Slow Coherency Based Controlled Islanding in Large Power Systems

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Motivation

- Power systems are under increasing stress as restructuring introduces several new economic objectives for operation
- When a power system is subjected to large disturbances, and the designed remedial action or protection system does not work, the system approaches a potential catastrophic failure
- Appropriate mitigation actions need to be taken to steer the system away from severe consequences, to **limit** the extent of the disturbance, and to **facilitate** power system restoration

Mitigation Strategy

- In our approach, the system is first separated into several smaller islands at a slightly reduced capacity by a controlled islanding approach. Second, an adaptive load shedding scheme is deployed to bring back the frequency to an acceptable level
- The basis for forming the islands is to **minimize the load-generation imbalance** in each island, thereby facilitating the restoration process

Slow Coherency Grouping Based Islanding Using Minimal Cutsets

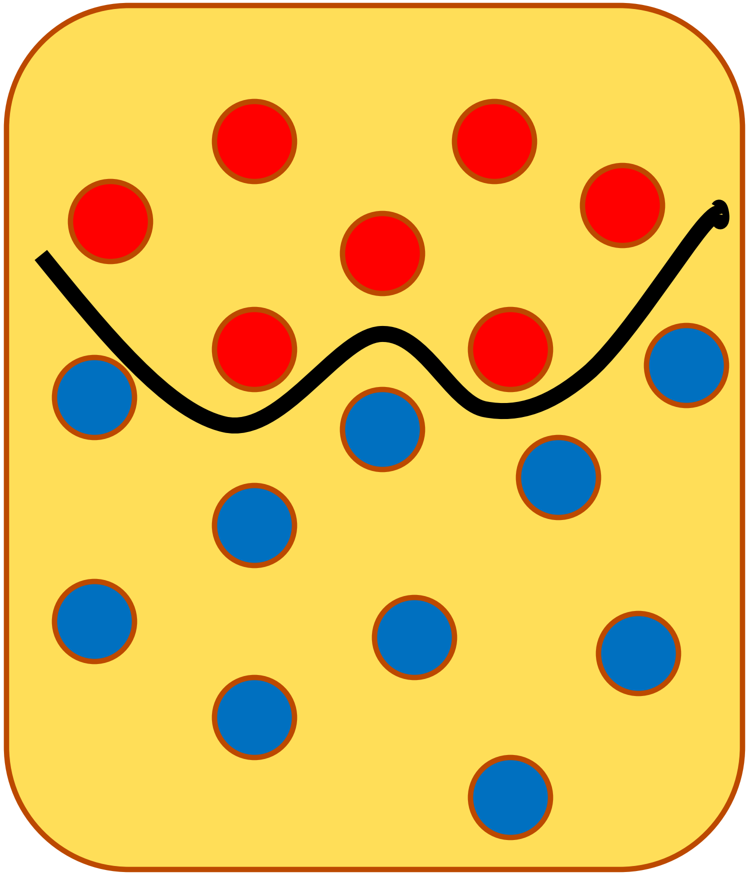
- Given a system operating condition we determine the **slowly coherent** groups of generators
- Depending on the disturbance location we then determine **minimal cutsets** using a graph theoretic approach which **minimizes load generation imbalance** in each island
- A **graph theoretic** method is applied to accurately determine the boundary of the island
  - A *k*-way partitioning technique is applied to decide the boundary of the island

Why Do We Need Islanding?

- Cascading outages that rapidly spread across the power system could result in significant disruption and inconvenience to modern society, leaving millions of people in the dark
  - ❖ West Coast outages in 1996
  - ❖ The Aug. 14, 2003 blackout in the Eastern Interconnection
  - ❖ A recent massive power failure in Rio de Janeiro, Brazil
- Controlled islanding provides an option of last resort to prevent the spreading of cascading outages
  - ❖ Intentionally separates a bulk power system into several self sustaining electrically isolated parts after a severe contingency
  - ❖ Loss of load and generation are limited in an acceptable range

How Do We Do Islanding?

- Identify slowly coherent generators
  - ❖ generators swinging together after a disturbance are said to be coherent
- Determine a cutset
  - ❖ involve the contingency lines
  - ❖ generators being identified to be slowly coherent are in isolated parts.
  - ❖ the impact of the imbalance power of each island is minimized.
- Build an islanding strategy
  - ❖ cutset determination
  - ❖ load shedding and generation tripping plan
  - ❖ when to island (another big problem)



Coherency Identification Matrix

------ modes -------

states

$$\begin{bmatrix} v_{S1} & v_{F1} \\ v_{S2} & v_{F2} \\ \vdots & \vdots \\ v_{Sr} & v_{Fr} \\ \vdots & \vdots \\ v_{Sn} & v_{Fn} \end{bmatrix}$$

V_S V_F

s slow modes

(n-s) fast modes

row eigenvectors

V_S

$$\begin{bmatrix} V_{S1} = v_{S(1\sim r)} \\ V_{S2} = v_{S[(r+1)\sim n]} \end{bmatrix}$$

pseudo-inverse weight

$$V_{S1}^{+} = WV_{S1}^{T}\left(V_{S1}WV_{S1}^{T}\right)^{-1}$$

$$\begin{bmatrix} I_{(r\times r)} \\ V_{S2}V_{S1}^{+} \end{bmatrix}$$

slow coherency identification matrix

If the *(n-r)* states are coherent with *r* reference states, then $v_{S(r+1)}\sim v_{Sn}$ will be duplications of $v_{S1}\sim v_{Sr}$, and therefore every row eigenvector of V_L will have only 1 non-zero entry 1.0.

How to Identify Coherent Machines?

- In power systems, when two machines are coherent exactly with *r* selected slow modes, the row eigenvectors related to the two machines of the *r* modes will be identical.

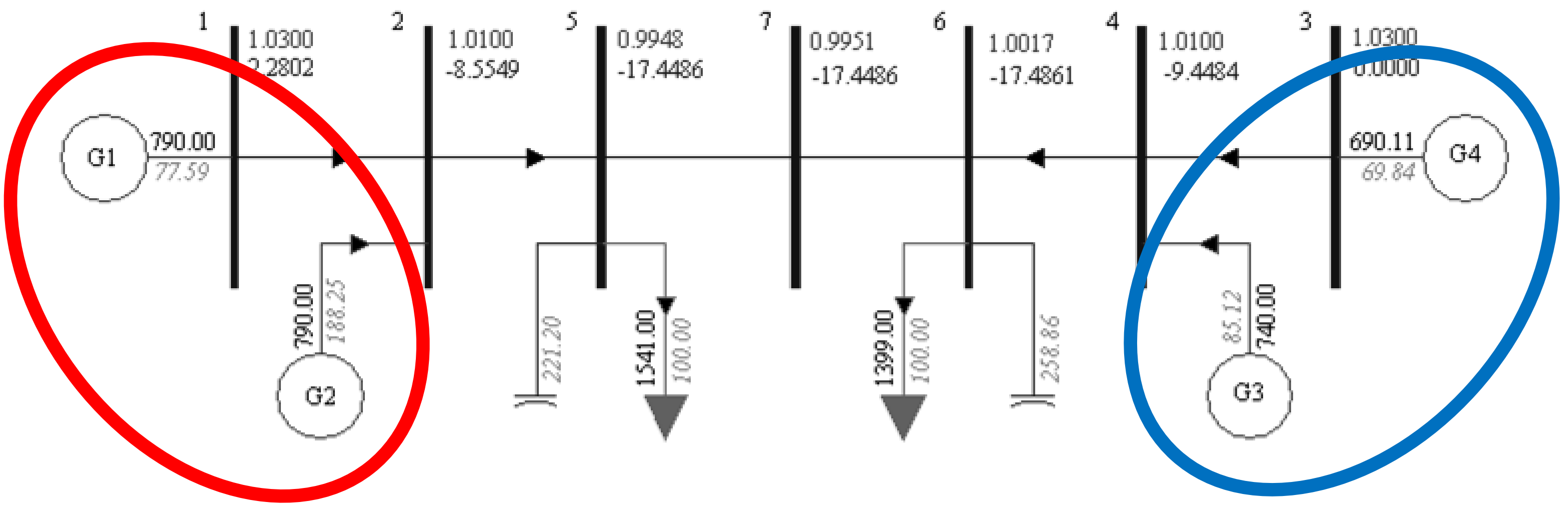
$$\begin{matrix} x_1 \\ x_2 \\ x_3 \end{matrix} \begin{bmatrix} 1 & 0.3 \\ 1 & 0.3 \\ 0.5 & 2 \end{bmatrix}$$

x_1 and x_2 are exactly coherent to the two slow modes

- In an actual power system, machines are nearly coherent.

$$\begin{matrix} x_1 \\ x_2 \\ x_3 \end{matrix} \begin{bmatrix} 1 & 0.3 \\ 1 & 0.35 \\ 0.5 & 2 \end{bmatrix}$$

x_1 and x_2 are nearly coherent to the two slow modes



generator internal reactance $x_1 = x_2 = x_3 = 0.3\ pu$, $x_4 = 0.22\ pu$, inertia $H_1 = H_2 = H_3 = H_4 = 6.5$, machine base 900 MVA, system base 100 MVA.

