward

More annoyance than angst in NYC, despite early fears

Exodus recalls images of 9/11

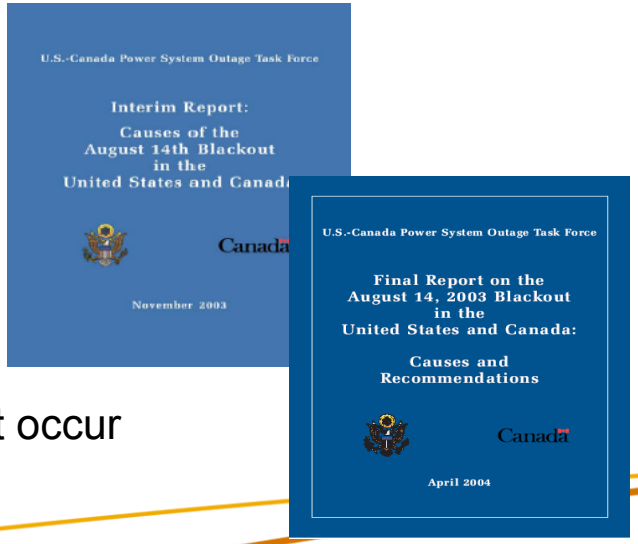
Cover story

August 14, 2003 Blackout Investigation

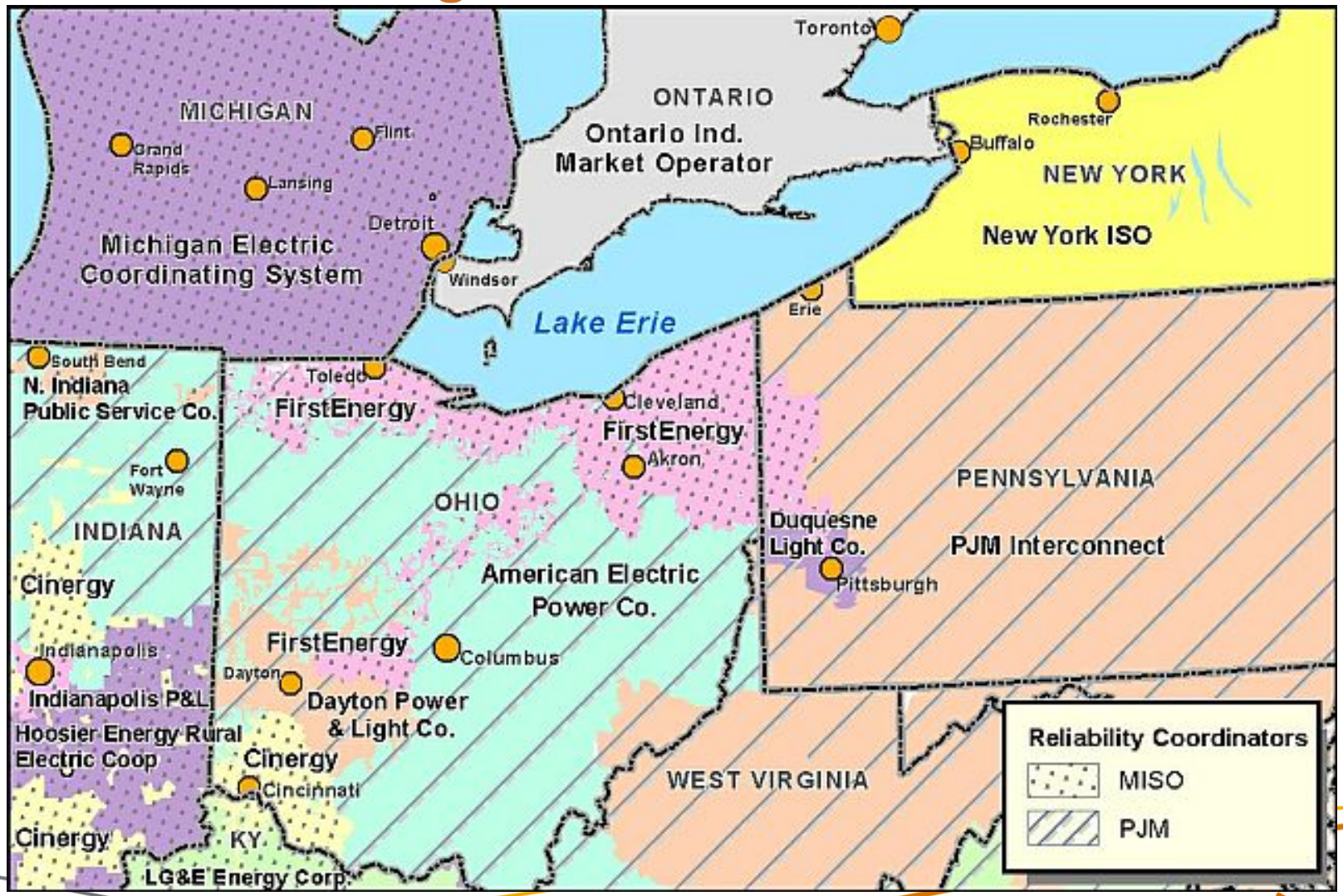
Joint U.S. - Canada Power System Outage Task Force

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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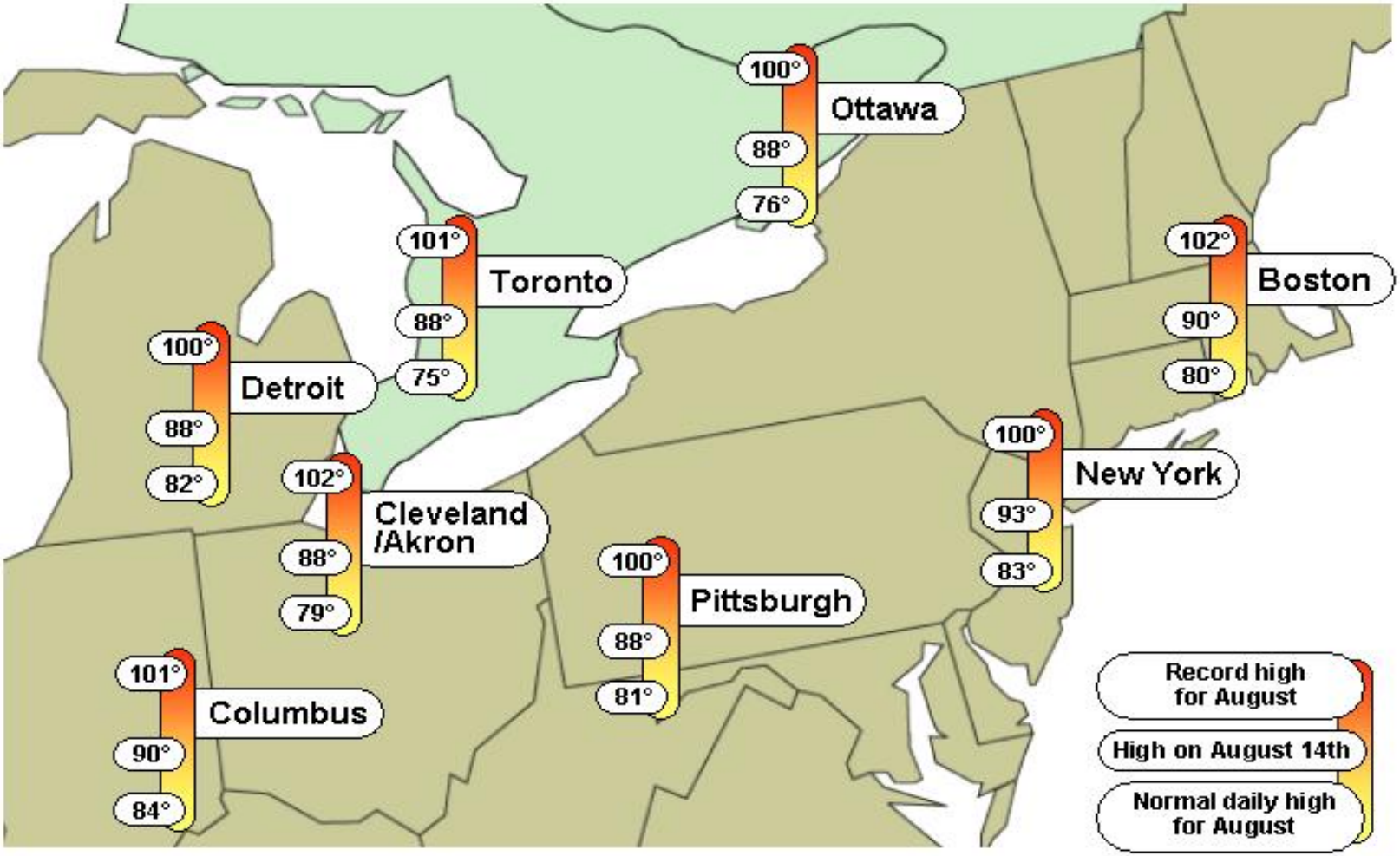
August 14 Conditions Prior to Blackout

