The Role of Software in the August 14, 2003 Blackout and Subsequent Investigation

Second Carnegie Mellon Conference in
Electric Power Systems:
Monitoring, Sensing, Software and Its Valuation for the Changing Electric Power Industry
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Carnegie Mellon University

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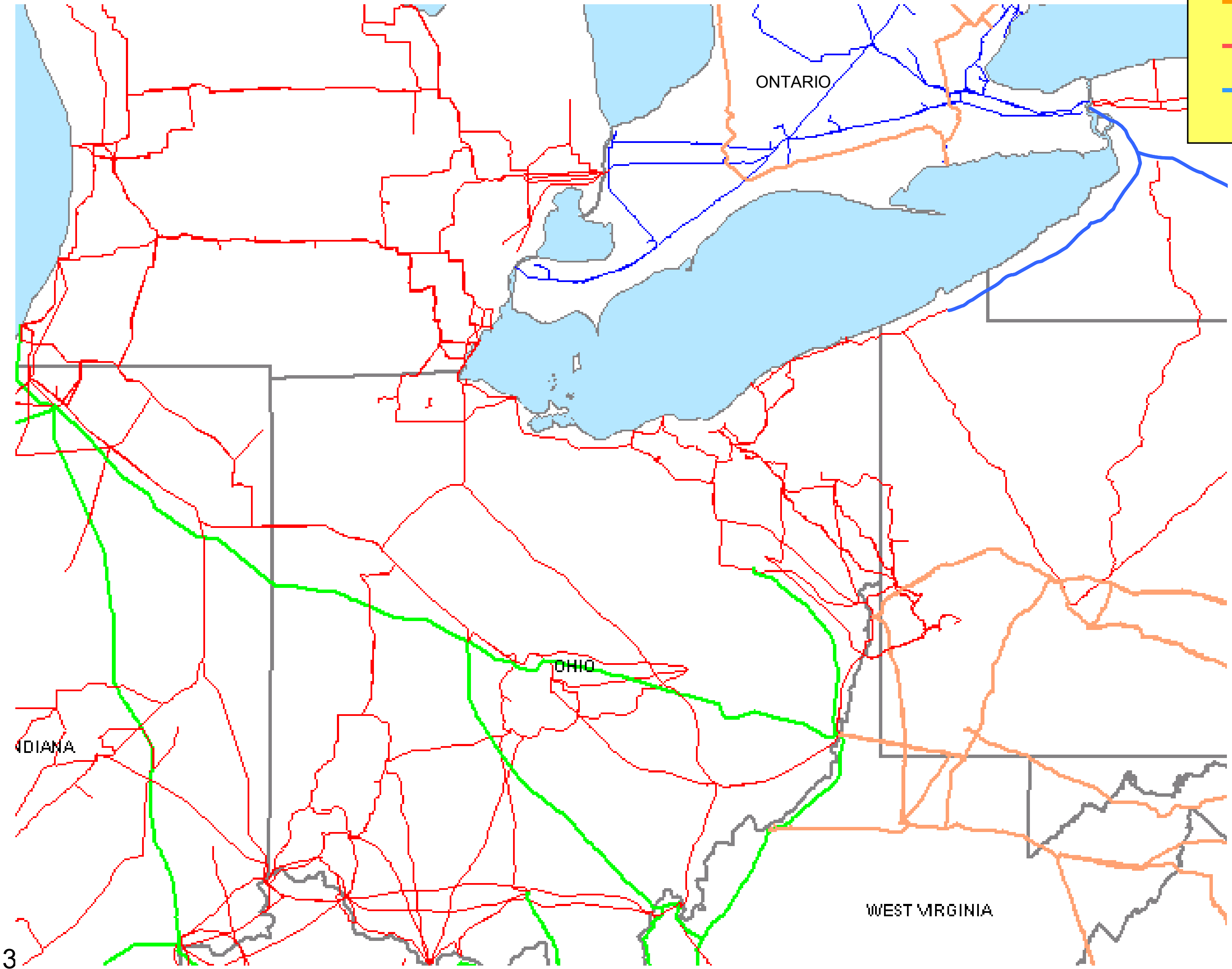
Summary of August 14 Blackout

- **Impacts**
  - 8 states/2 provinces
  - Over 50 million people
  - 60-65,000 MW
  - 96+ hours to restore
  - Manufacturing disrupted
  - 531 generators tripped
    - 19 nuclear generators at 10 plants

- **Statistics**
  - Line trips began at 3:05 PM
  - Cascading began at 4:06 PM
  - Instability began at 4:10:37 PM
    - Lasted approximately 12 seconds
  - Thousands of discrete events

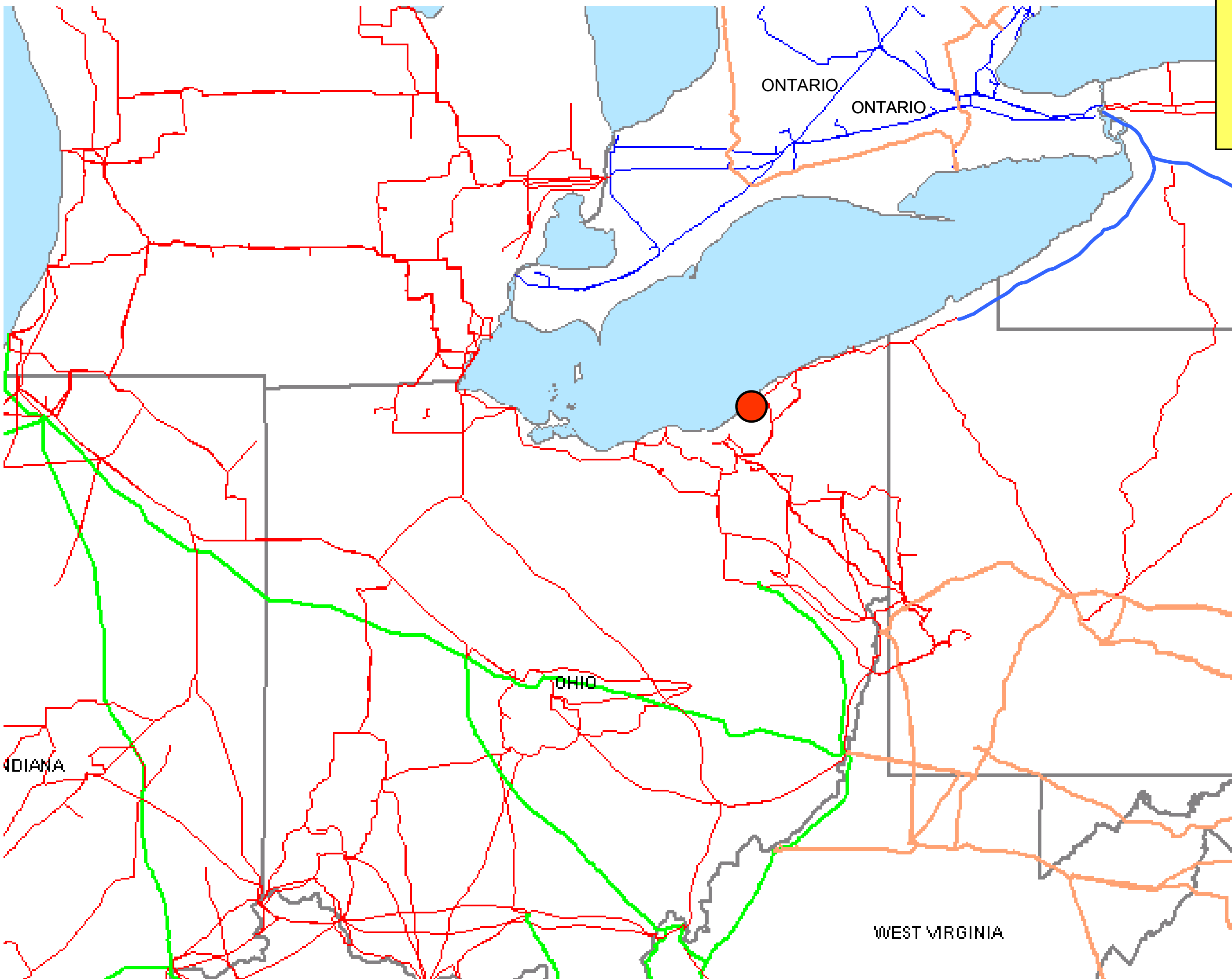
Outage Sequence of Events Transmission Map Key



Transmission Lines

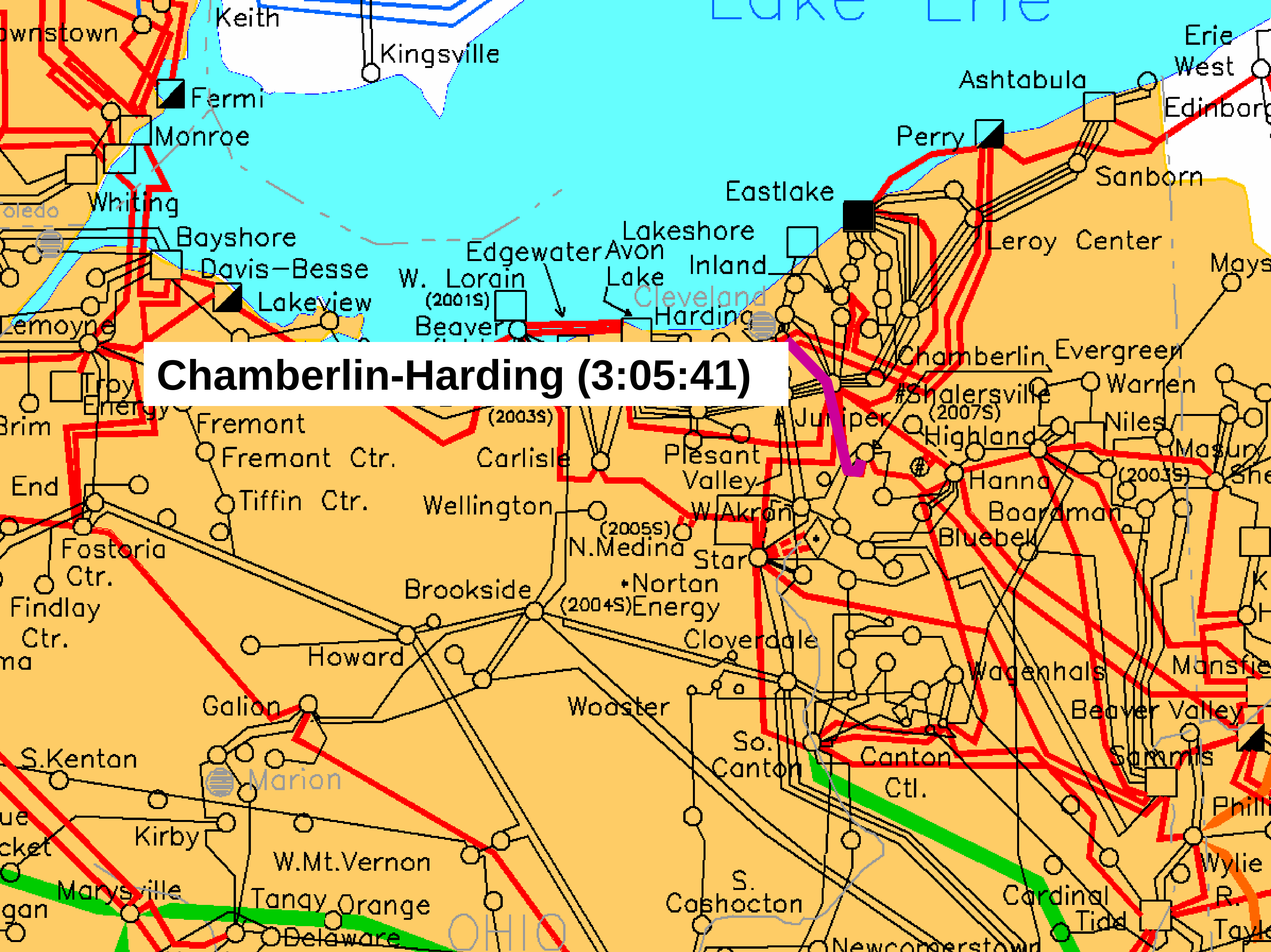
- 765 kV
- 500 kV
- 345 kV
- 230 kV

East Lake #5 Generator Trip: 1:31:34 PM



Power System High Level Sequence

- Premature failure of three 345 kV lines
  - starting at 3:05 PM, three 345 kV line outages within 36 minutes due to tree branches under conductors
- Northern Ohio 138kV cascade began
  - started 3:39 PM - caused by above premature failures
- Northern Ohio 345kV high speed cascade of overloaded lines 4:05:57 - 4:09:07 PM
  - accelerated by Zone 3 directional distance relays
- Eastern Interconnection Separates by 4:11PM


