ECEN 615
Methods of Electric Power Systems Analysis

Lecture 13: August 14, 2003 Blackout, ATC, Sensitivity Methods

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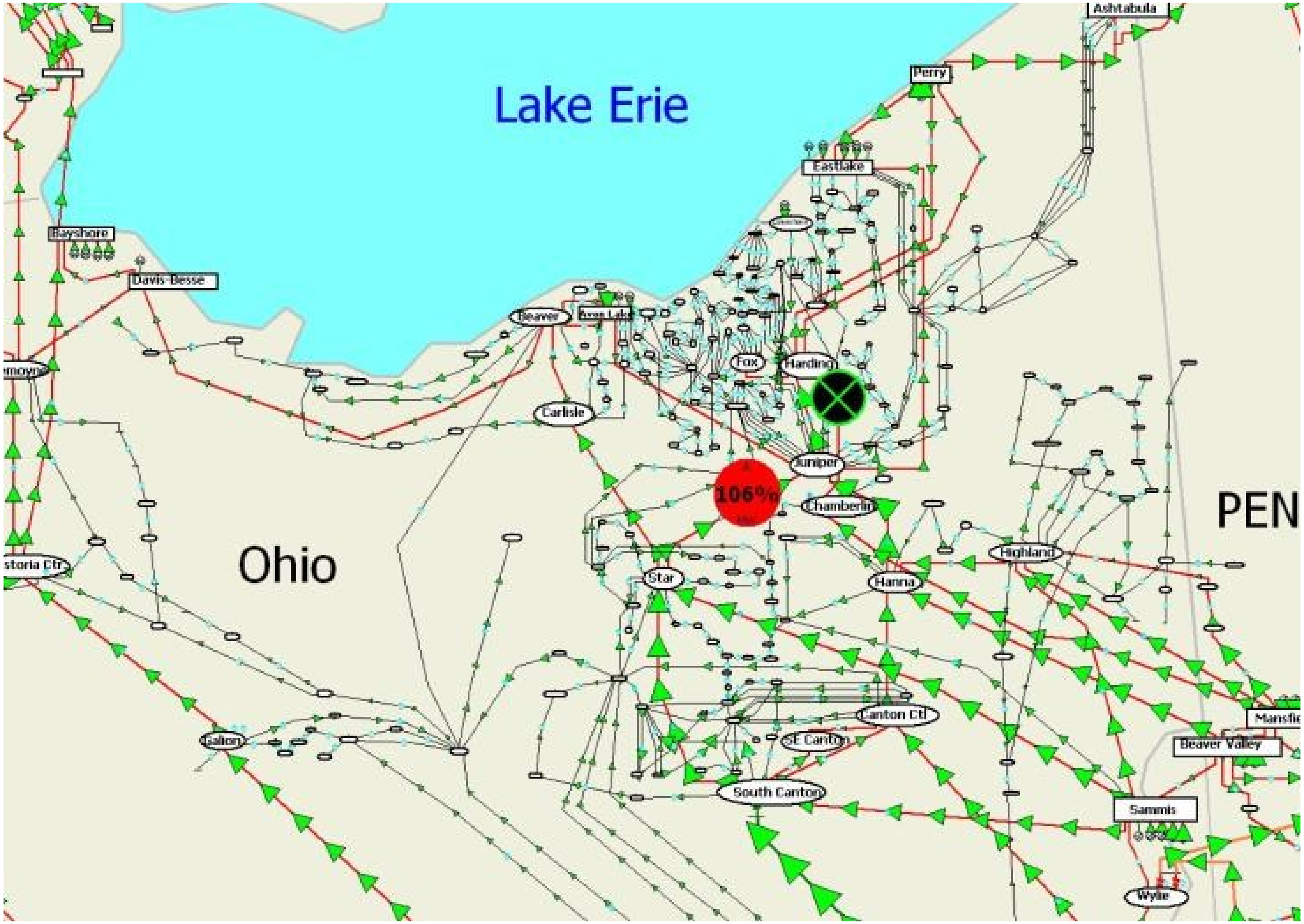
Announcements

- Read Chapter 7 from the book (the term reliability is now used instead of security)
- Exam average is 83 with a high of 93.

Estimated Flows in Northeast Ohio at 15:06 EDT



Line Outage Distribution Factors (LODFs)

- LODFs are used to approximate the change in the flow on one line caused by the outage of a second line
  - typically they are only used to determine the change in the MW flow
  - LODFs are used extensively in real-time operations
  - LODFs are state-independent (calculated using dc power flow approximations) but do dependent on the assumed network topology
  - Below value tells change of real power flow on line ℓ for the assumed outage of line k; f_k^0 is (obviously) pre-contingent

$$\Delta f_\ell = d_\ell \quad f^0$$

Flowgates

- The real-time loading of the power grid is accessed via "flowgates"
- A flowgate "flow" is the real power flow on one or more transmission element for either base case conditions or a single contingency
  - contingent flows are determined using LODFs
- Flowgates are used as proxies for other types of limits, such as voltage or stability limits
- Flowgates are calculated using a spreadsheet

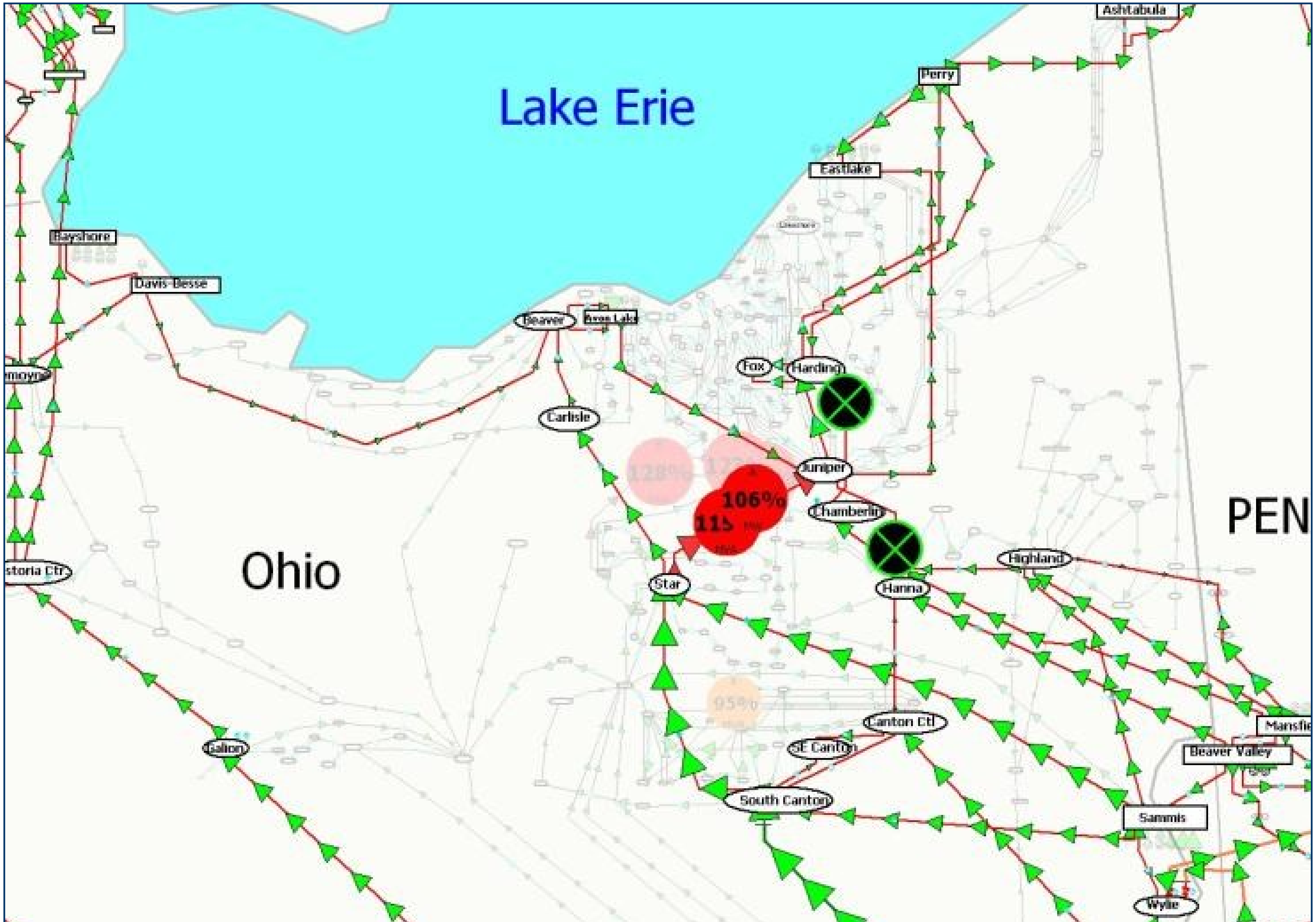
Flowgate #2265

- Flowgate 2265 monitors the flow on FE's Star-Juniper 345 kV line for contingent loss of the Hanna-Juniper 345 Line
  - normally the LODF for this flowgate is 0.361
  - flowgate has a limit of 1080 MW
  - at 15:05 EDT the flow as 517 MW on Star-Juniper, 1004 MW on Hanna-Juniper, giving a flowgate value of 520+0.361*1007=884 (82%)
  - Chamberlin-Harding 345 opened at 15:05; FE and MISO all missed seeing this

