Topic 6: Wide Area Measurements

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Wide-Area Measurement

- We would like to deploy several sensors across the grid:
  - To monitor the operation of the grid (almost) in real-time.

- Applications:
  - Angle and frequency monitoring
  - Post-mortem analysis (disturbances and system failures)
  - Voltage and voltage stability monitoring
  - Improved state estimation
  - Steady-state benchmarking

Wide-Area Measurement for Situational Awareness

- WAM can help us achieve Wide-area Situational Awareness:

- Situational Awareness:

> Understanding the current environment and being able to accurately anticipate future problems to enable effective actions.

- To be able to optimally and yet robustly operate the grid.
  - Key Sensor: Phasor Measurement Unit (PMU)

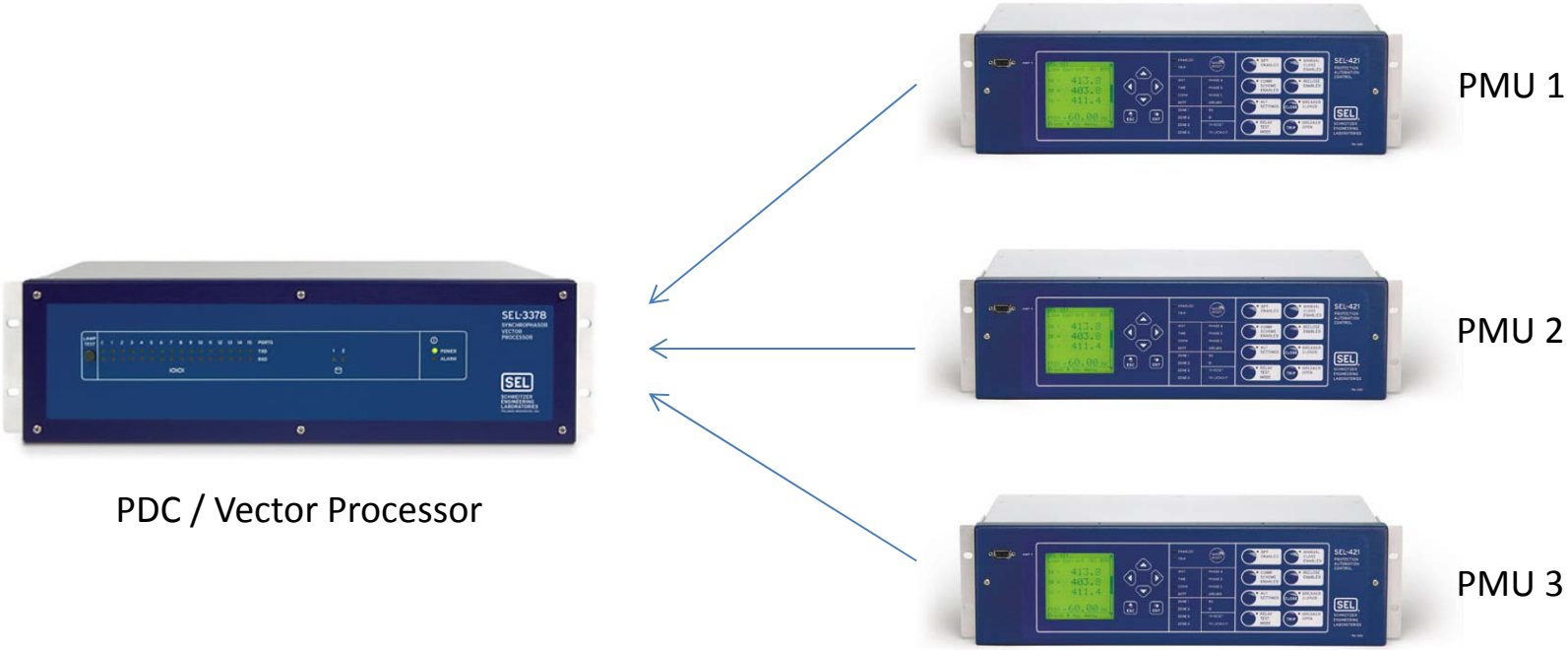
Synchronized Measurements

- A PMU at a substation measures voltage and current phasors:
  - Very precise synchronization with µs accuracy.
  - Compute MW/MVAR and frequency.

- Measurements are reported at a rate of 20-60 times a second.
  - Can track grid dynamics in real time
  - Traditional SCADA refresh rate is seconds to minutes

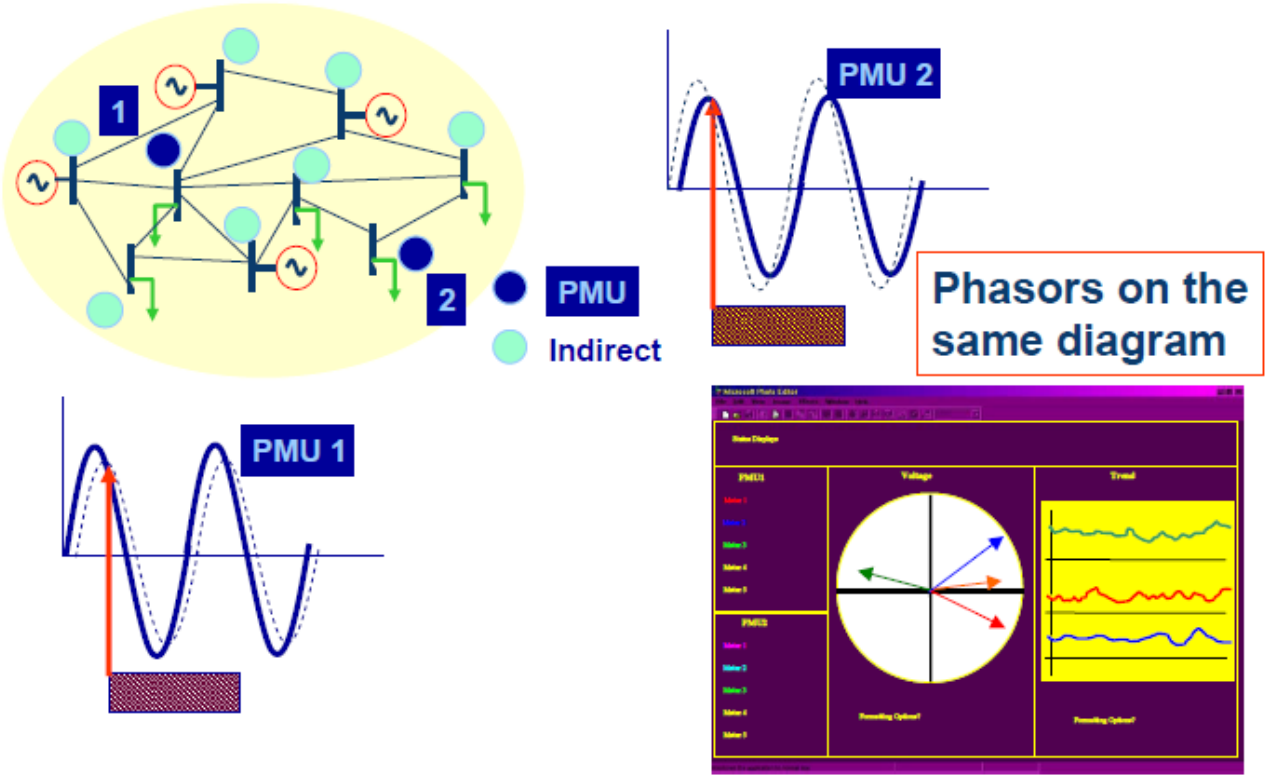
Synchronized Measurements

- Each utility has its own Phasor Data Concentrator (PDC) to
  - Aggregate/align data from various PMUs based on time tag