Chamberlin-Harding (3:05:41)
Lake Erie
Keith
Kingsville
Fermi
Monroe
Whiting
Toledo
Bayshore
Davis-Besse
Lakeview
Lemoyne
Troy
Energy
Fremont
Fremont Ctr.
Tiffin Ctr.
Fostoria Ctr.
Findlay Ctr.
End
W. Lorain
(2001S)
Beaver
Edgewater
Avon Lake
Lakeshore
Inland
Cleveland
Harding
Eastlake
Perry
Ashtabula
Erie West
Edinboro
Sanborn
Leroy Center
Mays
Chamberlin
Evergreen
Shalersville
(2007S)
Warren
Juniper
Highland
Niles
Masury
(2003S)
Carlisle
Plesant Valley
W. Akron
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Bluebell
Wellington
(2005S)
N.Medina
Star
Norton Energy
(2004S)
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Galion
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Beaver Valley
So. Canton
Canton Ctl.
Sammis
S.Kenton
Marion
Kirby
W.Mt.Vernon
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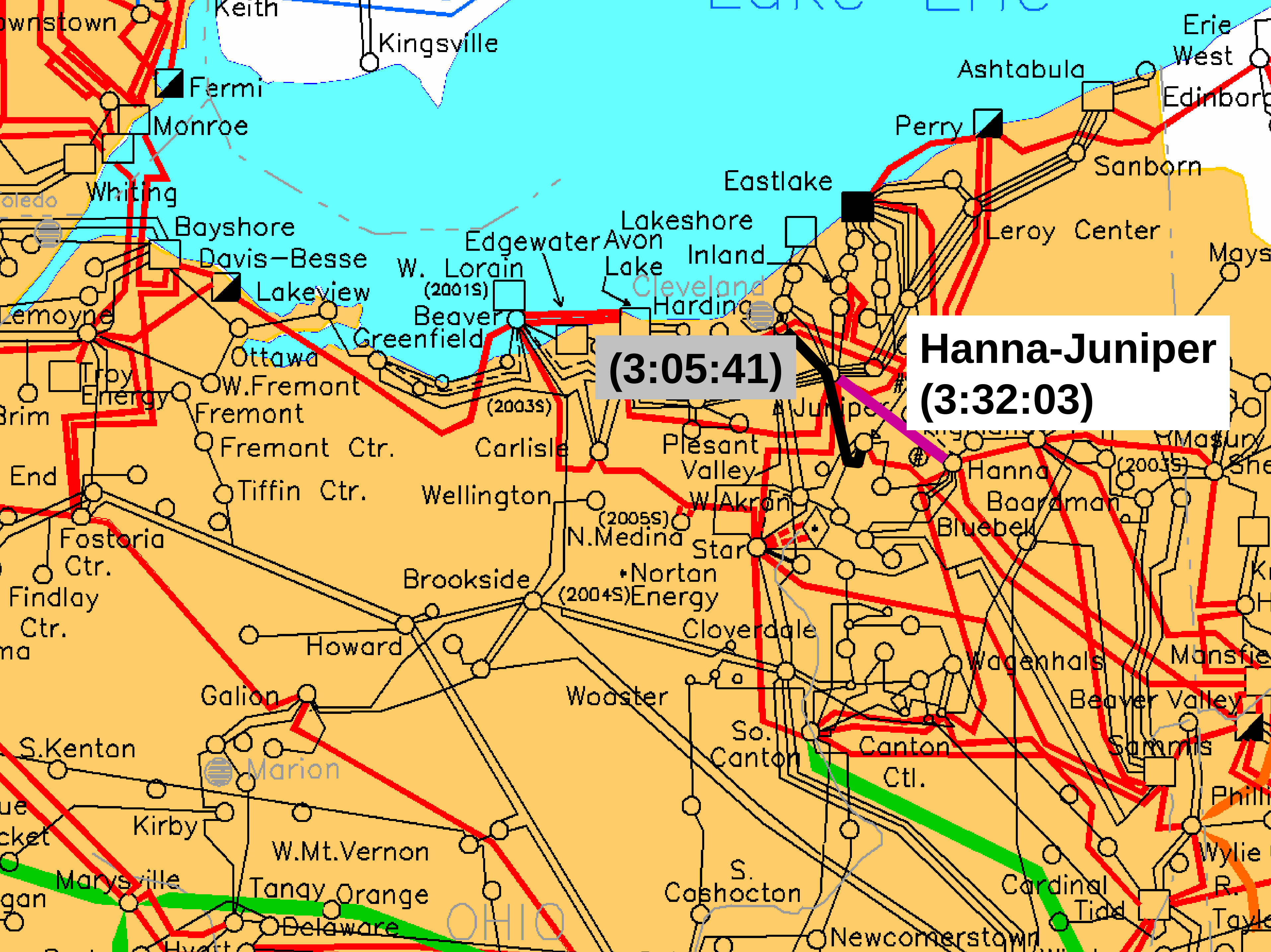
S. Coshocton
Cardinal
Tidd
Newcomerstown
Wylie
Phill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Bayshore
Davis–Besse
Edgewater
Avon Lake
Inland
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(2001S)
Cleveland
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Beaver
Harding
Lemoyne
Greenfield
(3:05:41)
Hanna-Juniper
(3:32:03)
Ottawa
Troy Energy
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(2003S)
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Carlisle
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End
Tiffin Ctr.
Wellington
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Bluebell
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Kirby
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Marysville
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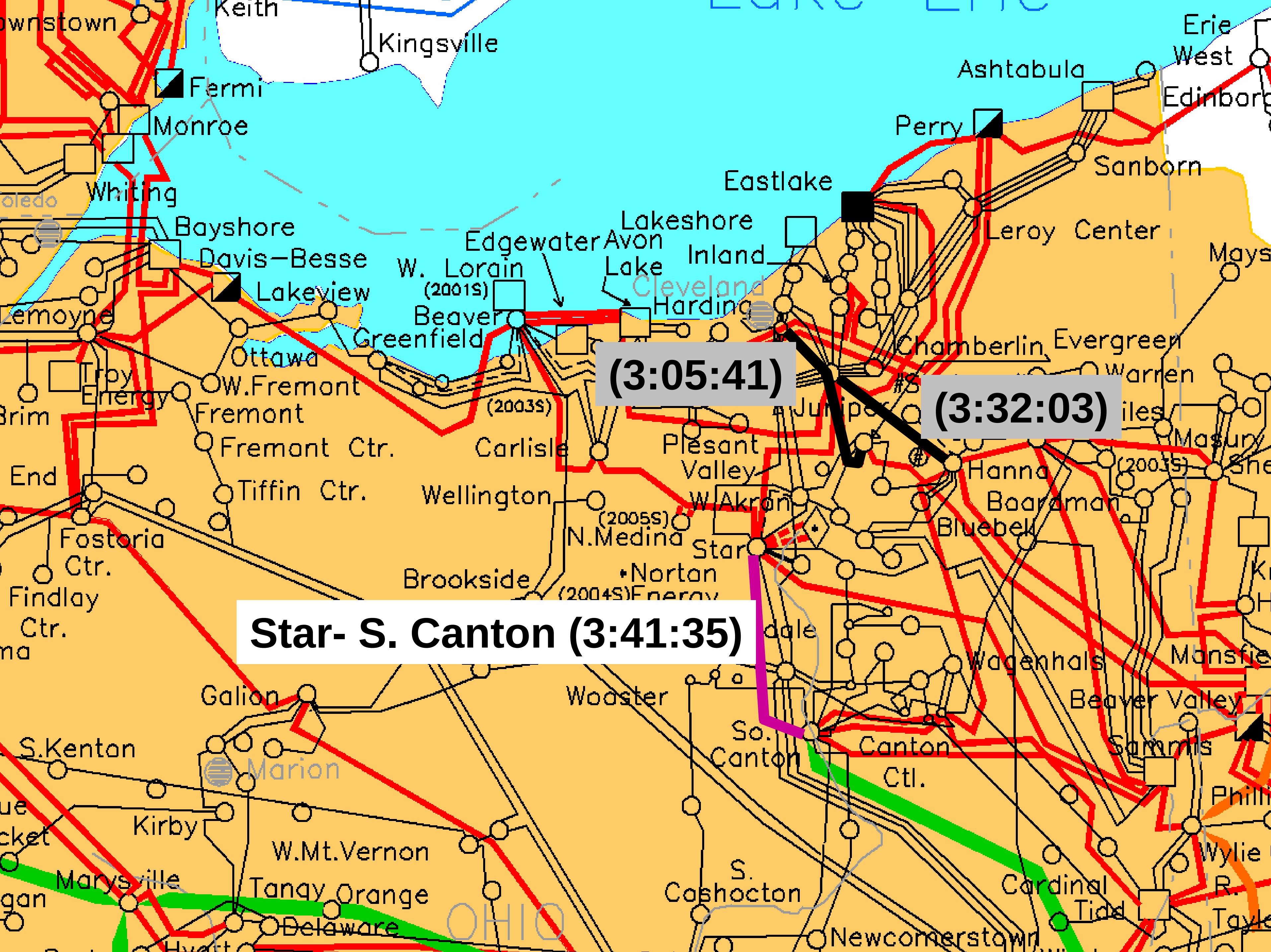
Orange
Delaware
Hyatt
OHIO
Newcomerstown



Star- S. Canton (3:41:35)
(3:05:41)
(3:32:03)
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Kingsville
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Bayshore
Davis-Besse
Lakeview
Lemoyne
Ottawa
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Energy
W.Fremont
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Fremont Ctr.
Tiffin Ctr.
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Beaver
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Cleveland
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Eastlake
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Ashtabula
Erie
West
Edinboro
Sanborn
Leroy Center
Chamberlin
Evergreen
Warren
Juniper
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(2003S)
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Carlisle
Pleasant
Valley
W.Akron
Wellington
N.Medina
Star
Norton
Energy
Brookside
Wooster
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Kirby
W.Mt.Vernon
Marysville
Tangy
Orange
Delaware
OHIO
So.
Canton
Canton
Ctl.
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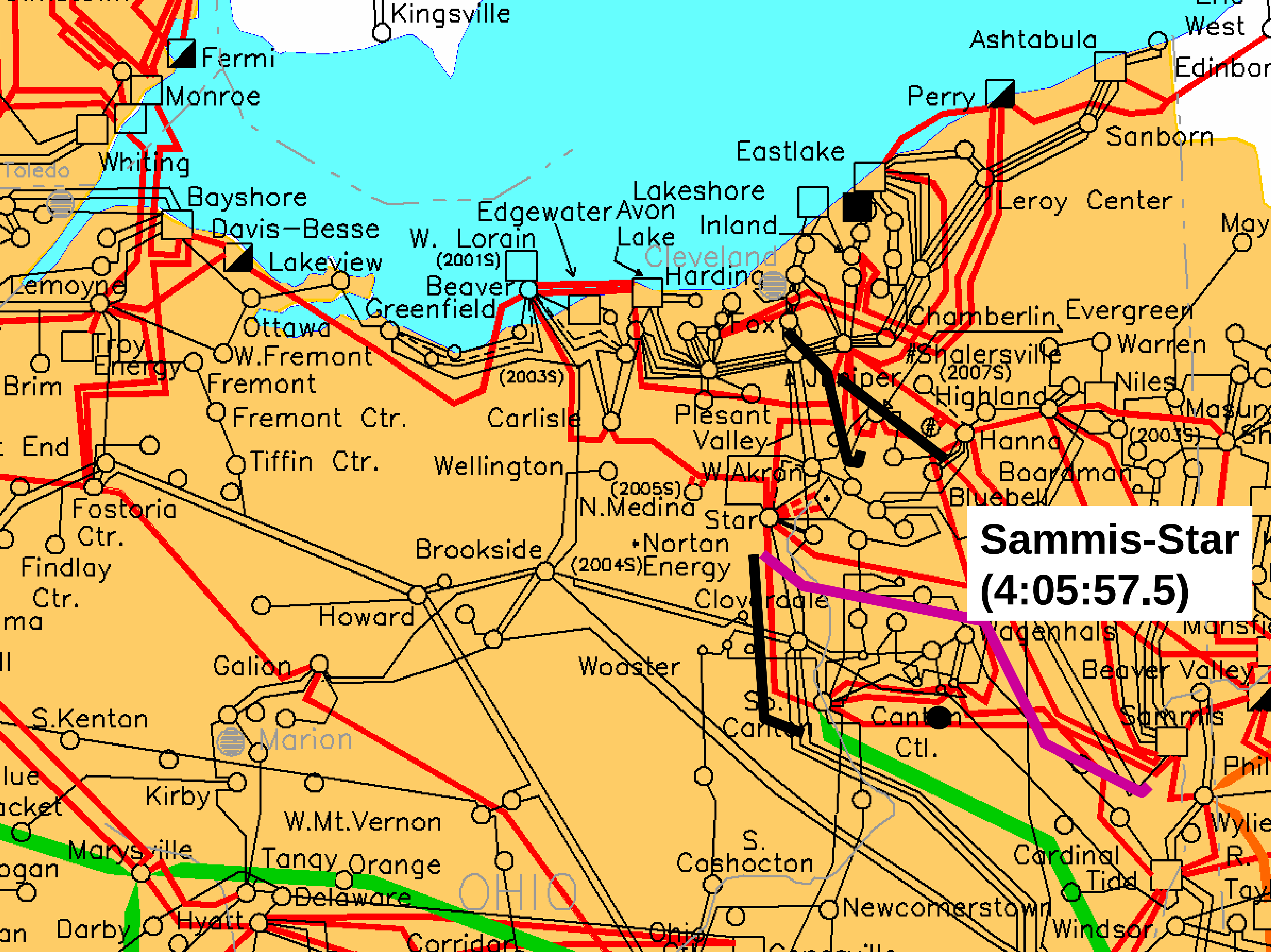
Coshocton
Newcomerstown
Wylie
R.
Toledo


Sammis-Star
(4:05:57.5)
Kingsville
Ashtabula
West
Fermi
Monroe
Perry
Sanborn
Eastlake
Whiting
Toledo
Bayshore
Lakeshore
Leroy Center
Davis-Besse
Edgewater
Avon
Lake
Inland
W. Lorain
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Cleveland
Lakeview
Beaver
Harding
Lemoyne
Greenfield
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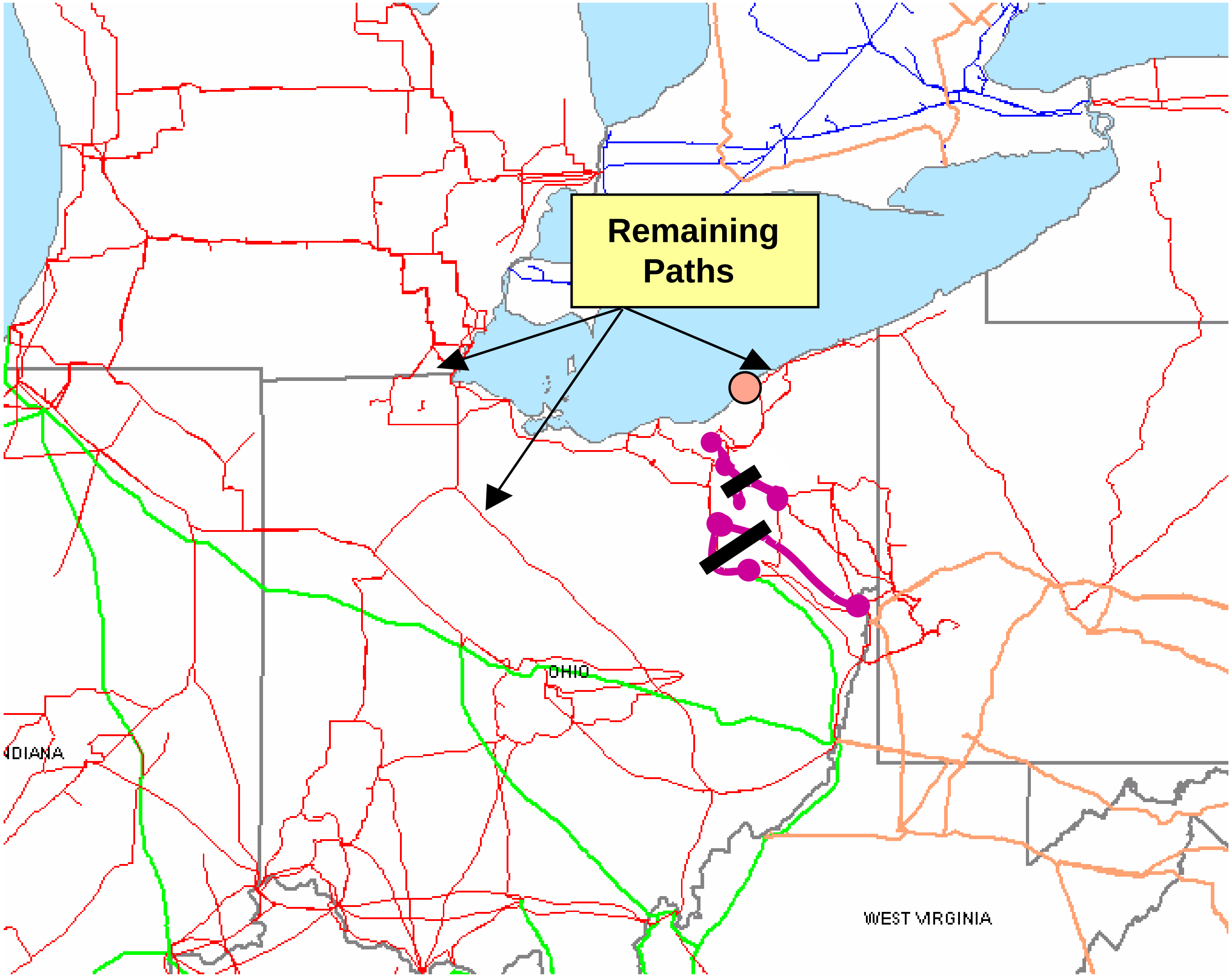
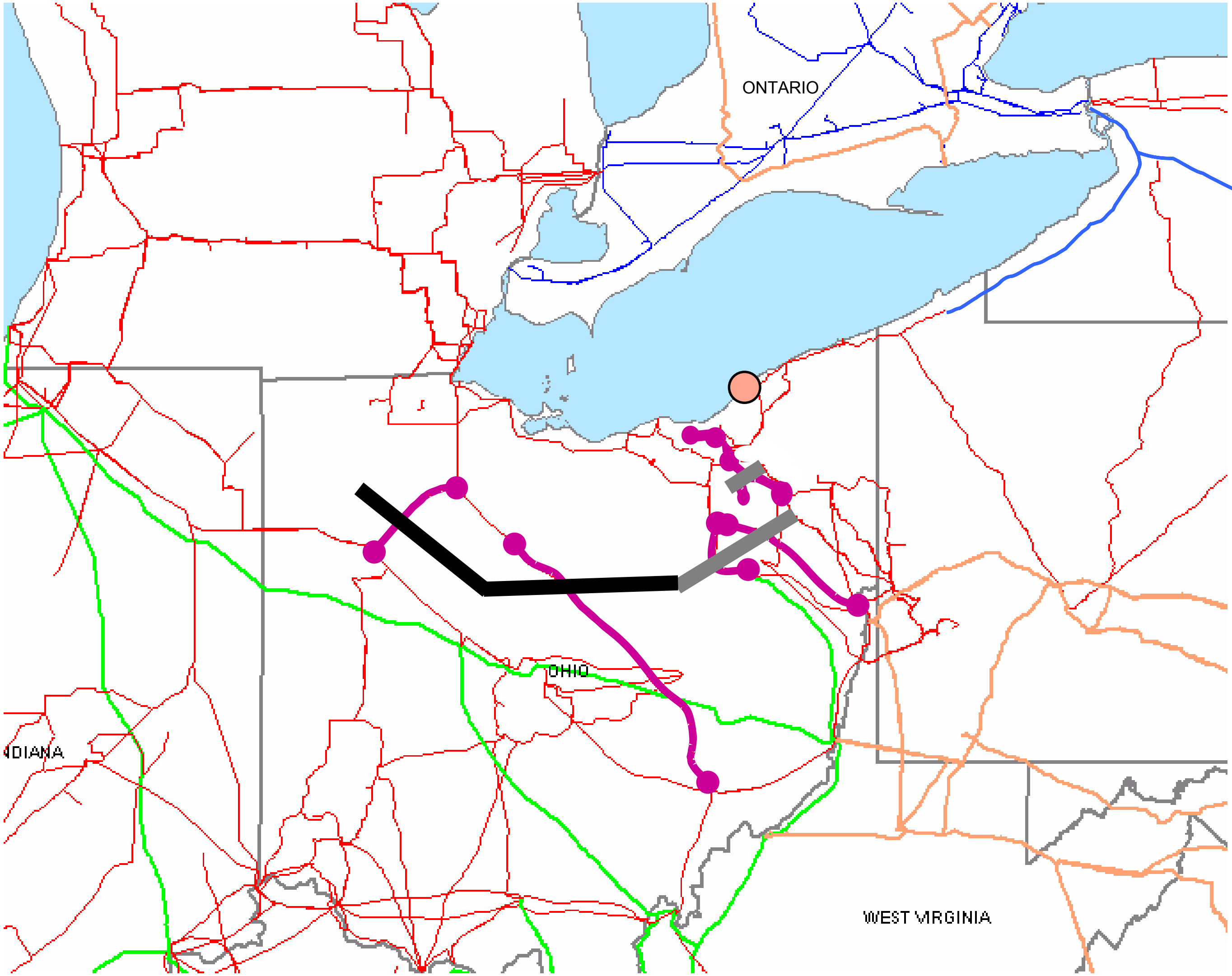
Tangy
Orange
S.
Coshocton
Cardinal
Tidd
Delaware
OHIO
Newcomerstown
Darby
Hyatt
Windsor
Corridor
Ohio