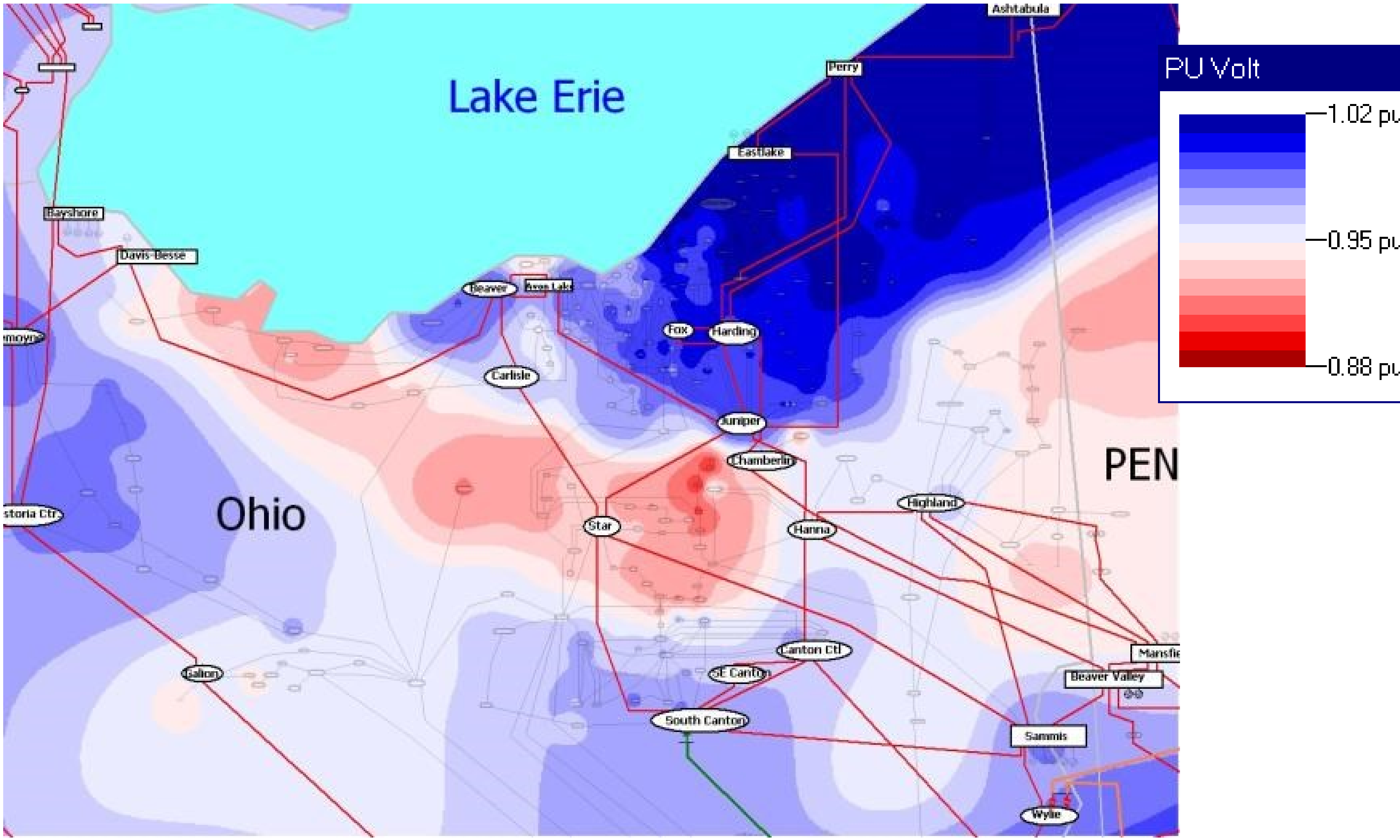
The Bad LODF that Maybe Blacked Out the Northeast

- At 15:06 EDT (after loss of Chamberlin-Harding 345) #2265 has an incorrect value because its LODF was not automatically updated.
  - Value should be 633+0.463*1174=1176 (109%)
  - Value was 633 + 0.361*1174=1057 (98%)
- At 15:32 the flowgate's contingent line opened, causing the flowgate to again show the correct value, about 107%

Flows at 15:33 EDT



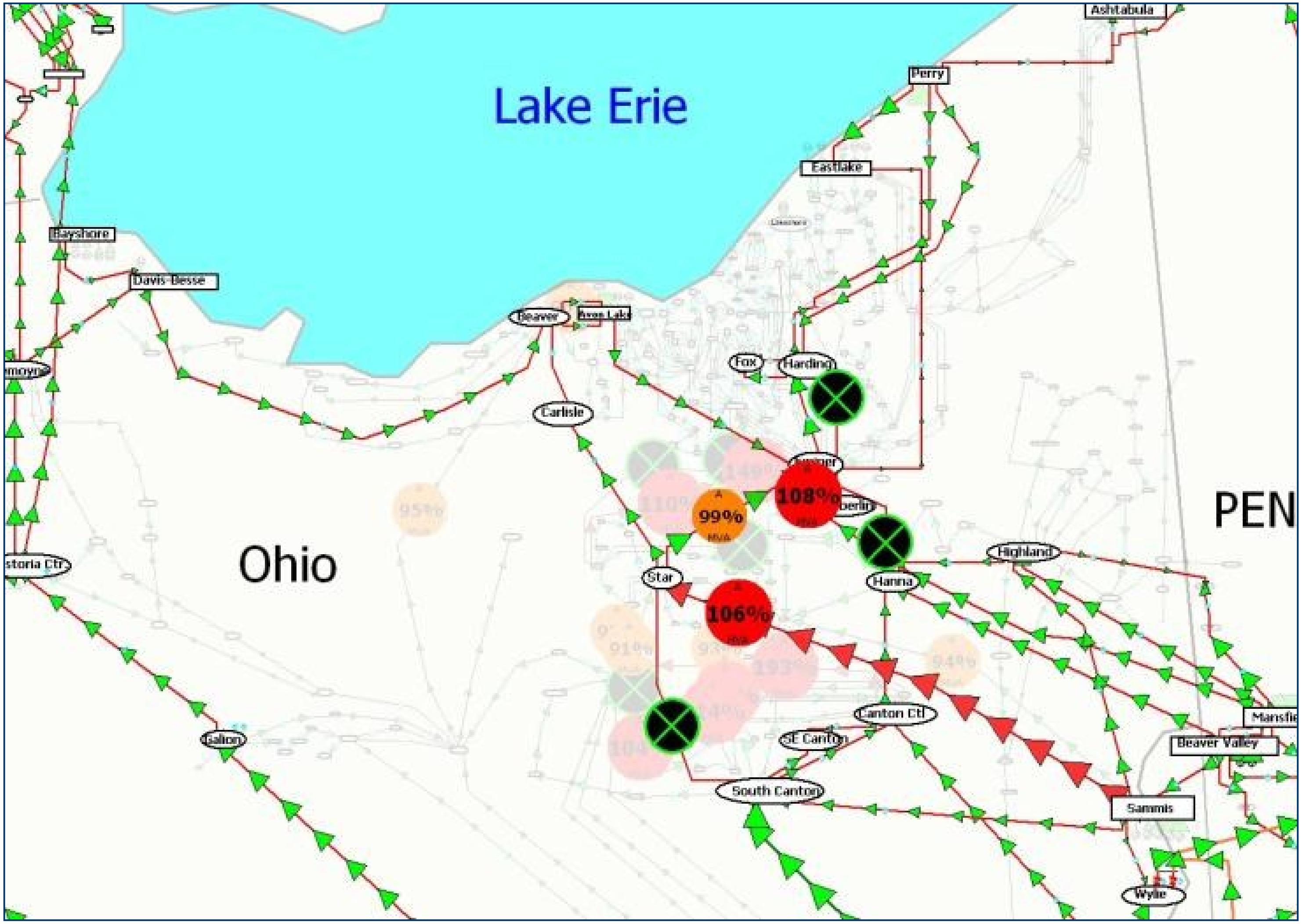
Estimated Northeast Ohio 138 kV Voltage Contour: 15:33 EDT



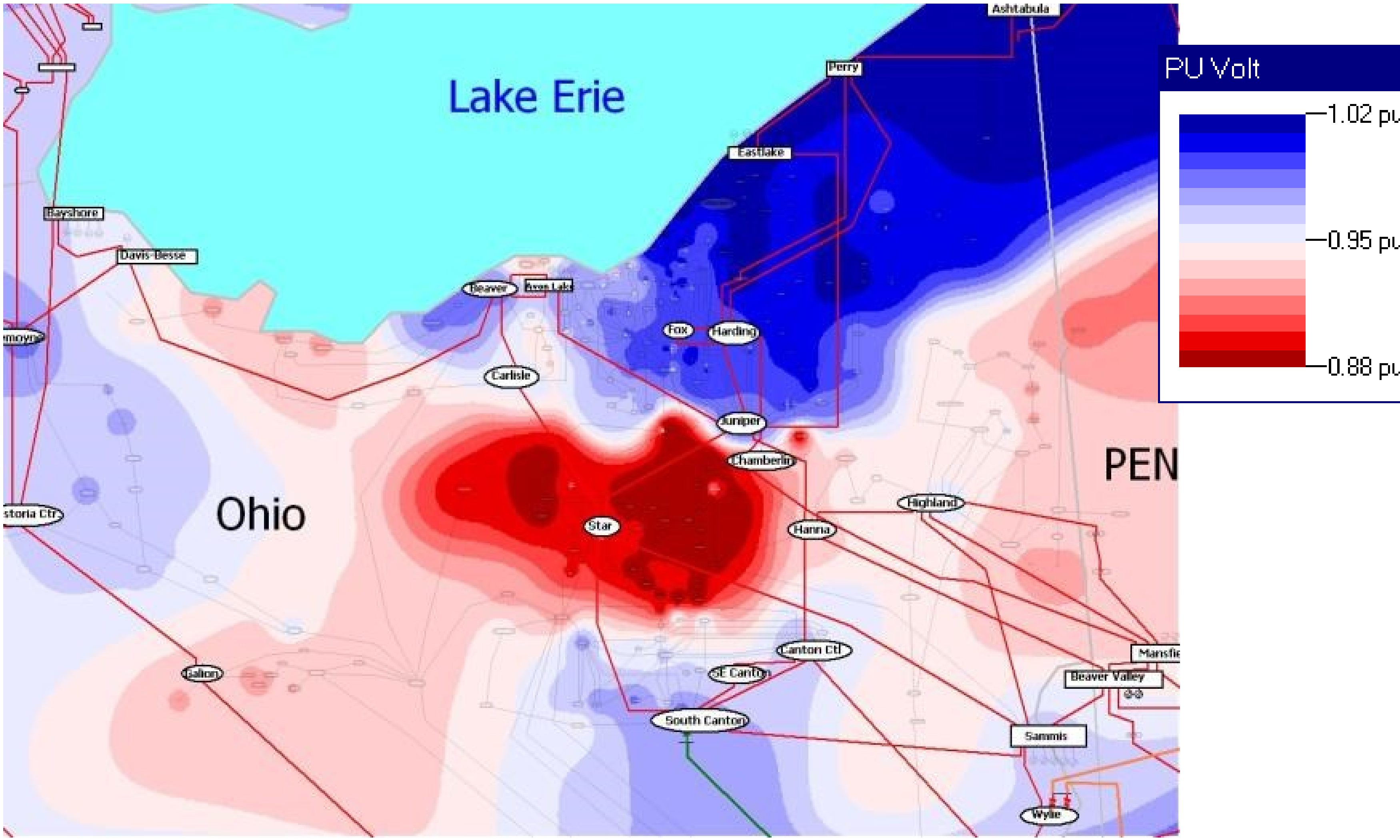
IT Issues

- MISO RCs had gotten many hundreds of "alarms"
- Contingency analysis results were giving pages of violations.
- SE would fail because of severe system stress
- Inadequate procedures for dealing with SE failure.
- FE control center would get "many phone calls;" information was not effectively shared.