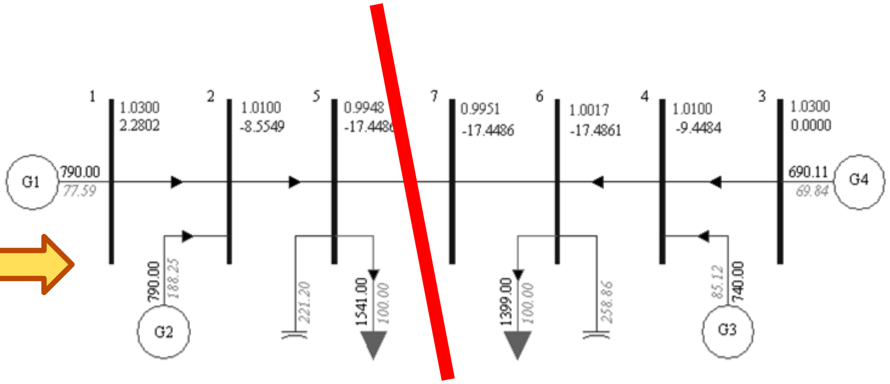
$$\begin{matrix} G1 \\ G3 \\ G2 \\ G4 \end{matrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0.9644 & 0.0356 \\ 0.0444 & 0.9556 \end{bmatrix}$$

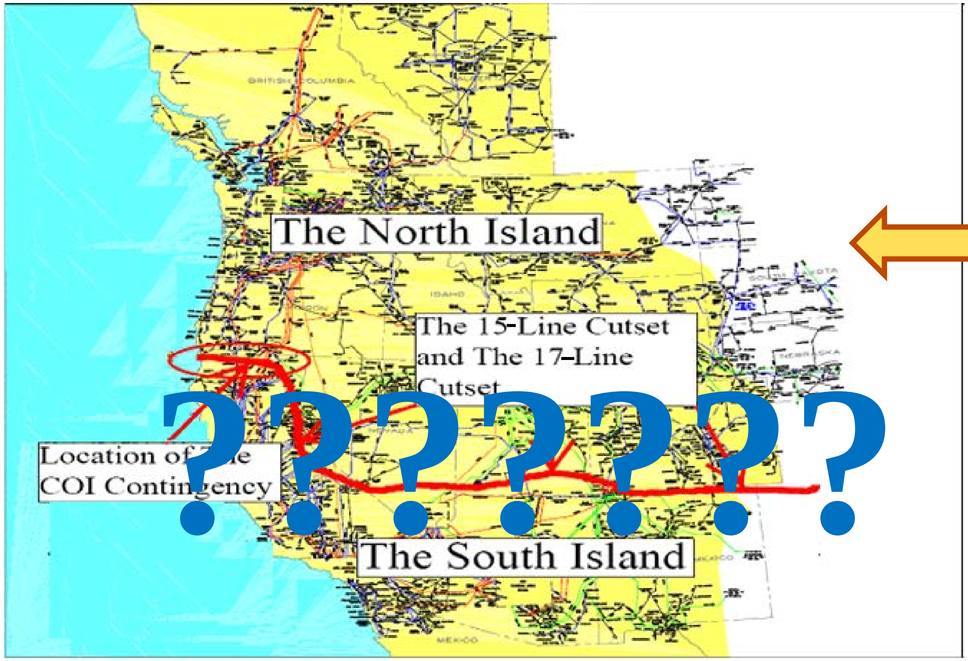
Grouping matrix of the four machine system

Generators G1 and G2 in one group.
Generators G3 and G4 in the other group.
The result is in accordance with intuition.

Determine Cutsets for Coherent Generators

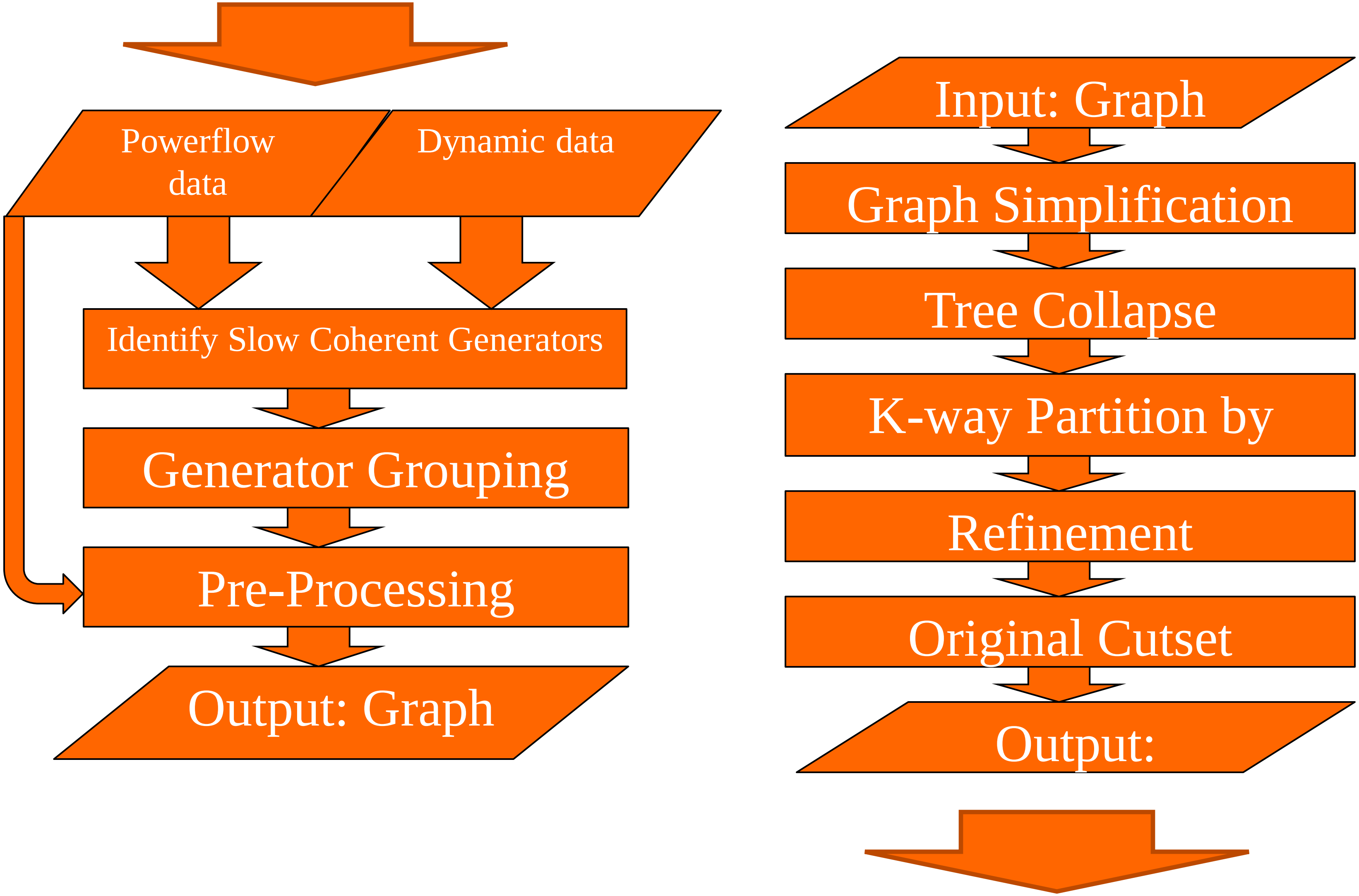
- For small systems, cutsets can be determined manually.





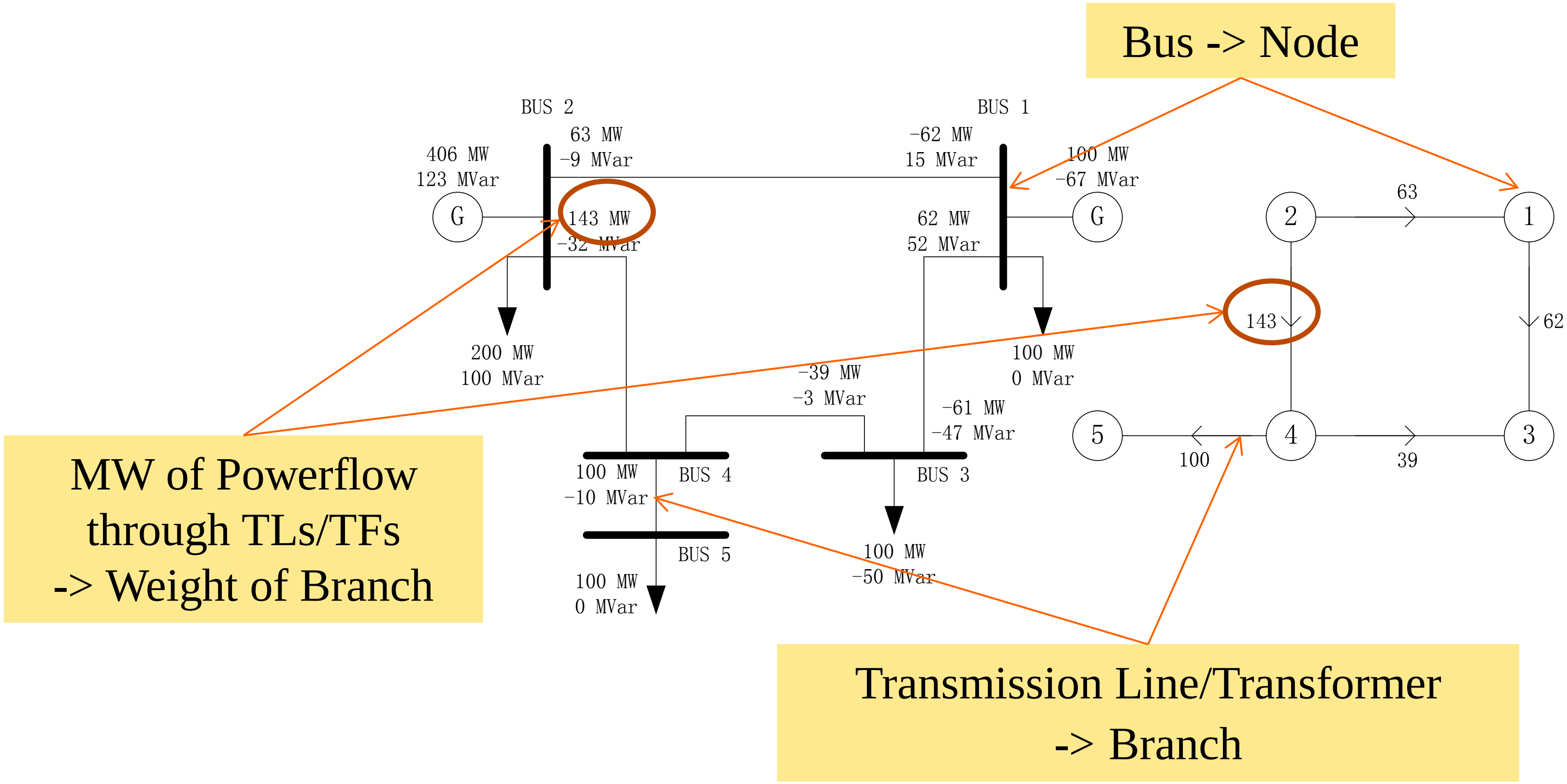
- For large power systems that contain thousands of buses and branches, an automatic cutset searching program becomes necessary when coherent groups have been provided

Steps to Perform Cutset Search



Graph Representation

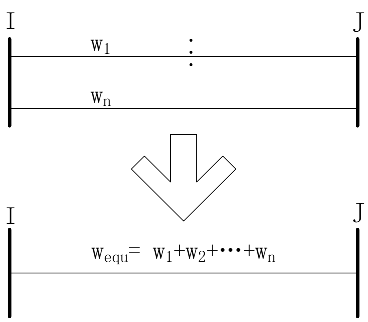
Power systems are represented as a directed graph to simplify analysis



Note that graph representation does not affect the cutset determination.