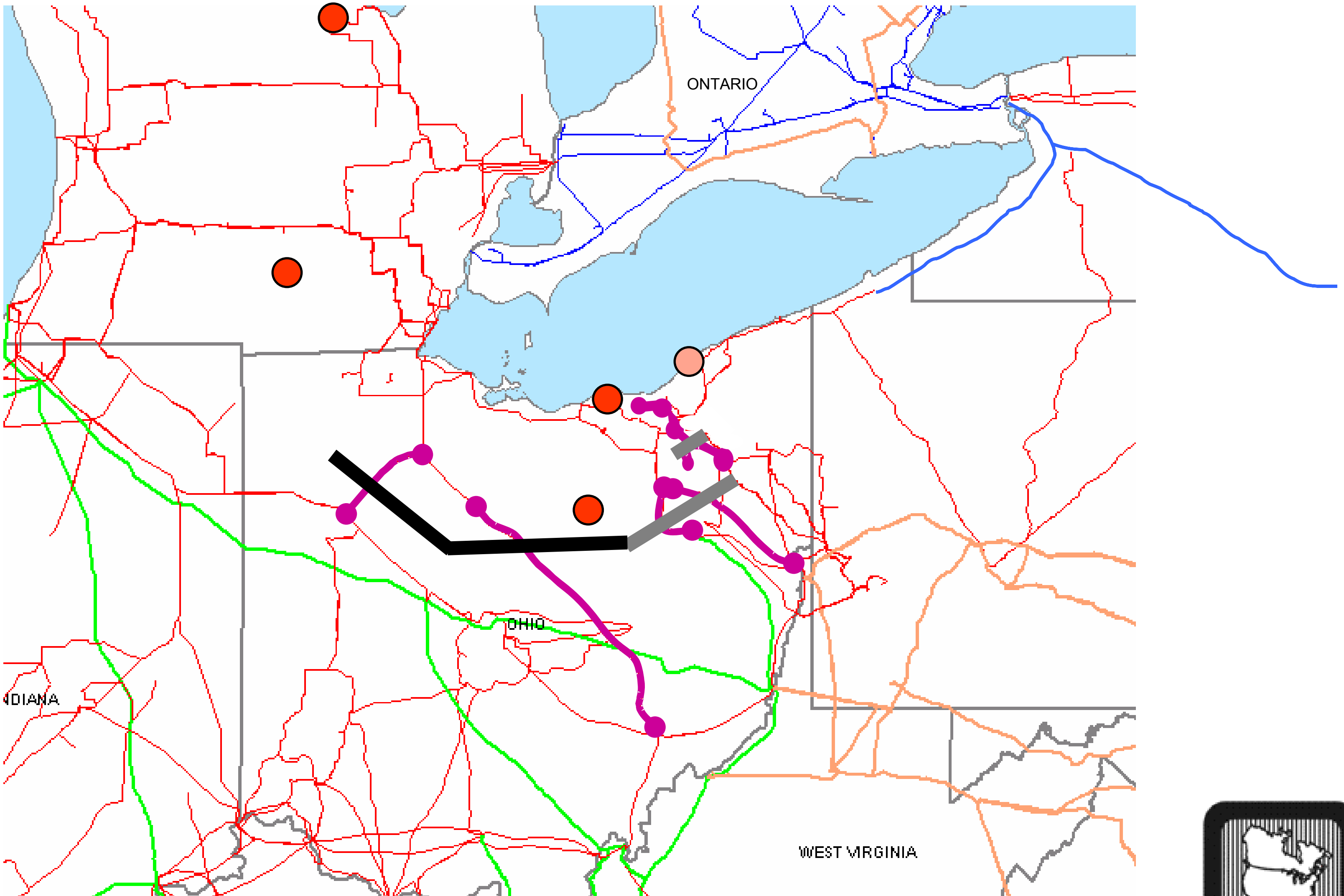
Major Path to Cleveland Blocked after Loss of Sammis-Star 4:05:57.5 PM



345 kV Lines Trip Across Ohio to West 4:08:59 - 4:09:07 PM

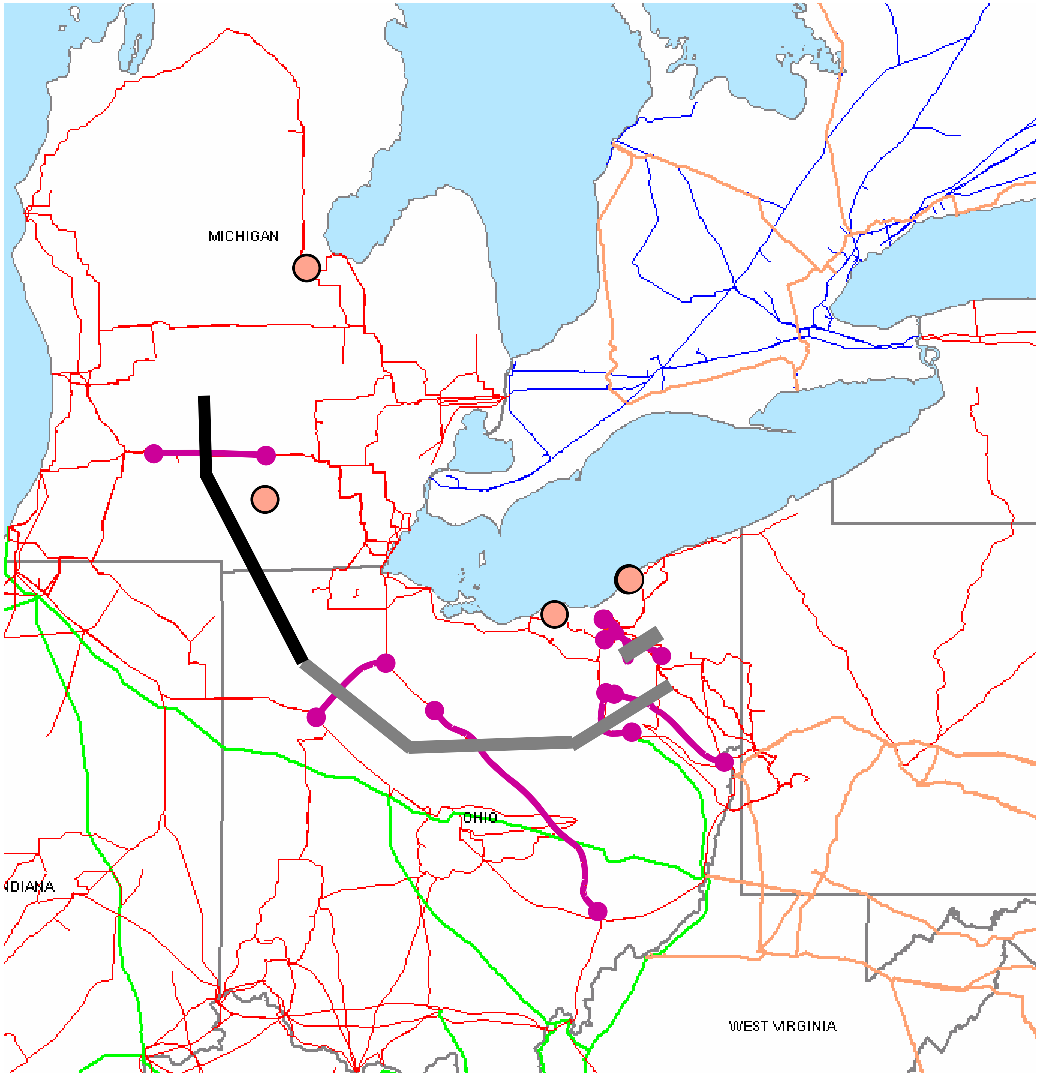


Generation Trips 4:09:08 – 4:10:27 PM



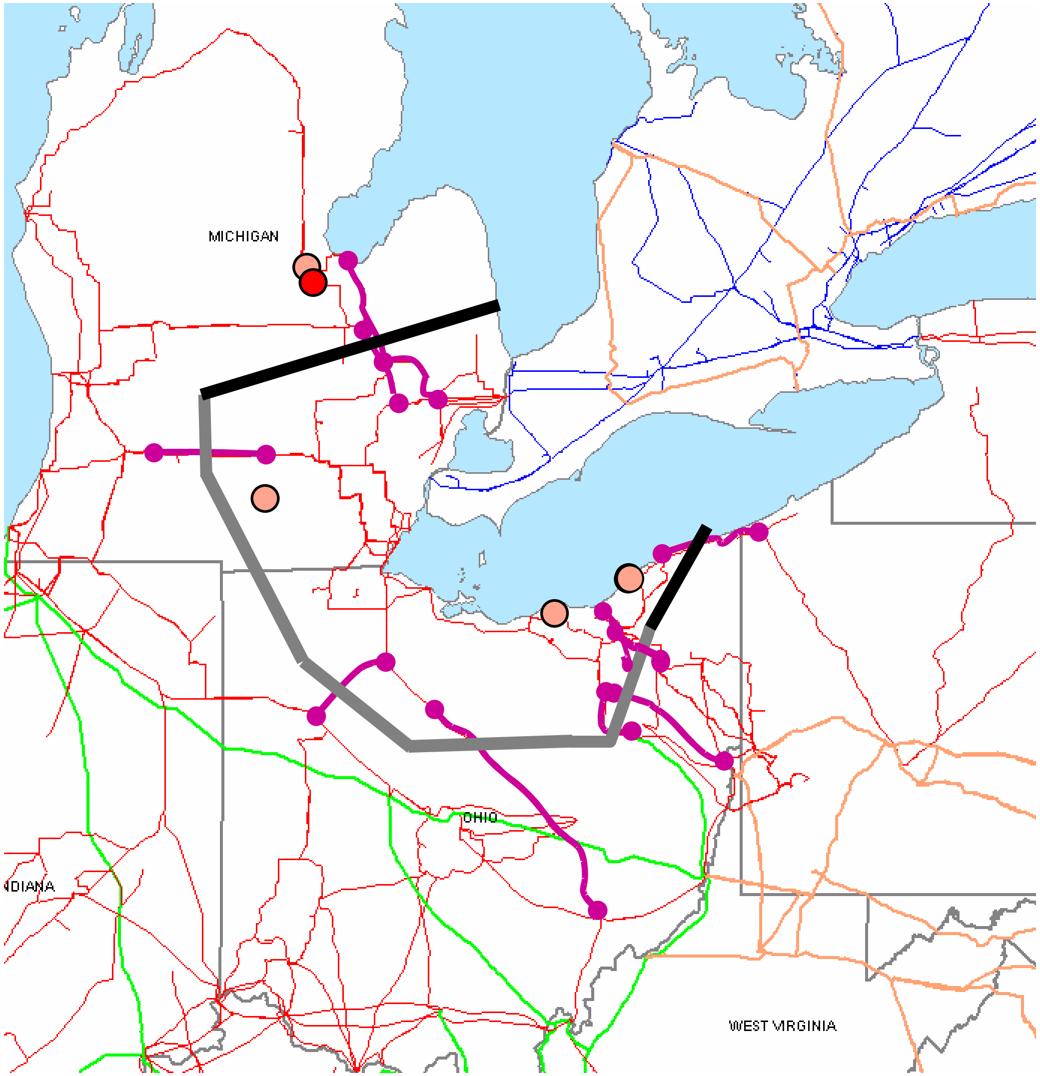
345 kV Cascade Moves North into Michigan

Argenta-Battle Creek lines trip 4:10:36 – 4:10:37PM

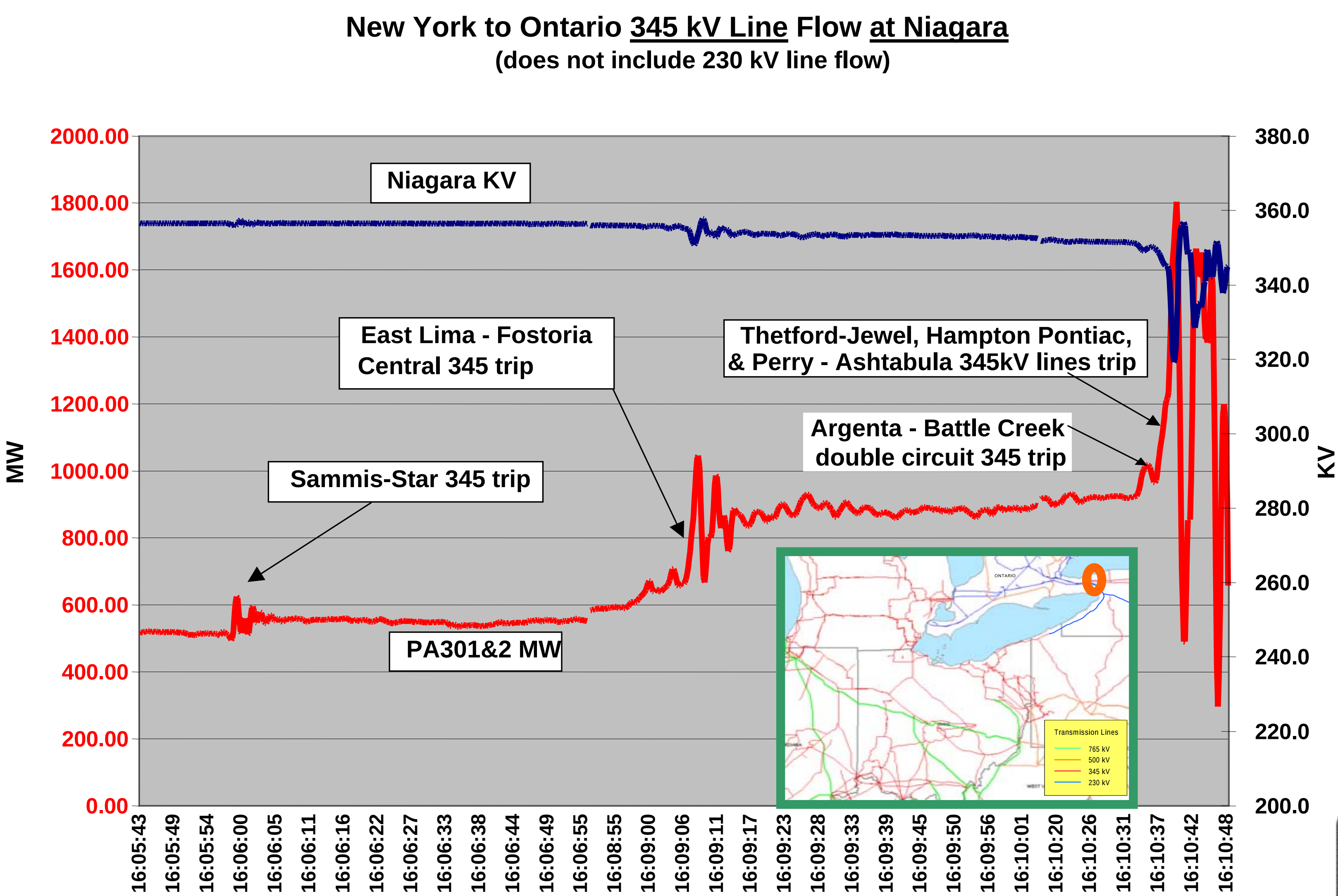


New Phase Begins - "Transient Instability"