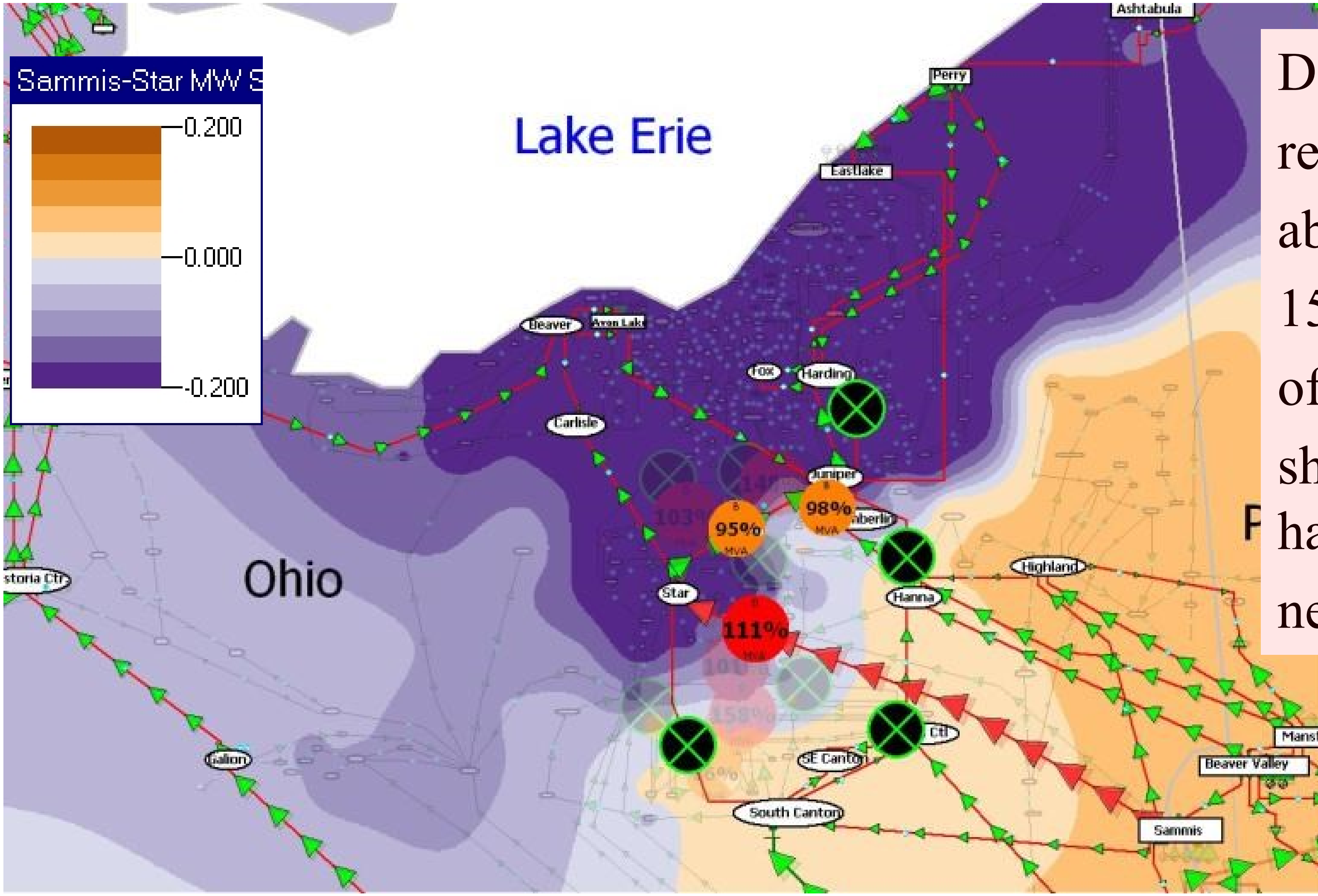
Estimated Flows in Northeast Ohio at 15:46 EDT on August 14th 2003