- 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



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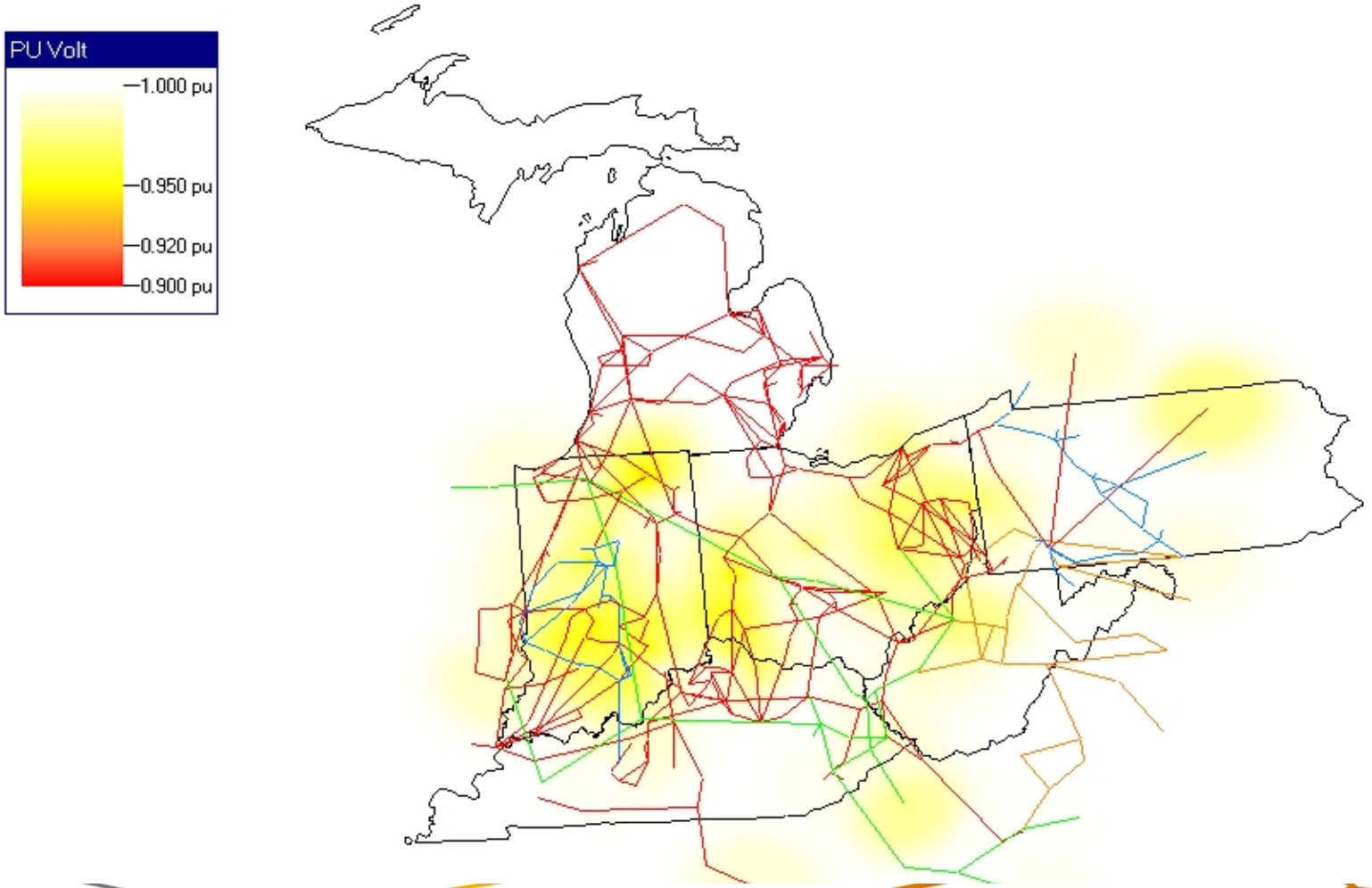
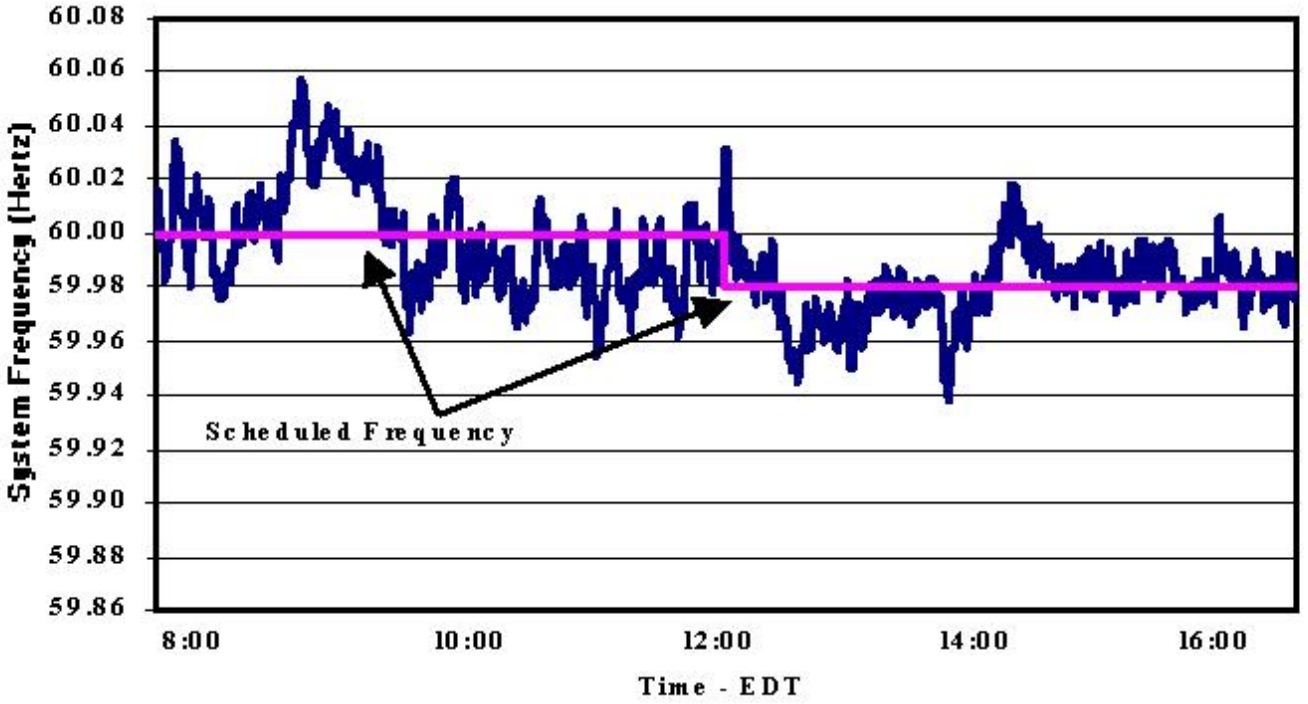
Voltages Prior to 3:05 pm - Low But Within Limits



Frequency – Nothing Unusual



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1:31:34pm – Eastlake Unit 5 Trips