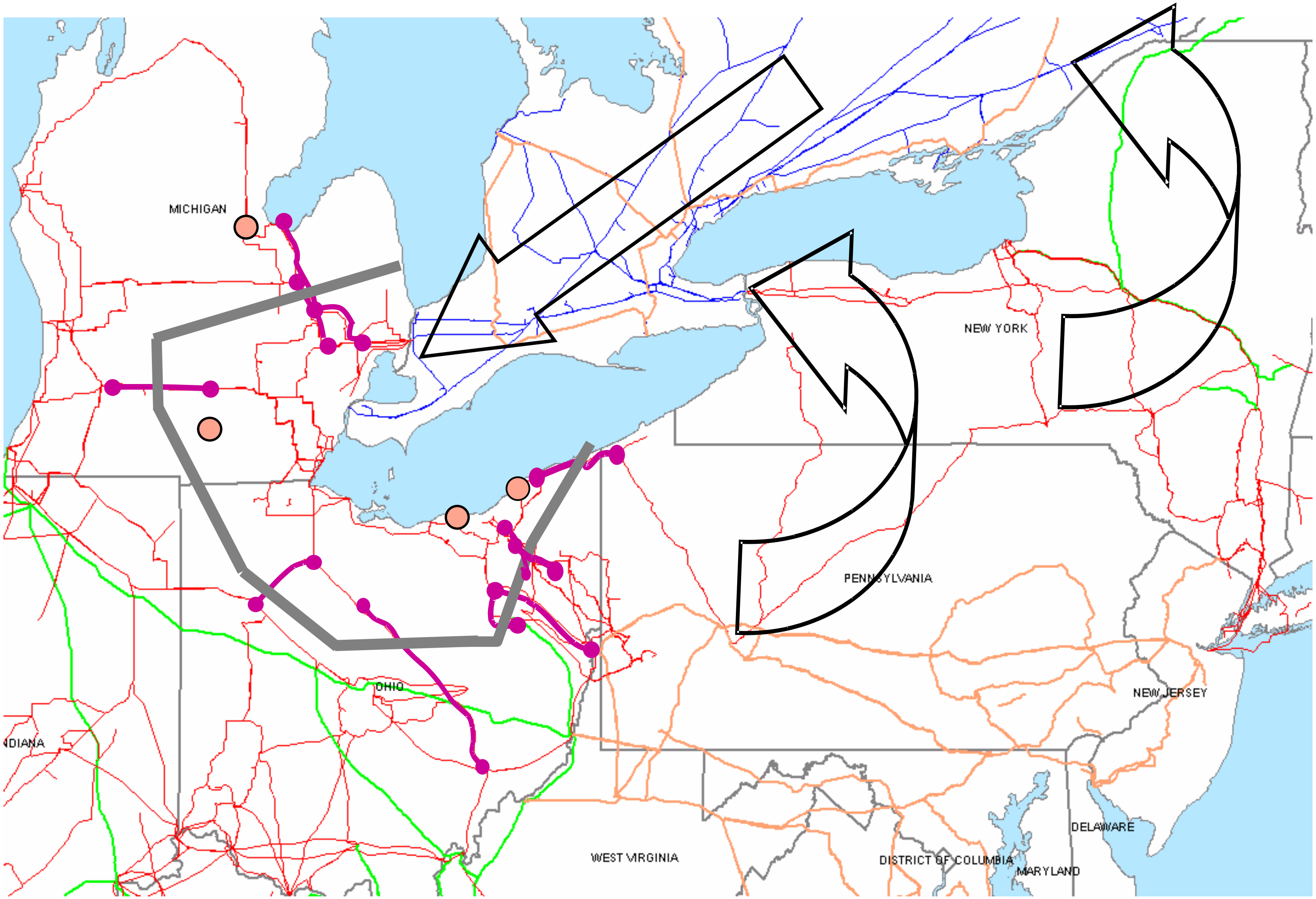
Three 345 kv Lines trip from 4:10:37.5 - 4:10:38.6 PM



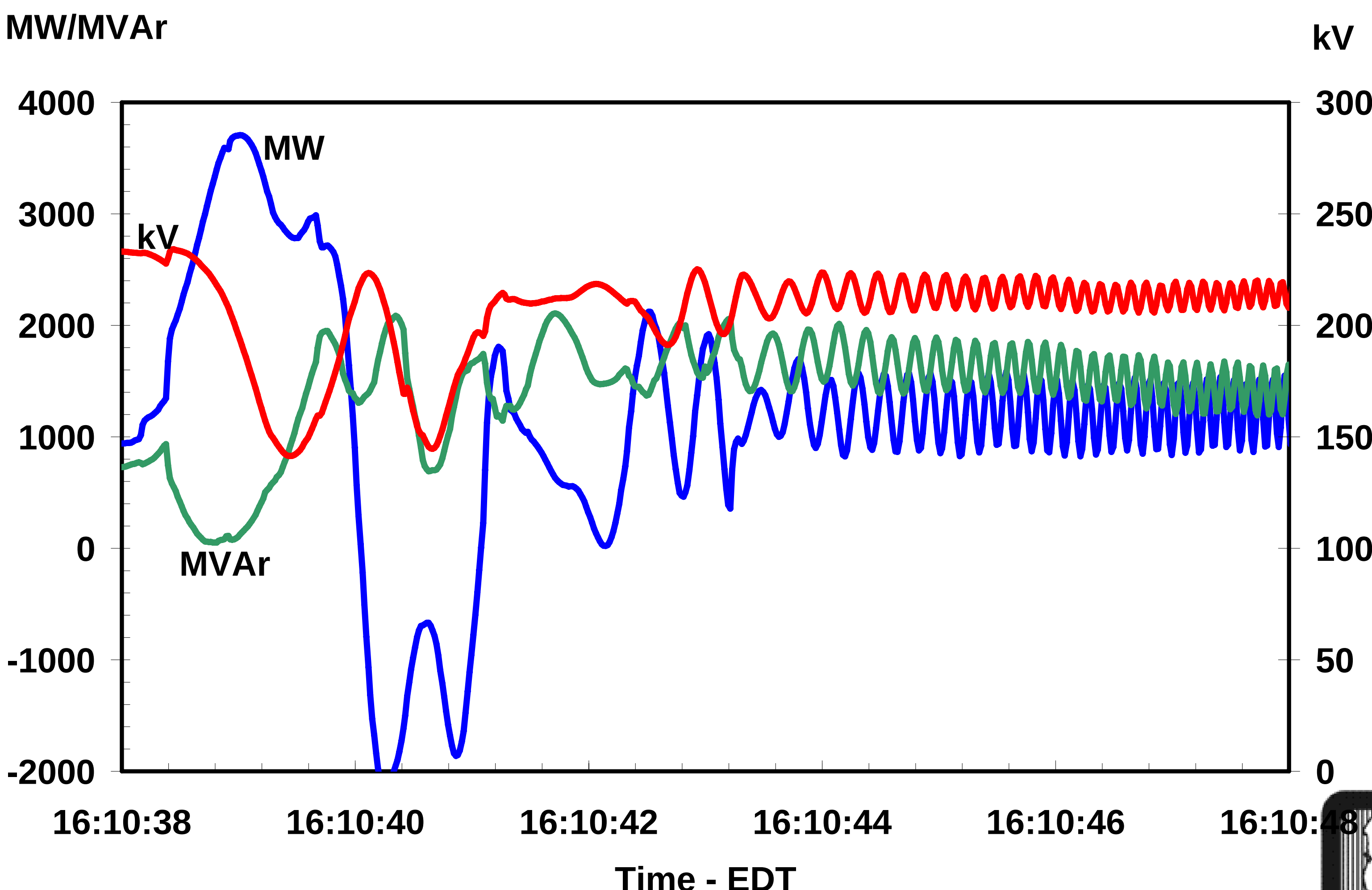
NY to Ontario 345kV Line Flows at Niagara Progressively Worsening Stability Conditions



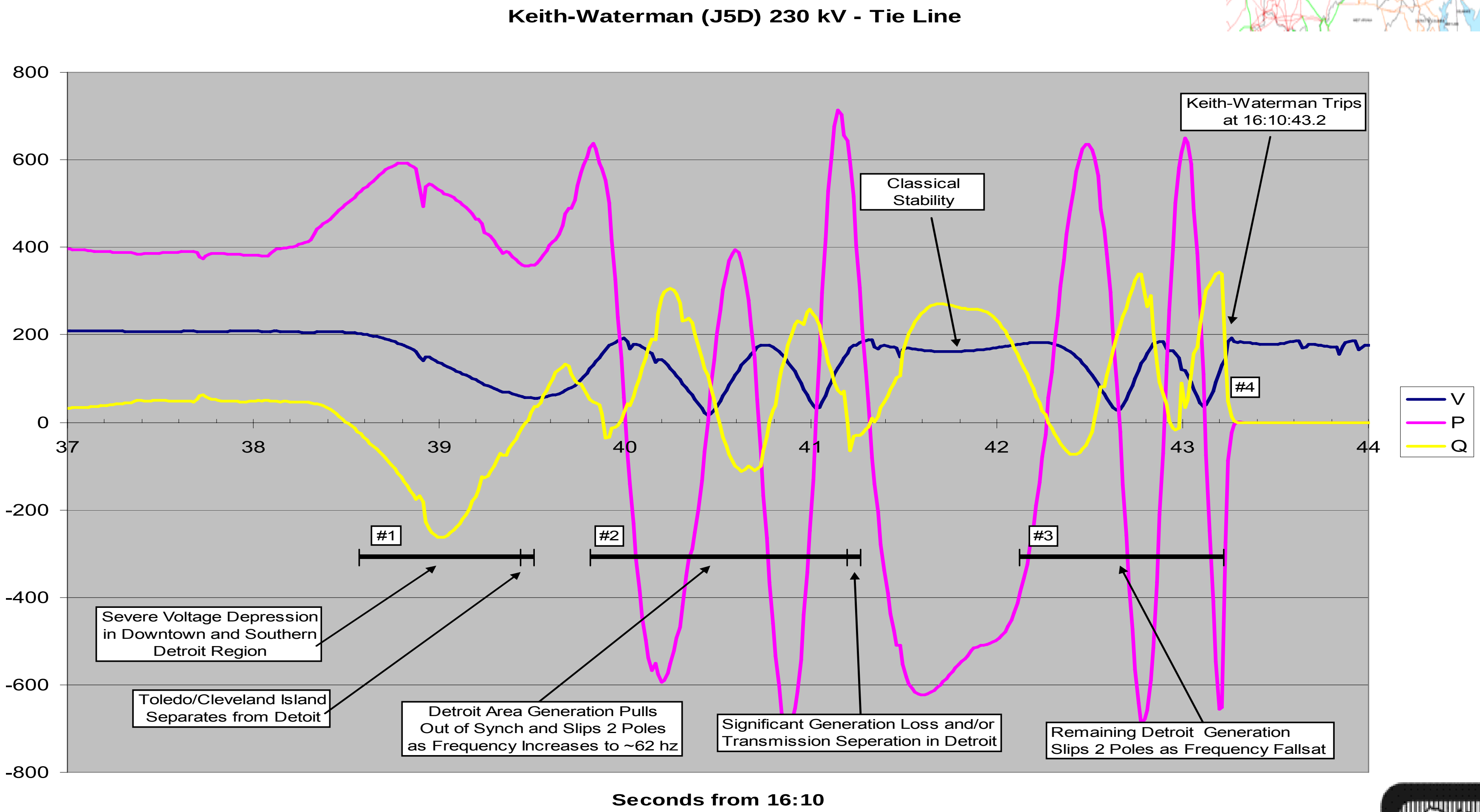
Power Transfers Shift at 4:10:38.6 PM



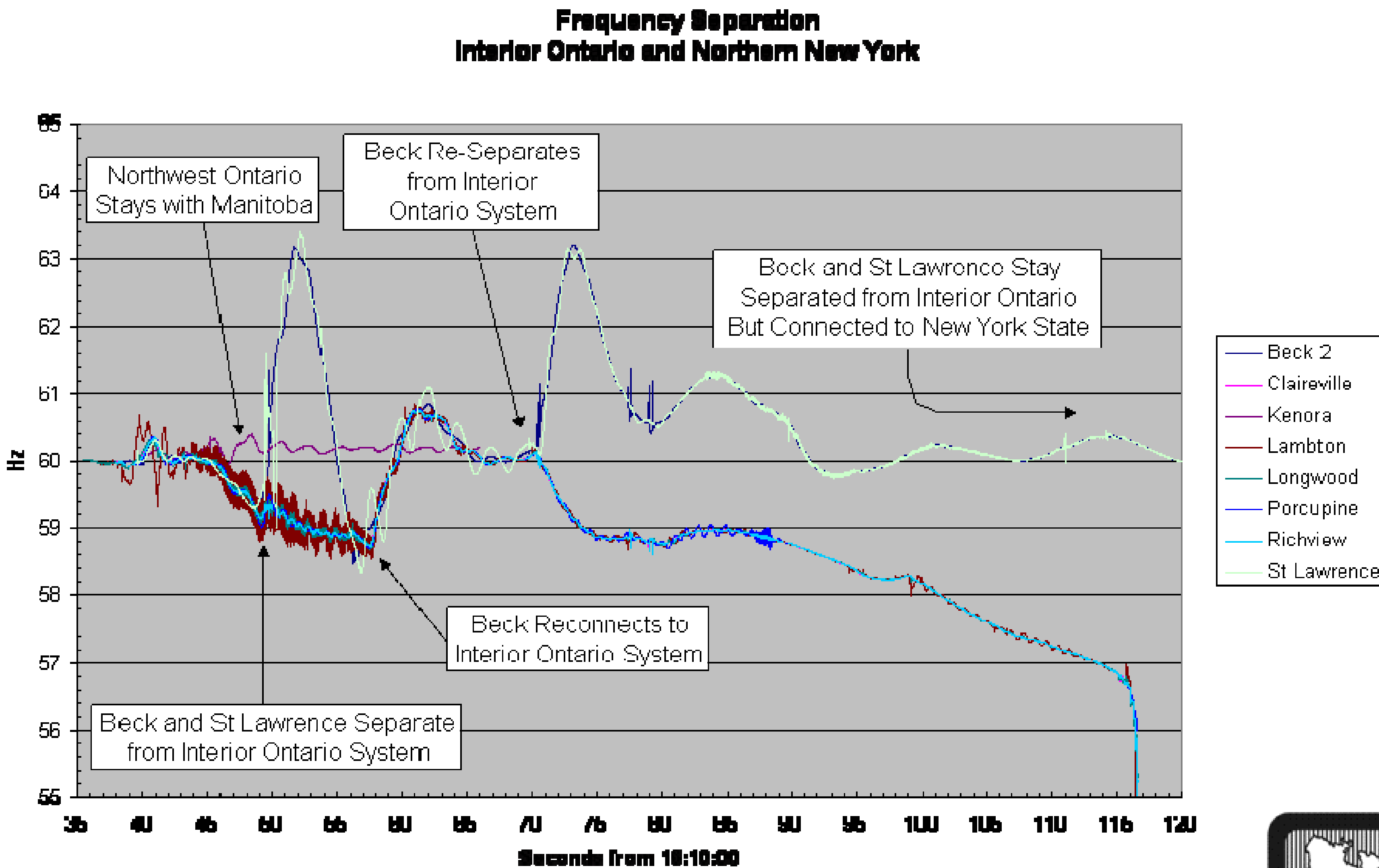
Eastern Michigan (Detroit)
"*Transient Instability*" Phase Begins