Estimated Northeast Ohio 138 kV Voltage Contour: 15:46 EDT

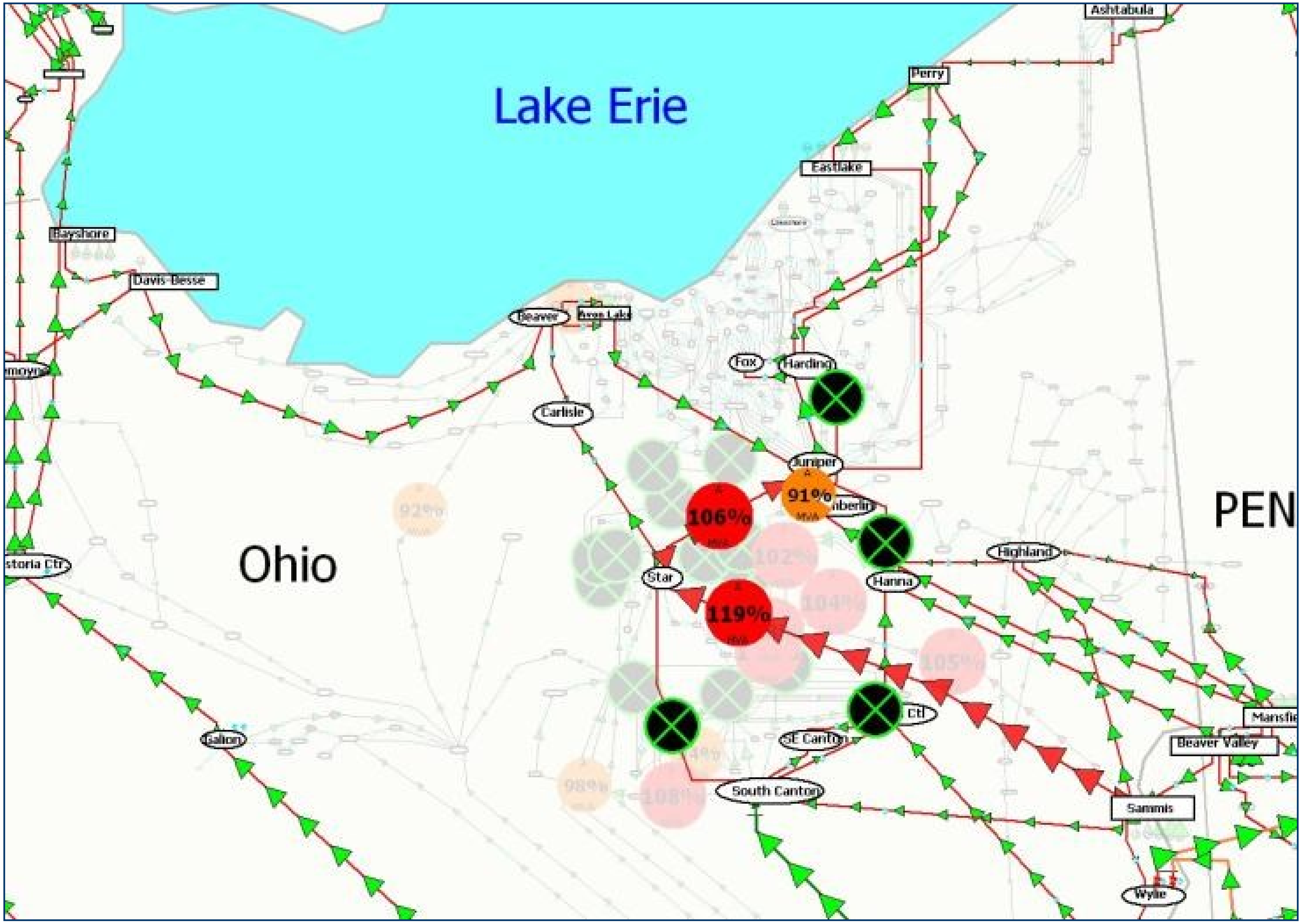


What Could Have Been Done? Sammis-Star Flow Sensitivities

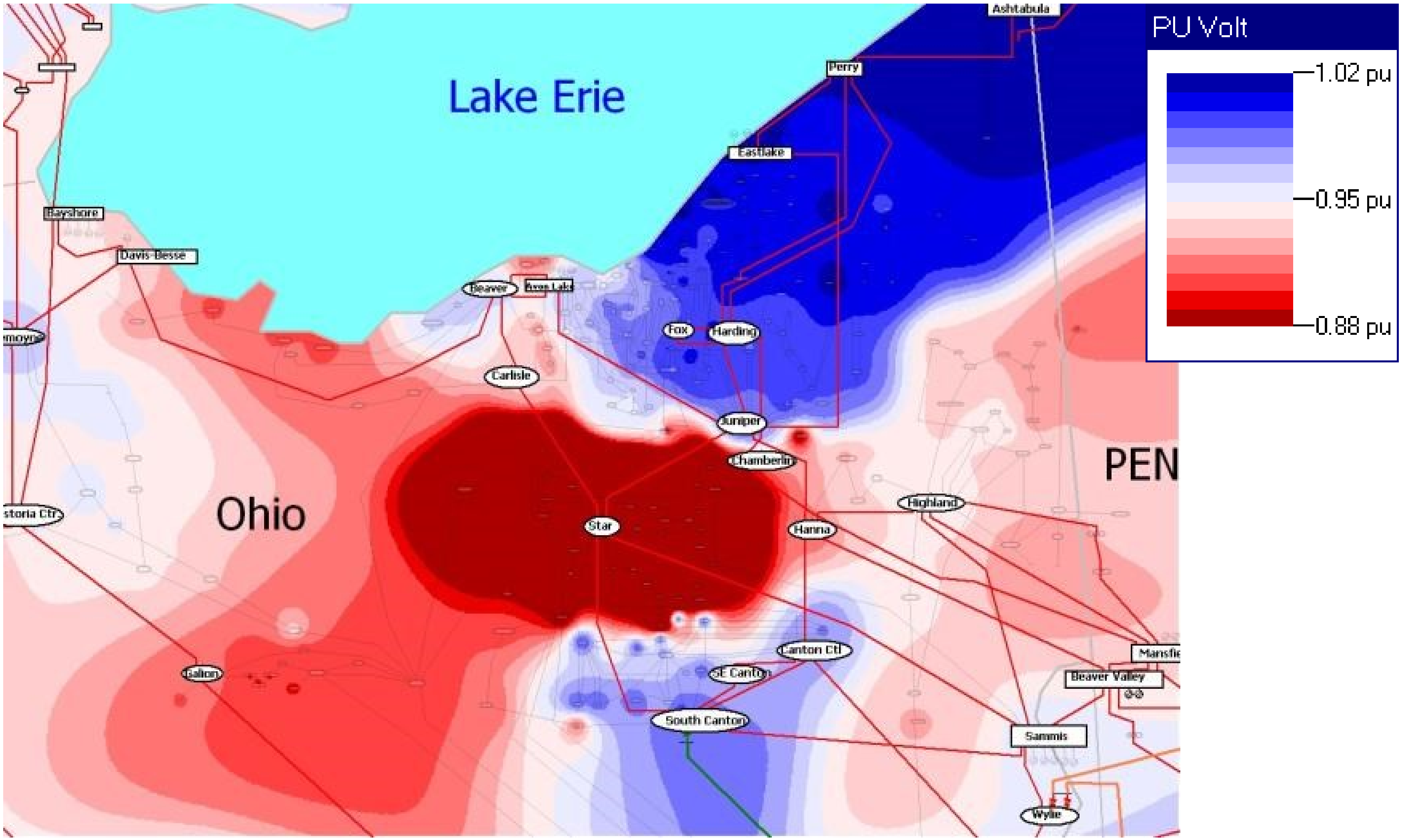


DOE/NERC report said about 1500 MW of load shed would have been needed

Estimated Flows in Northeast Ohio at 16:05 EDT on August 14th 2003



Estimated Northeast Ohio 138 kV Voltage Contour: 16:05 EDT



Path to Cleveland Blocked after Loss of Sammis-Star 16:05:57

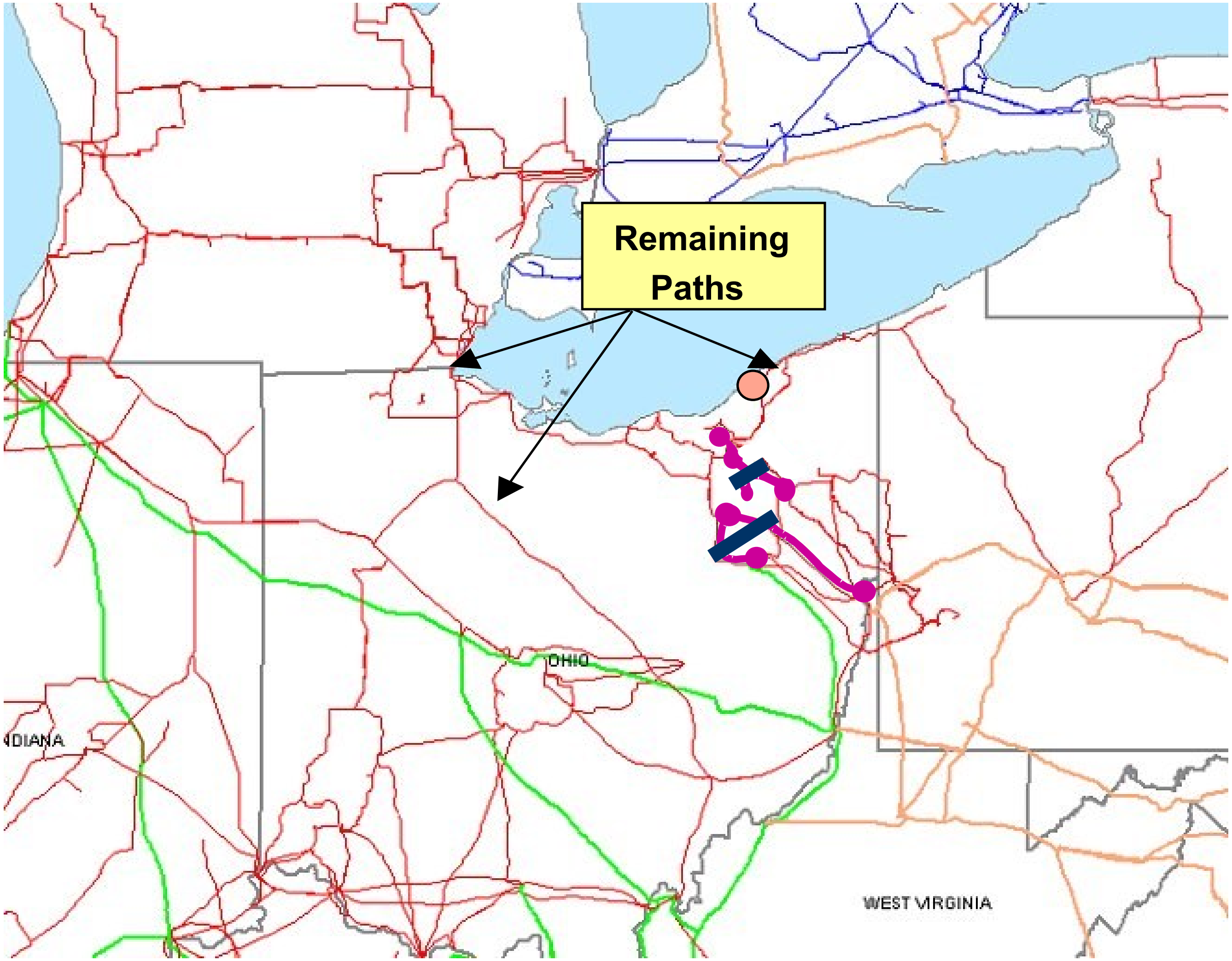
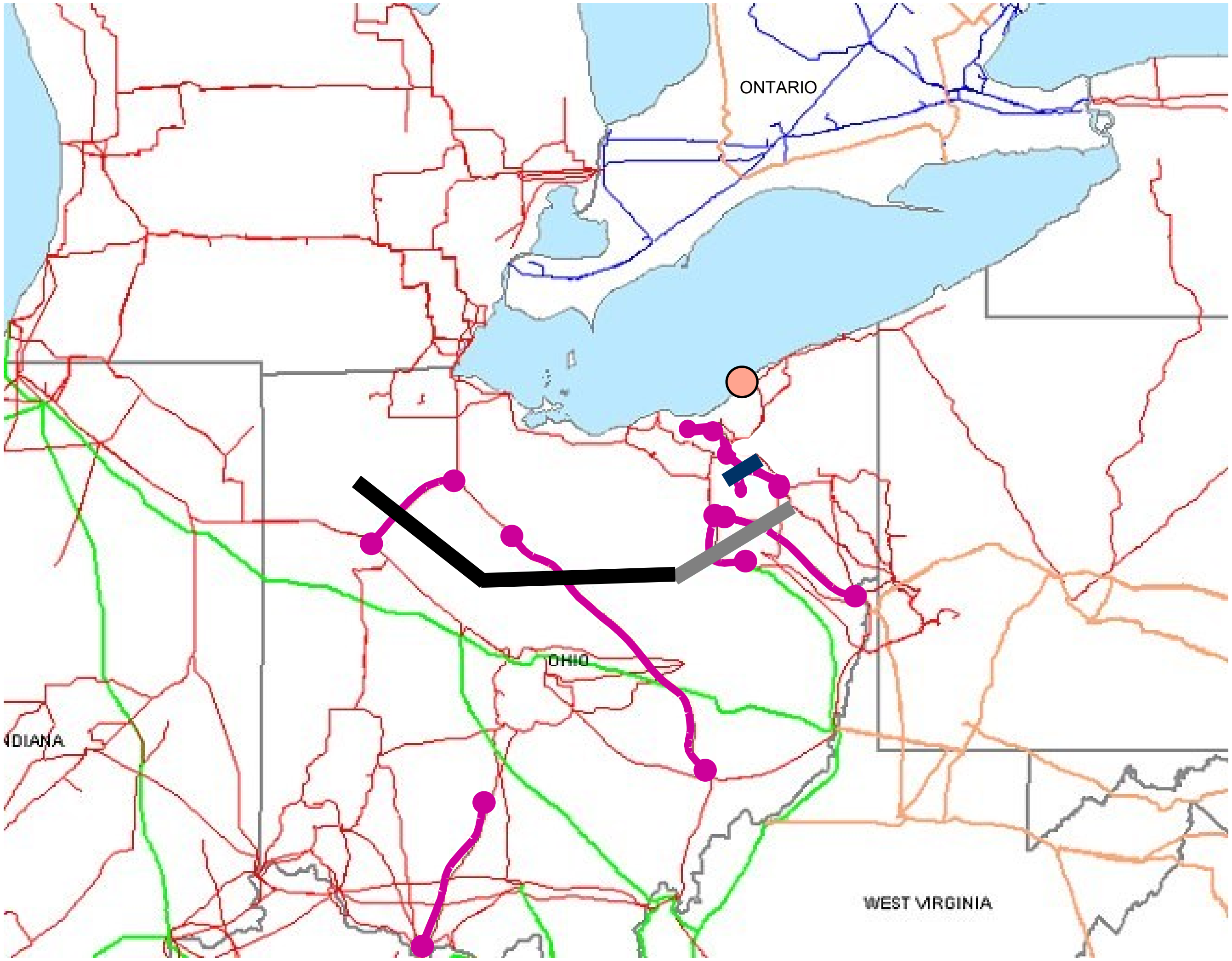