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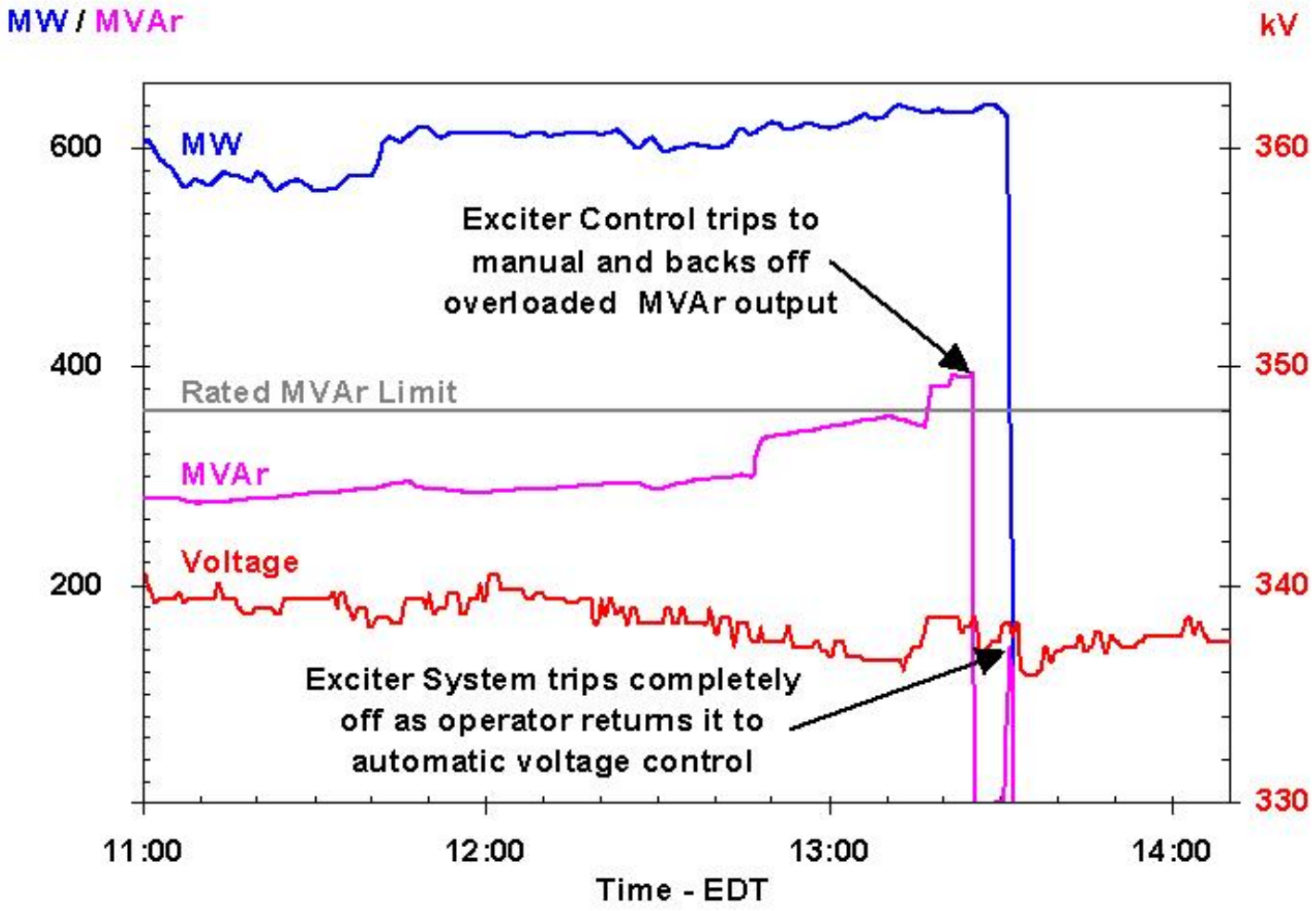
East Lake 5 Exciter Failure Causes Trip



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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)

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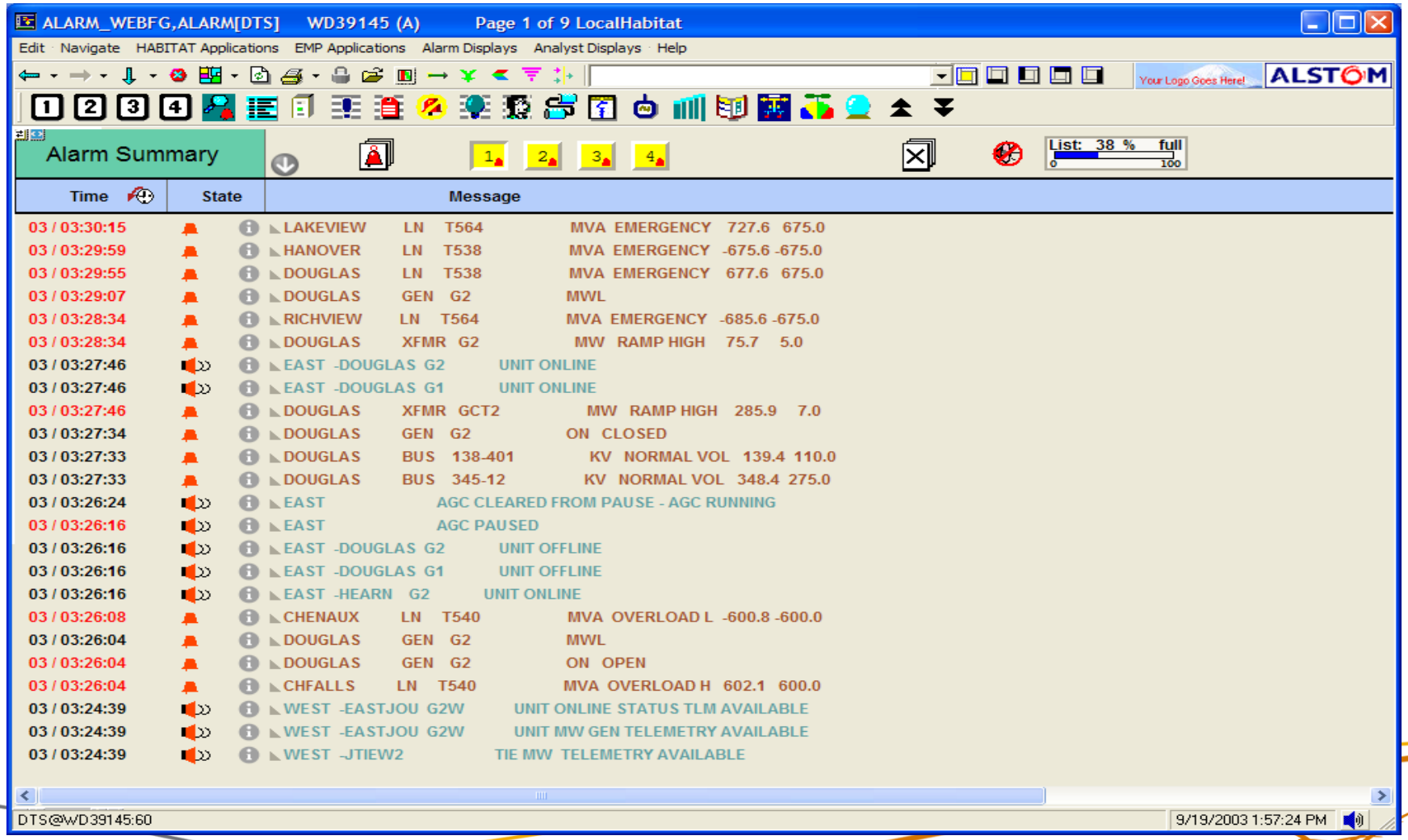
FirstEnergy (FE) Computer Failures

- 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

What a typical EMS alarm processor looks like
(Note: This example is *NOT* associated with the 2003 blackout in any way)