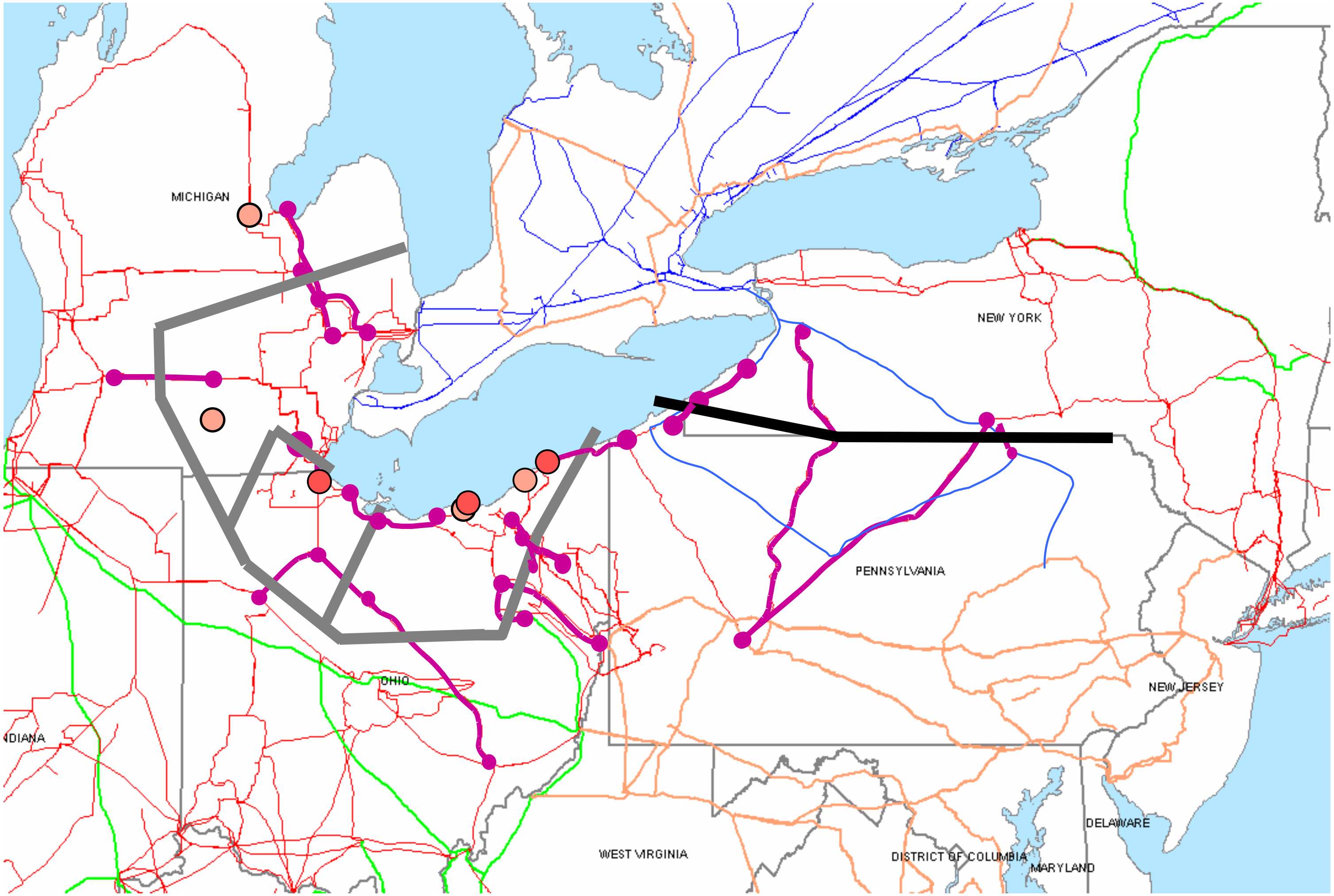
Detroit Units Slip Poles



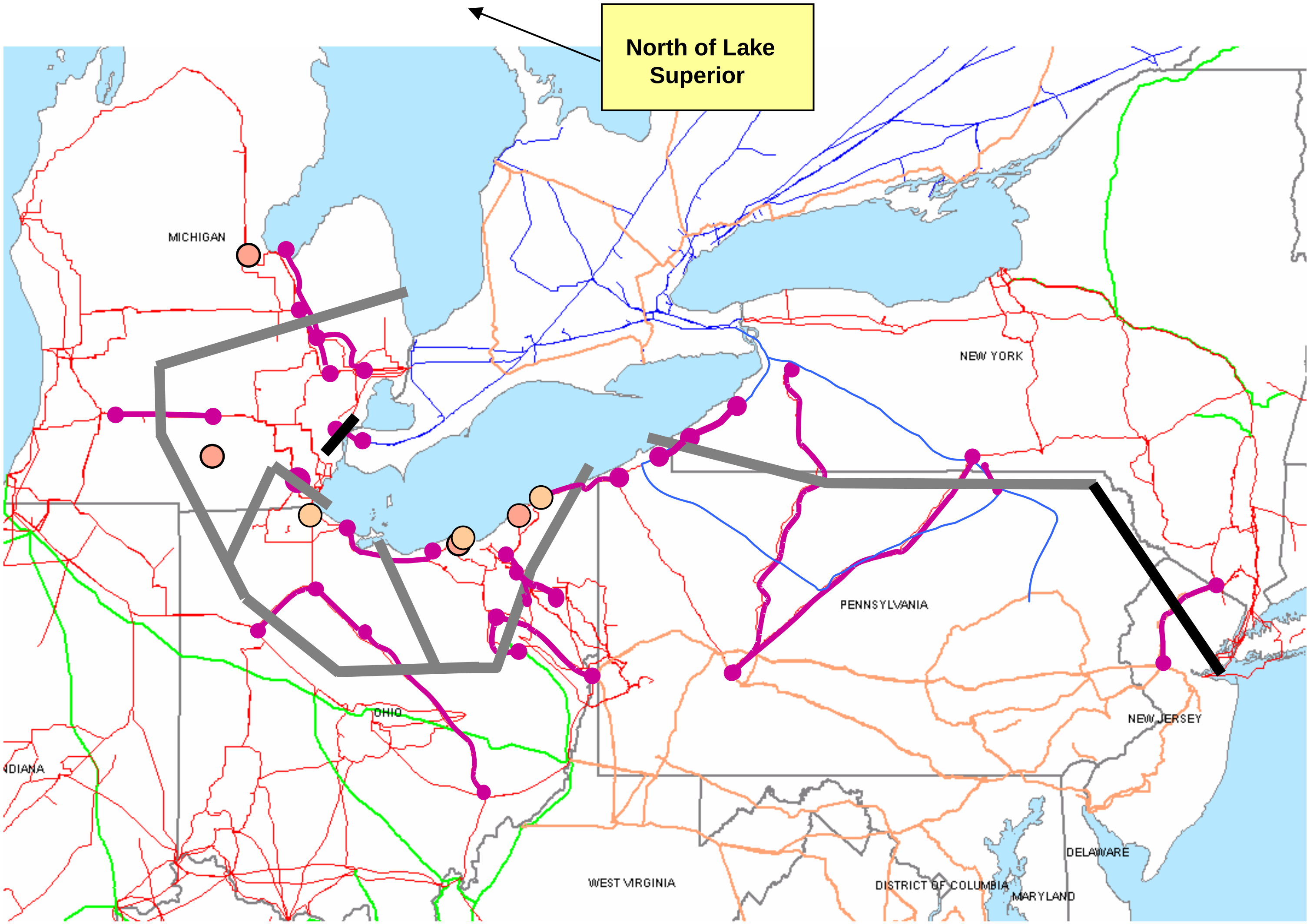
Frequency in Ontario and New York



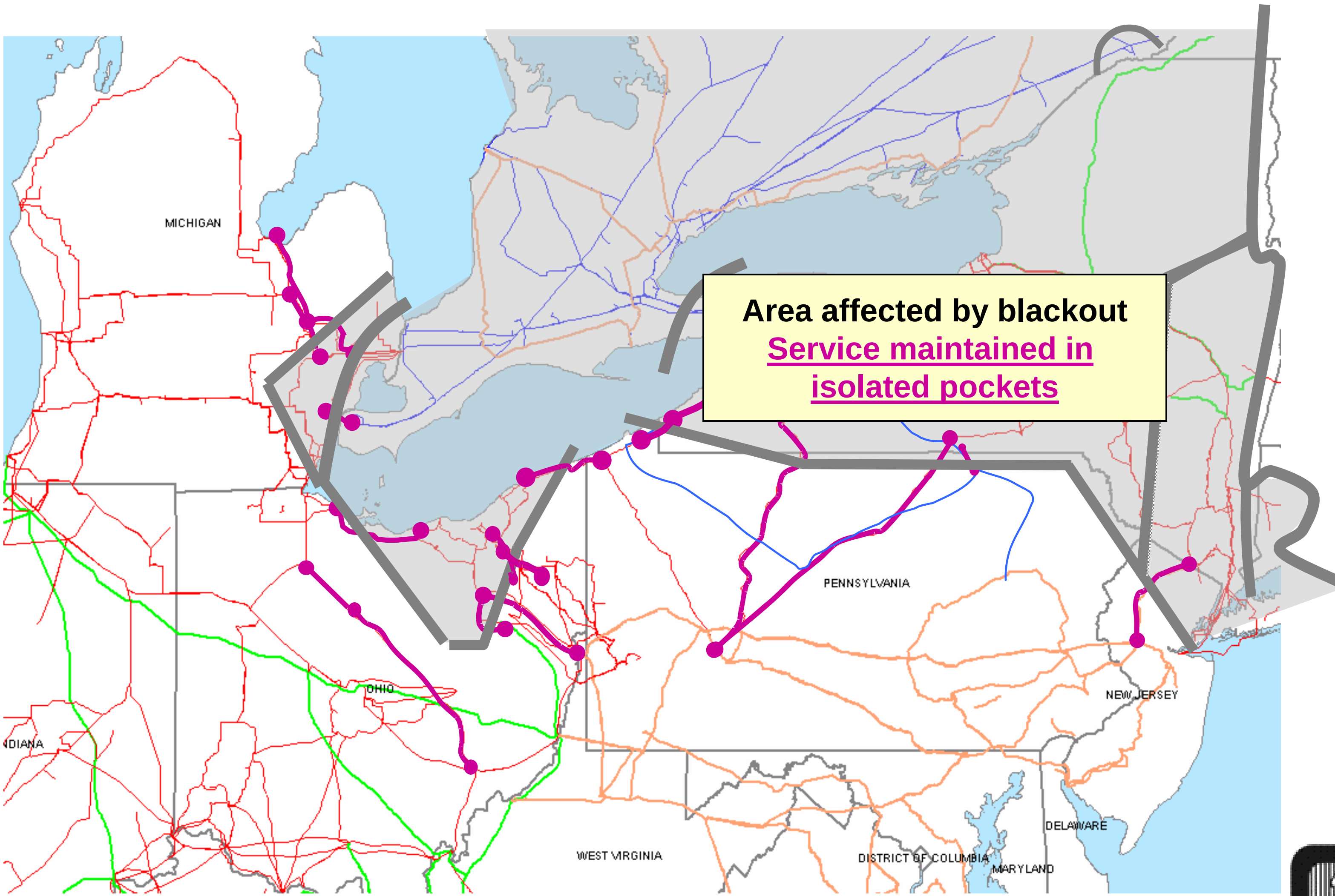
Penna–New York Separation 4:10:39 to :44 PM



Northeast Island Completes Separation from Eastern Interconnection 4:10:43 – 4:10:45 PM

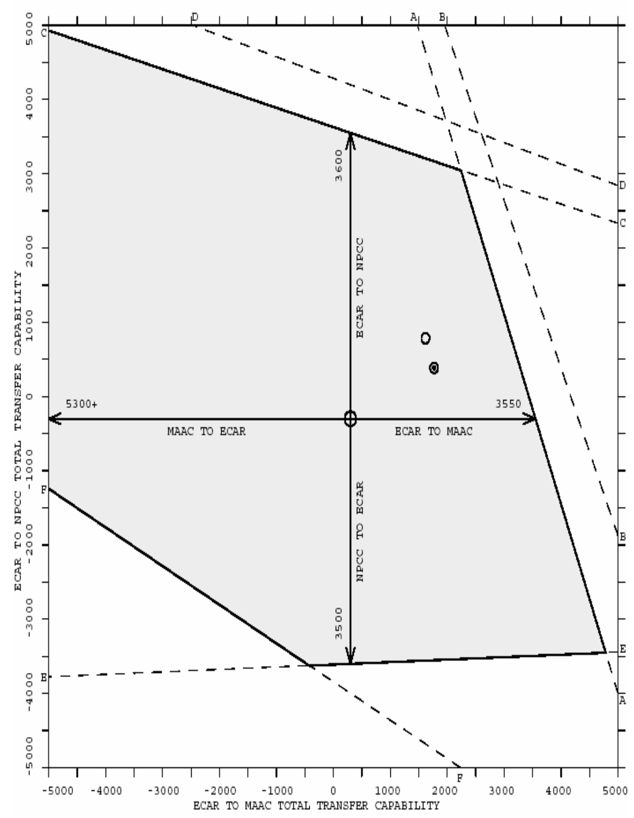


End of the Cascade

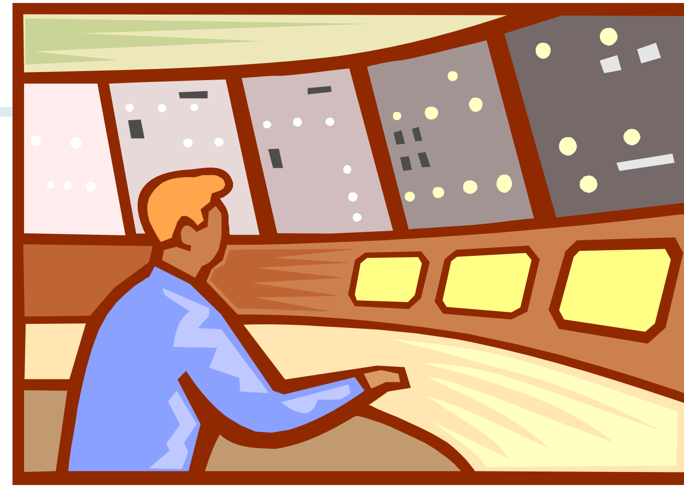


Key Findings

- **Inadequate system planning and design studies, operations planning, facilities ratings, and modeling data accuracy**
- **Operating with insufficient reactive margins**
- **More effective system protection and controls could slow or minimize spread of cascading outage**
- **Problems from prior blackouts were repeated**



The Old - Repeated



- The three “**T’s**”
  - **Tools** – for the operator to monitor and manage the system
  - **Trees** – vegetation management to prevent tree contacts
  - **Training** – operators need to provided training and drills to be prepared to respond to system emergencies

The New

- **Failure of Tools**
  - Information Technology support – communications
  - “Game Over”
- **Failure of “Defense in Depth”**
- **Generation Protection**
  - Consideration of performance during dynamic and extreme low voltage events
  - Coordination of plant controls with the transmission system

Multiple Concurrent Software Failures

1. FirstEnergy alarm failures
2. FirstEnergy remote EMS terminal failures
3. MISO state estimator failures for L/O Bloomington-Denois Creek 230 kV and Stuart-Atlanta 345 kV
4. MISO topology processor failure – did not recognize Harding-Chamberlin 345 kV line trip when breakers were open

Control Area (CA) Computer Failures

- 2:14 PM - alarm logger fails and operators are not aware
- 2:41 PM - server hosting alarm processor and other functions fails to backup - IT staff is auto-paged.
- 2:54 PM - backup server fails (2 of 4 servers down)
  - 2 servers continue to function but with long refresh (~59 second)
  - selected CA data continues to be sent to other control centers
  - unidentified Harding - Chamberlin 345kV line outage at 3:05 PM
- 3:08 PM - IT warm reboot of servers appears to work but alarm process not tested and still in failed condition
- CA Operators are now ‘blind’ & lose situational awareness
- Reliability Coordinator (RC) computers are still working.