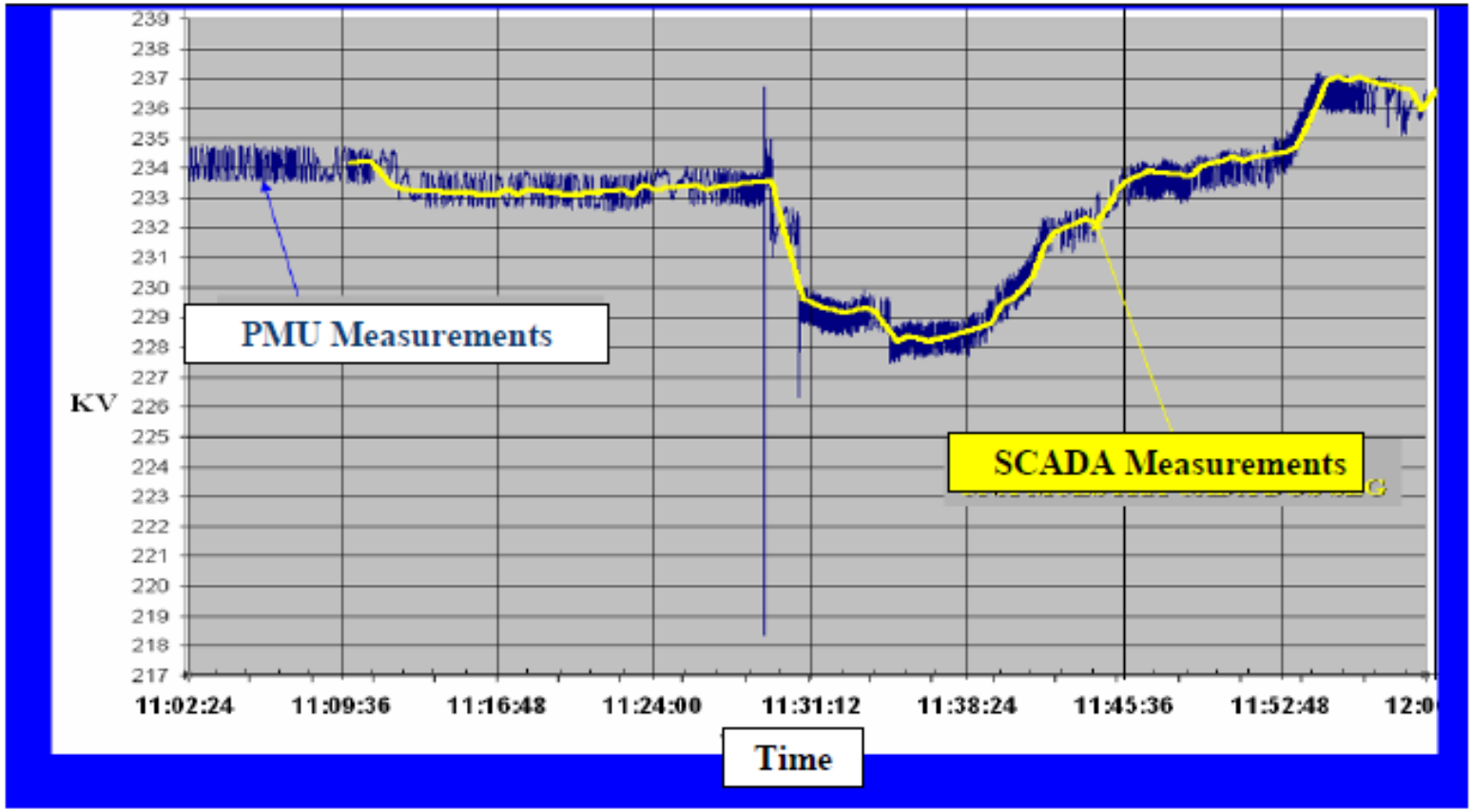
Synchronized Measurements

- Measurements from each utility's PDC is sent to the Central Facility:
  - Where the measurements are synchronized across utilities



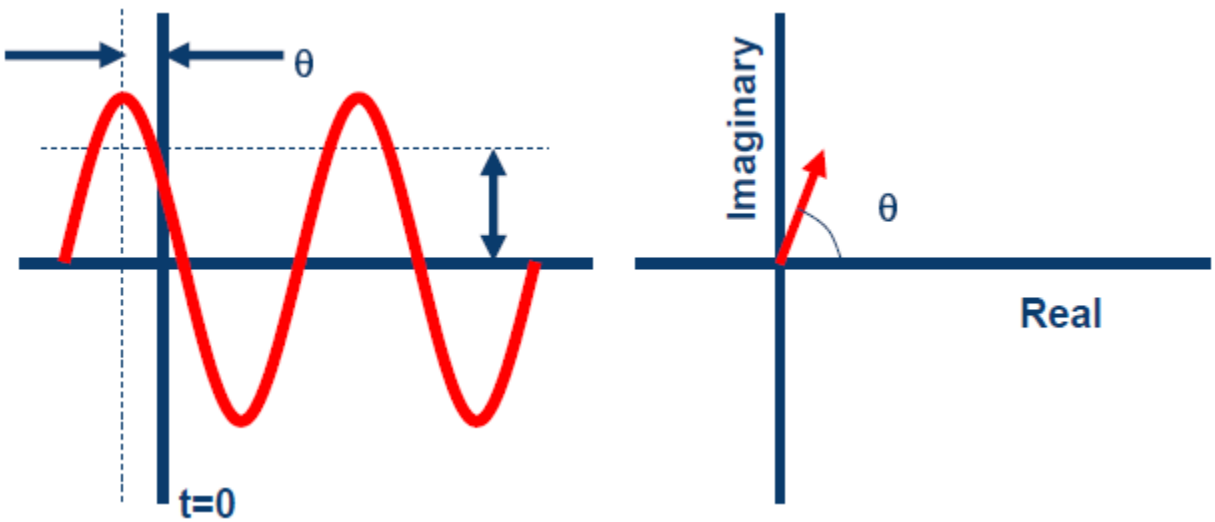
Comparison Between SCADA and PMUs

- PMUs have much faster sampling rate:



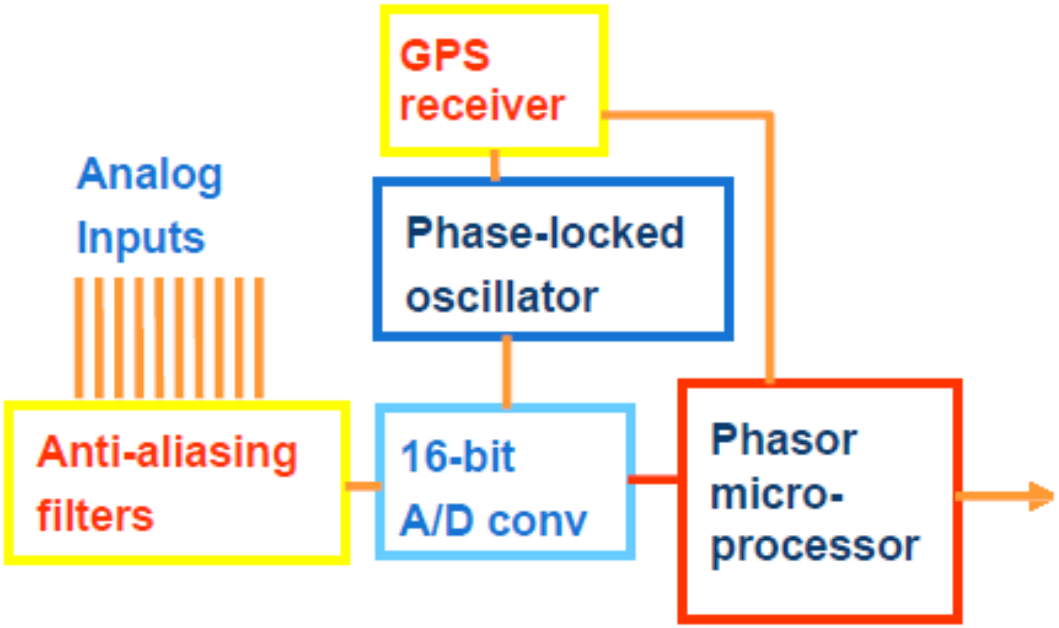
Synchrophasor Definition

- Synchrophasor:
  - Time-tagged sequence phasor measured at different locations.