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

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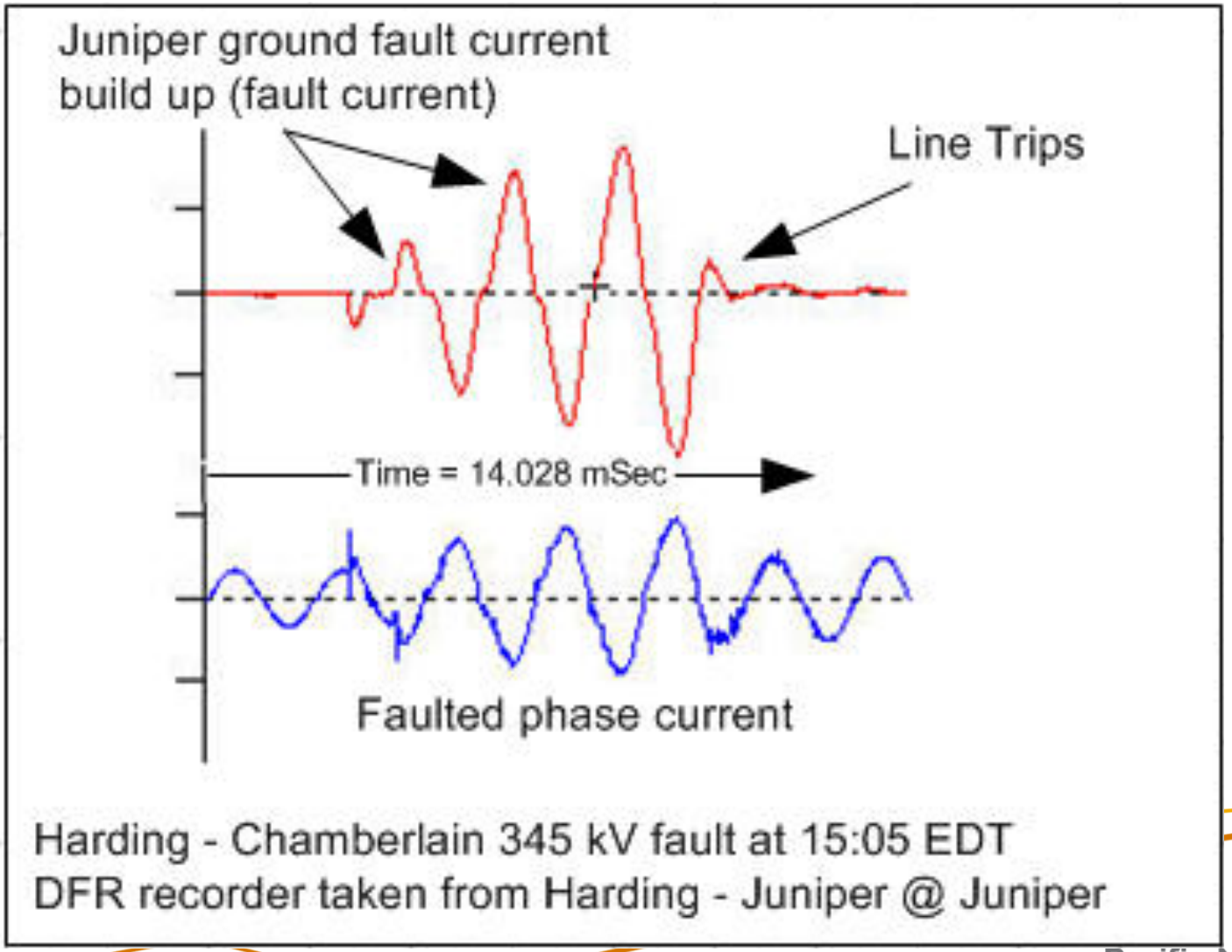
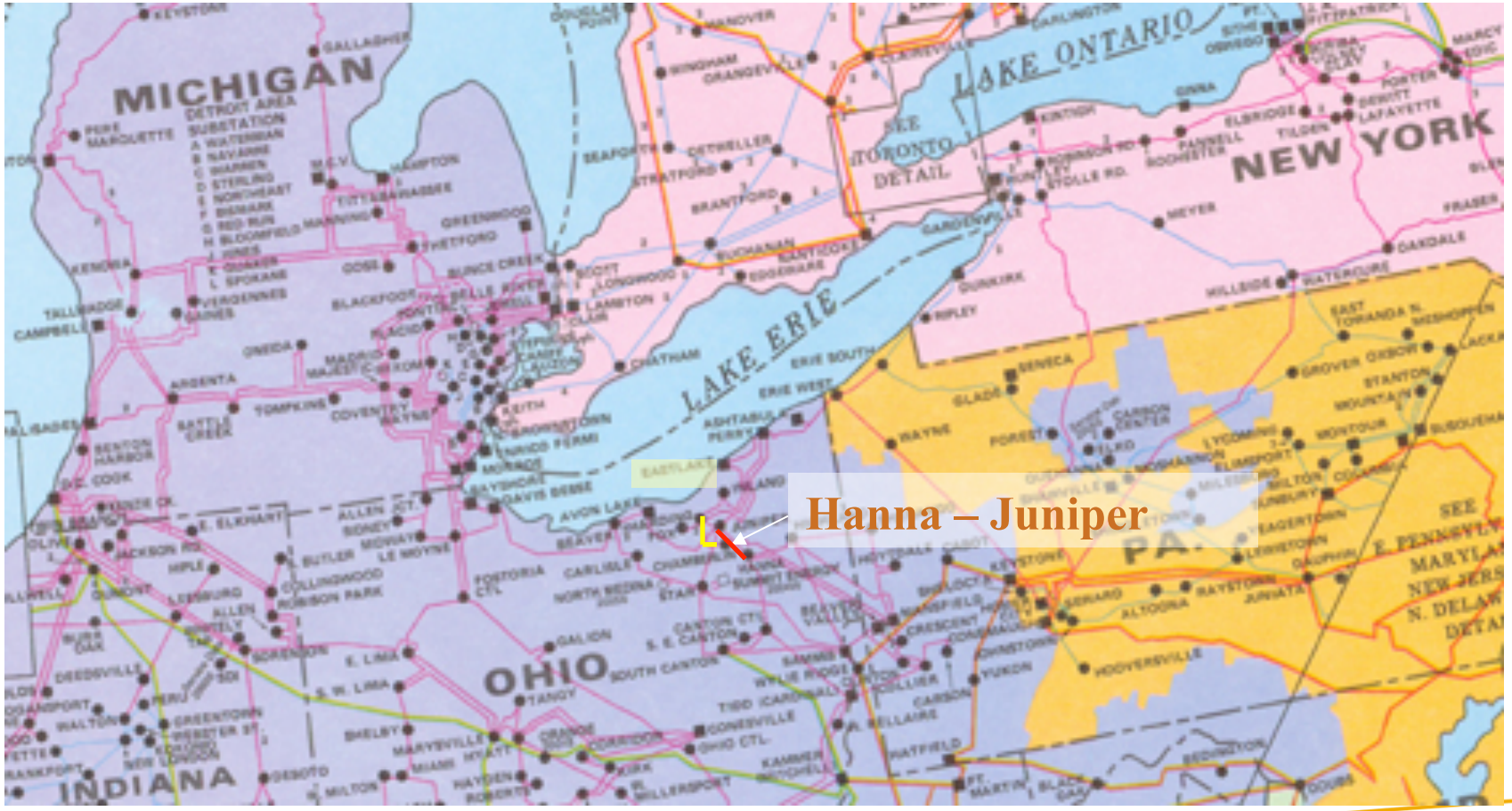
Chamberlain-Harding Ground Fault due to Tree Contact as Measured by Digital Fault Recorder



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

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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