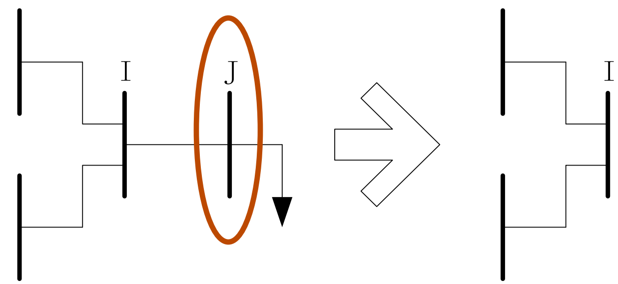
Graph Simplification: 5 Steps

1. Equivalence of parallel lines

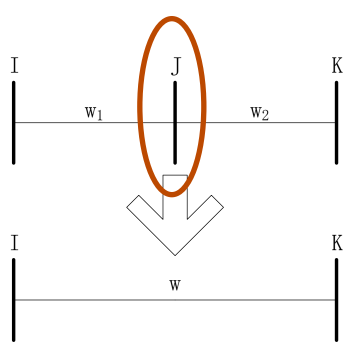


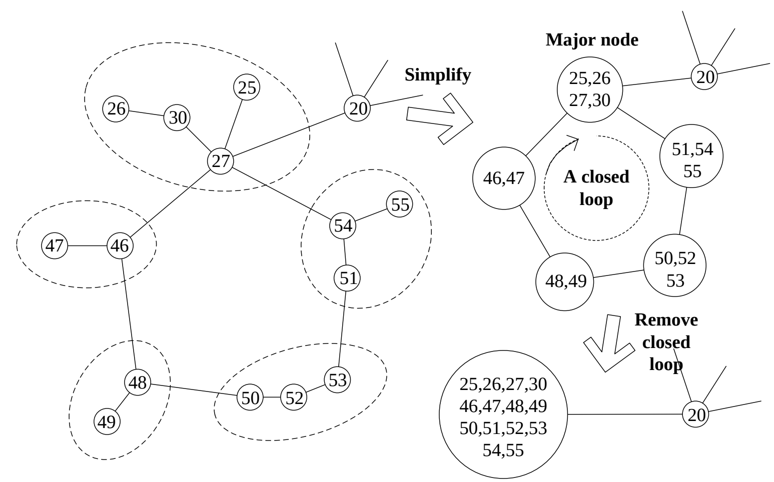
degree of graph:
the degree of a node is equal the number of branches connected to that node.

2. Removal of degree-one-nodes



4. Removal of step-up transformers



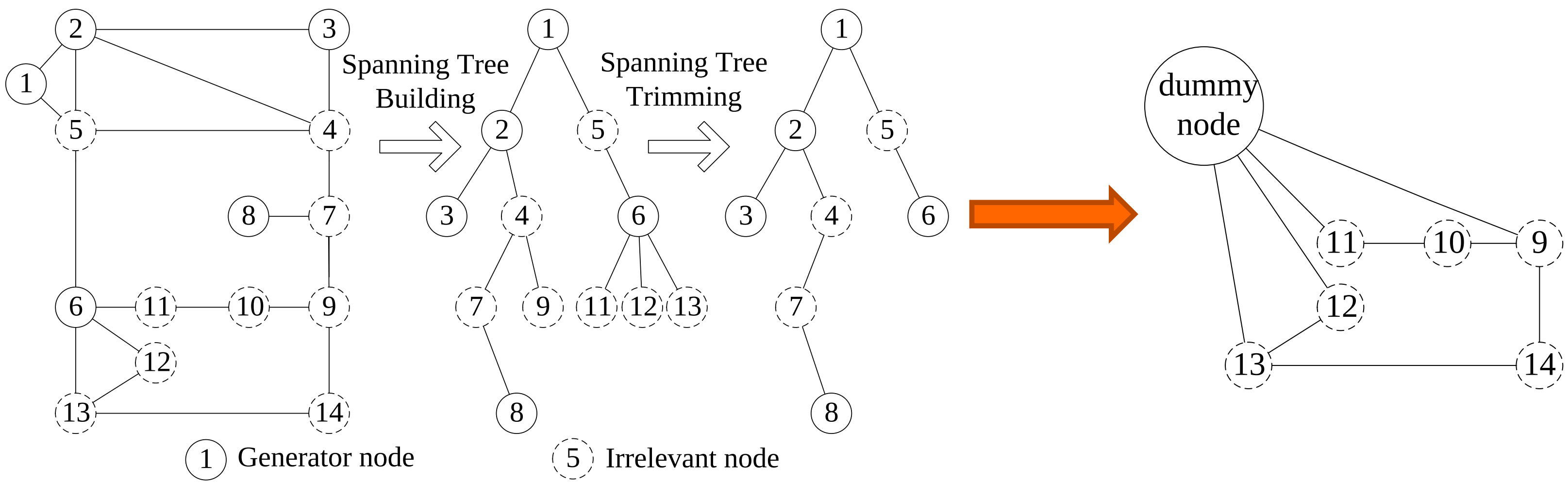


3. Removal of degree-two-nodes

5. Removal of closed loops

Tree Collapse: Consolidate Coherent Machines

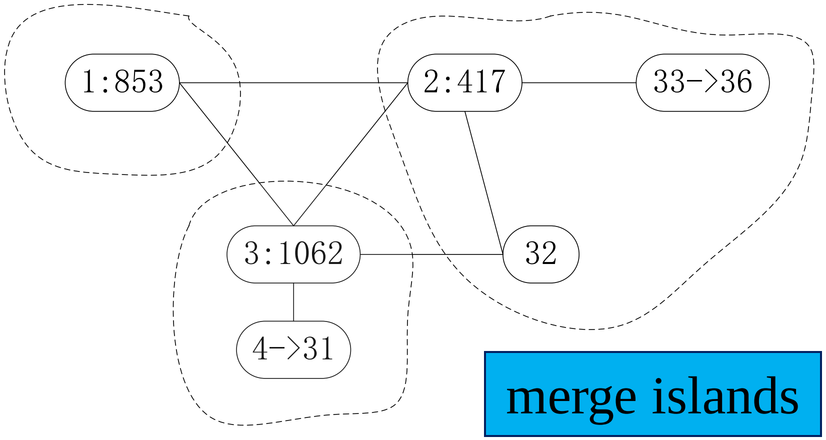
- **Purpose**: avoid generators in one coherent group being separated in different islands.
- **Method**: collapse generators in the same group into a large dummy node.
  - ❖ Building a spanning tree
  - ❖ Trim the spanning tree
  - ❖ Collapse of the minimum spanning tree



Graph Splitting and Island Merging

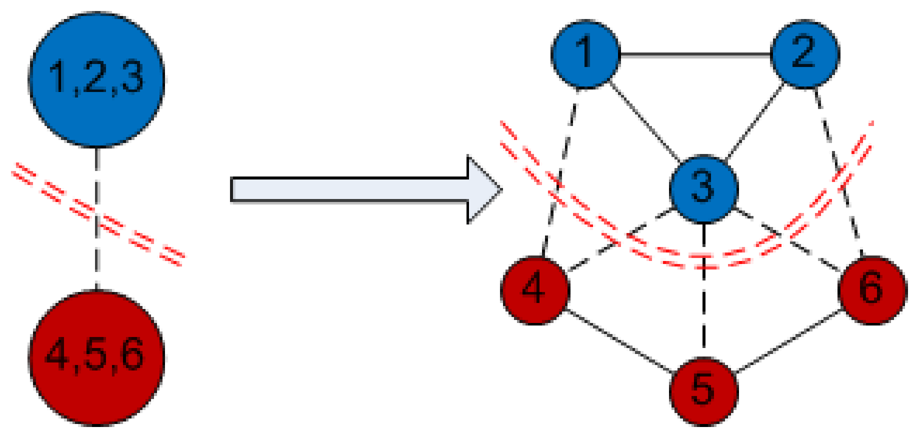
- After tree collapse, a graph partition program METIS (Developed by Prof. Karypis' laboratory at the university of Minnesota) is employed to split the graph into specified number of parts

- Some extra islands will be formed in the splitting process, and an island merging module is invoked to merge minor islands to their adjacent major islands.



Cutset Recovery

- A partition result of the highly simplified graph is given at this time.
- In all the previous processes, actions are recorded. Final cutset can be recovered from the results of simplified graph.