PMU Architecture

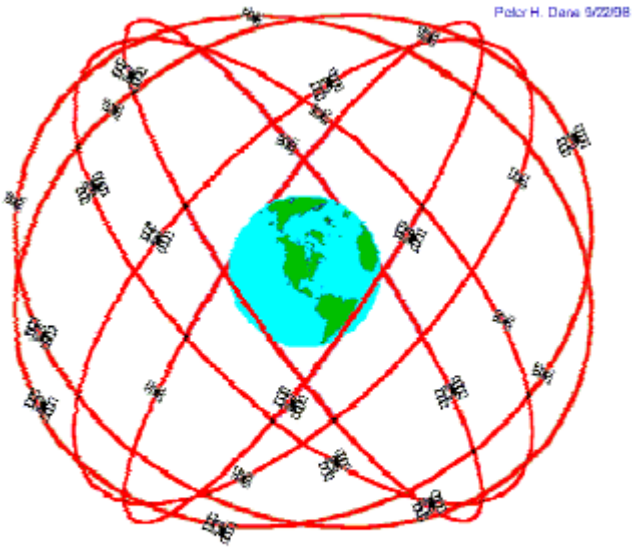
- A GPS receiver is used to time-stamp measurements:



Measurements from all PMUs will be synchronized

Measurement Synchronization

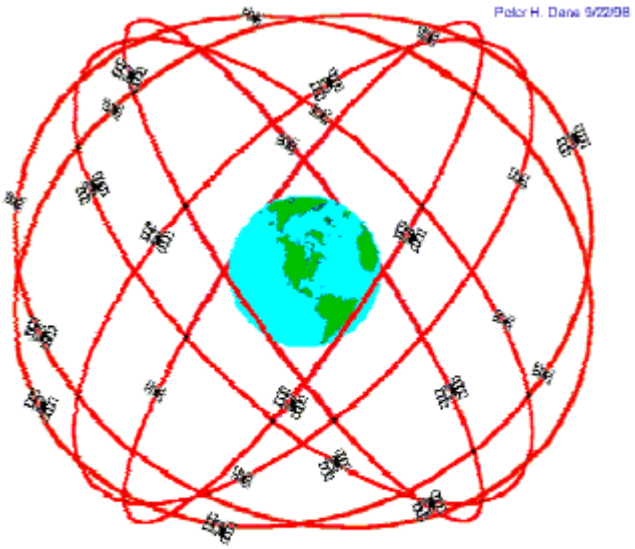
- It is achieved via:
  - 24 Satellites
  - 12 Hour Orbit Time
  - Signal: Position, Velocity, Time
  - Visibility:
    - 5 to 8 Satellites from
      - Any point at any time!



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

Measurement Synchronization

- Performance:
  - 95% Reliable
  - 100 nanosecond time accuracy
    - Q: Good enough?



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

- Positioning is not a concern in PMUs.

Preventing Blackouts

- An application of PMUs and Situational Awareness:
  - Quickly respond to emergencies
  - Prevent disturbance propagation
  - Planned islanding, if needed
  - Limited scope load shedding, if needed
  - Faster system restoration
    - In general, we have no idea what happened after blackout.

Northeast Blackouts 2003

- Affected:
  - About 10 Million People in Ontario, Canada
  - About 45 Million People in 8 U.S. States
- Initiated in Ohio because of
  - A device and also human error.
  - A sequence of events finally led to the blackout.

Northeast Blackouts: Map of the Areas Affected

Some of the Major Cities Affected: New York, Toronto, Detroit, Cleveland, Ottawa

Northeast Blackouts: Map of the Areas Affected

Downtown Toronto

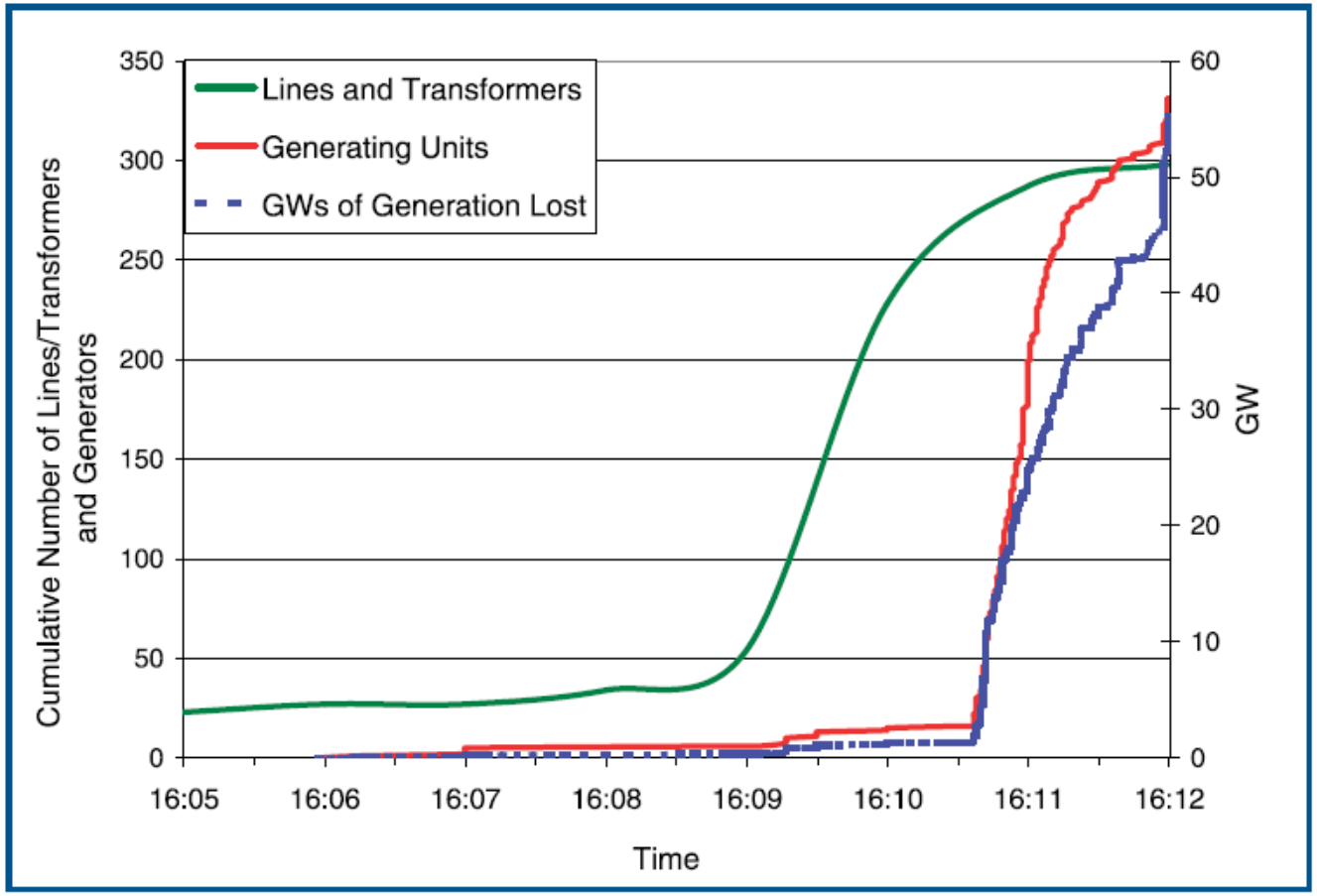
Evening of August 14, 2003

- Video: http://www.youtube.com/watch?v=6nt0njgVmv4.