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

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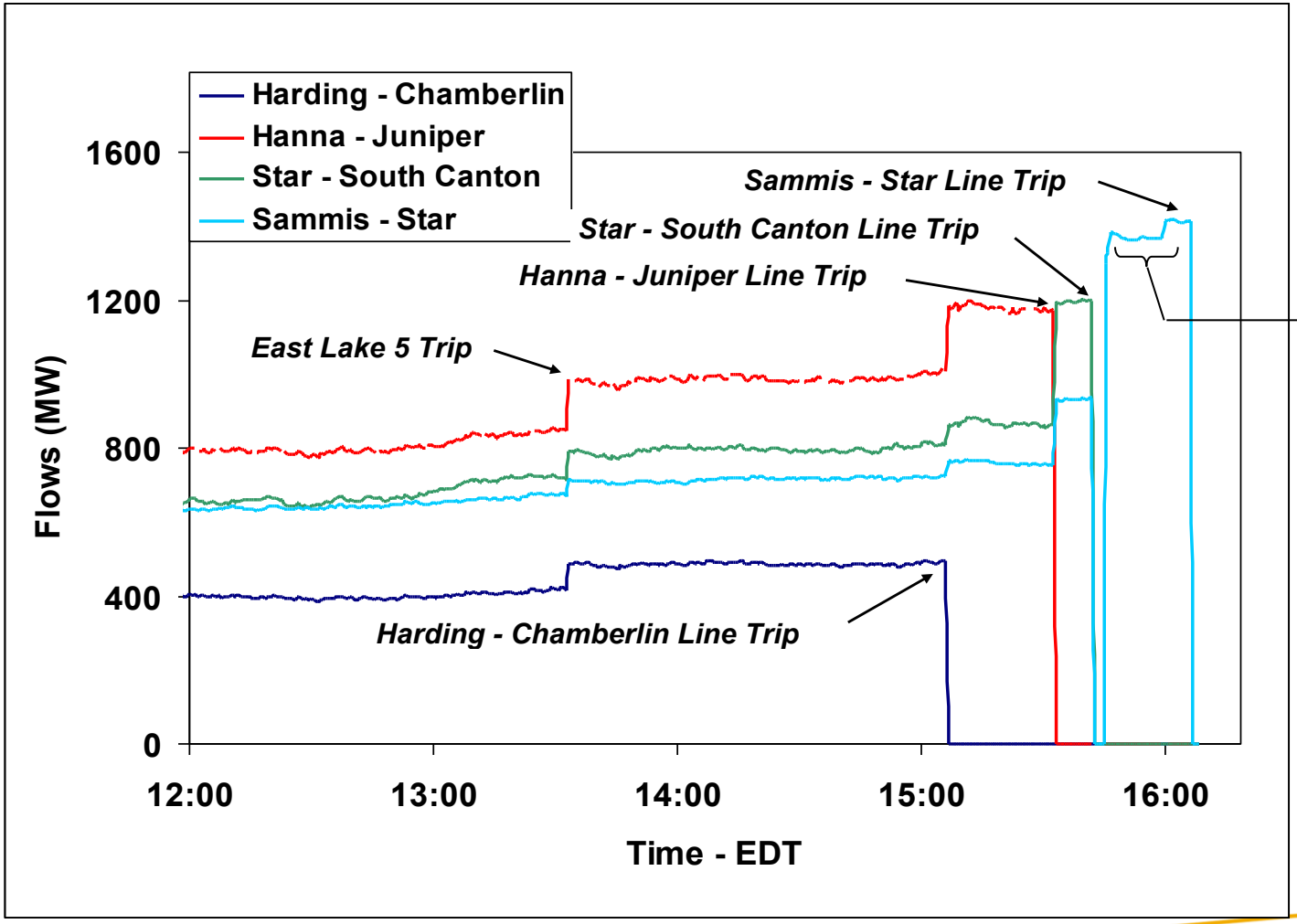
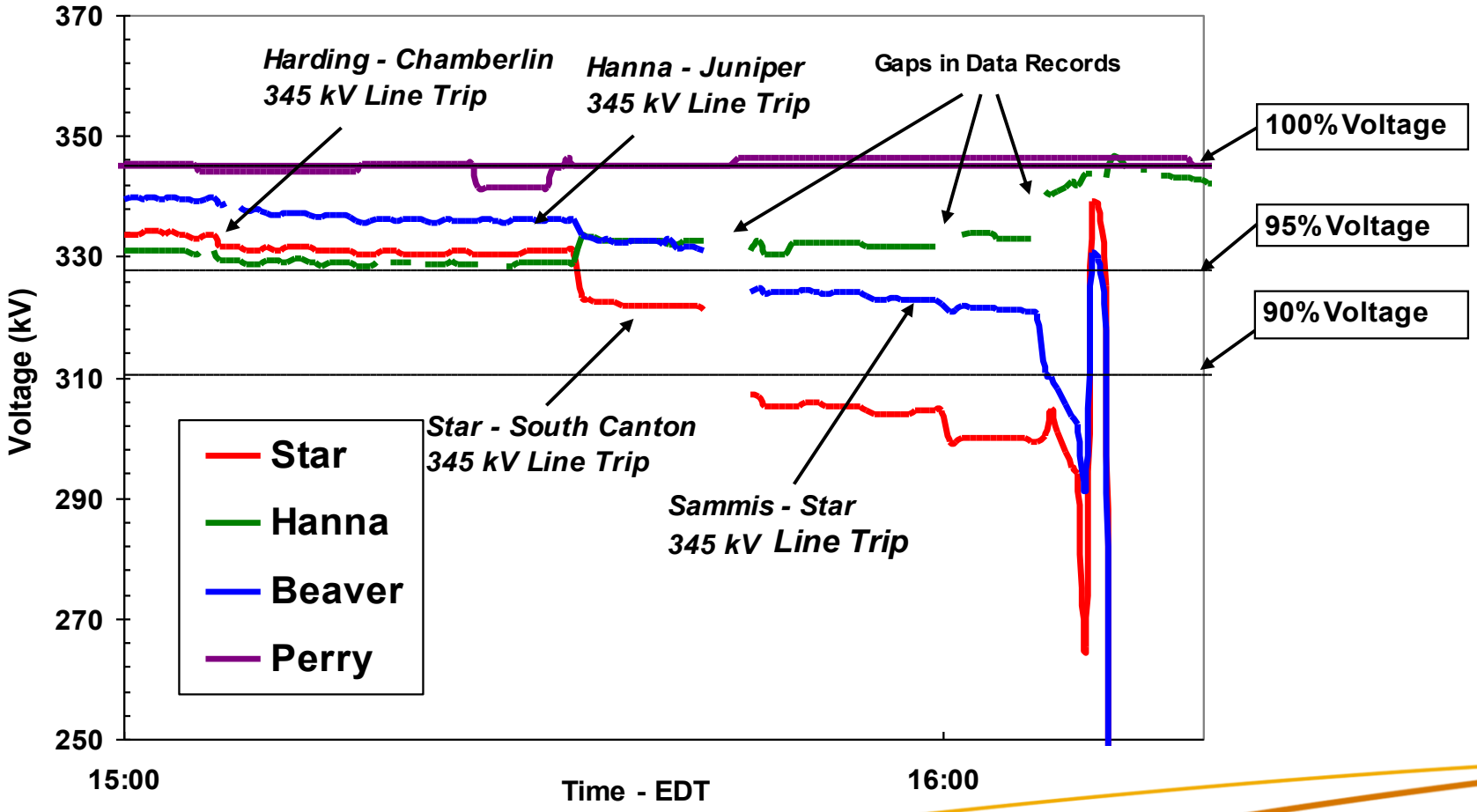
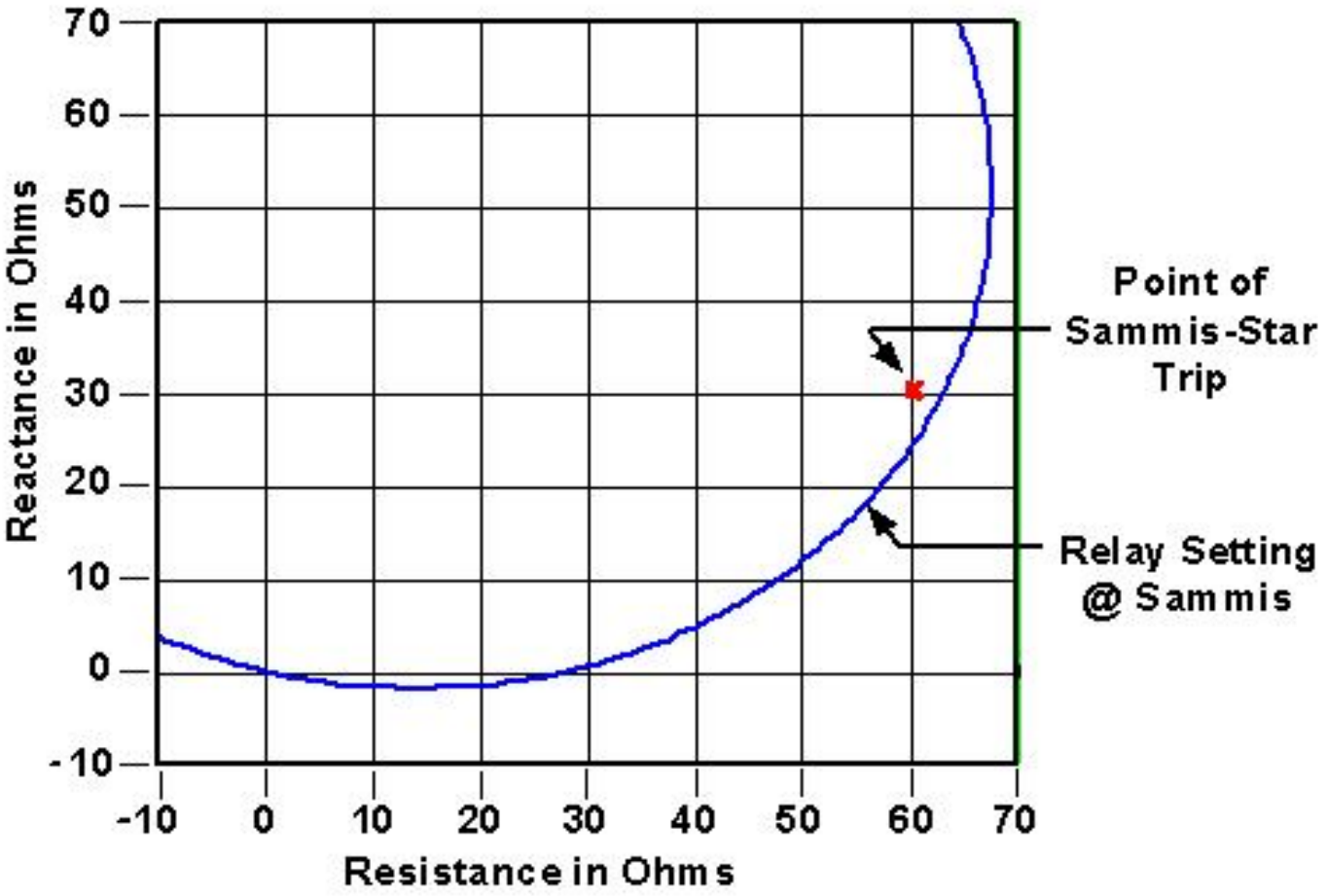
Loading on Critical Lines