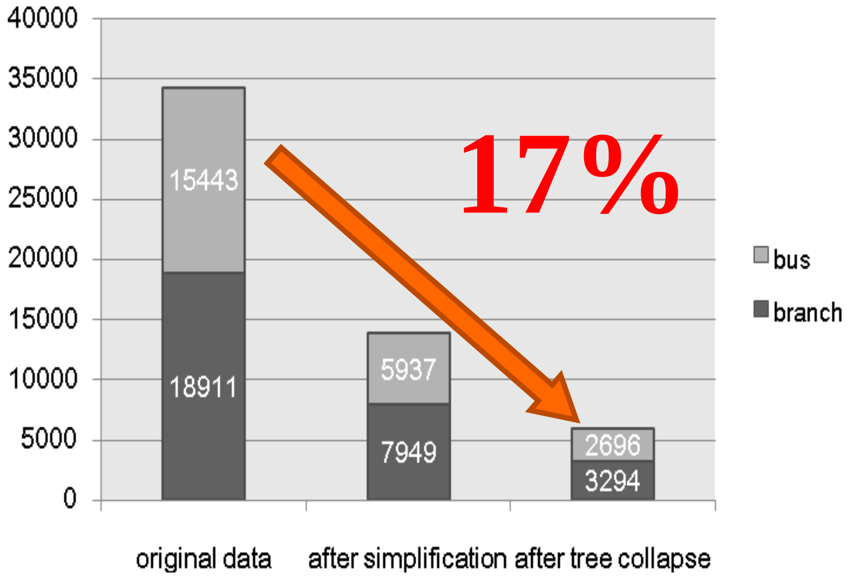
Simplified system and cutset

Original system and cutset

Efficiency and Effectiveness of the Algorithm

- A software package is developed based on the algorithm. Test result:
  - Bus: 15000 +
  - Branch: 18000 +
  - PC configuration: Intel Core2 6700 2.66 GHz CPU and 2 GB memory
  - Speed: less than 3 seconds

- Graph simplification efficiency



- Effectiveness of cutsets from the algorithm will be tested by time domain simulations

Islanding Demonstrations on the WECC System

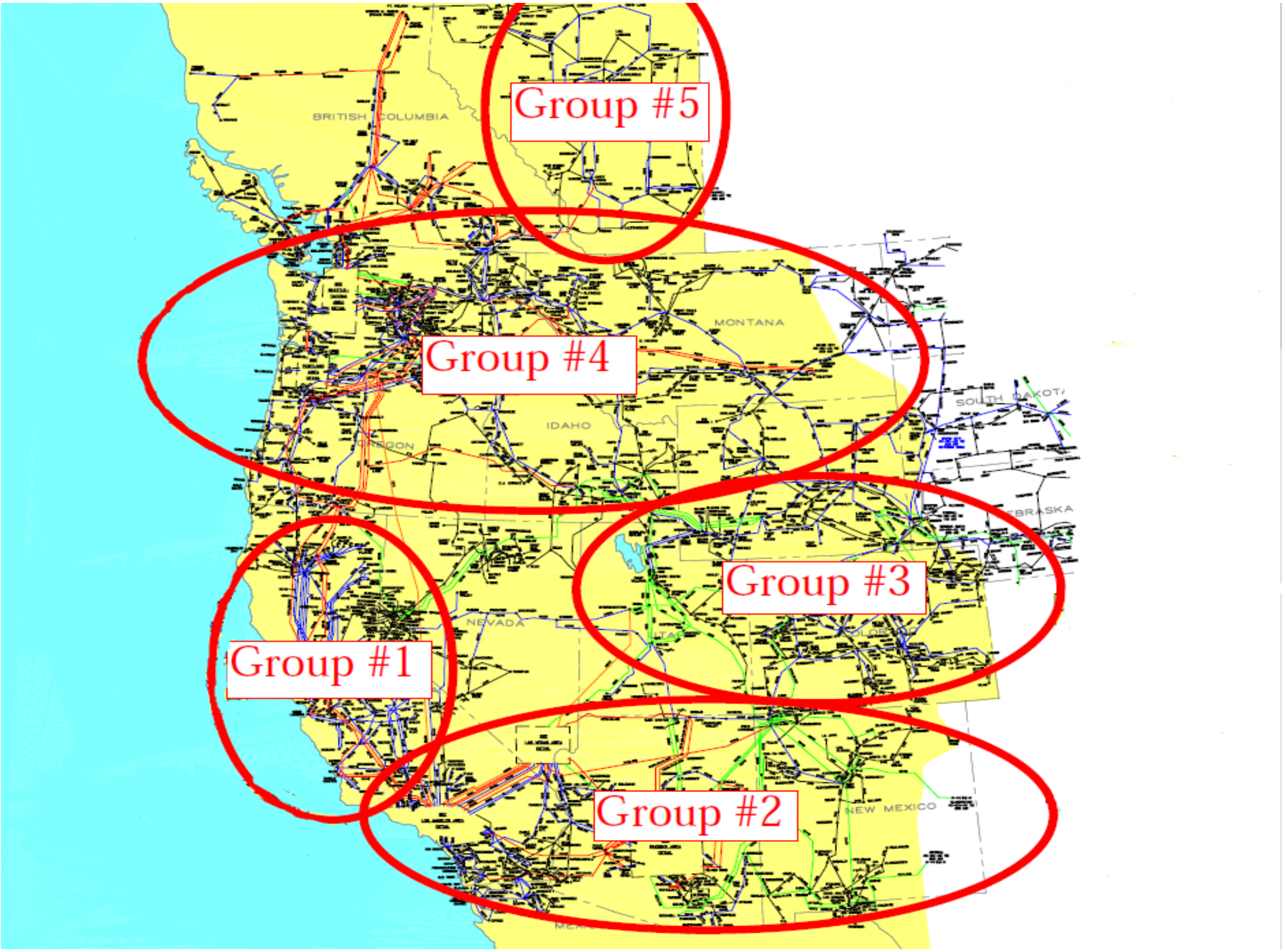
- **Simulation tools**: DSA Tools, especially PSAT and TSAT.
- **Simulation cases**: the WECC system under two different operating conditions: heavy summer (HS) case and light winter (LW) case
- **Contingencies**: triple line outage (TLO) and severe double line outage (SDLO) at California Oregon intertie (COI) and Path 15 (P15)

Simulation Cases	Operating Conditions	Contingency Locations	Outages
Case #1	HS	COI	TLO
Case #2	HS	COI	SDLO
Case #3	LW	P15	TLO
Case #4	LW	P15	SDLO

COI: critical contingency to heavy summer case

P15: critical contingency to light winter case

Slowly Coherent Groups in the WECC



Candidate Cutsets

Candidate cutsets for HS COI Case

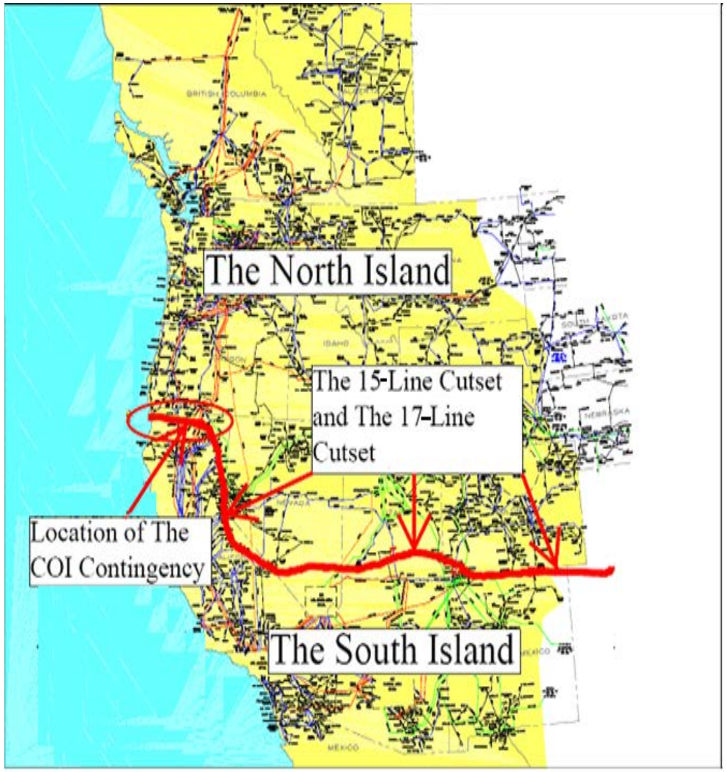
No. of Islands	Slow Coherency Groups Contained	Load/Generation Imbalance (MW)	No. of Lines in Cutsets
2	**(1,2), (3,4,5)**	**-5602/5602**	**15**
3	(1,2), (3,4), (5)	-5602/5903/-301	18
4	(1), (2), (3,4), (5)	-4748/-907/5957/-301	21
5	(1), (2), (3), (4), (5)	-4748/-907/ -487/6444/-301	34

Candidate cutsets for LW P15 Case

No. of Islands	Slow Coherency Groups Contained	Load/Generation Imbalance (MW)	No. of Lines in Cutsets
2	**(2), (1,3,4,5)**	**6028/-6028**	**15**
3	(2), (1,3,4), (5)	6028/-6027/-1	18
4	(2), (1,4), (3), (5)	6028/-5886/-141/-1	34

Locations of Contingencies and Cutsets

Two islanding strategies are built for the COI contingency and another two for the P15 contingency

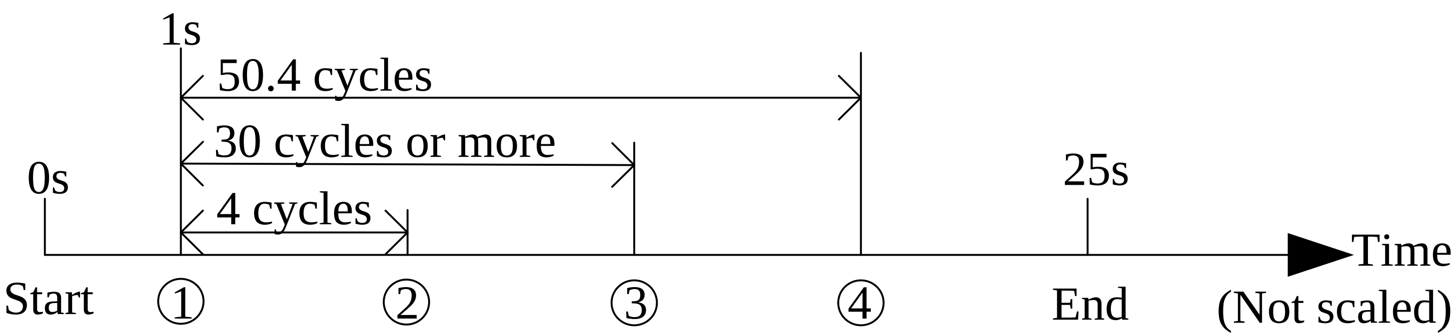


For HS COI cases

For LW P15 cases

Time Sequence of HS COI TLO

Heavy Summer
California Oregon Intertie
Triple Line Outage



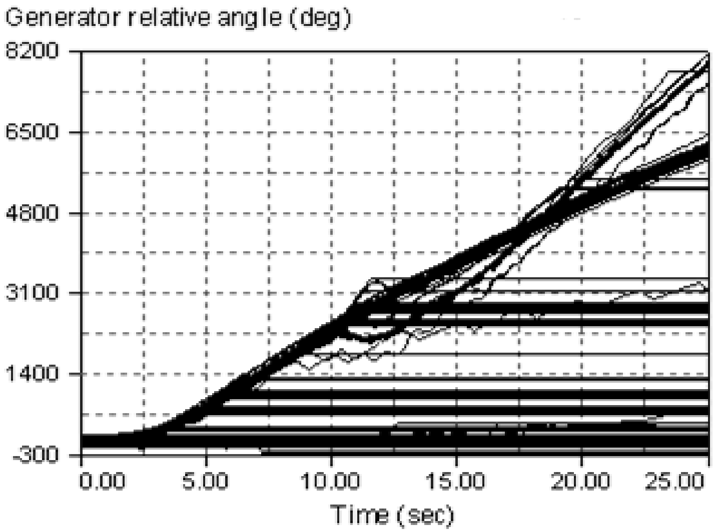
① 3-Φ fault at COI bus ② Clear fault, open three COI lines, RAS start