Northeast Blackouts: Brief Timeline

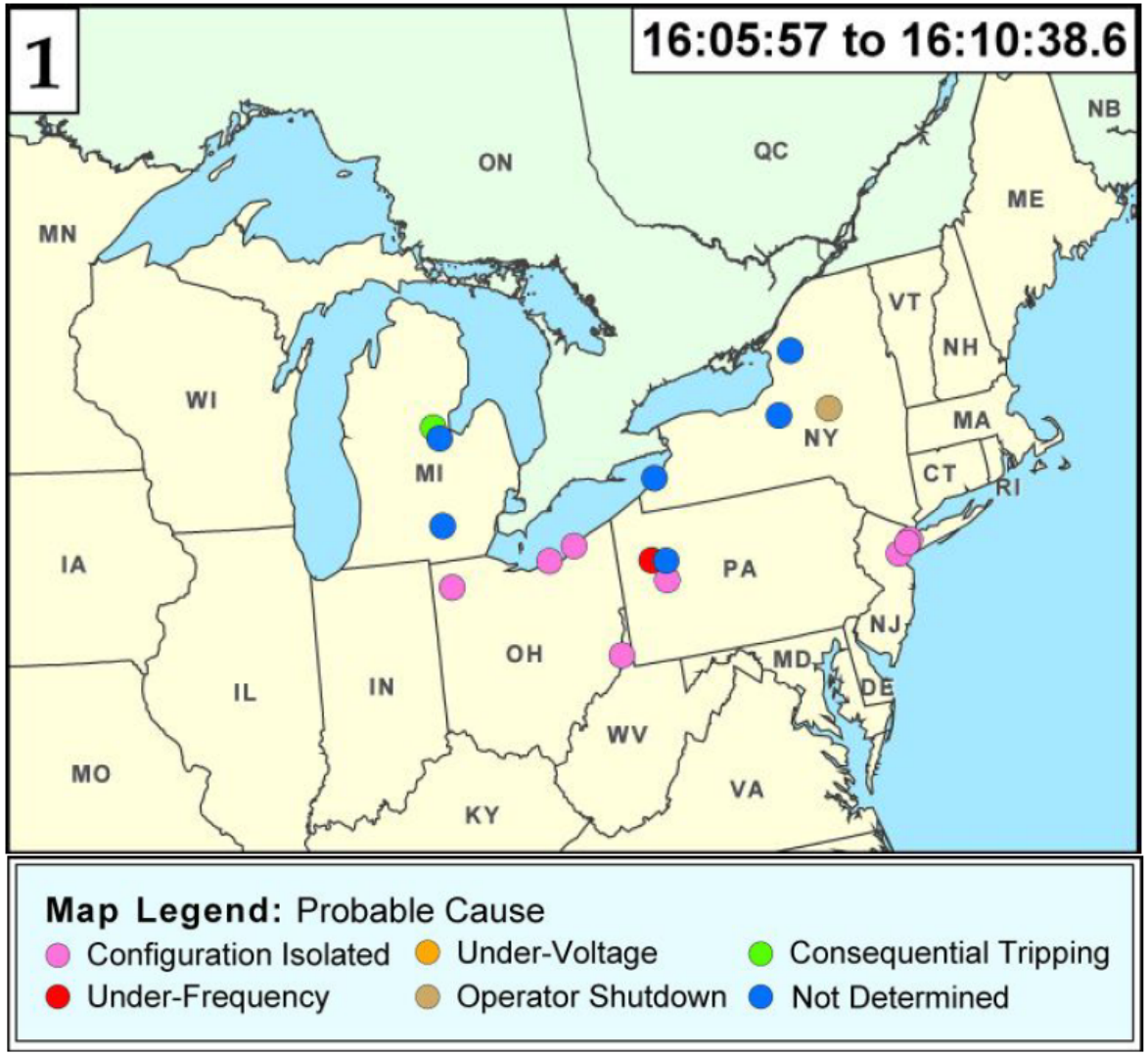
- 12:15:00 EDT: Some error in State Estimator in Northern Ohio
- 13:31:00 EDT: The Eastlake, Ohio generating plant shuts down
- 16:05:57 EDT: Last point blackout could have been prevented!
- 16:13:00 EDT: A total of 256 power plants are offline
  - Restoration: It took up to 6 days in some locations.

Northeast Blackouts: Brief Timeline



Rate of Line and Generator Trips During the Cascade

Northeast Blackouts: Brief Timeline



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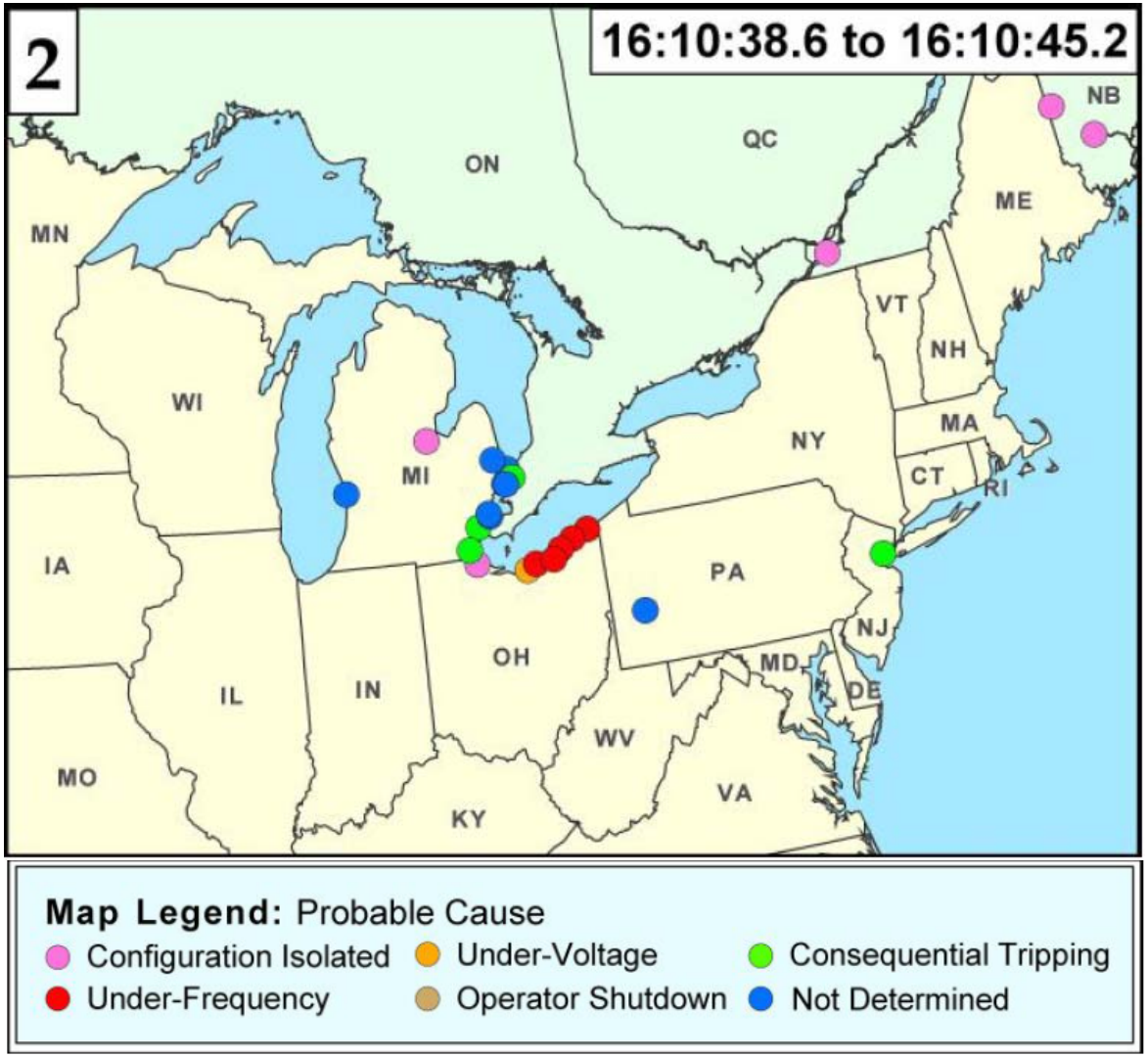