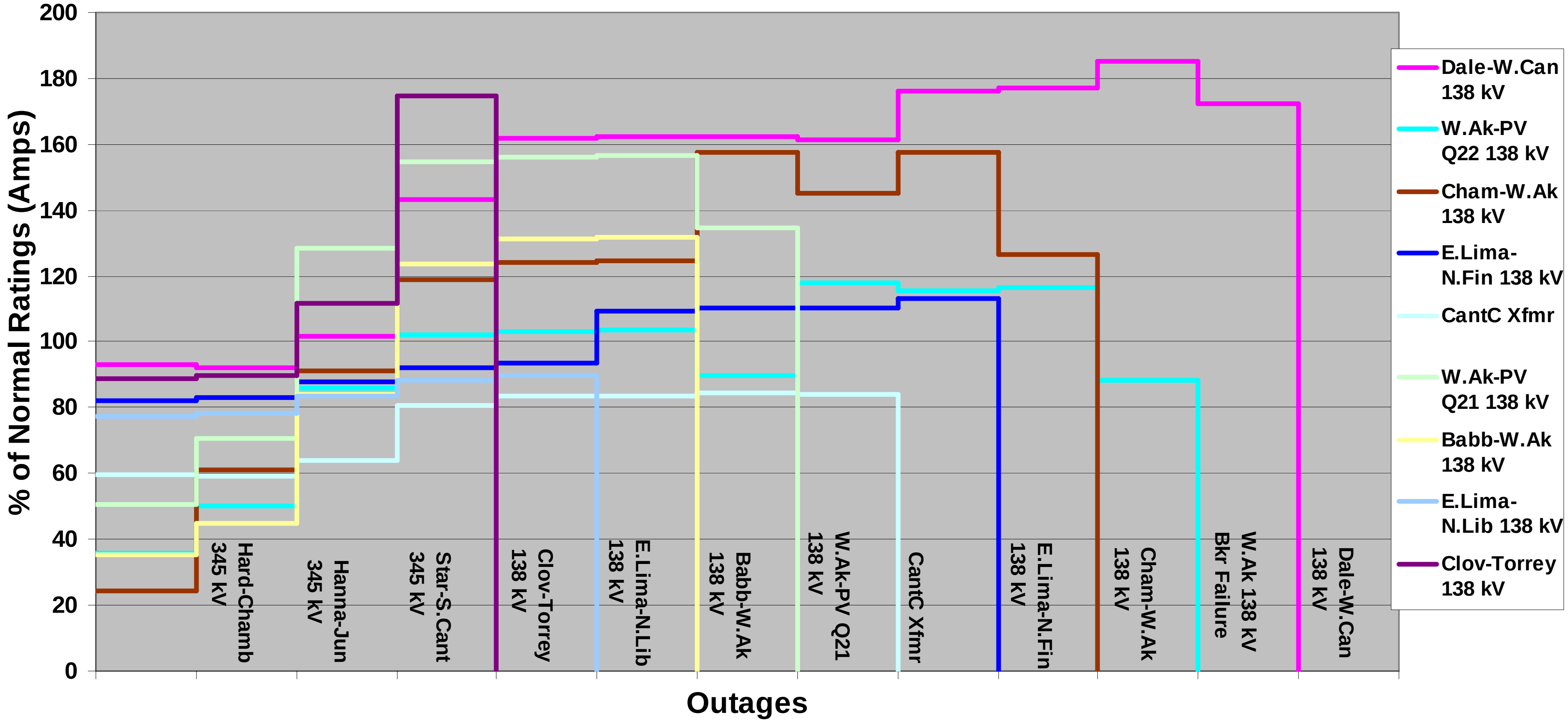
"Reliability Coordinator (RC) Diagnostics"

- MISO Reliability Coordinator (RC) for CA
  - "state estimator" failed due to data errors, & periodic automatic restart turned OFF
  - monitoring tools did not have real-time line information to detect growing overloads
  - not within contingency limits from 3:06 - 4:06
    - "missed" Harding - Chamberlin line outage 3:05 PM
    - did not have wide area map-board for the above
    - state estimate & contingency analysis not successful.
  - To monitor the power system, MISO was using software that was considered "under development and not fully mature"

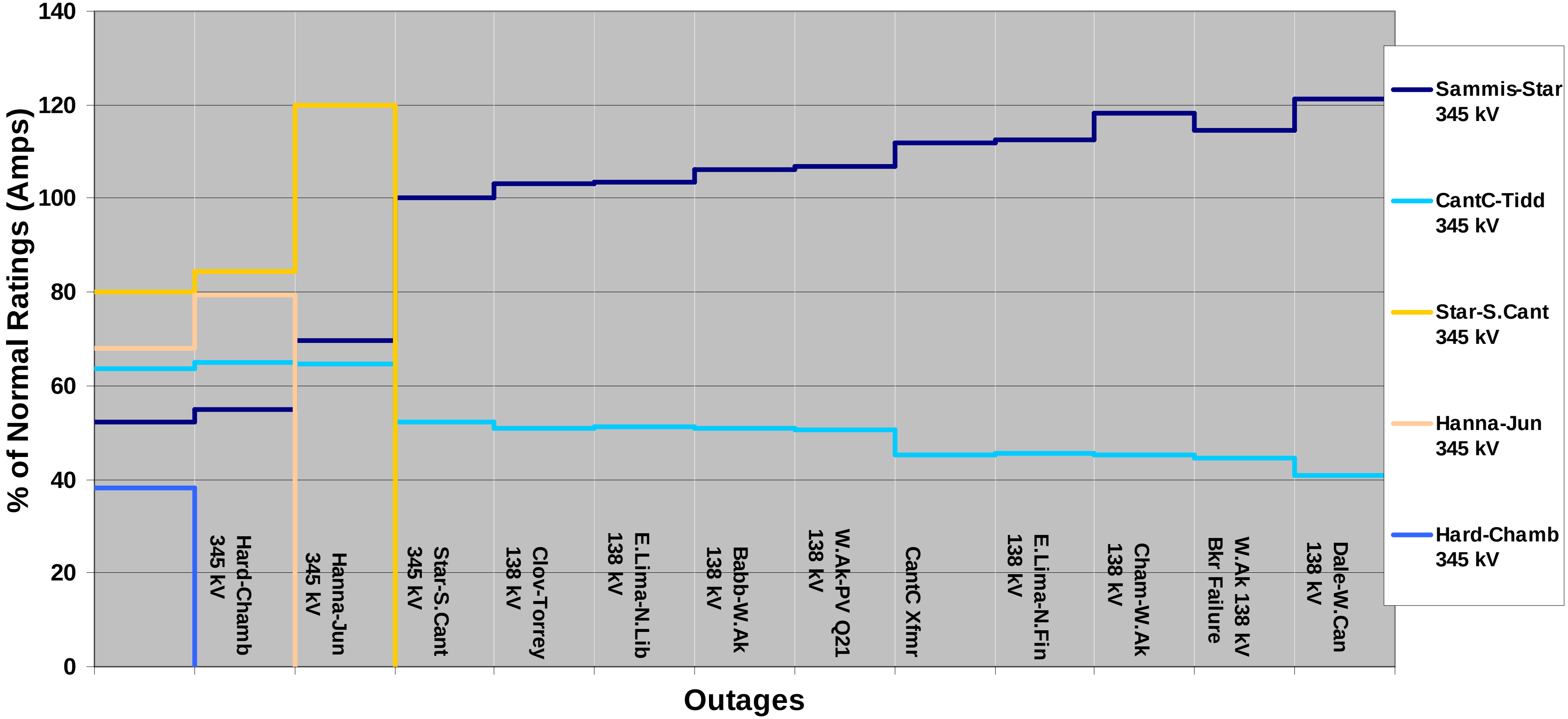
Modeling & Studies Work

- Successful Forensic Dynamic Analysis
  - Able to duplicate measured system response through 16:11
  - Far beyond expectations
  - Significant modeling lessons learned
  - Validation of Sequence of Events
  - Understanding of Eastern Interconnection behaving as a *single system*
  - Set stage for further study of “what ifs”

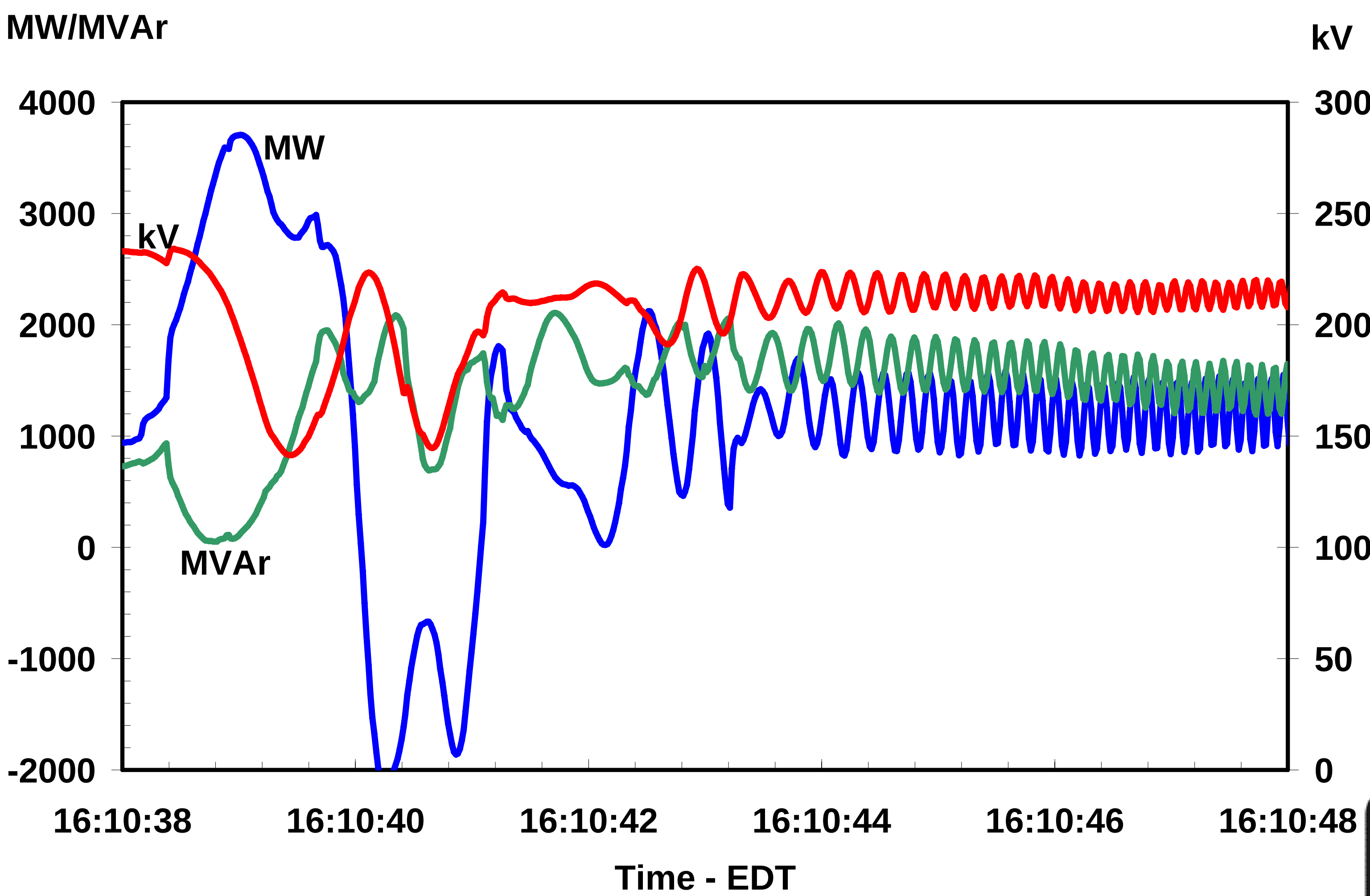
Simulated 138 kV Line Loadings



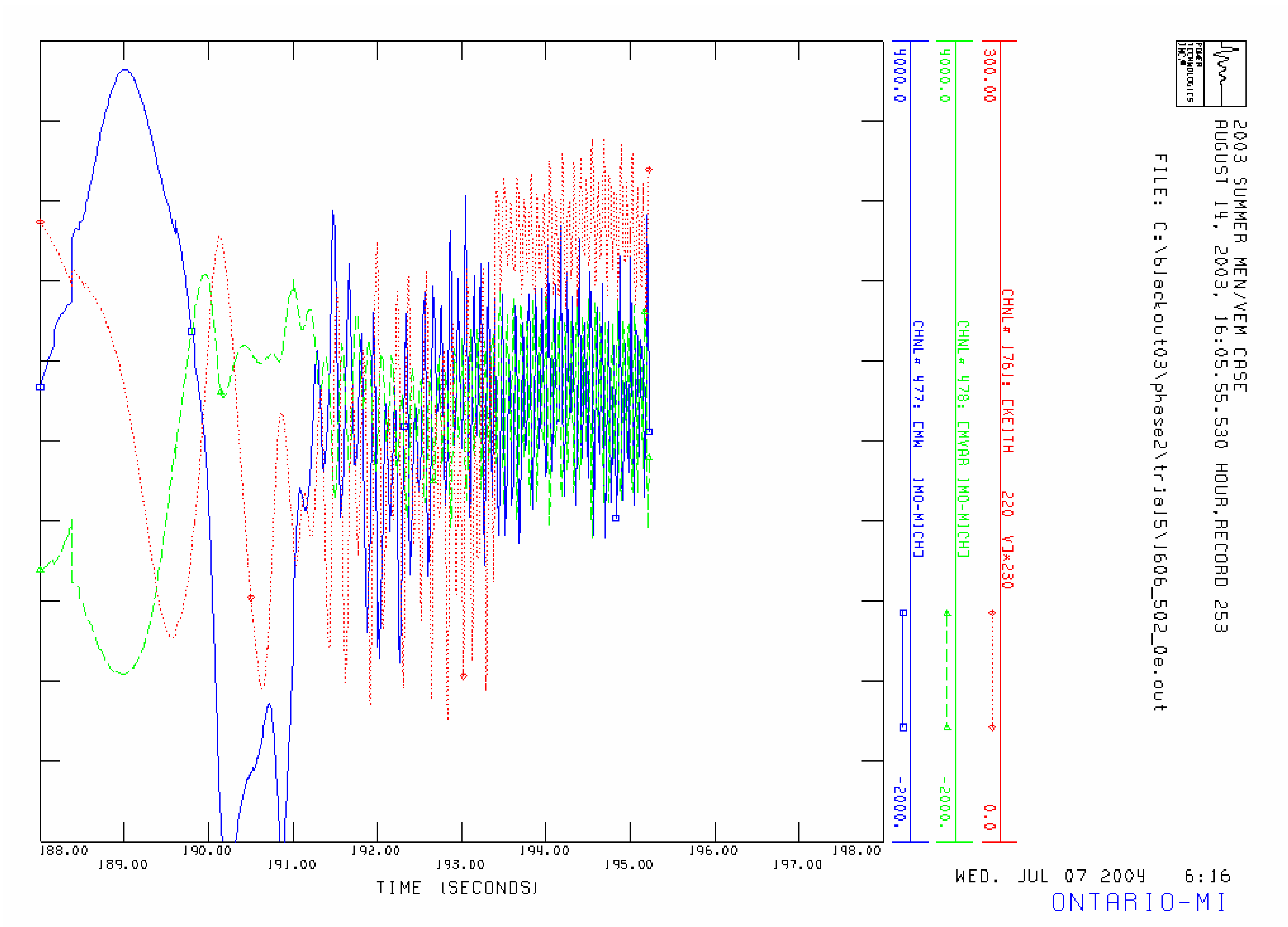
Simulated 345 kV Line Loadings



Ontario-Michigan Voltage and Flows Measured from Lambton



Simulated Ontario-MI Data



Power Flow Modeling Problems

- **Line Rating Discrepancies**
  - Sammis-Star 345 kV line rating different for PJM, AEP, MISO, FE
- **Topology Errors** — Some dating back to 1991
  - No feedback loop in MMWG/SDD case creation process
- **Power Factor**
  - Optimistic reactive power loads
- **Generator Reactive Limits**
  - Not verified with actual capability
- **Model Quality**
  - Systemic problem of model and data quality control
- **Powerflow Program Version Discrepancies**

Dynamics Modeling

- **Accurate Models Necessary**
  - One family of exciter models was found to have an unstable step response
  - Some units' models were unstable due to bad data in the models
  - Generators dispatched beyond real and reactive limits
  - Incorrect machine MVA base values
  - No dynamics data for most small units
    - Generic generator data used in the MMWG case
  - No standard of formats for powerflow and dynamics data

Dynamics Modeling

- **Program deficiencies**
  - Program does not allow modeling of underfrequency load shedding (UFLS) and undervoltage load shedding (UVLS) on the same bus
  - Some models caused the program to freeze or crash
- **Program features**
  - Program allows a simulation to be stopped during the middle of a run and restarted at a later time