Image Source: August 14 2003 Blackout Final Report

345 kV Lines Trip Across Ohio to West at 16:09



Generation Trips 16:09:08 – 16:10:27

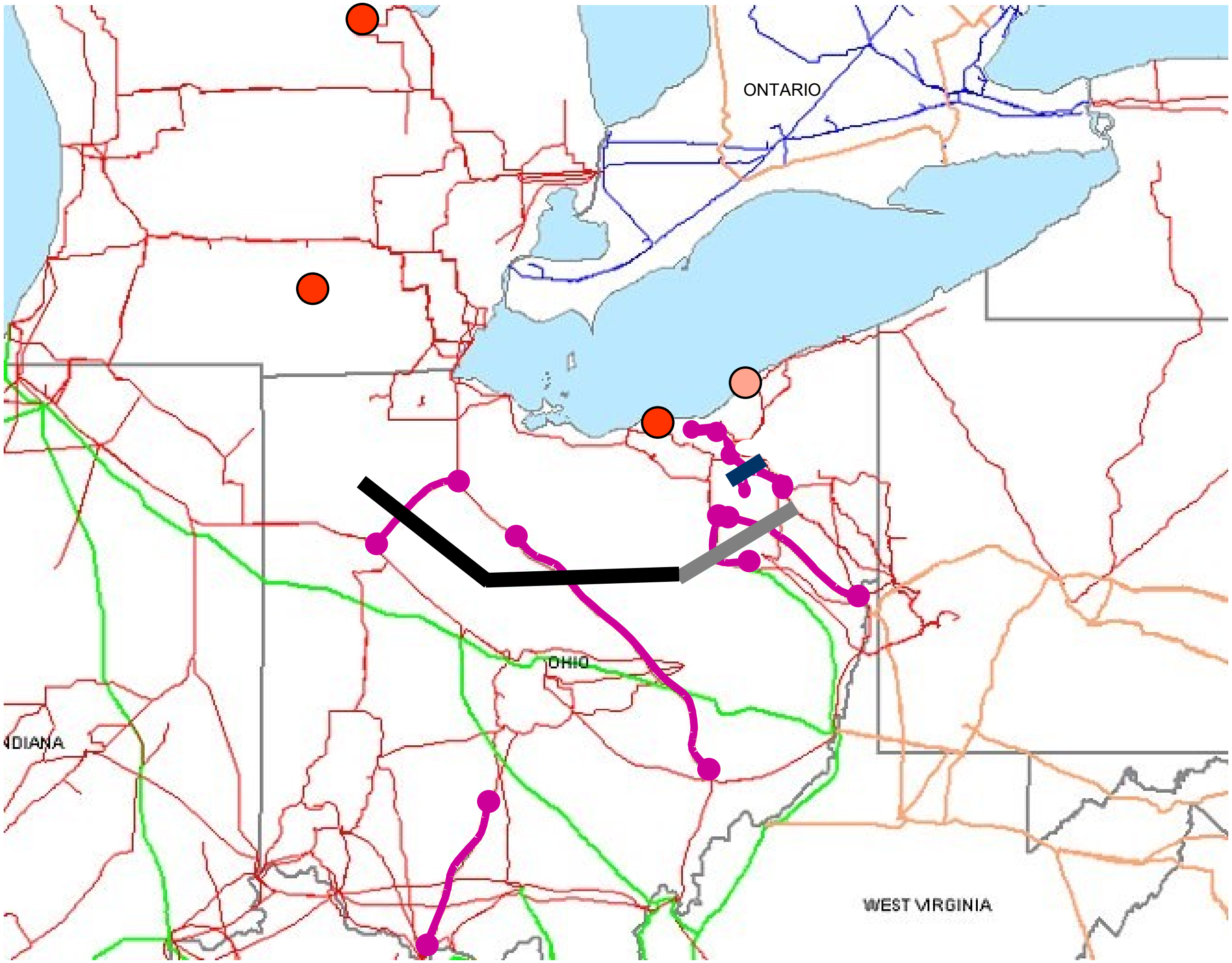


Image Source: August 14 2003 Blackout Final Report

Parts of Ohio/Michigan Served Only from Ontario after 16:10:37

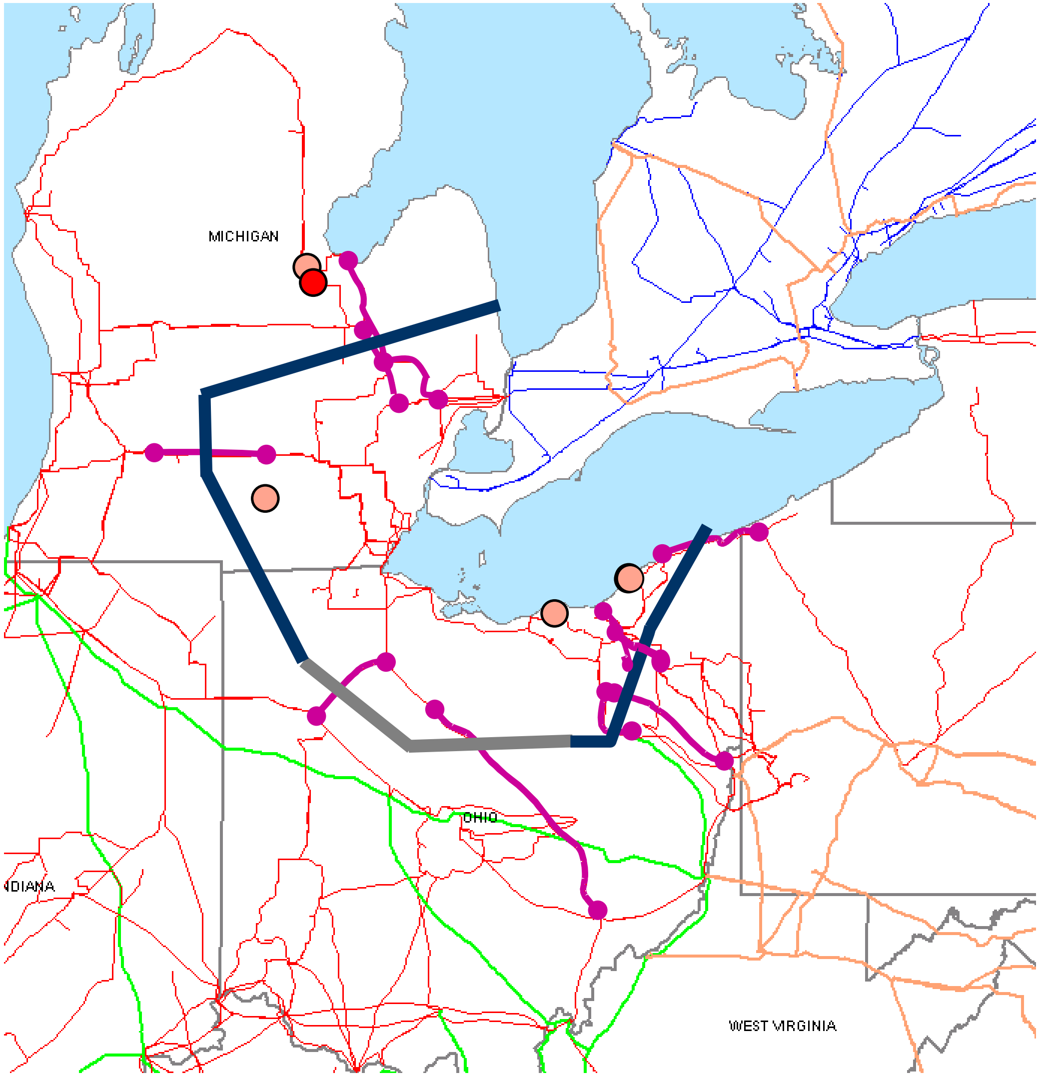


Image Source: August 14 2003 Blackout Final Report

Major Power Reversal: 16:10:38

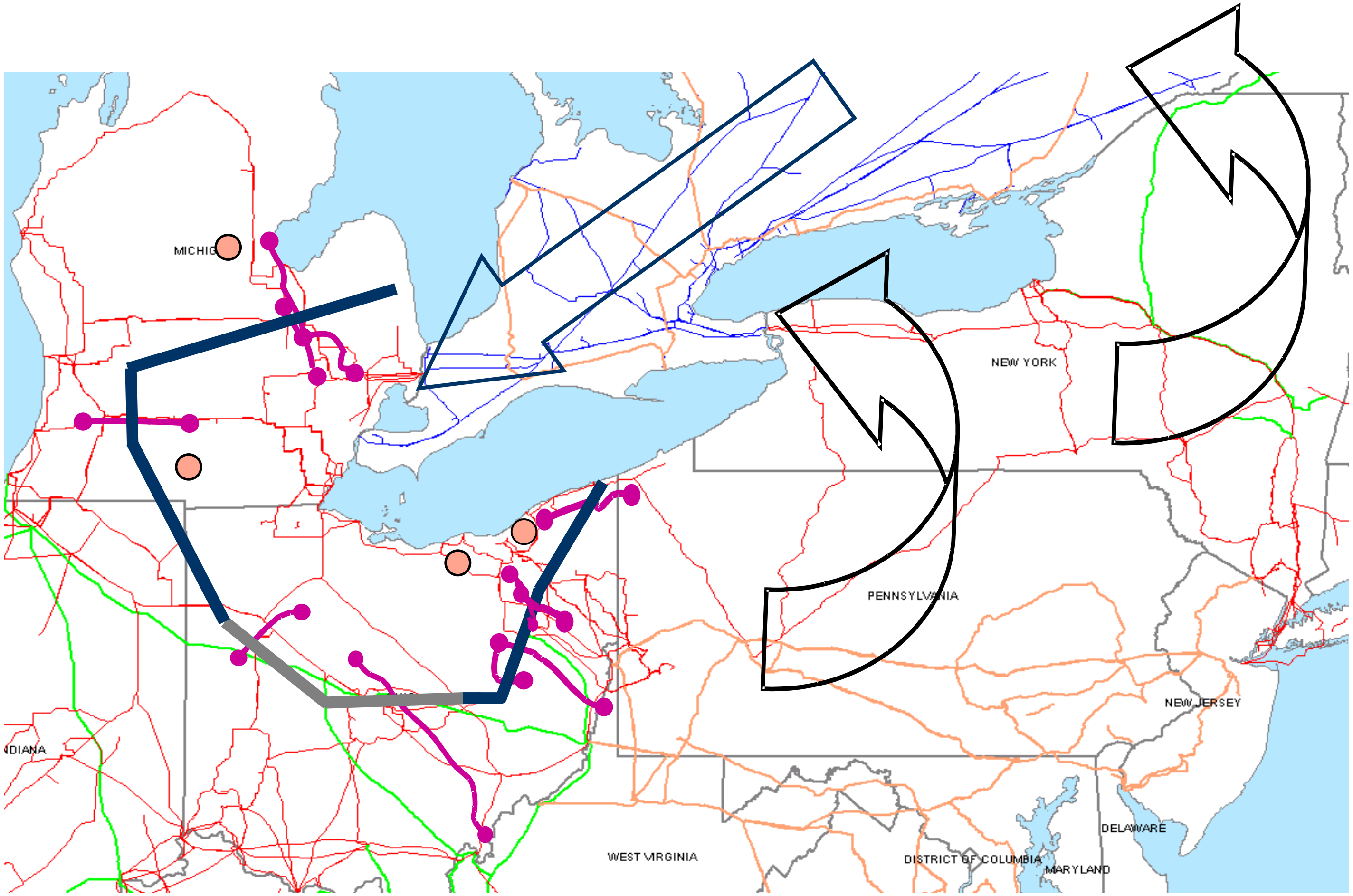


Image Source: August 14 2003 Blackout Final Report

Ontario/Michigan Interface Flows and Voltage

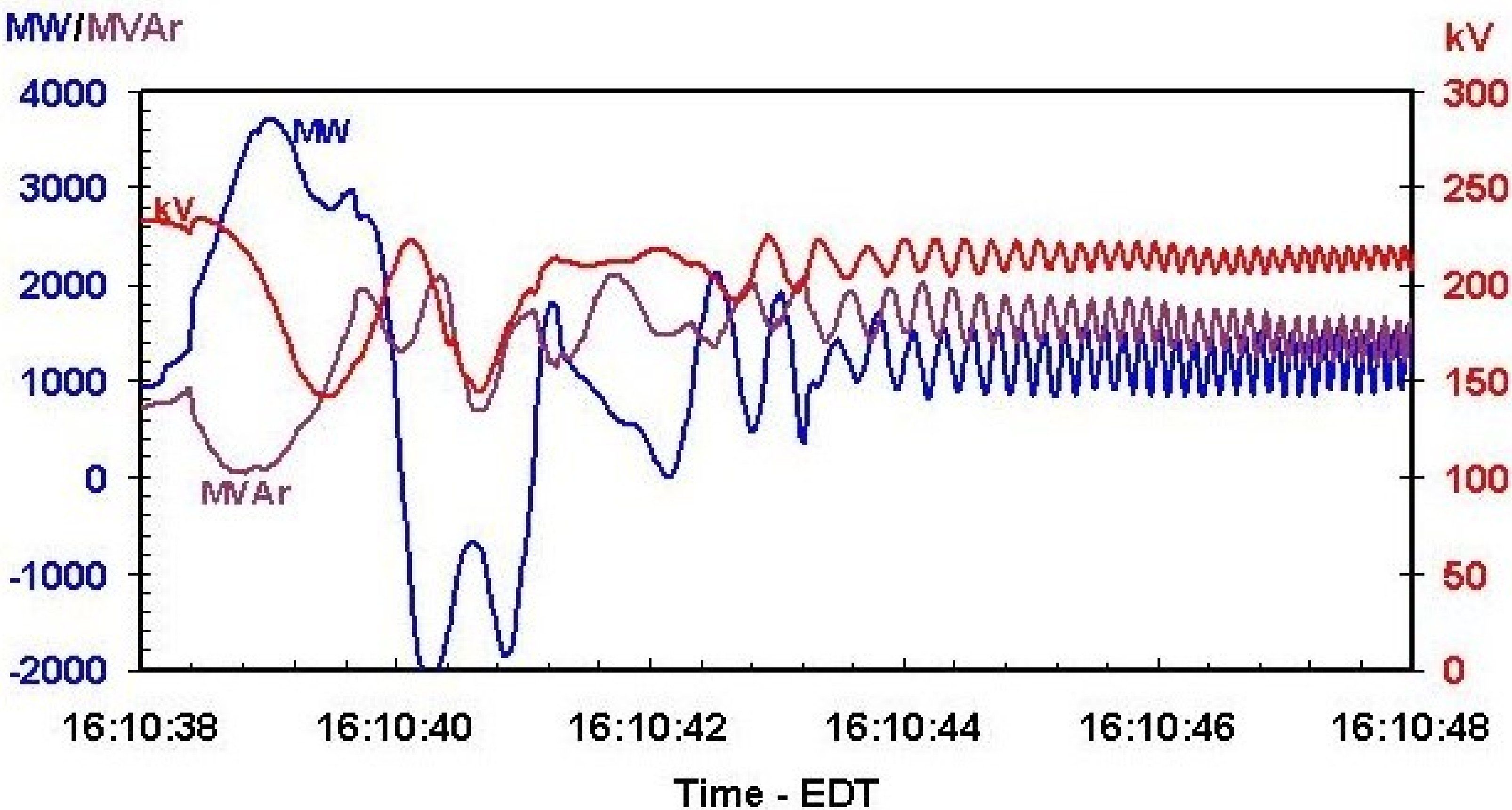


Image Source: August 14 2003 Blackout Final Report

Ties from PJM to New York Open: 16:10:44 (North Ohio Black)

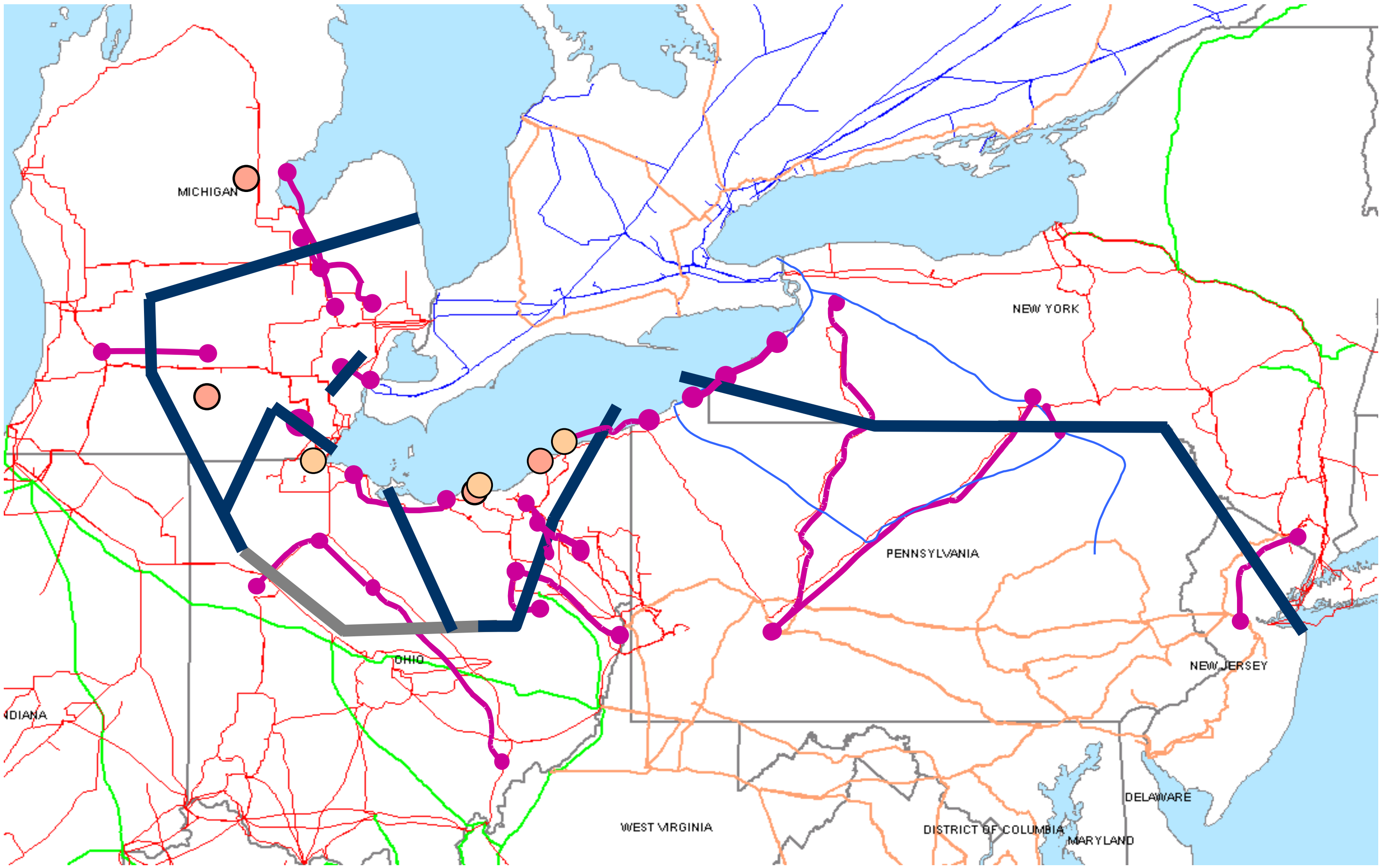