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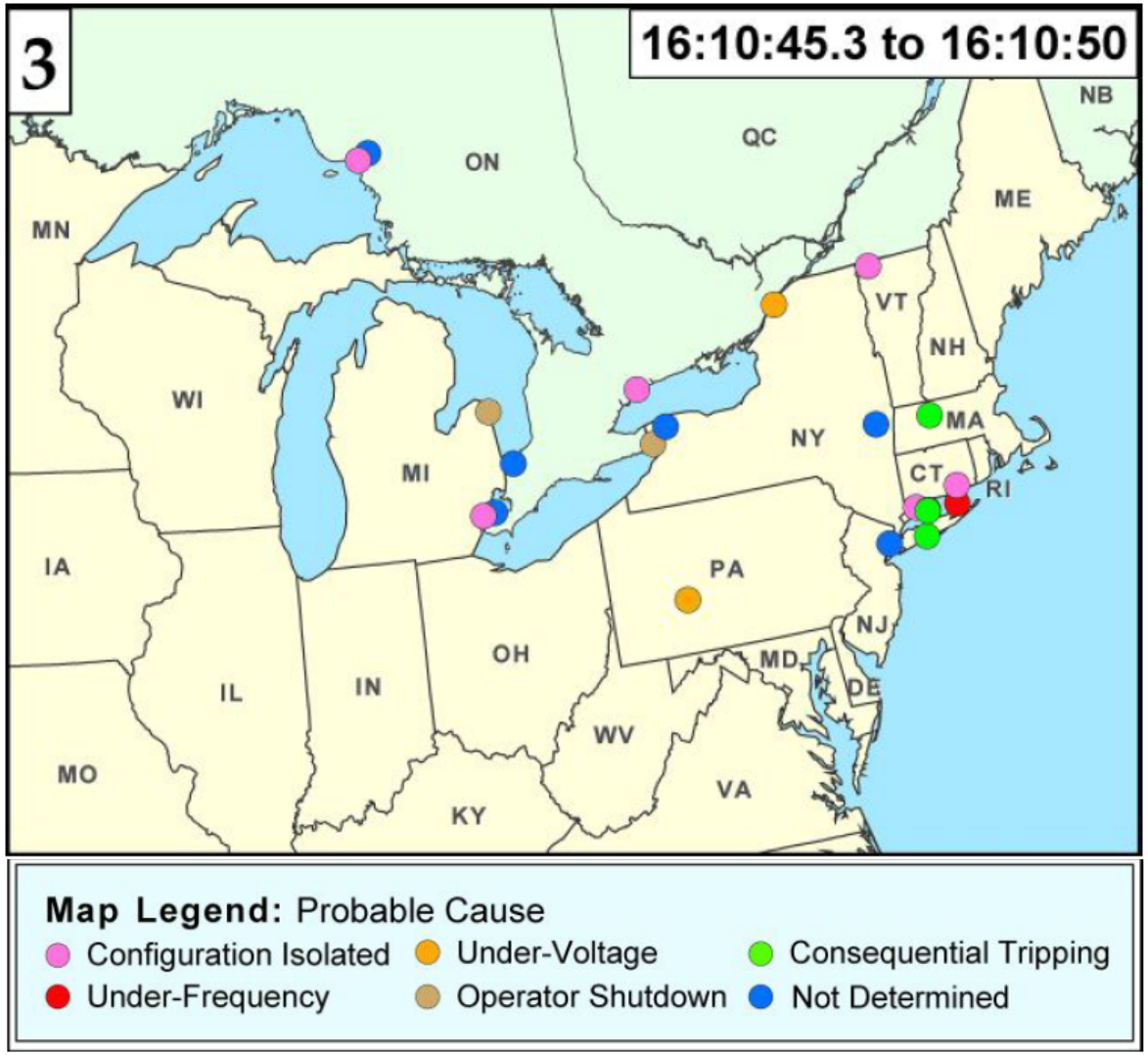

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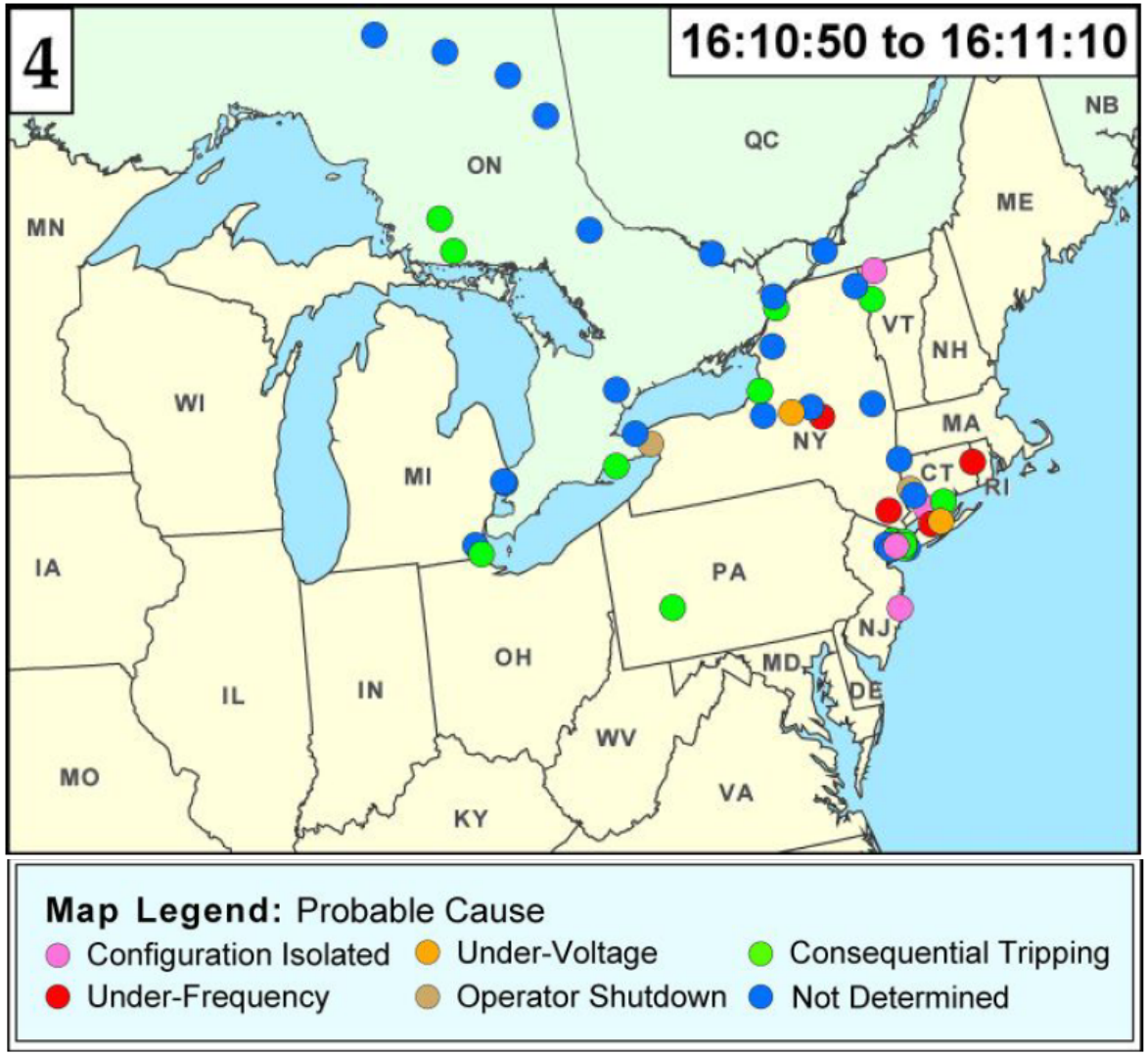

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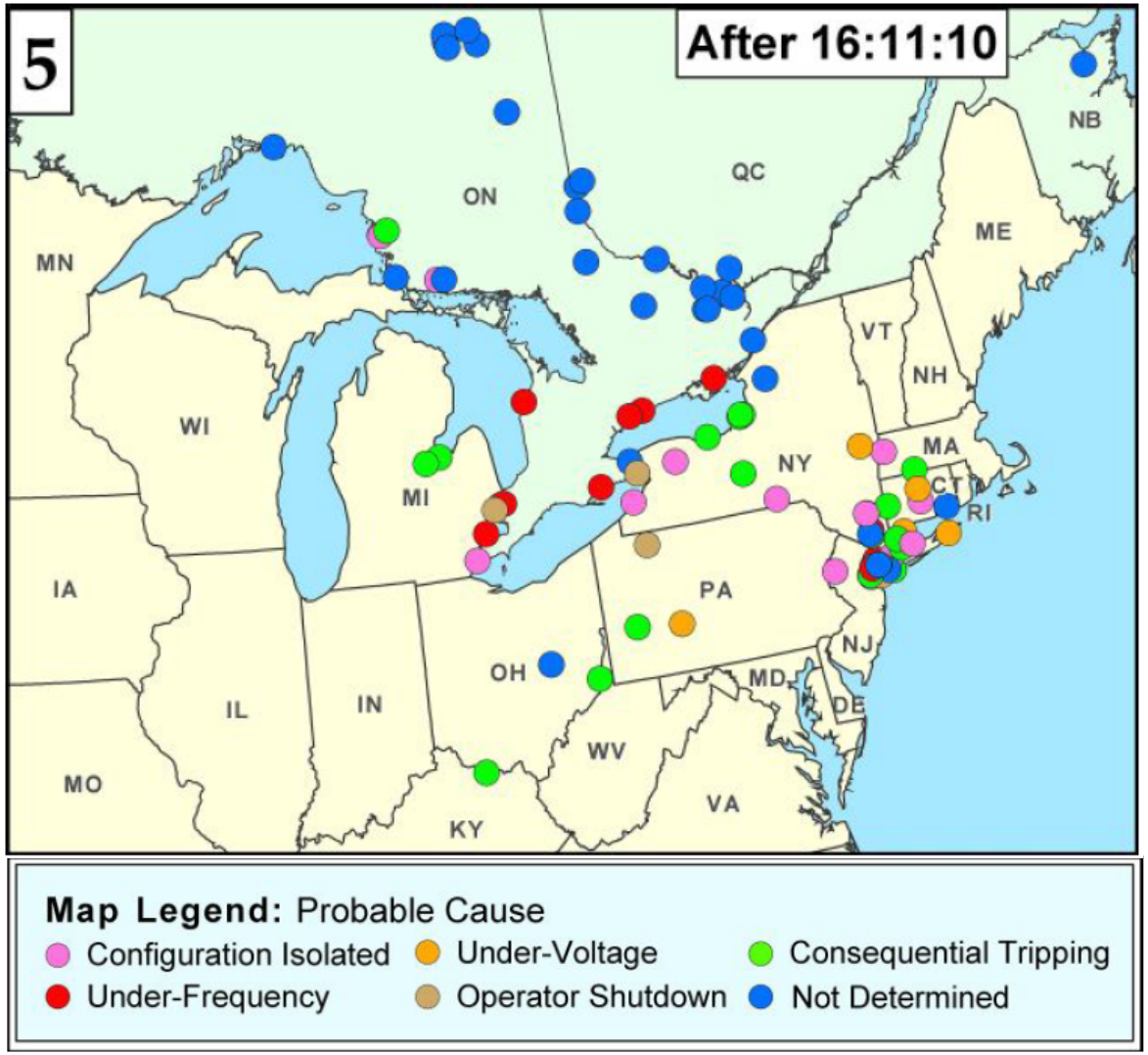