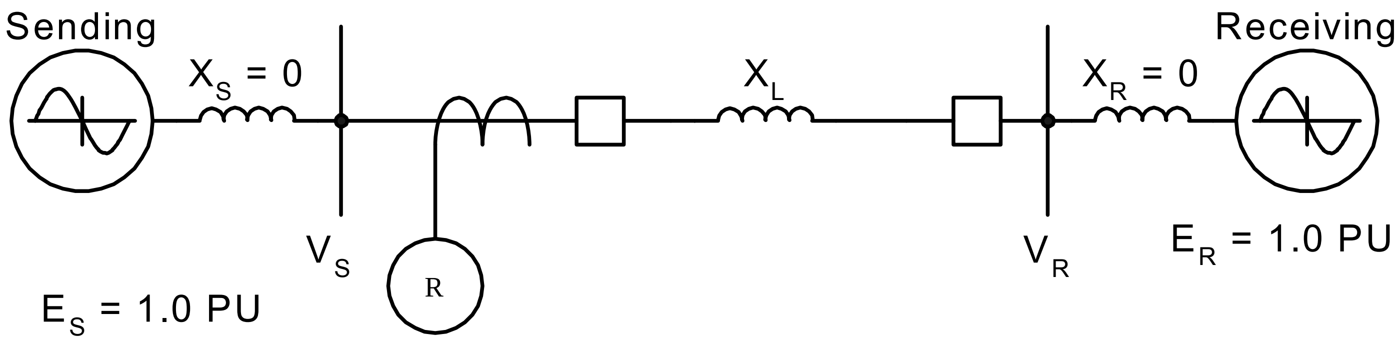
Dynamics Modeling Innovations

- **New Models Developed**
  - Simulate phenomena not normally represented in standard dynamics program models
  - Modified dynamic load model
    - More responsive to voltage deviations
  - Modified existing generator models
    - Represent generator mechanical overspeed protection systems

Dynamic Analysis Finding

- Cascade arrested by dropping all of Cleveland load prior to loss of Argenta – Battle Creek / Argenta – Tompkins 345 kV
  - Nothing then measurable to suggest taking such action
  - Angular separation analysis showed possible trigger (~90 second window)

Maximum Power Transfer Diagram



$$P = \frac{V_S \times V_R \times \sin \Theta}{X_L}$$

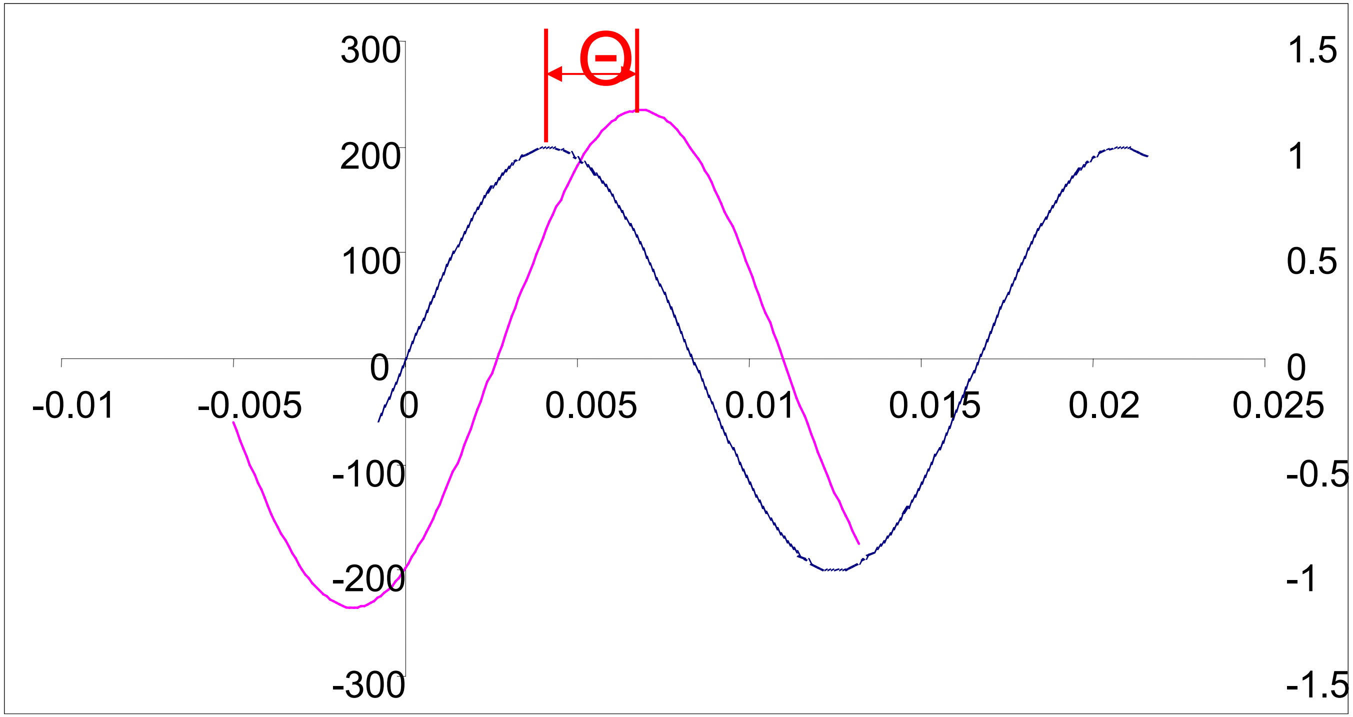
$$\Theta = Arc\sin\left(\frac{X_L}{|V_S||V_R|}\right)$$

The maximum real power that a transmission line can transfer occurs when the voltage angle across the line reaches 90º.

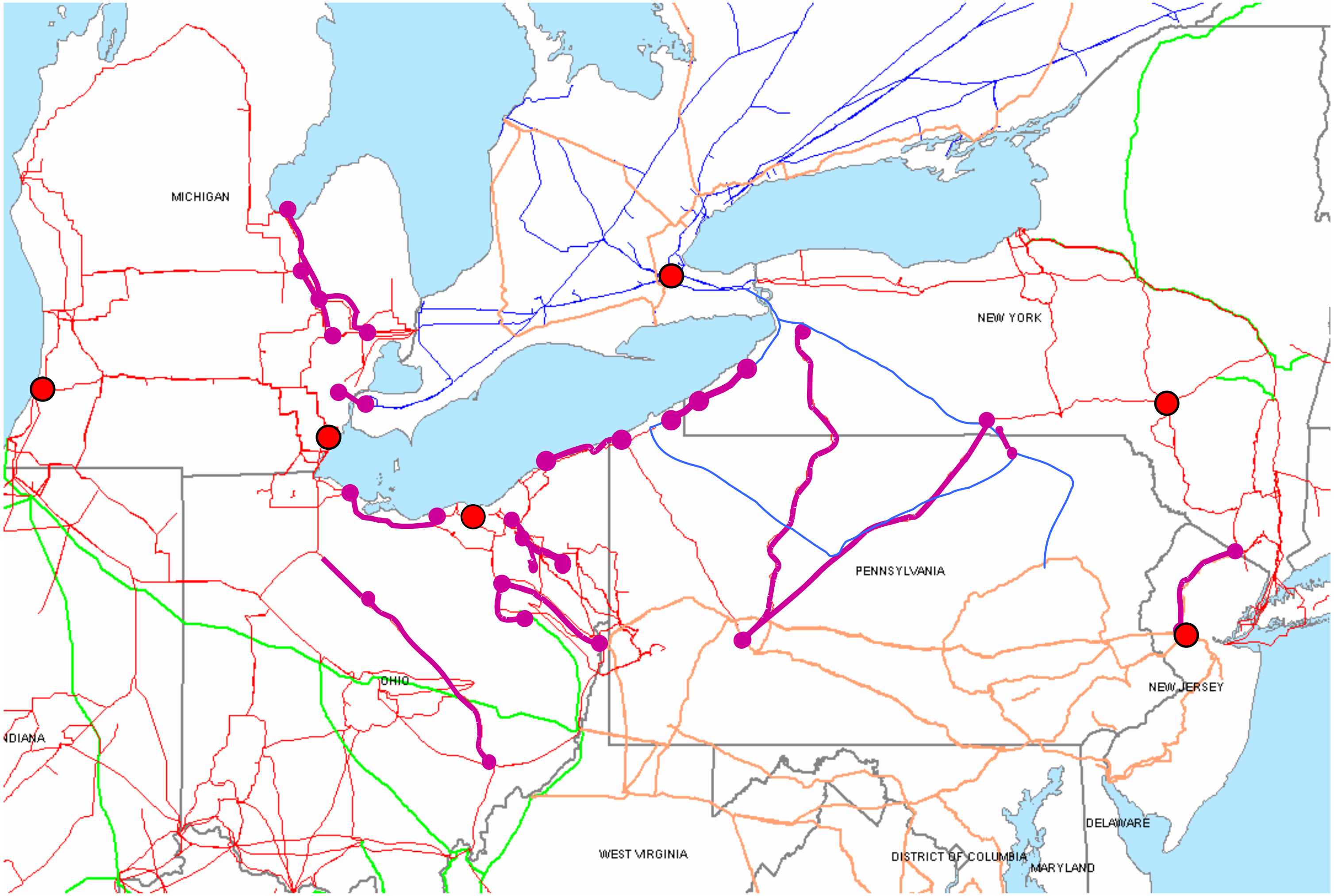
Angular Separation Analysis

Generalize Power Transfer Equation to Zonal

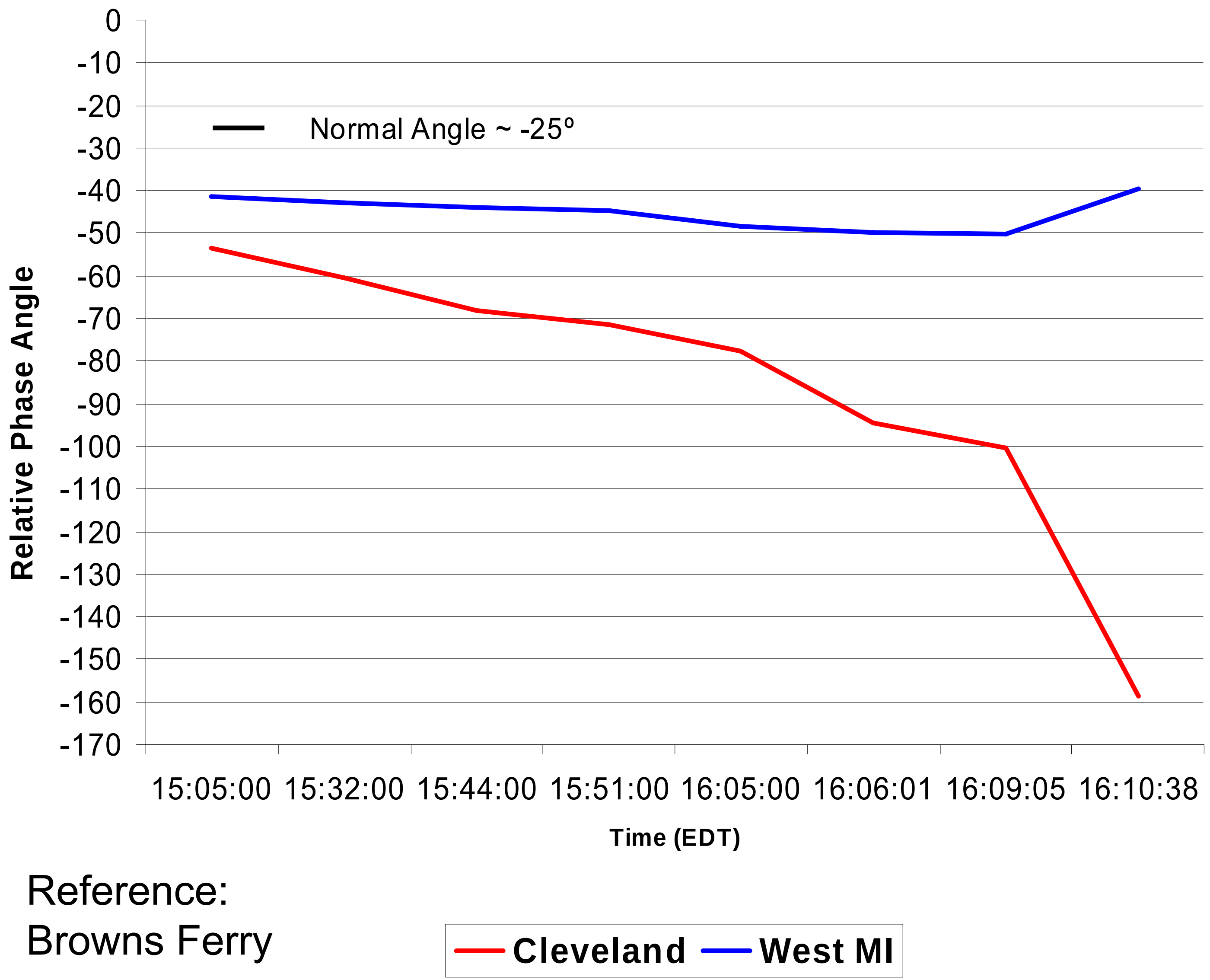
$$P_{SR} = P_{SR\,\max} \times \sin \Theta$$