Image Source: August 14 2003 Blackout Final Report

System Islands Break Up and Collapse: 16:10-16:13

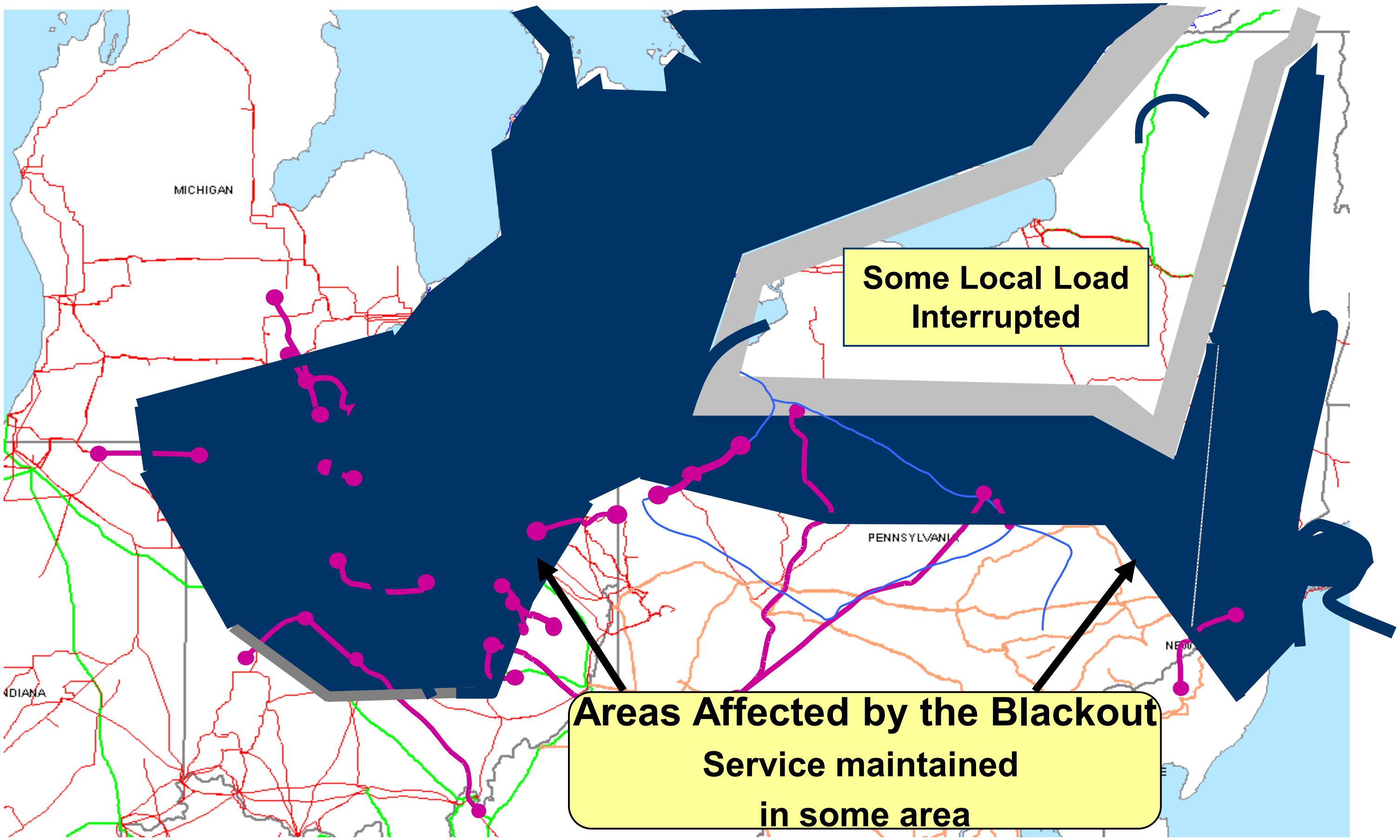


Image Source: August 14 2003 Blackout Final Report

Are DC LODFs Accurate? August 14th Crash Test

- Here are some results from August 14th

Time	Contingency	Element	LODF	ΔMW (pred)	ΔMW (act)
15:05	Chamberlin-Harding 345	Hanna-Juniper 345	0.362	179	176
15:32	Hanna-Juniper 345	Star-Juniper 345	0.465	545	527
15:46	CantonCentral-Cloverdale 138	Sammis-Star 345	0.164	48	54
15:46	same	Cloverdale-Star 138	0.234	68	64
16:06	Sammis-Star 345 Star-Urban 138 W.Canton-Dale 138	Star-Juniper 345	numerous	517	676
16:06	same	Ashtabula-Perry 345	numerous	319	408

The Results are Actually Quite Good!