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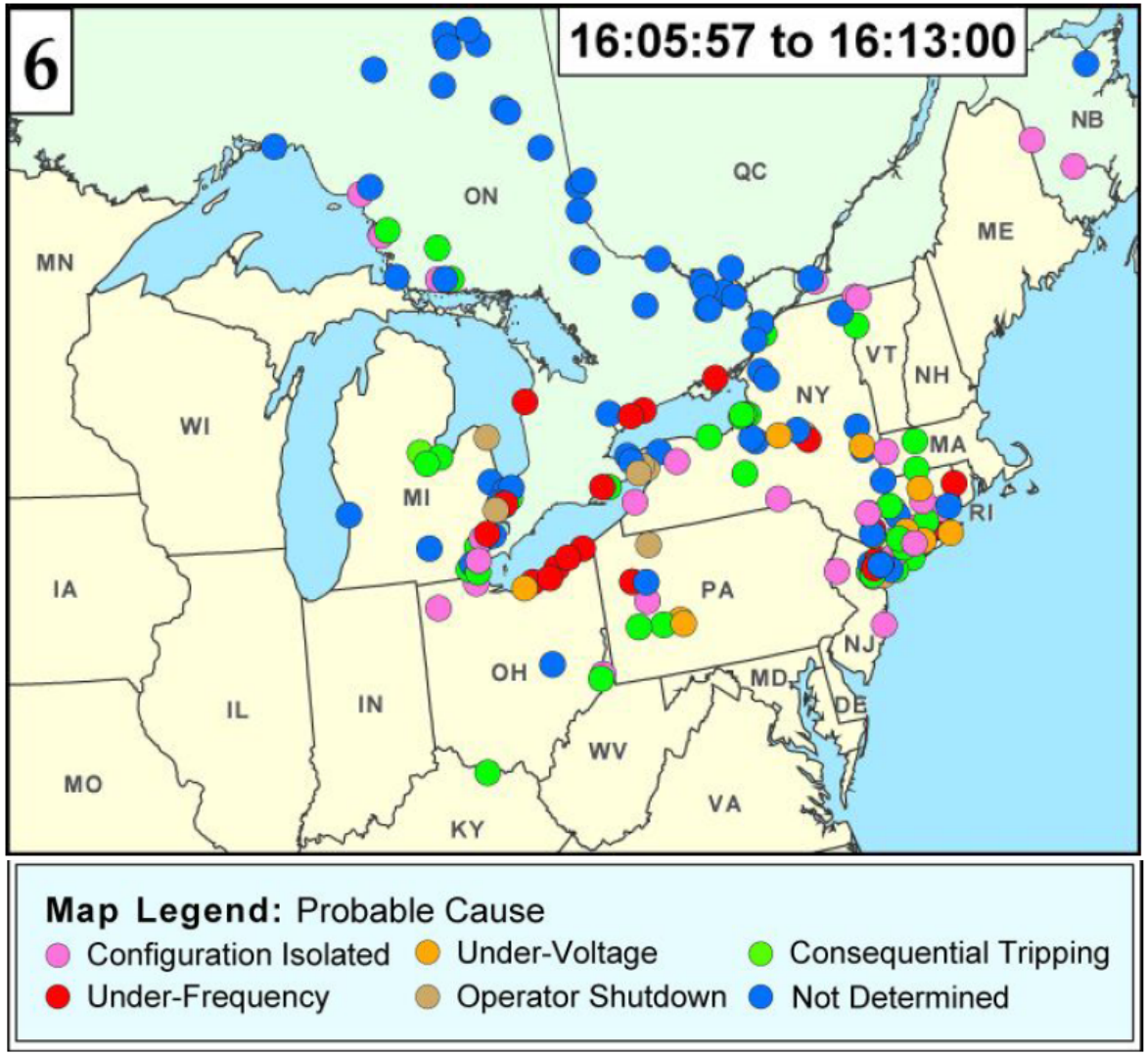
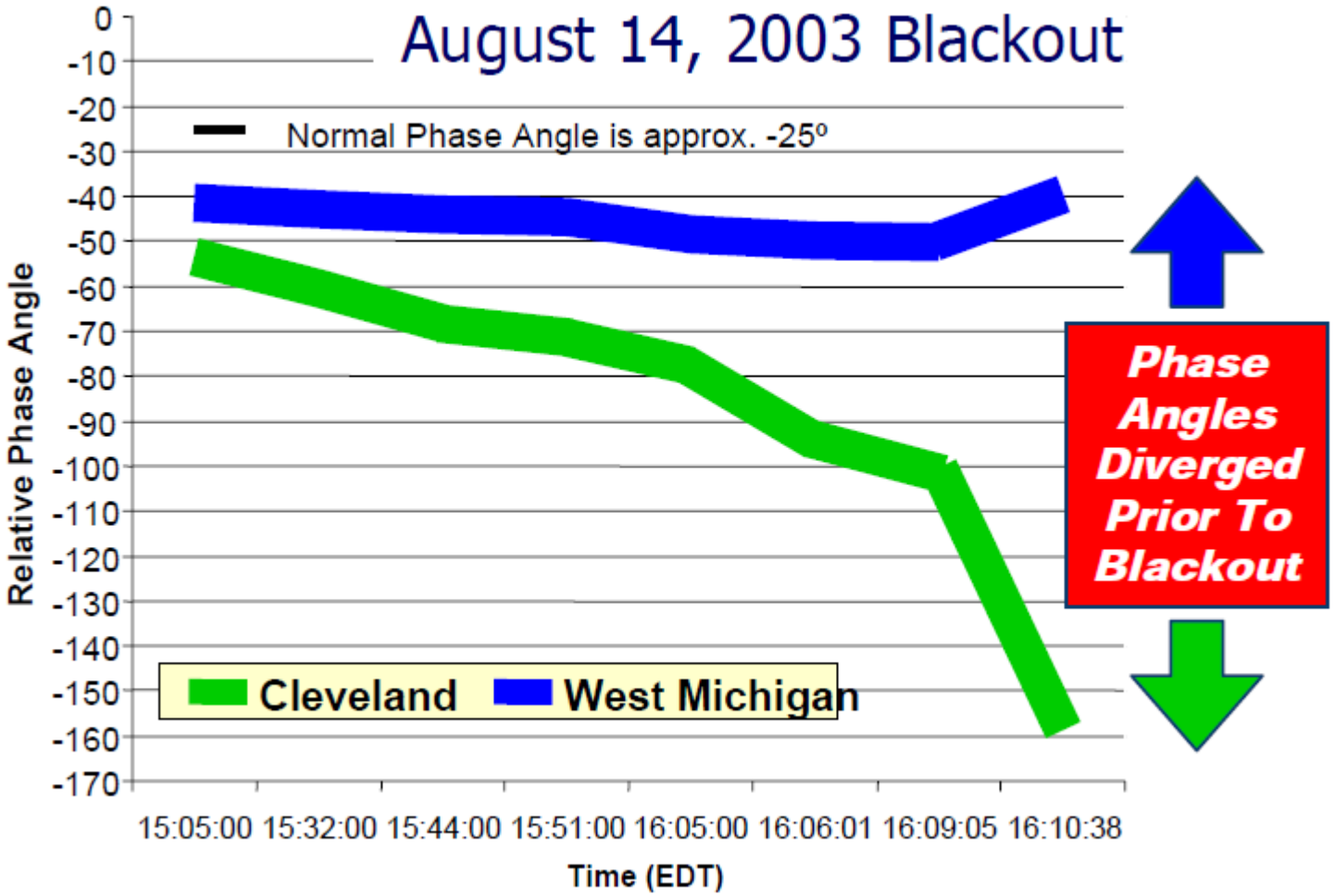