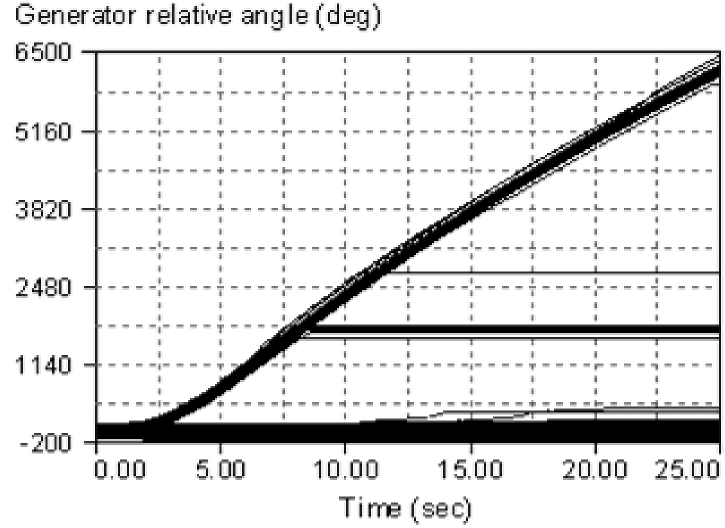
③ Implement islanding(*) ④ RAS end

(*) Not employed in the uncontrolled islanding case

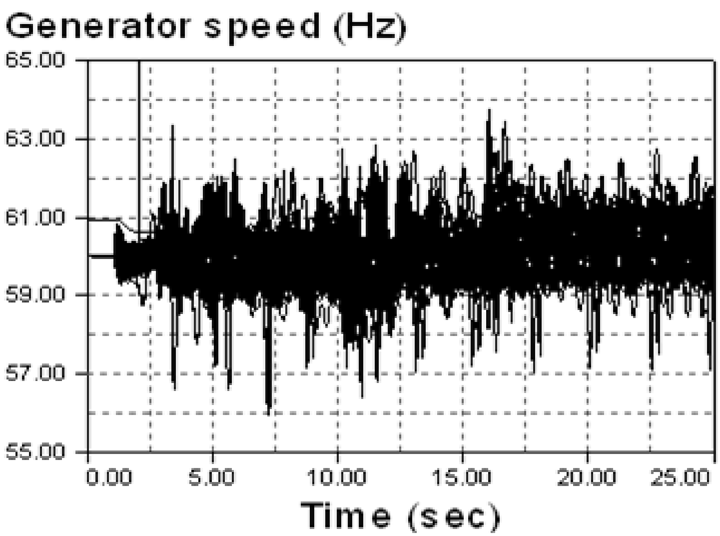
Note that RAS(remedial action schemes) are only employed in TLO cases.

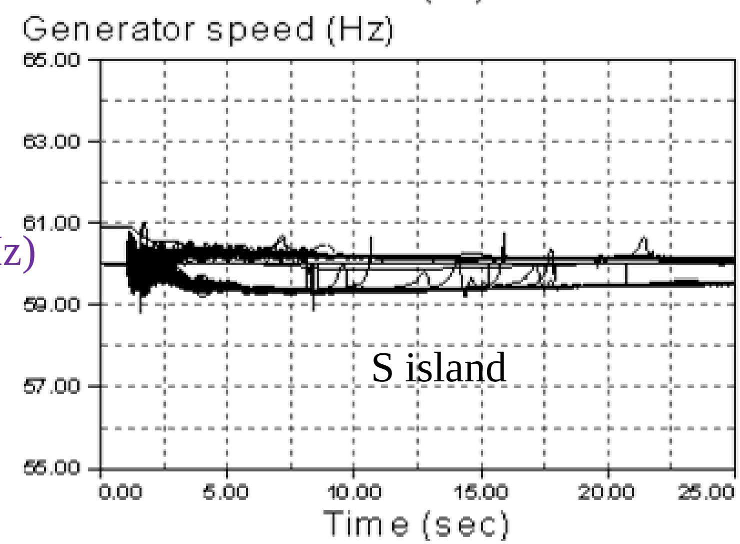
The HS COI TLO Case: generator variables





Relative rotor angle



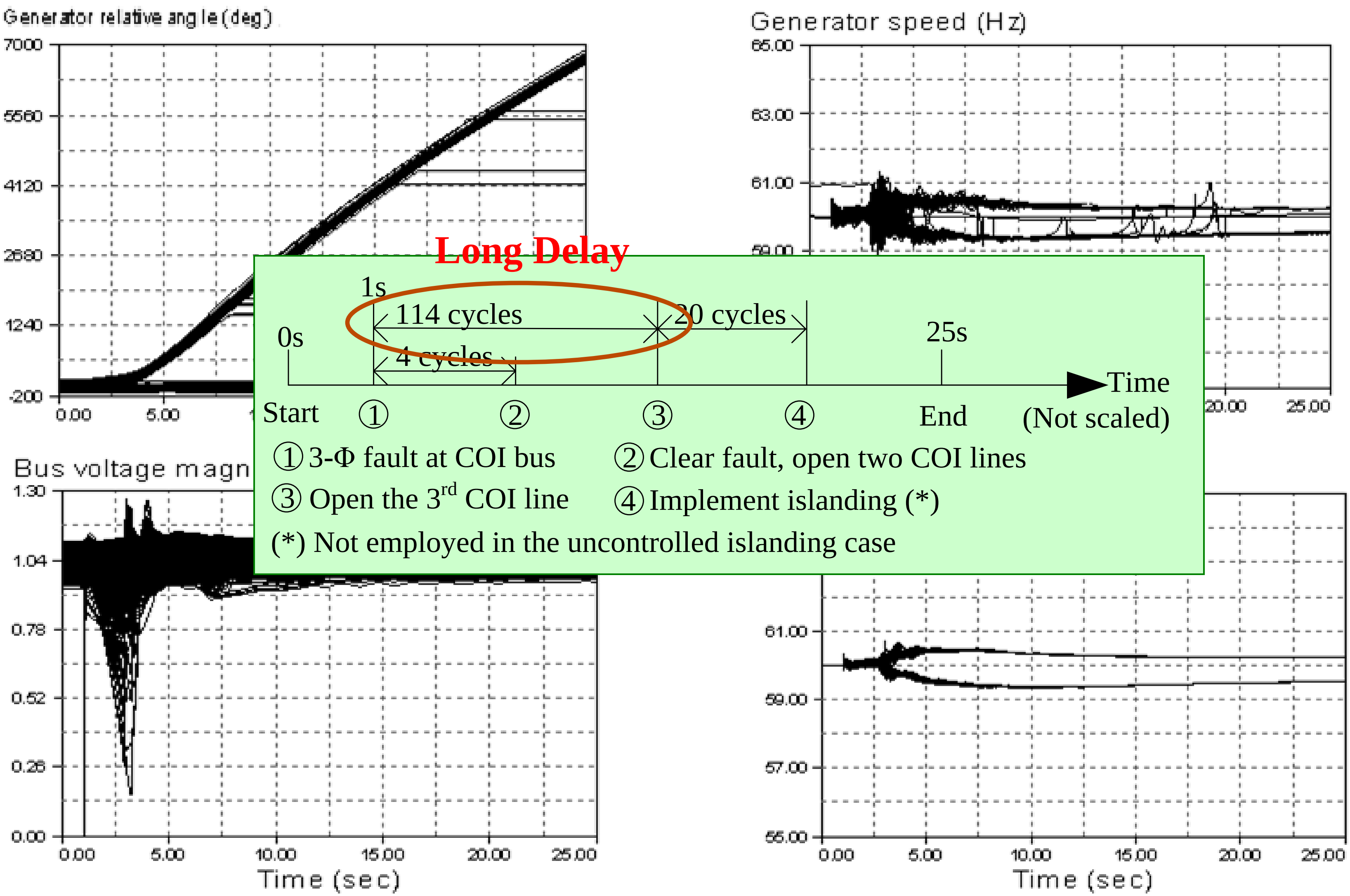


gen speed (Hz)