Key Voltages



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

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

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

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

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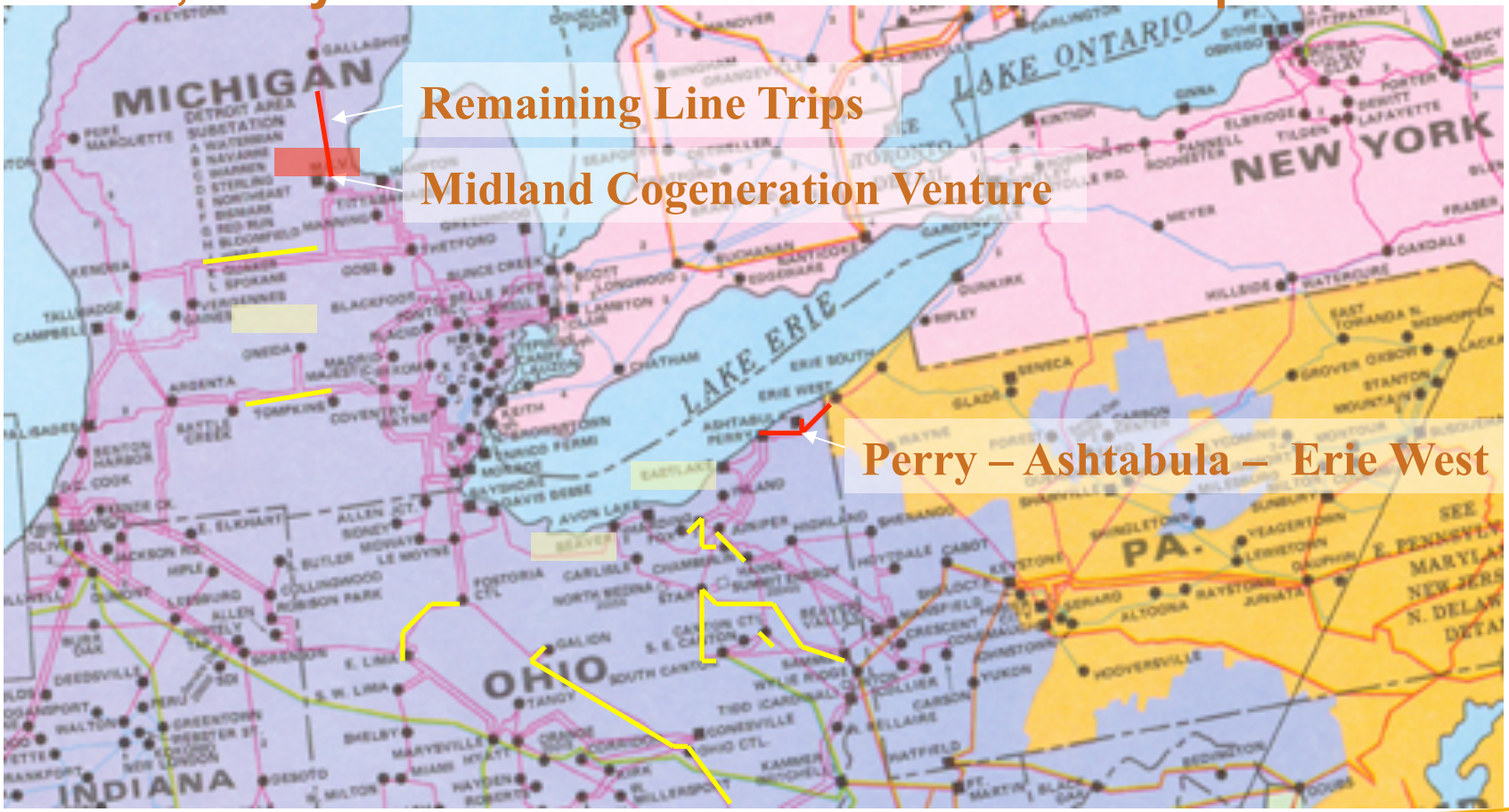
4:10:38pm - Midland Cogeneration Venture unit trip (loaded to 1265 MW), Transmission system separates northwest of Detroit, Perry-Ashtabula-Erie West 345 kV line trip



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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

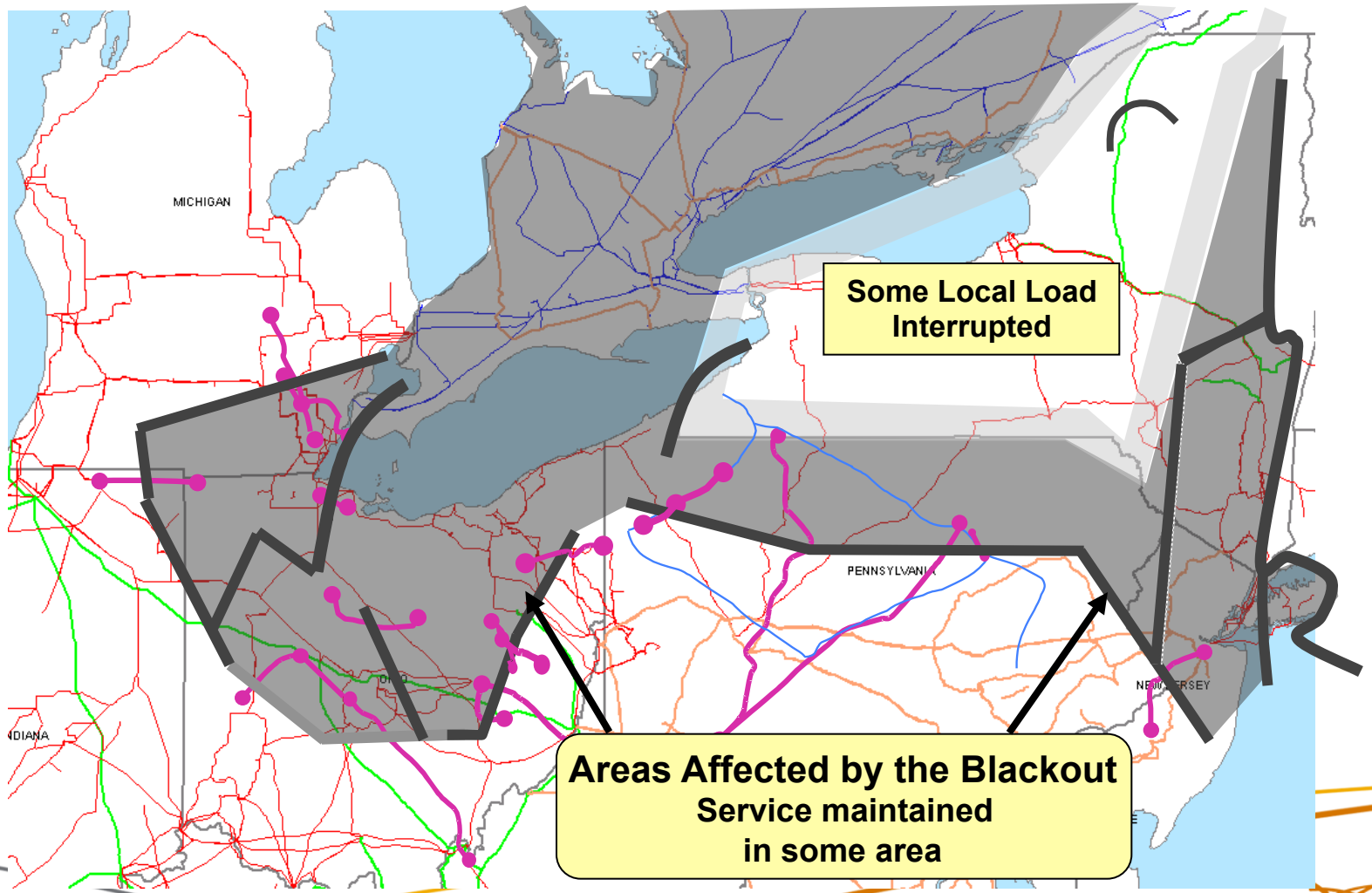
4:10:41pm
Fostoria Central-Galion 345 kV line trip
Perry 1 nuclear unit trip (rated 1252 MW)
Avon Lake 9 unit trip (rated 616 MW)
Beaver-Davis Besse 345 kV line trip