PMU Measurements Could Warn Instability

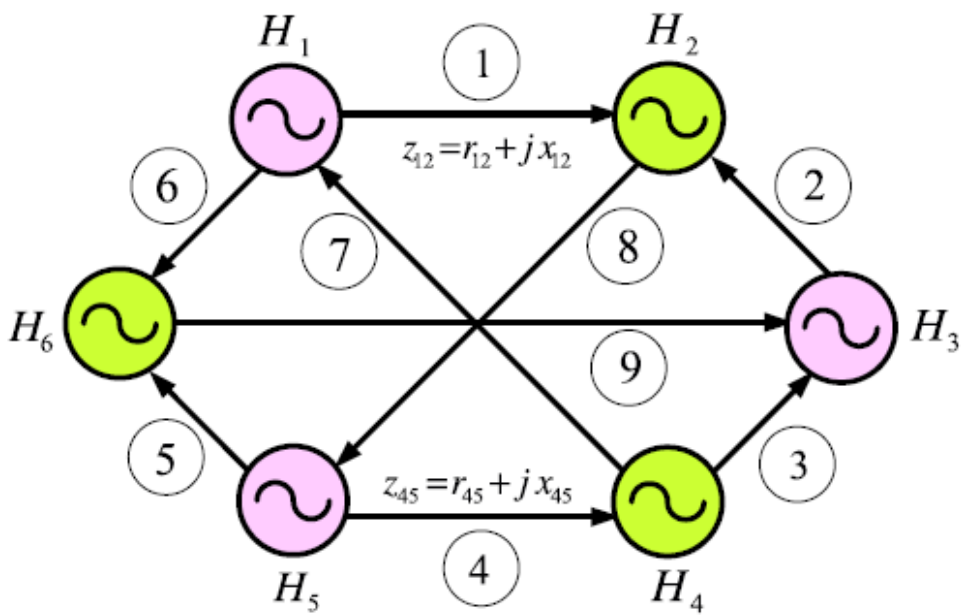


PMU Measurements Could Warn Instability

- We can also use analytical models to capture:
  - Dynamics of the phase angles and frequency.
- Usually we aim to reach linear models.
- The models can be used to
  - Analyze stability as we collect PMU readings
  - Find stability regions using simulations

Dynamic Models

- Consider a network of *n* generators connected to each other:
  - Connections are through *m* tie-lines, with $m \leq n\,(n\text{-}1)\,/\,2$



Ref: A. Chakrabortty et al.

Example: with n = 6 generators and m = 9 tie-lines

Dynamic Models

- The internal voltage phasor of the ith generator is denoted as:

$$E_i \angle \delta_i, \quad i = 1, 2, \cdots, n.$$

- For the link connecting p^{th} and q^{th} generators, impedance is:

$$z_{pq} = r_{pq} + jx_{pq}.$$

- And we have

$$y_{pq} = \frac{1}{z_{pq}} = \frac{1}{r_{pq} + jx_{pq}}.$$

Dynamic Models

- The dynamic electro-mechanical model of the ith generator:

$$\dot{\delta}_i = \omega_i - \omega_s$$

$$2H\,\dot{\omega}_i = P_i - \sum_{k \in N_i} \left(\frac{E_i^2 r_{ik} - E_i\, E_k \sqrt{r_{ik}^2 + x_{ik}^2}\, \cos\left(\delta_i - \delta_k + \tan^{-1}\left(\frac{x_{ik}}{r_{ik}}\right)\right)}{r_{ik}^2 + x_{ik}^2} \right)$$

where

$$\omega_s = 120\pi = \text{Nominal Angular Velacity at 60 Hz}$$

$$\omega_i = \text{Rotor Angular Velacity of Generator } i$$

Dynamic Models

- A linear model around an initial equilibrium $(\delta_{i0}, \omega_{i0})$:

$$\Delta\delta = \begin{bmatrix} \Delta\delta_1 \\ \vdots \\ \Delta\delta_n \end{bmatrix}, \qquad \Delta\omega = \begin{bmatrix} \Delta\omega_1 \\ \vdots \\ \Delta\omega_n \end{bmatrix}.$$

Assuming that a disturbance *u* enters the system at node j:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \end{bmatrix} = \begin{bmatrix} 0 & I \\ L & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 \\ \varepsilon_j \end{bmatrix} u$$

Dynamic Models

- A linear model around an initial equilibrium $(\delta_{i0}, \omega_{i0})$:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \end{bmatrix} = \begin{bmatrix} 0 & I \\ L & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 \\ \varepsilon_j \end{bmatrix} u$$

where

$$I = n\text{-dimensional identity matrix}$$

$$\varepsilon_j = \text{A unit vector with all elements zero and the } j^{th} \text{ element is } 1$$

Dynamic Models

- A linear model around an initial equilibrium $(\delta_{i0}, \omega_{i0})$:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \end{bmatrix} = \begin{bmatrix} 0 & I \\ L & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 \\ \varepsilon_j \end{bmatrix} u$$

where

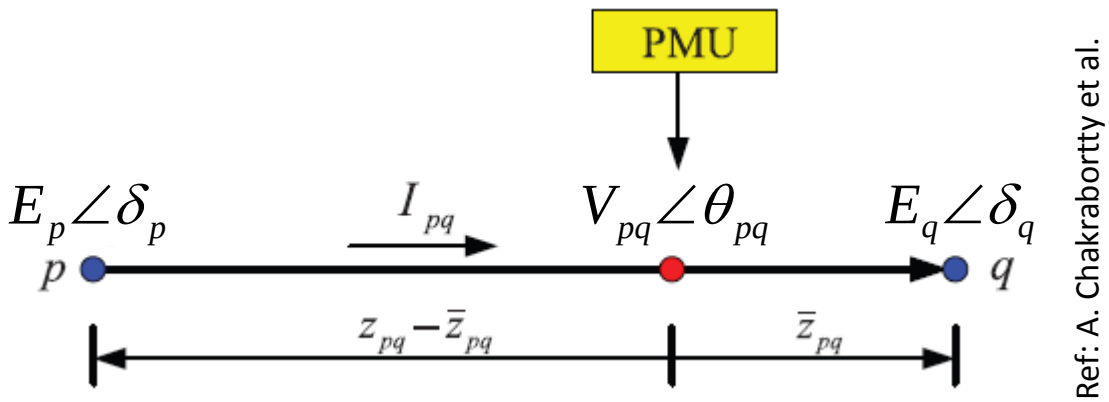
$$L_{ii} = -\sum_{k \in N_i} \frac{E_i E_k}{\sqrt{r_{ik}^2 + x_{ik}^2}} \sin\left(\delta_{i0} - \delta_{k0} + \tan^{-1}\left(\frac{x_{ik}}{r_{ik}} \right) \right)$$

$$L_{ik} = \begin{cases} \dfrac{E_i E_k}{\sqrt{r_{ik}^2 + x_{ik}^2}} \sin\left(\delta_{i0} - \delta_{k0} + \tan^{-1}\left(\dfrac{x_{ik}}{r_{ik}} \right) \right) & \text{if } k \in N_i \\ 0 & \text{otherwise} \end{cases}$$

Dynamic Models

- So far we have only modeled angle and angular velocity.

- Q: What if we measure voltage phasors using PMUs?



Ref: A. Chakrabortty et al.

Measurement is done somewhere between two generators.