Uncontrolled Islanding

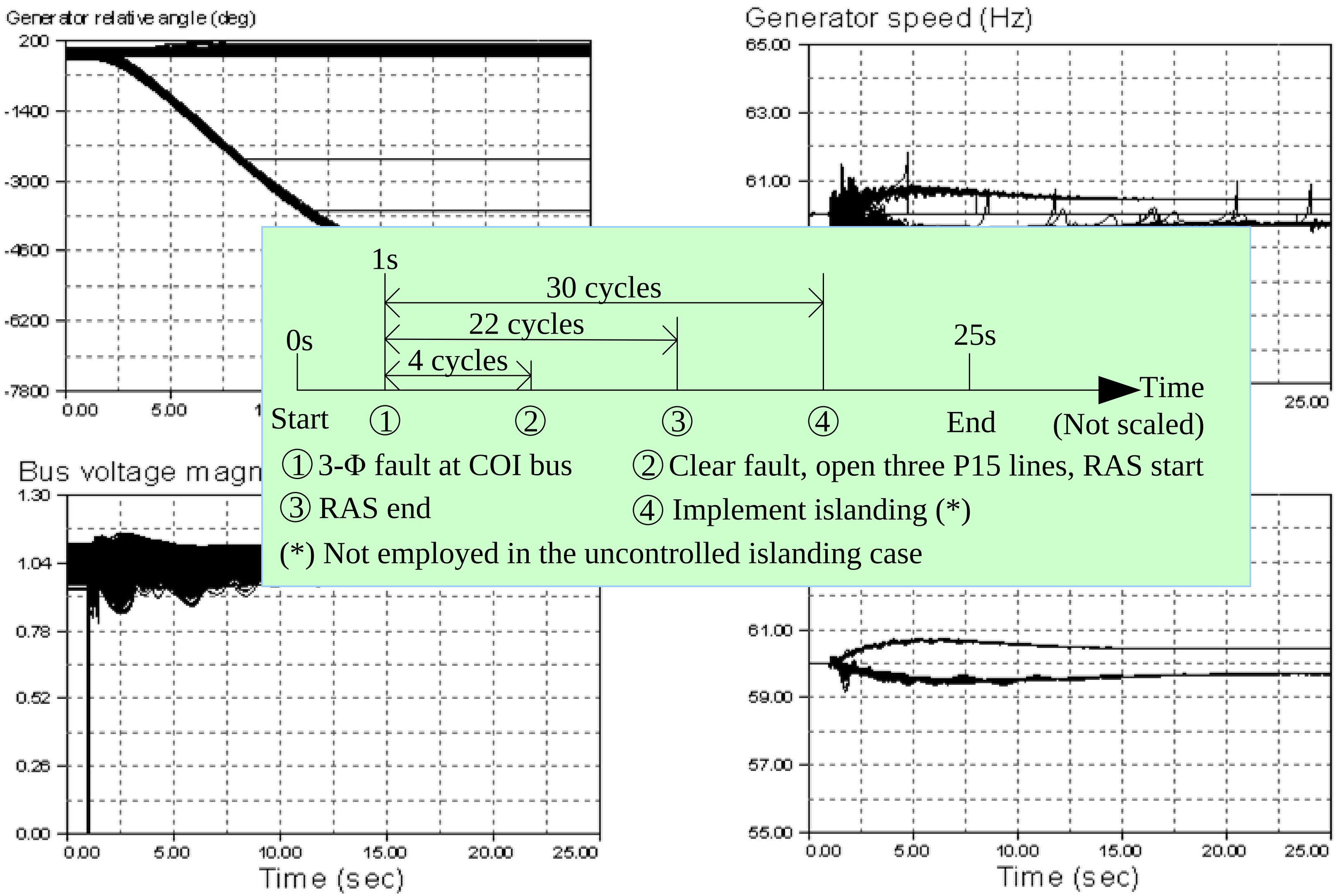
Controlled Islanding

HS COI SDLO



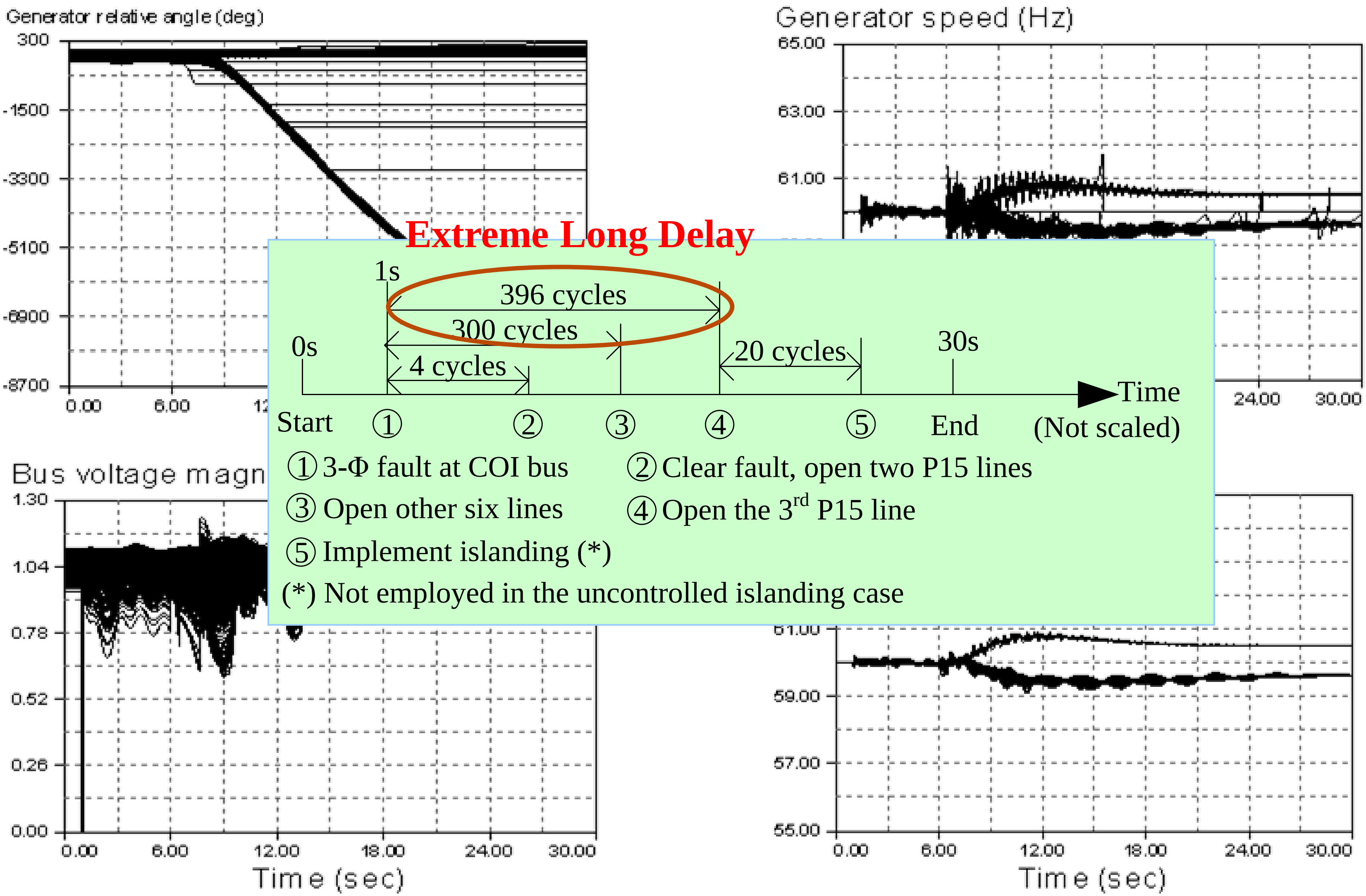
Only controlled islanding results are shown here

LW P15 TLO



Only controlled islanding results are shown here

LW P15 SDLO



Only controlled islanding results are shown here

Simulation Results

Features*			Stable	Islands Formed	Load Shedding (MW)	Gen Tripping (MW)
HS COI	UI	TLO	No	3	7500	14420
		SDLO	No	4	6300	11290
	CI	TLO	Yes	2	1530	2770
		SDLO	Yes	2	1220	480
LW P15	UI	TLO	No	3	14730	5310
		SDLO	No	3	15930	3790
	CI	TLO	Yes	2	2970	1020
		SDLO	Yes	2	2840	260

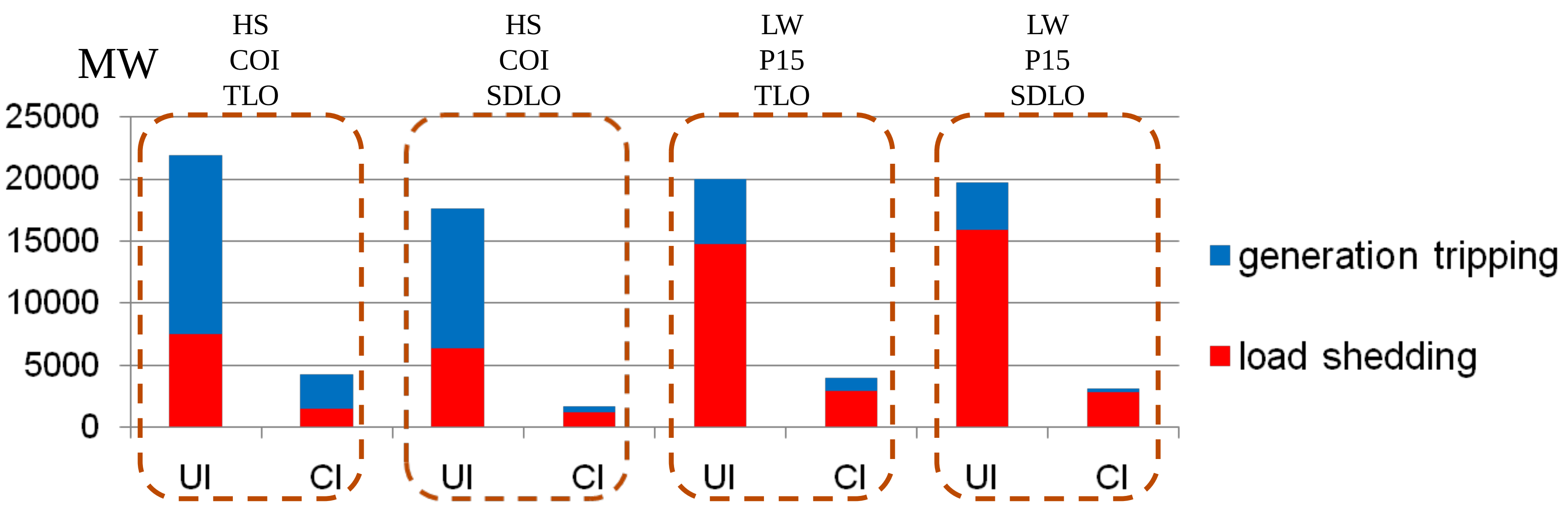
* UI = uncontrolled islanding, CI = controlled islanding

- Existing RAS without separation are NOT effective enough to prevent the WECC system from cascading outages when TLO or SDLO occurred at COI or P15.
- Controlled islanding has a potential for preventing the formation of multiple asynchronous groups of generators and reducing load shedding and generation tripping after a severe contingency.
- Present armed RASs in the WECC system are not designed for controlled islanding operation, therefore some unwanted load shedding or generation tripping may occur after islanding.