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

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



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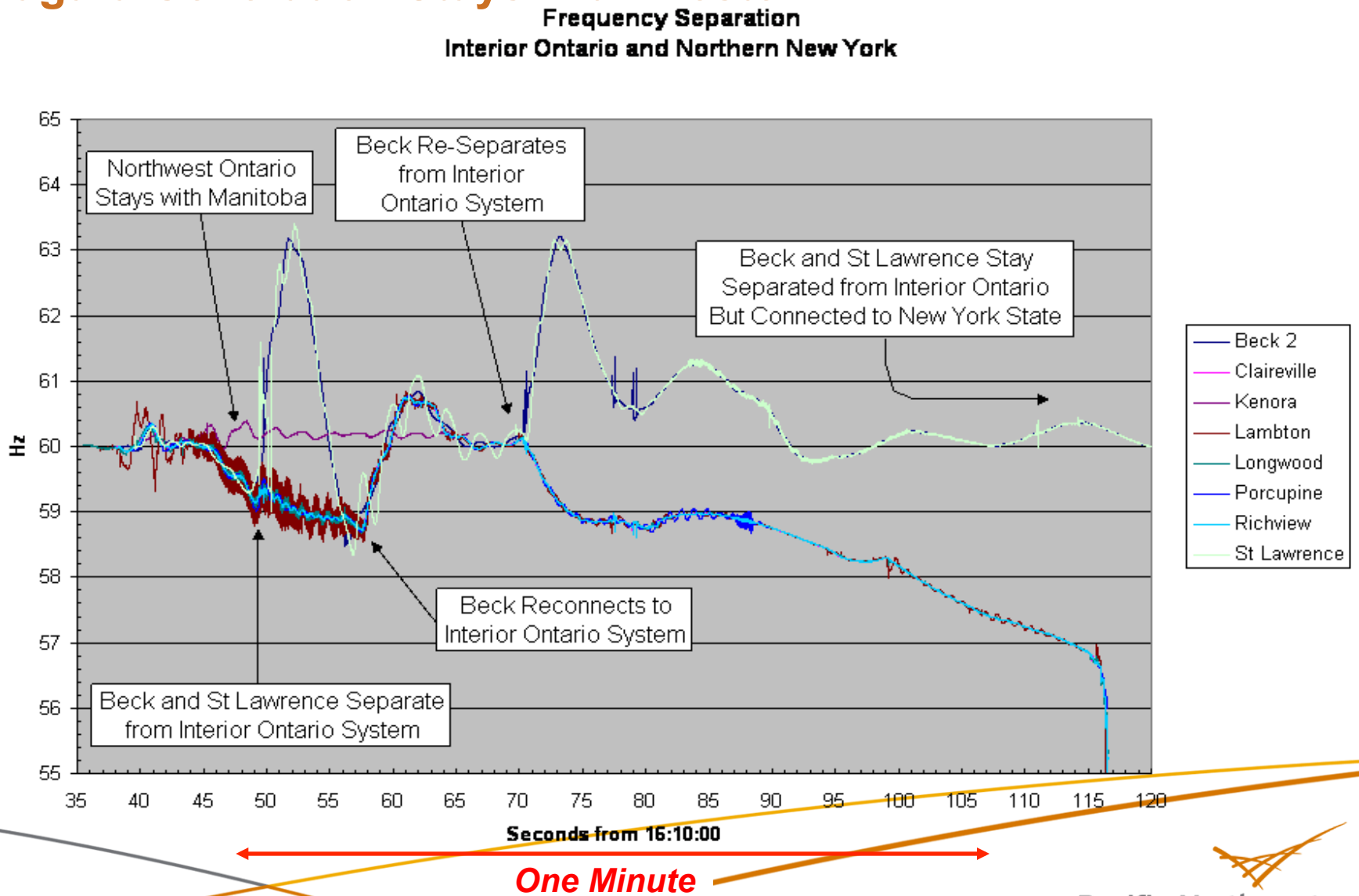
Frequency in Ontario and New York during Breakup
Niagara Generation Stays with Western NY



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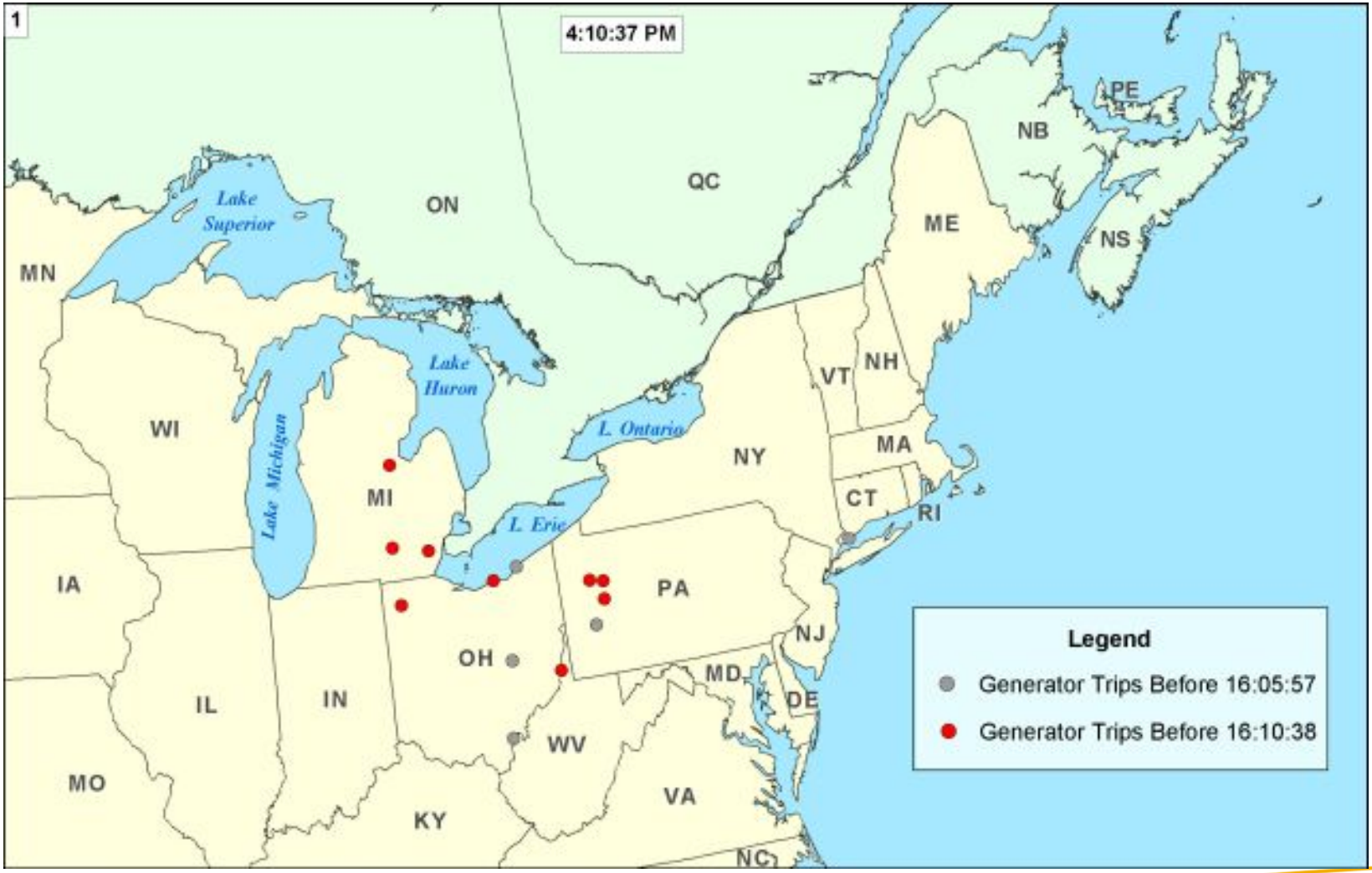
Generator Trips to 4:10:38pm



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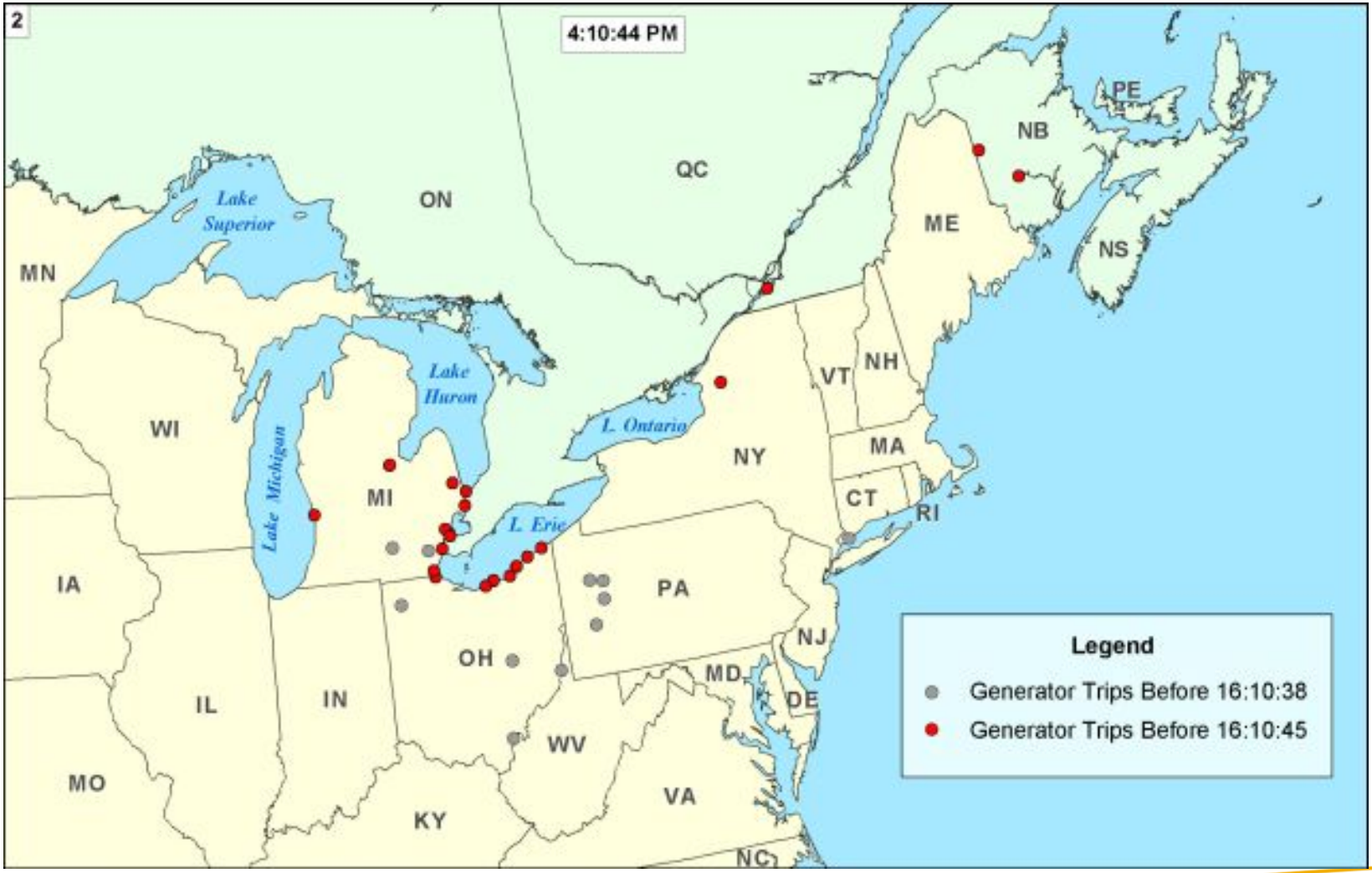
Generator Trips – Next 7 Seconds