- The initial LODF values were accurate to within a few percent
- Even after more than a dozen contingencies, with many voltages well below 0.9 pu, the purely DC LODF analysis was giving fairly good (with 25%) results

What Could Have Occurred on August 14th?

- With 20/20 Hindsight the blackout probably could have been prevented. A smarter grid might have provided the necessary situational awareness, and/or provided the dynamic load reduction necessary to keep the system from cascading.
- But key issues are 1) which grid improvement costs are cost justified, and 2) what are we missing?

How Could a Smart Grid Help?

- Under frequency and under voltage relays can provide quick reduction in the load, but they need to be smart enough to make the right decision
- Dynamic pricing (LMPs) can help customers make economic decisions, but they depend upon a variety of "advanced applications" in order to calculate the LMPs: state estimation converging to provide the model for the SCOPF

Some Thoughts on Current Needs

- The data used in the models for interconnect wide studies still have significant problems
- In US we have 100 GW of wind resources, but do not always have adequate models for transient stability studies; there are also potential low voltage ride through issues with solar
- Power grid is rapidly changing which can result in some operational "surprises"
- High impact, low frequency events are also a concern
- We need people with a deep knowledge of power systems and (fill in the blank)!

General Sensitivity Analysis: Notation

- We consider a system with n buses and L lines given by the set given by the set $L \ @ \{\ell_{\_}\ \ell_{\_}\ \cdots\ \ell_{\_}$
  - Some authors designate the slack as bus zero; an alternative approach, that is easier to implement in cases with multiple islands and hence slacks, is to allow any bus to be the slack, and just set its associated equations to trivial equations just stating that the slack bus voltage is constant
- We may denote the k[th] transmission line or transformer in the system, ?$_k$, as

$$\ell_{..} \ @ \ \quad _{..} \quad _{k}),$$

from node

to node

Notation, cont.

- We'll denote the real power flowing on ℓ_k from bus i to bus j as f_k
- The vector of real power flows on the *L* lines is:

$$\mathbf{f} @ [f_{\ell} \quad f_{\ell} \quad \cdots$$

which we simplify to $\mathbf{f} = [f_1, f_2, \cdots$

- The bus real and reactive power injection vectors are

$$\mathbf{p} @ [p^1, p^2, \cdots \quad {}^T$$

$$\mathbf{q} @ [q^1, q^2, \cdots \quad {}^T$$

Notation, cont.

- The series admittance of line ⍰ is $g_{⍰} + jb_{⍰}$ and we define

$$\tilde{L} \;@\; \ldots g\{b_1, b_2, \cdots\}$$

- We define the L×N incidence matrix

$$\mathbf{A} \;@\; \begin{bmatrix} \mathbf{a}_1^T \\ \mathbf{a}_2^T \\ \vdots \\ \mathbf{a}_L^T \end{bmatrix}$$

The component j of $\mathbf{a}_i$ is nonzero whenever line $⍰_i$ is coincident with node j. Hence **A** is quite sparse, with two nonzeros per row

Analysis Example: Available Transfer Capability

- The power system available transfer capability or ATC is defined as the maximum additional MW that can be transferred between two specific areas, while meeting all the specified pre- and post-contingency system conditions
- ATC impacts measurably the market outcomes and system reliability and, therefore, the ATC values impact the system and market behavior
- A useful reference on ATC is *Available Transfer Capability Definitions and Determination* from NERC, June 1996 (available online)

ATC and Its Key Components

- Total transfer capability (TTC)
  - Amount of real power that can be transmitted across an interconnected transmission network in a reliable manner, including considering contingencies
- Transmission reliability margin (TRM)
  - Amount of TTC needed to deal with uncertainties in system conditions; typically expressed as a percent of TTC
- Capacity benefit margin (CBM)
  - Amount of TTC needed by load serving entities to ensure access to generation; typically expressed as a percent of TTC

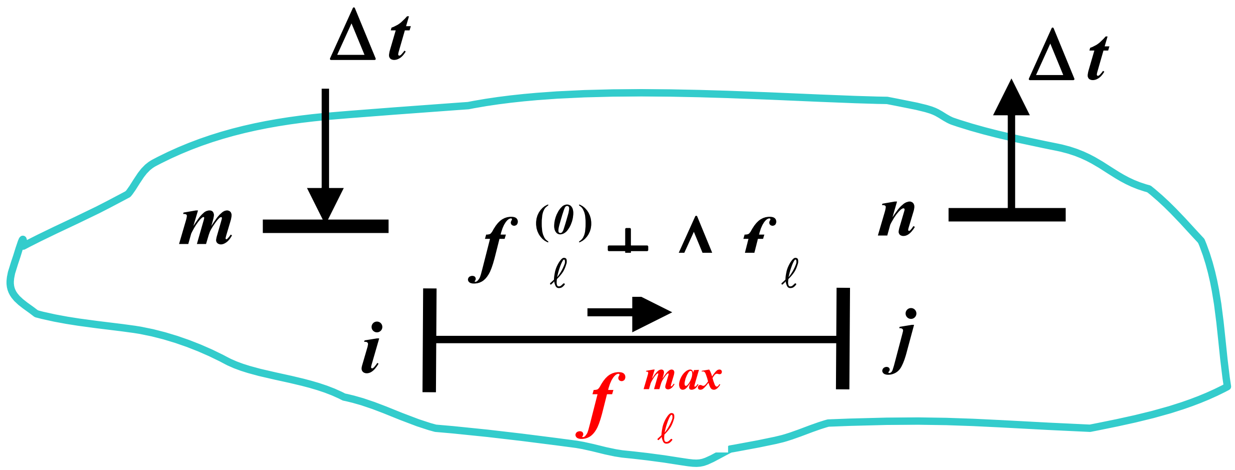
ATC and Its Key Components

- Uncommitted transfer capability (UTC)

  UTC ⍰ TTC – existing transmission commitment
- Formal definition of ATC is

  ATC ⍰ UTC – CBM – TRM
- We focus on determining $U_{m,n}$, the UTC from node m to node n
- $U_{m,n}$ is defined as the maximum additional MW that can be transferred from node m to node n without violating any limit in either the base case or in any post-contingency conditions

UTC (or TTC) Evaluation



Goal is to load the lines up to a limit is hit

$$U_{m,n} = \max \; \Delta t$$

$s.t.$

$$f_\ell^{(j)} + \Delta f_\ell < f_\ell^{max} \quad \forall \ell \in L$$

for the base case $j = 0$ and each contingency case

$$j = 1, 2 \; \ldots \; , J$$

Conceptual Solution Algorithm

1. Solve the initial power flow, corresponding to the initial system dispatch (i.e., existing commitments); set the change in transfer $\Delta t^{(0)} = 0$, k=0; set step size δ; j is used to indicate either the base case (j=0) or a contingency, j= 1,2,3…J
2. Compute $\Delta t^{(k+1)} = \Delta t^{(k)} + \delta$
3. Solve the power flow for the new $\Delta t^{(k+1)}$
4. Check for limit violations: if violation is found set $U^{j}_{m,n} = \Delta t^{(k)}$ and stop; else set k=k+1, and goto 2

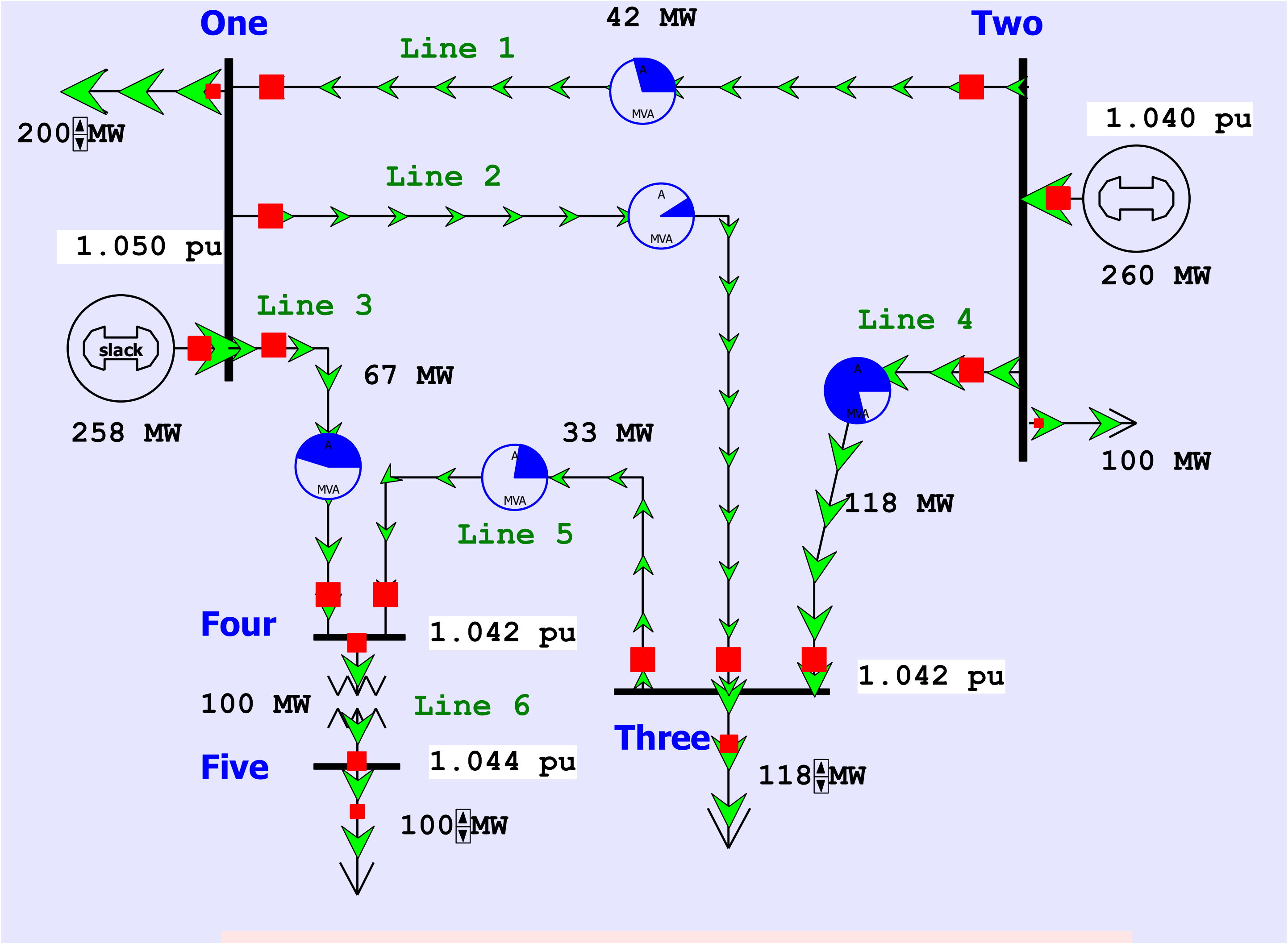
Conceptual Solution Algorithm, cont.