Simulation Results Analysis

Stable?	Uncontrolled Islanding	Controlled Islanding
HS COI TLO	N	Y
HS COI SDLO	N	Y
LW COI TLO	N	Y
LW COI SDLO	N	Y

Stability during simulation



UI = uncontrolled islanding, CI = controlled islanding

Conclusions

- Controlled islanding has proven to be effective in preventing system from losing synchronism after severe disturbances.
- In each island formed, frequencies and voltages in the transmission network are within an acceptable operating range, although services would be slightly degraded.
- Compared to uncontrolled islanding, controlled islanding results in less load shedding, in tripping of fewer generators, and in lower blackout probabilities.
- The algorithm works for large power system and is efficient.
- Several cutsets identified by the algorithm are effective in controlled islanding.

Application to the August 14, 2003 Northeast Blackout

- It is the 2004 Summer Peak Load Case for the Eastern Interconnection.
- It has nearly 38,000 buses and nearly 5000 generators.
- All the modeling detail provided in the base case was **retained without any change**.
- The proposed approach was applied to the August 14th, 2003 scenario.

Preparation of Case

- The conditions given in the joint US-Canadian final report were implemented in the base case obtained.
- The power flow was then obtained.
- **<u>This shows the state of the system before the final set of disturbances occurred.</u>**
- The details of changes implemented are shown in the next few slides.

Preparation of Case

- Adjust generation from AEP to compensate for this loss of generation in FE
- Remove Columbus-Bedford 345 kV Line
- Remove Bloomington- Denois Creek 230 kV line
- Trip Eastlake 5 generation
- Remove Chamberlin – Harding 345 kV Line
- Remove Stuart-Atlanta 345 kV Line
- Remove Hanna- Juniper 345 kV Line
- Remove Star-South Canton 345 kV Line

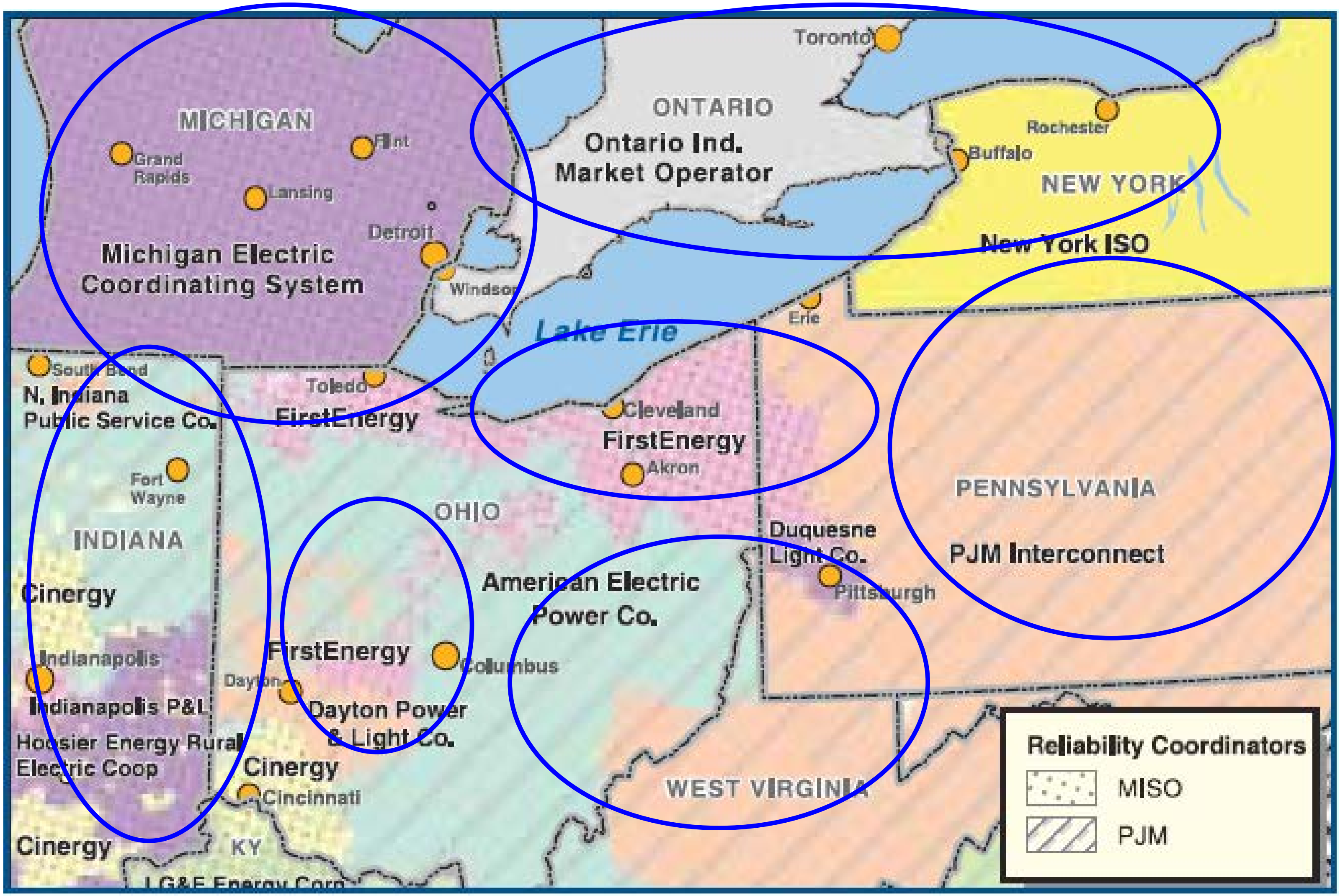
Preparation of Case

- Remove the following 138 kV lines
  - Cloverdale-Torrey
  - E. Lima – New Liberty
  - Babb – W. Akron
  - W. Akron – Pleasant Valley
  - Canton Central Transformer
  - Canton Central – Cloverdale
  - E. Lima – N. Findlay
  - Chamberlin- W. Akron
  - Dale – W. Akron
  - West Akron-Aetna
  - West Akron-Granger-Stoney-Brunswick-West Medina
  - West Akron-Pleasant Valley
  - West Akron-Rosemont-Pine-Wadsworth

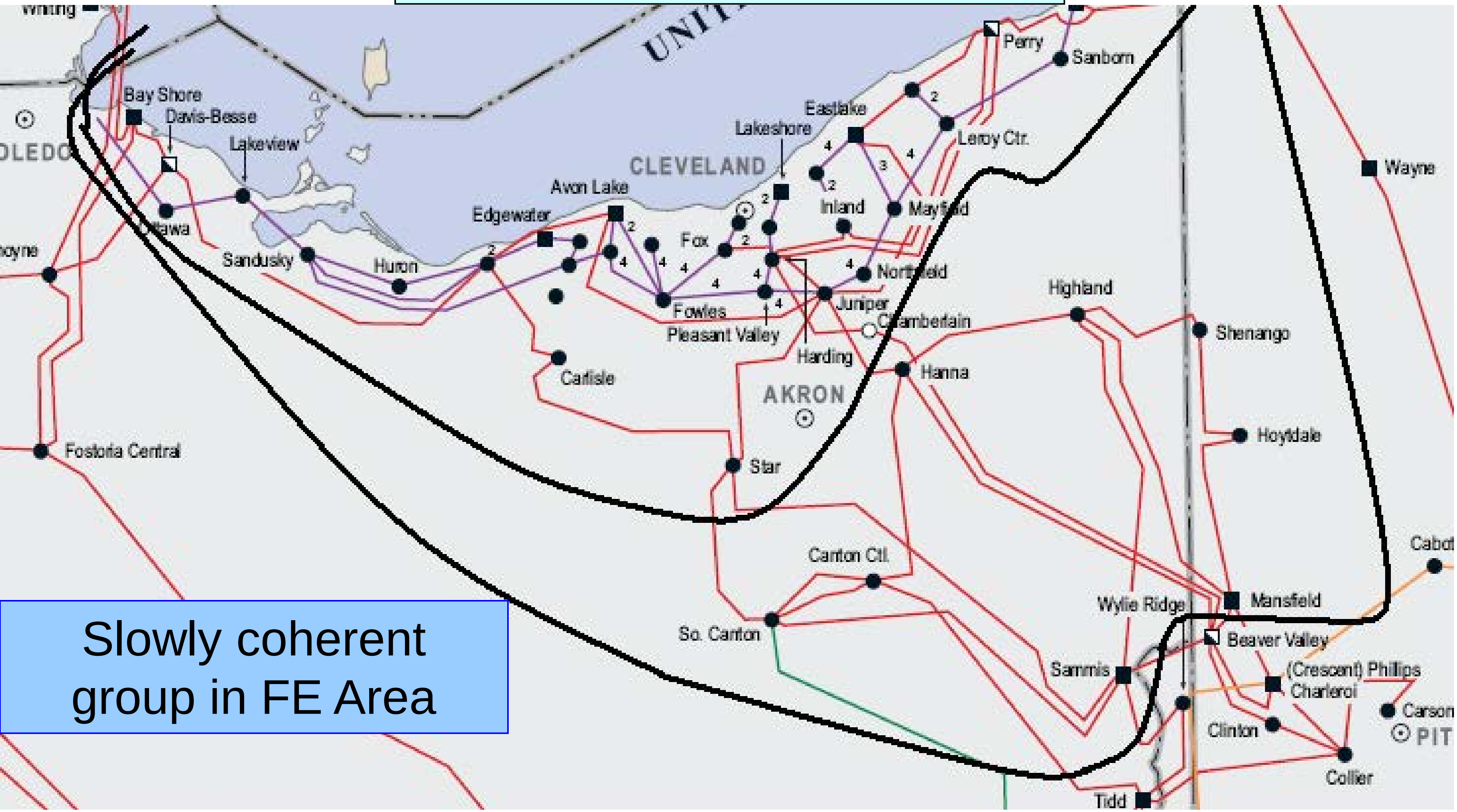
Preparation of Case

- The slow coherency program was then run using the solved power flow case and the dynamic data provided to obtain the **slowly coherent groups**.
- All the modeling details provided in the data were included.
- **No simplifications were made**.
- **One of the slowly coherent groups identified was the entire FE area.**

Slowly Coherent Generator Groups



Island created by automatic islanding program



Slowly coherent group in FE Area

August 14, 2003 Scenario

- The Dale-West Canton 138 kV line sags into a tree and trips.
- In 2s this led to the overloading of Sammis-Star 345 kV line which then tripped.
- This tripped on Zone 3.
- This was the start of the cascade.