Simulation Angular Measurement Points

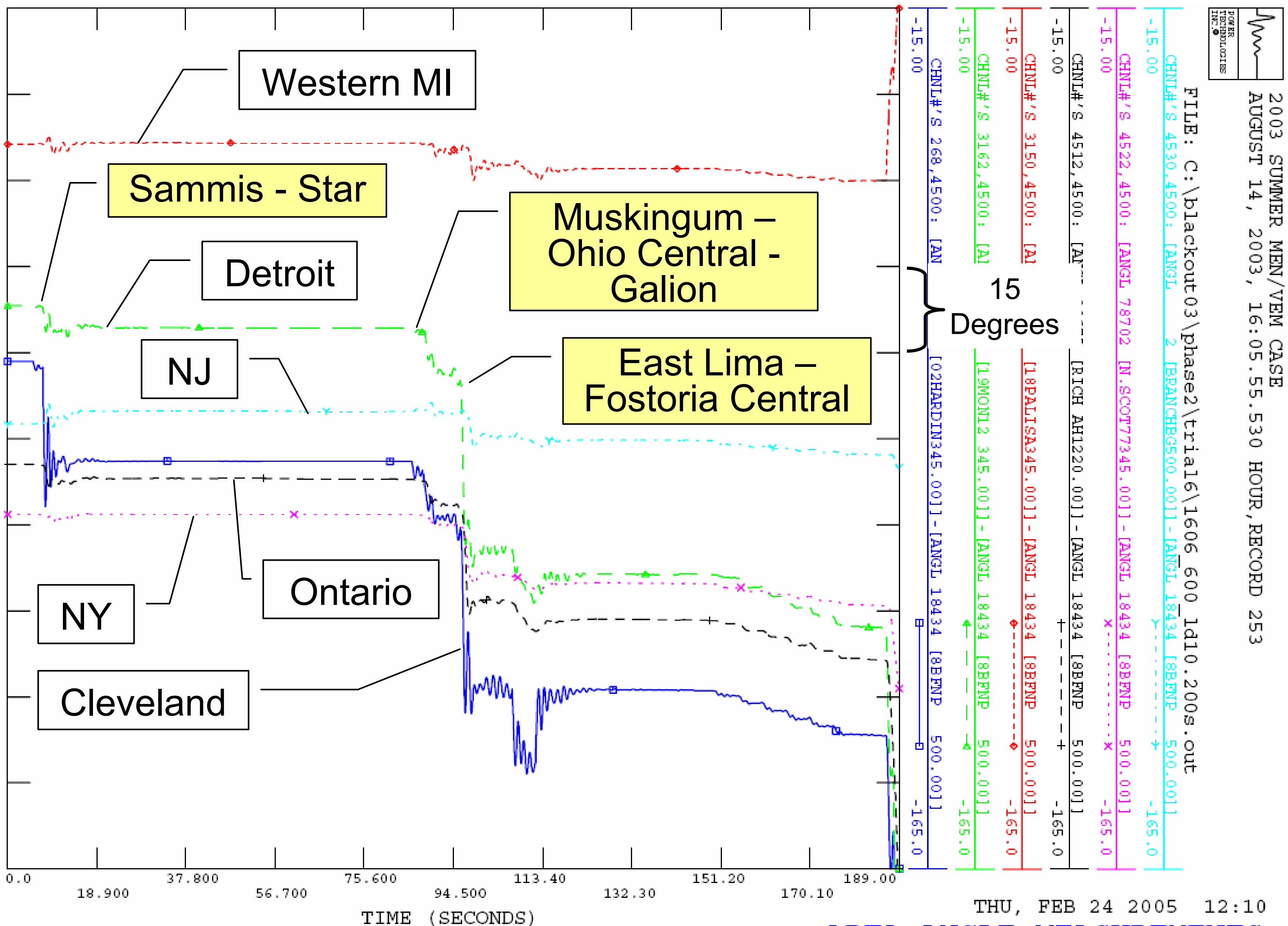


Angular Separation Analysis



Reference:
Browns Ferry

16:05:50 to 16:08:52



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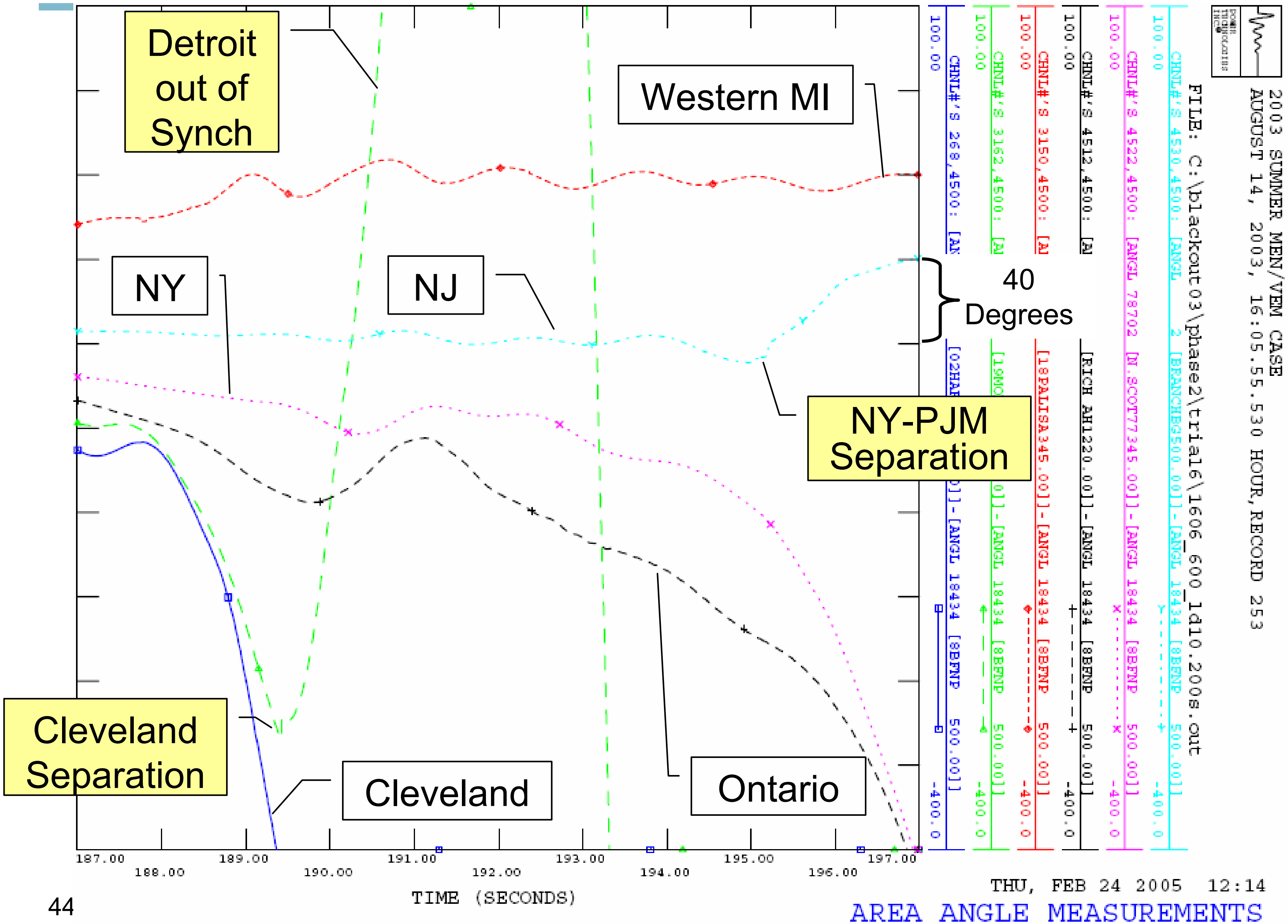
AREA ANGLE MEASUREMENTS

16:08:50 to 16:10:50



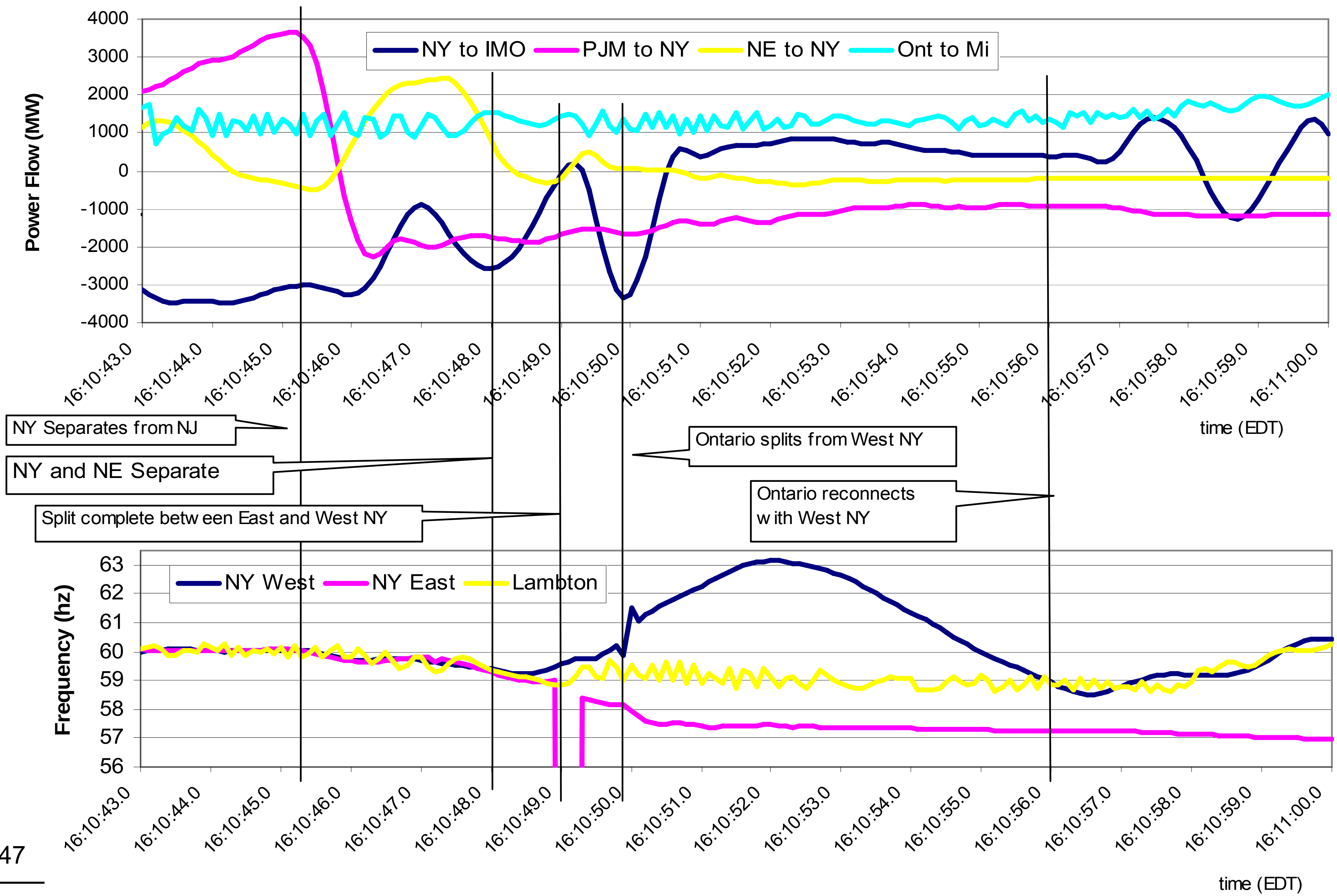
Dynamic Recording Devices

- Non-synchronized Disturbance Recorders
  - Monumental forensic analysis required
- Dynamic data supplied in multiple proprietary formats
  - Some files had format errors
- Ad-hoc software written to extract frequency and line power flows (real and reactive) from digital fault recorder (DFR) data

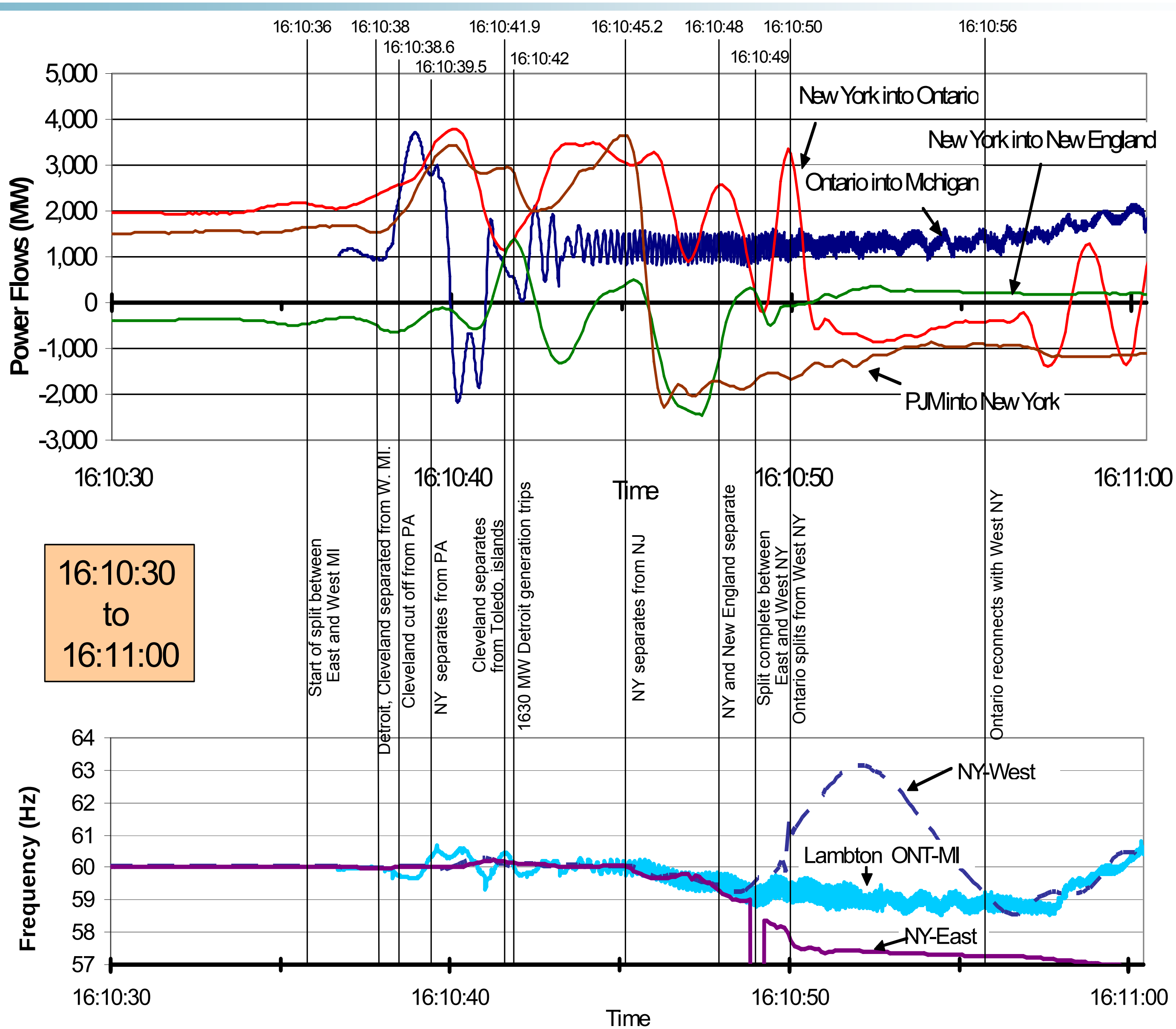
Digital Fault Recording Devices

- All such devices should …
  - Be GPS time synchronized.
  - Include a frequency trace.
  - Be periodically checked for calibration and operability
  - Have all data provided in IEEE/ANSI Comtrade standard C37.111-1999 format
  - Have file names in the IEEE common naming convention.
- Add digital readout of frequency requirement to the Comtrade standard.
- The disturbance data recording system should facilitate data storage and archiving capabilities.

NY Phasor Measurements (PMUs)

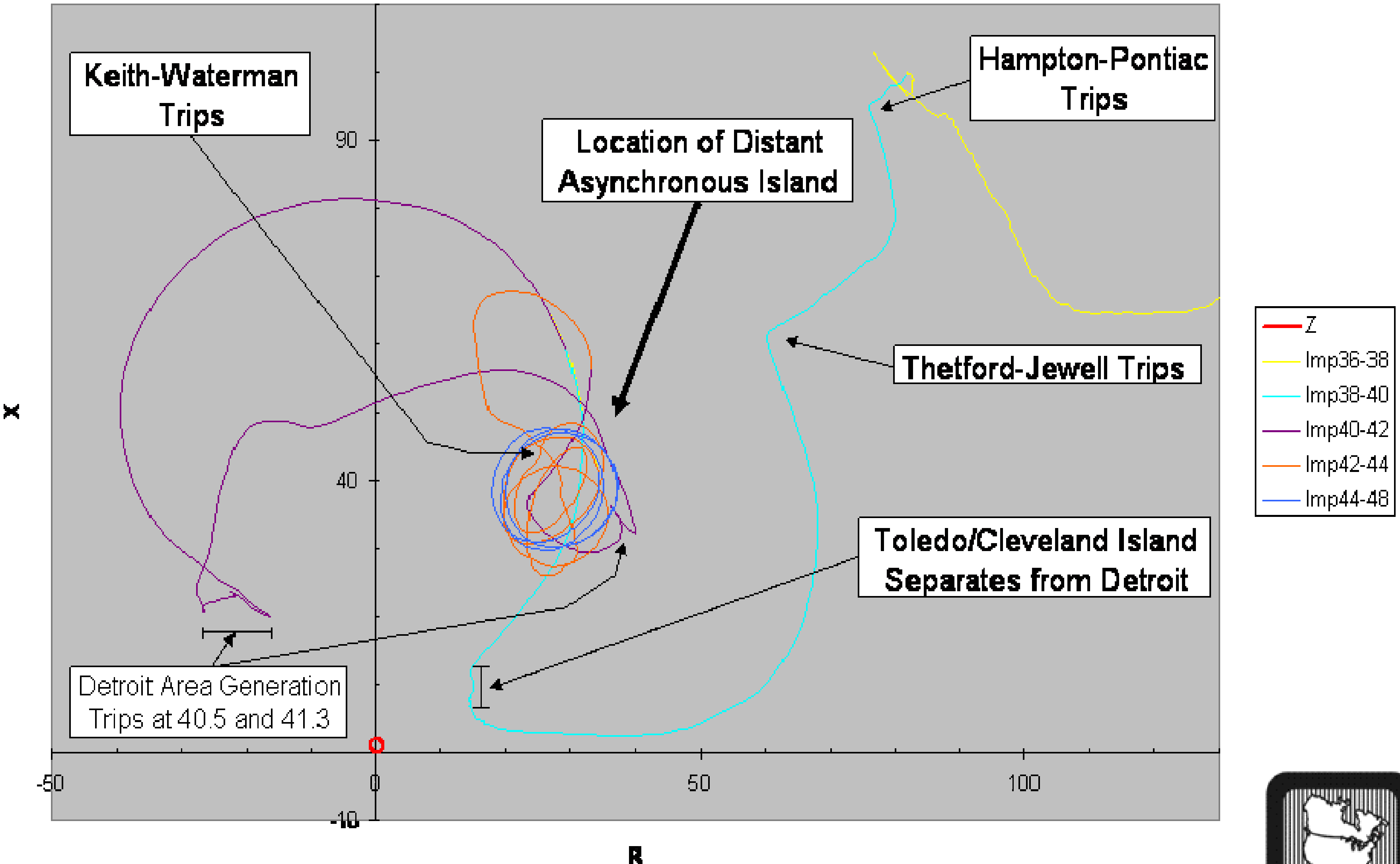


Ontario Power System Dynamic Recorders (PSDRs)



16:10:30
to
16:11:00

View Into Detroit from Lambton



System-Wide Analysis & Tools

- Power flow and dynamic analyses point toward
  - Need for situational awareness of line outages and their influence on operational security
  - Need for monitoring locational reactive reserves and resultant voltage profiles
  - Improved situational awareness for operators though early warning system based on zonal angular separation
    - Need for phasor measurements for wide-area

Questions?