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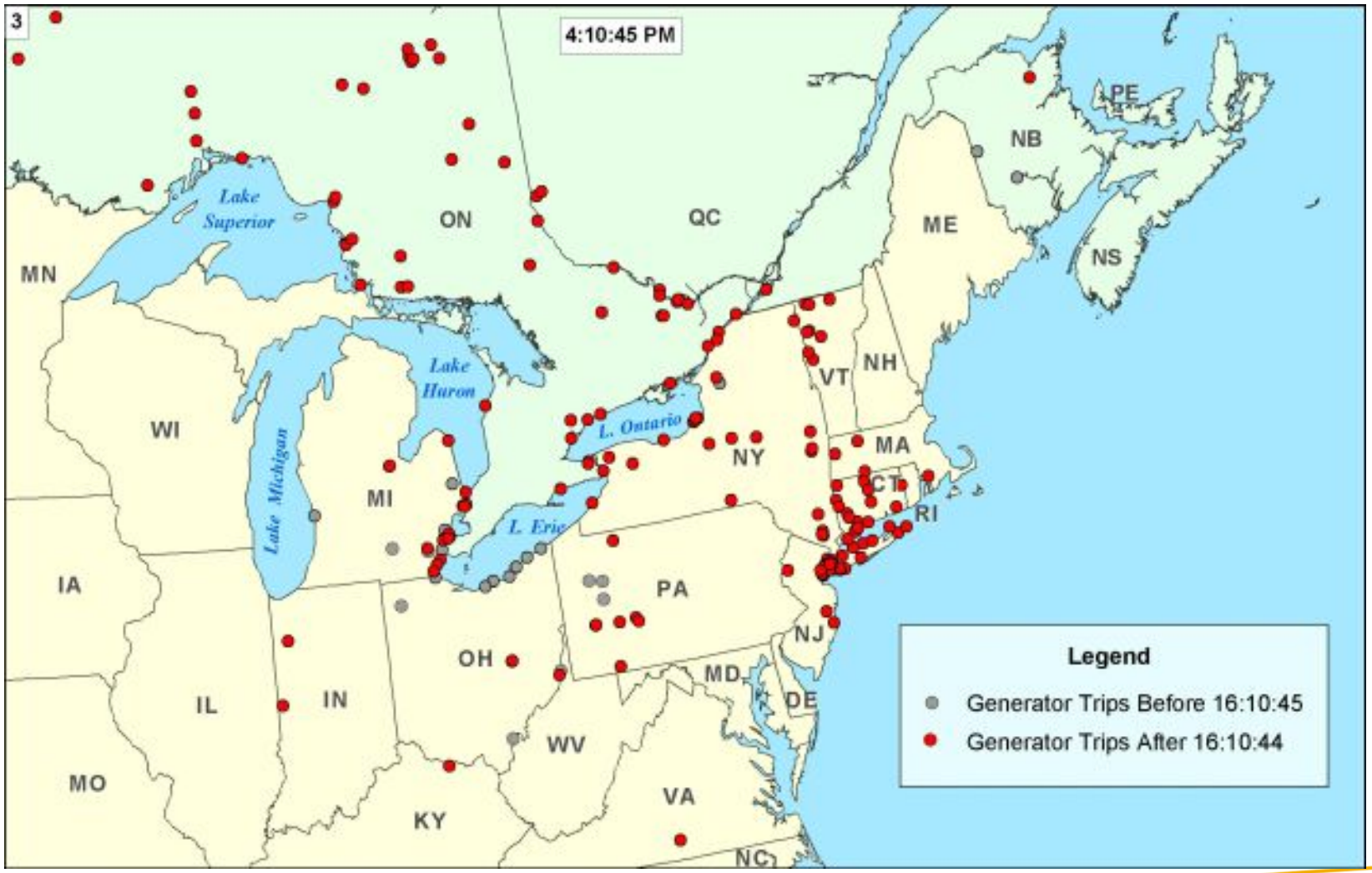
Generator Trips – After 4:10:44pm



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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

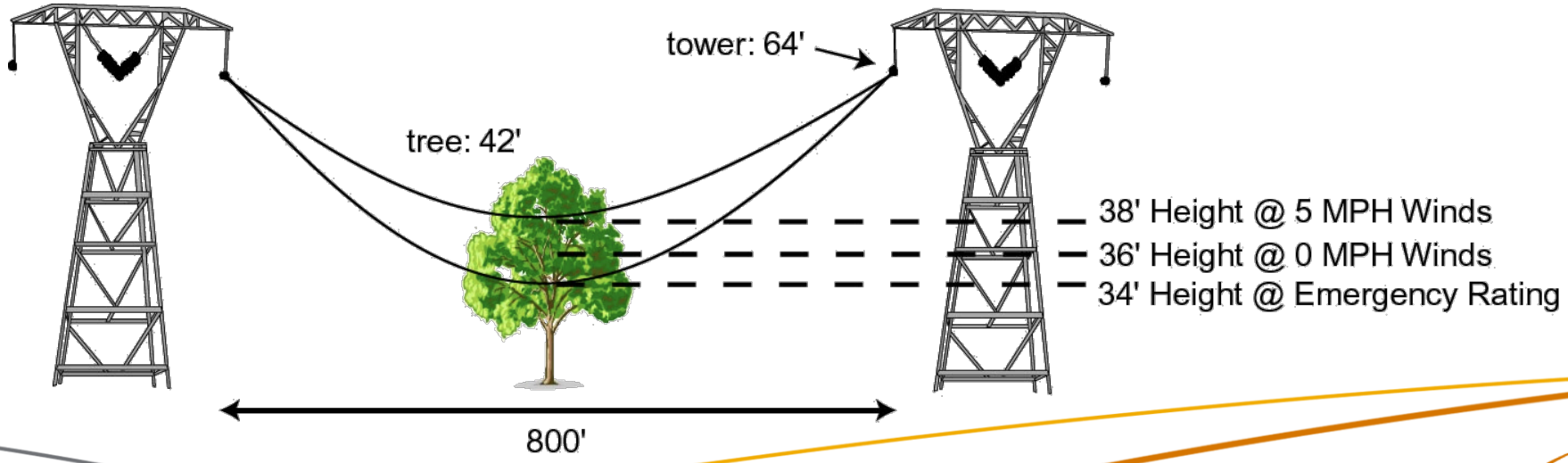
Blackout Root Cause Finding #2
Lack of Situational Awareness by FirstEnergy Operators

- 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

- 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



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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 was NOT Caused by

- Heavy wide-area transfers
- Low voltages, voltage collapse
- Lack of voltage/reactive support from generators
- Frequency anomalies
- Cinergy outages starting at 12:08
- East Lake 5 trip at 13:31
  - Contributing factor to later events, but not by itself causal to the blackout
- Dayton Power & Light Stuart-Atlanta trip at 14:02
  - Contributing factor to loss of MISO real-time monitoring, but not electrically significant

Blackout Investigation Task Force Recommendations

- 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

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 good 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

Suddenly, knowing a lot about the U.S. power grid became sexy at cocktail parties.