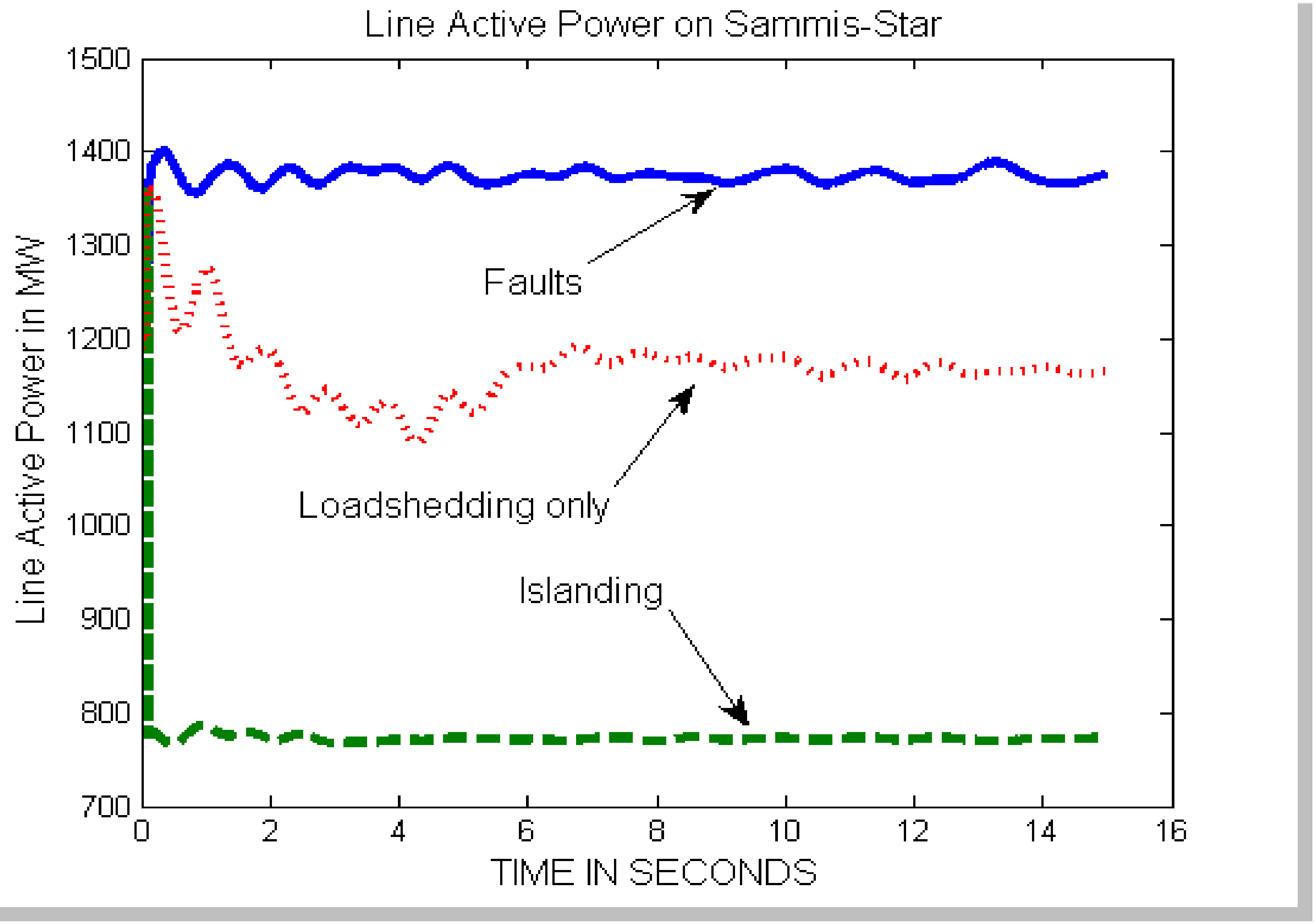
Creation of Island

- At time t=0s a three phase fault occurs at Dale and the Dale-West Canton 138 kV line is tripped.
- We then create an island near the Cleveland area.
- In order to create the island we have to trip 20 lines:
    - 7 - 345 kV lines
    - 9 – 138 kV lines
    - 4 – 69 kV lines
- This island has:
    - Total generation = **6259.23 MW**
    - Total load = **8309.07 MW**
- The rate of frequency decline base load shedding sheds **(23%)** or **1911 MW** of load in the island

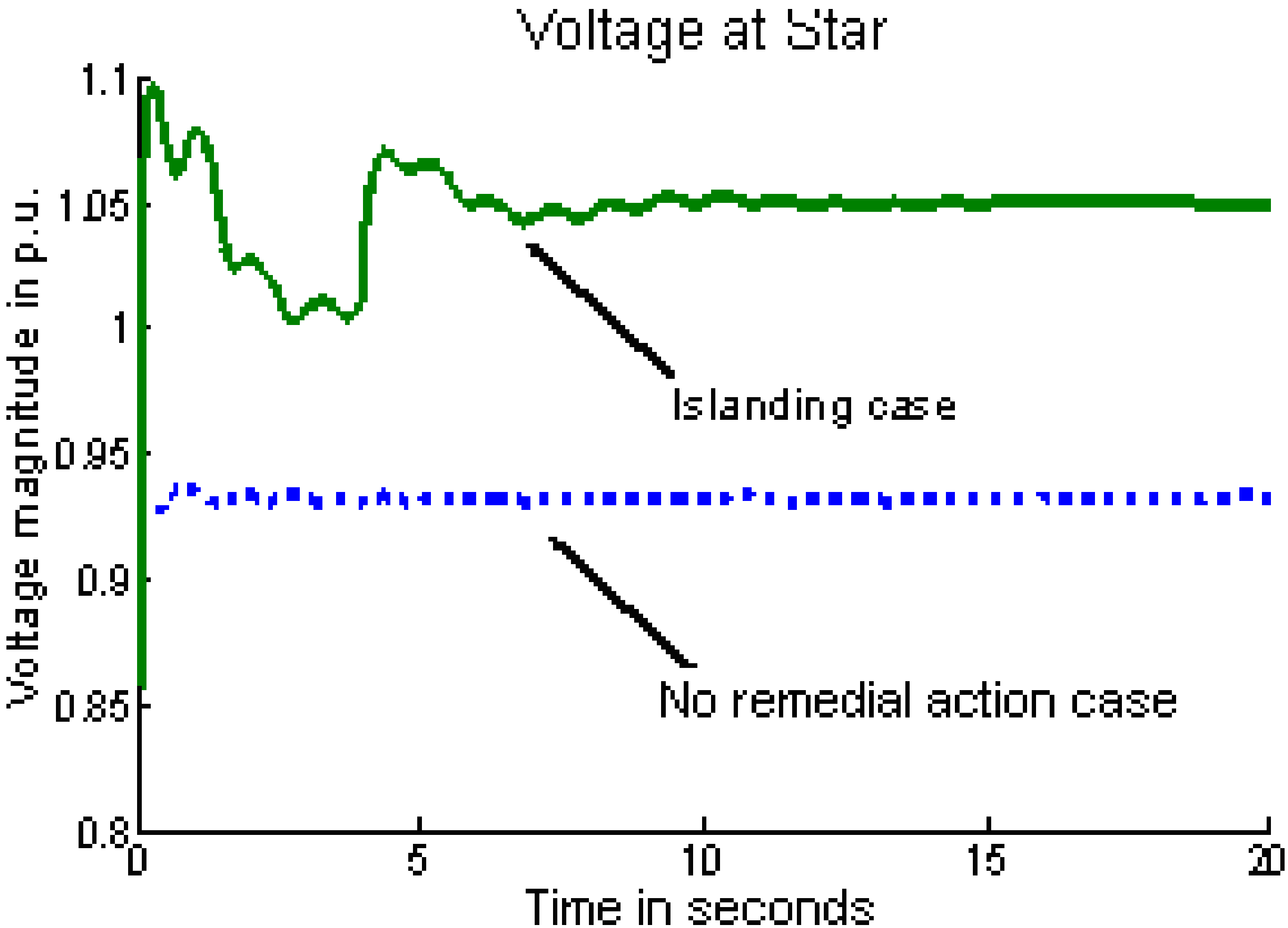
Statement from Joint US-Canada Report

"The team found that 1,500 MW of load would have had to be dropped within the Cleveland-Akron area to restore voltage at the Star bus from 90.8%(at 120% of normal and emergency ampere rating) up to 95.9%(at 101% of normal and emergency ampere rating)."

Line Flow Reduced on Sammis-Star



Bus Voltage Improved at Star



August 14, 2003 Analysis

- With the flow reduced on the Sammis – Star line and the voltage at start maintained at nominal values the line did not trip
- As a result the cascading outages did not occur
- The system remained intact and by shedding around 1900 MW of load in Cleveland and creating an island the rest of the system remained intact

Publications

- You, H.,V. Vittal, and Z. Yang, "Self-healing in power systems: an approach using islanding and rate of frequency decline based load shedding," *IEEE Trans. Power Systems*, Vol. 18, no. 1, pp.174-181, February 2003.
- You, H., V. Vittal, X. Wang, “Slow Coherency Based Islanding,” *IEEE Transactions on Power Systems*, Vol. 19, no. 1, pp 483-491, February 2004.
- Wang, X. , V. Vittal, G.T. Heydt, " Tracing Generator Coherency Indices Using the Continuation Method: A Novel Approach," *IEEE Transactions on Power Systems*, Vol. 20, No. 3, pp 1510-1518, August 2005.
- Yang, B., V. Vittal, G.T. Heydt, “Slow Coherency Based Controlled Islanding – A Demonstration of the Approach on the August 14, 2003 Blackout Scenario,” *IEEE Transaction on Power Systems*, Vol. 21, No. 4, pp. 1840-1847, November 2006.
- Xu, G., V. Vittal, “Slow Coherency based Cutset Determination Algorithm for Large Power Systems,” *IEEE Transactions on Power Systems*, Vol. 25, No. 2, pp.877-884, May 2010.
- Xu, G., V. Vittal, A. Meklin, J.E. Thalman, “Controlled Islanding Demonstrations on the WECC System,” *IEEE Transactions on Power Systems*, Vol. 26, No.3, pp.1426-1433, August, 2011.

Thanks!

Questions?