- This algorithm is applied for the base case (j=0) and each specified contingency case, j=1,2,..J
- The final UTC, $U_{m,n}$ is then determined by

$$U_{m,n} = \min_{0 \le j \le J} \left\{ U_{m,n}^{(j)} \right\}$$

- This algorithm can be easily performed on parallel processors since each contingency evaluation is independent of the other

Five Bus Example: Reference



PowerWorld Case: **B5_DistFact**

Five Bus Example: Reference

ℓ	i	j	g_ℓ	b_ℓ	$f_\ell^{max}\ (MW)$
ℓ	1	2	*0*	6.25	150
ℓ	*1*	3	*0*	12.5	400
ℓ	*1*	4	*0*	12.5	150
ℓ	2	3	*0*	12.5	150
ℓ	3	4	*0*	12.5	150
ℓ	4	5	*0*	10	1,000

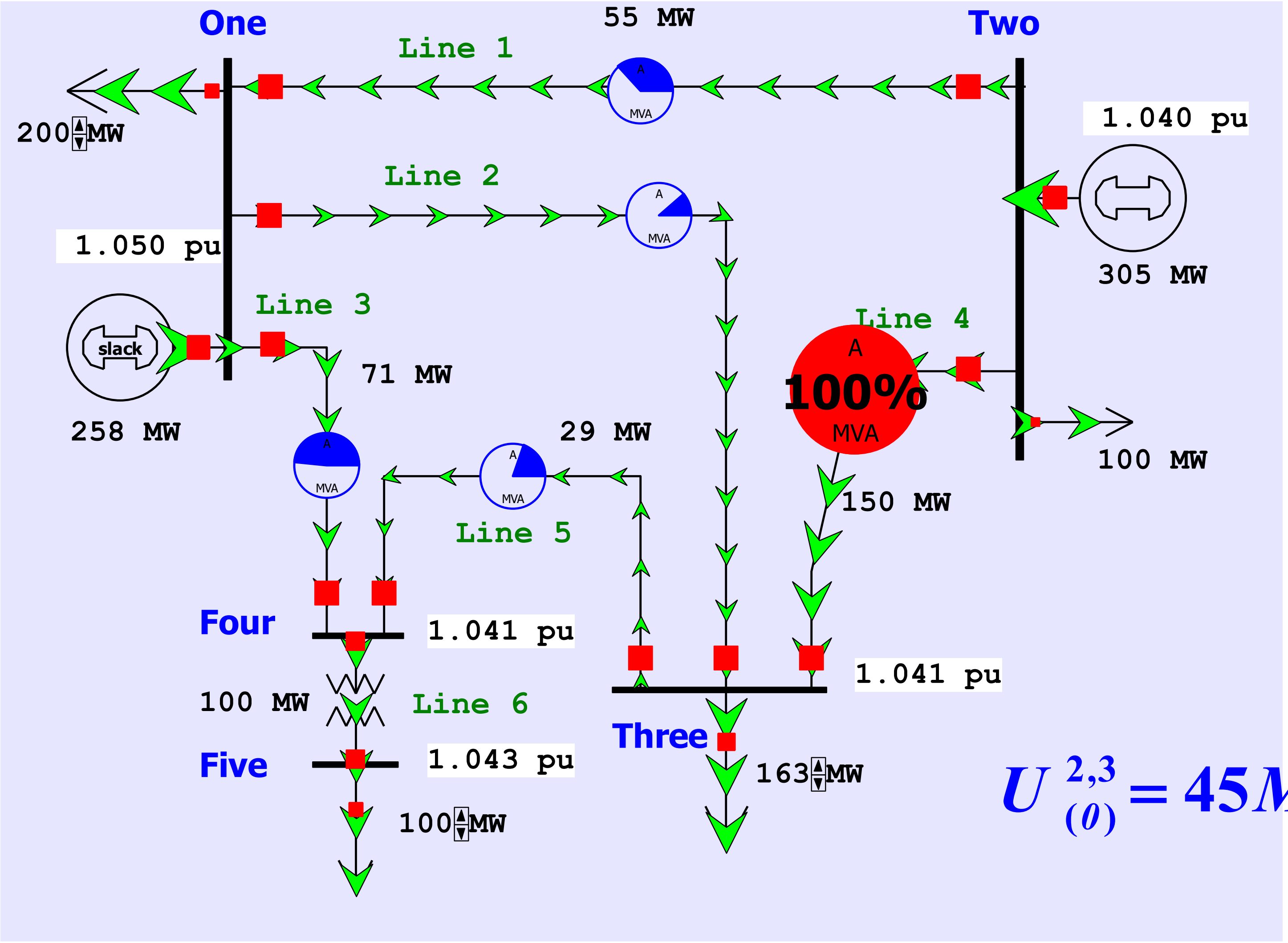
Five Bus Example

- We evaluate $U_{2,3}$ using the previous procedure
  - Gradually increase generation at Bus 2 and load at Bus 3
- We consider the base case and the single contingency with line 2 outaged (between 1 and 3): $J = 1$
- Simulation results show for the base case that

$$U_{2,3}^{(0)} = 45\ MW$$

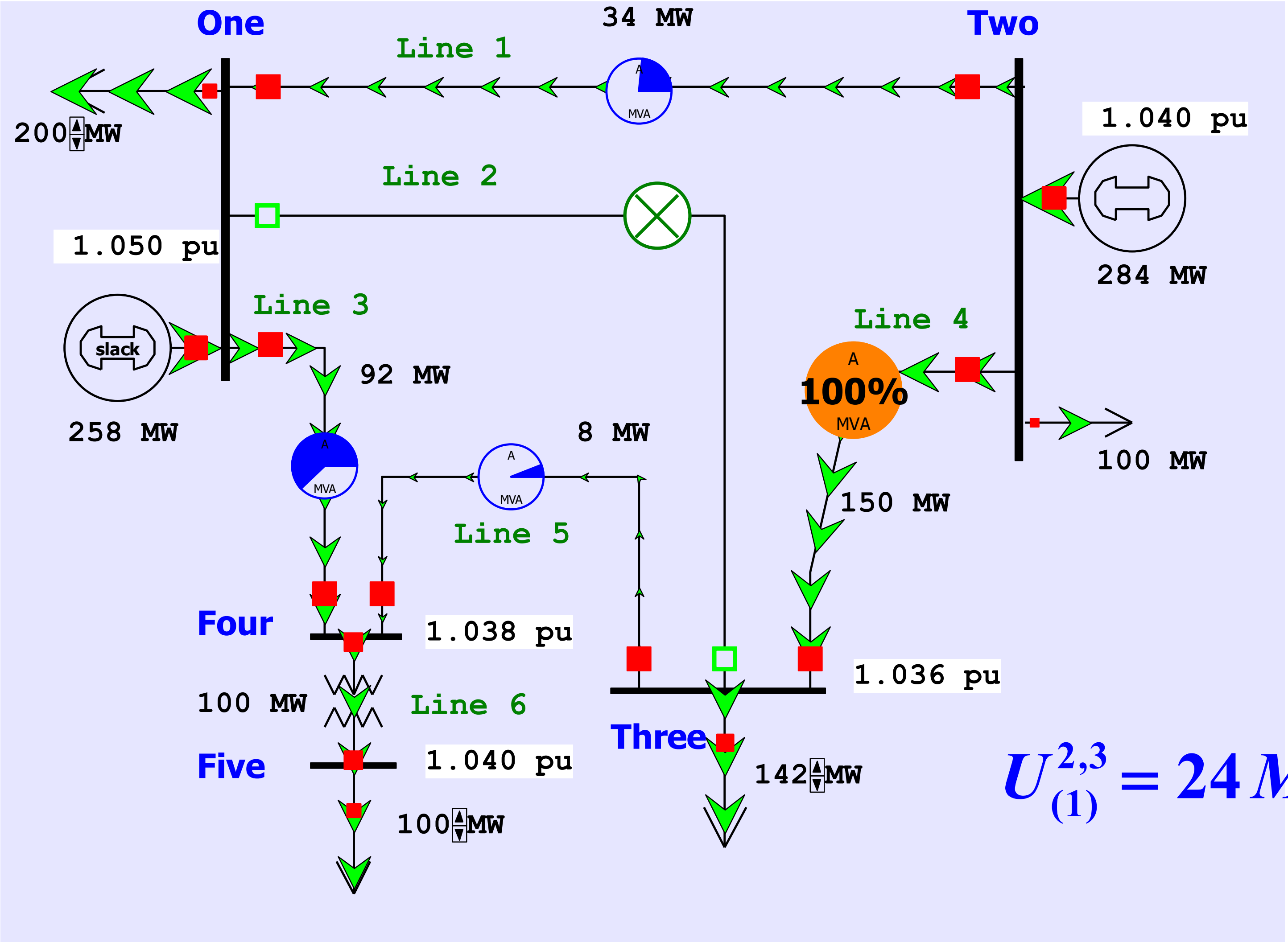
- And for the contingency that $U_{2,3}^{(1)} = 24\ MW$
- Hence $U_{2,3} = min\left\{ U_{2,3}^{(0)}, U_{2,3}^{(1)} \right\} = 24\ MW$

Five Bus: Maximum Base Case Transfer



$$U^{2,3}_{(0)} = 45MW$$

Five Bus: Maximum Contingency Transfer



$$U_{(1)}^{2,3} = 24\ MW$$

Computational Considerations

- Obviously such a brute force approach can run into computational issues with large systems
- Consider the following situation:
  - 10 iterations for each case
  - 6,000 contingencies
  - 2 seconds to solve each power flow
- It will take over 33 hours to compute a single UTC for the specified transfer direction from m to n.
- Consequently, there is an acute need to develop fast tools that can provide satisfactory estimates