Dynamic Models

- Voltage magnitude is obtained as

$$V_{pq} = \sqrt{E_q^2(1-\alpha_{pq})^2 + E_p^2\alpha_{pq}^2 + 2E_pE_q\alpha_{pq}(1-\alpha_{pq})\cos(\delta_p - \delta_q)}$$

where

$$\alpha_{pq} = \frac{\bar{z}_{pq}}{z_{pq}}$$

$$\bar{z}_{pq} = \text{Impedance from reference node to PMU location}$$

Dynamic Models

- The linearized model around $(\delta_{i0}, \omega_{i0})$ becomes:

$$V_{pq} = \underbrace{\frac{a_{pq}(1-a_{pq})}{V_{pq}(\delta_{p0},\delta_{q0})} E_p E_q \sin(\delta_{p0}-\delta_{q0}) \begin{bmatrix} 1 & -1 & 0 & 0 \end{bmatrix}}_{C_{pq}} \begin{bmatrix} \Delta\delta_p \\ \Delta\delta_q \\ \Delta\omega_p \\ \Delta\omega_q \end{bmatrix}$$

where

$$V_{pq}(\delta_{p0},\delta_{q0}) = \text{Evaluation of Nonlinear Voltage Model at } \delta_{p0} \text{ and } \delta_{q0}$$

Dynamic Models

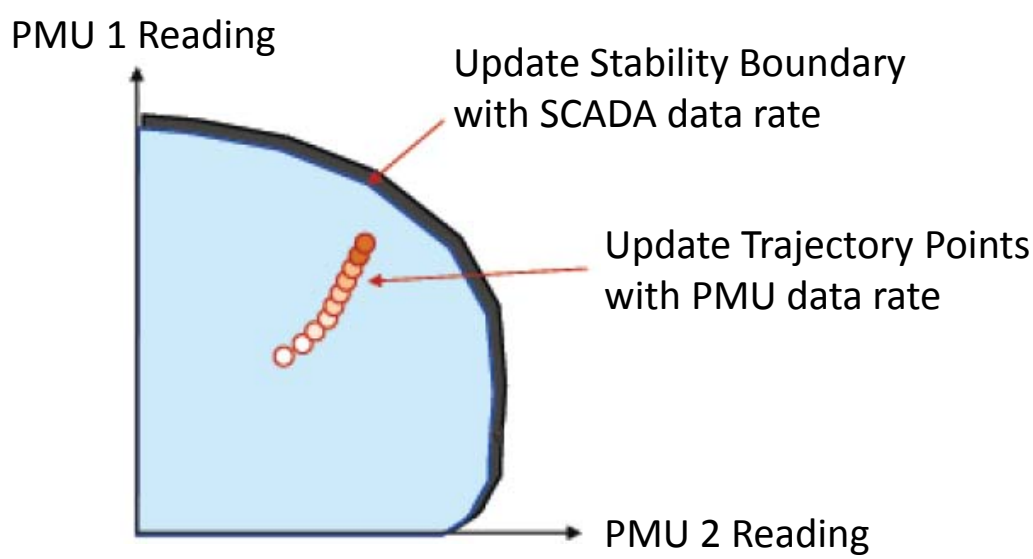
- Finally, the state space model becomes:

$$\begin{bmatrix} \dot{\Delta\delta} \\ \dot{\Delta\omega} \end{bmatrix} = \begin{bmatrix} 0 & I \\ L & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \end{bmatrix} + \begin{bmatrix} 0 \\ \varepsilon_j \end{bmatrix} u \qquad V_{pq} = C_{pq} \begin{bmatrix} \Delta\delta_p \\ \Delta\delta_q \\ \Delta\omega_p \\ \Delta\omega_q \end{bmatrix}$$

- The model can be used for
  - Stability Analysis
  - System Identification
  - Closed-loop controller / stabilizer design.

Region of Stability

- Using the non-linear/linear models and simulations:
  - We obtain regions for PMU readings that assure stability
- Contingency and security scenarios can also be considered.



Region of Stability

- Alarm is triggered as the trajectory approaches boundaries.
- Stability regions can also be used to visualize stability status.
- There can be several such two-dimensional regions.
- One challenge: where are the optimal locations for PMUs?

PMU Deployment Status

- PMU devices are available from many vendors:
  - ABB, Schweitzer, AMETEK, Arbiters, GE, Macrodyne, SEL
- New IEEE C37.118 standard has been approved.
  - Partly covered that in Topic 2.
- There are systems that are already installed and operating.

PMU Deployment Status

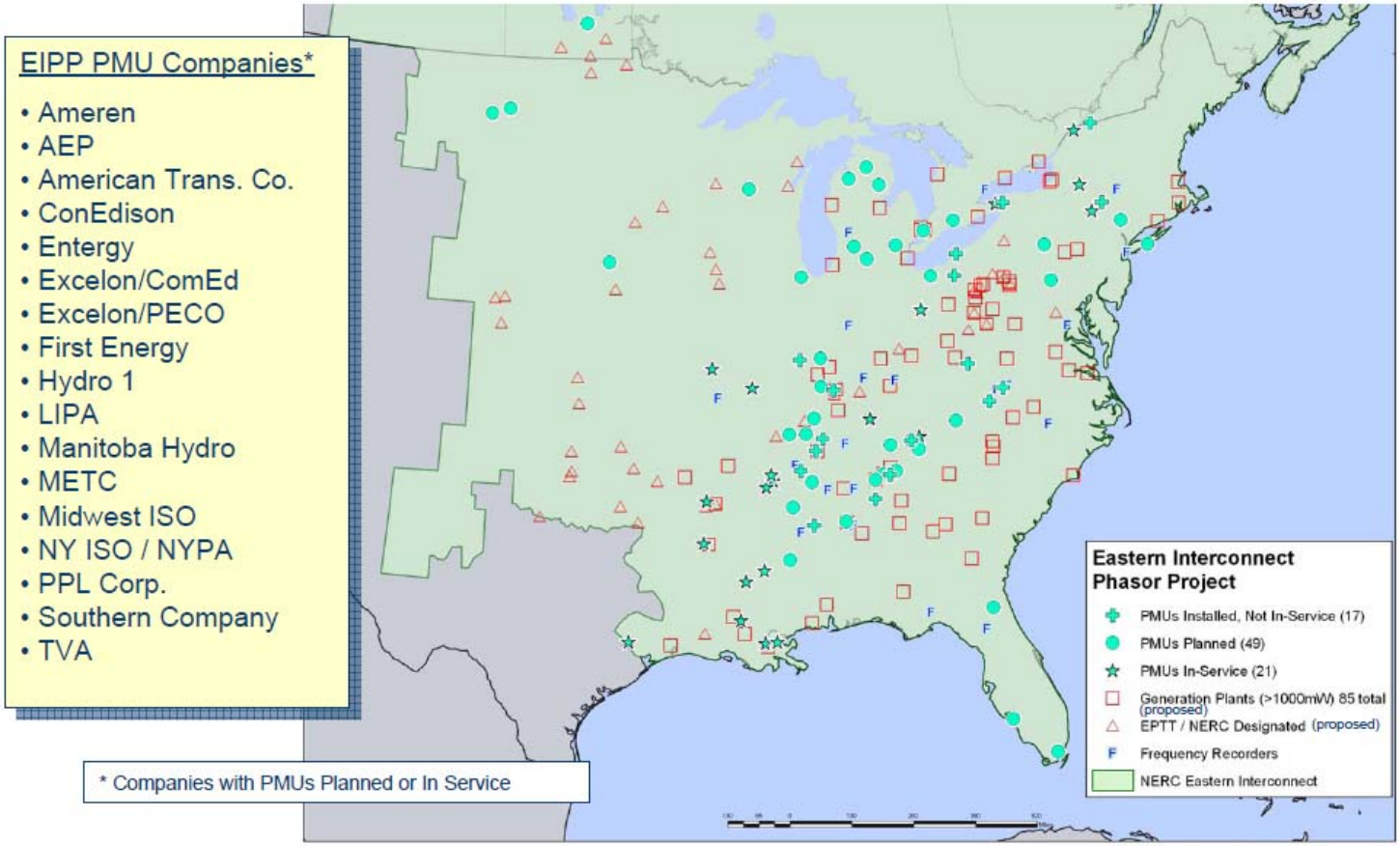
- Eastern Interconnection Phasor Project (EIPP):

• Number of utilities:	➢ 32
• Number of research organizations:	➢ 14
• Number of vendors:	➢ 27
• DOE investment in EIPP:	➢ $3 million (since 2002)
• Industry investment in EIPP:	➢ $15 million (5 to 1 leverage)
• Future DOE investment needed:	➢ $5 million (yearly)
• Number of years needed:	➢ 5 years

Source: EIPP

PMU Deployment Status

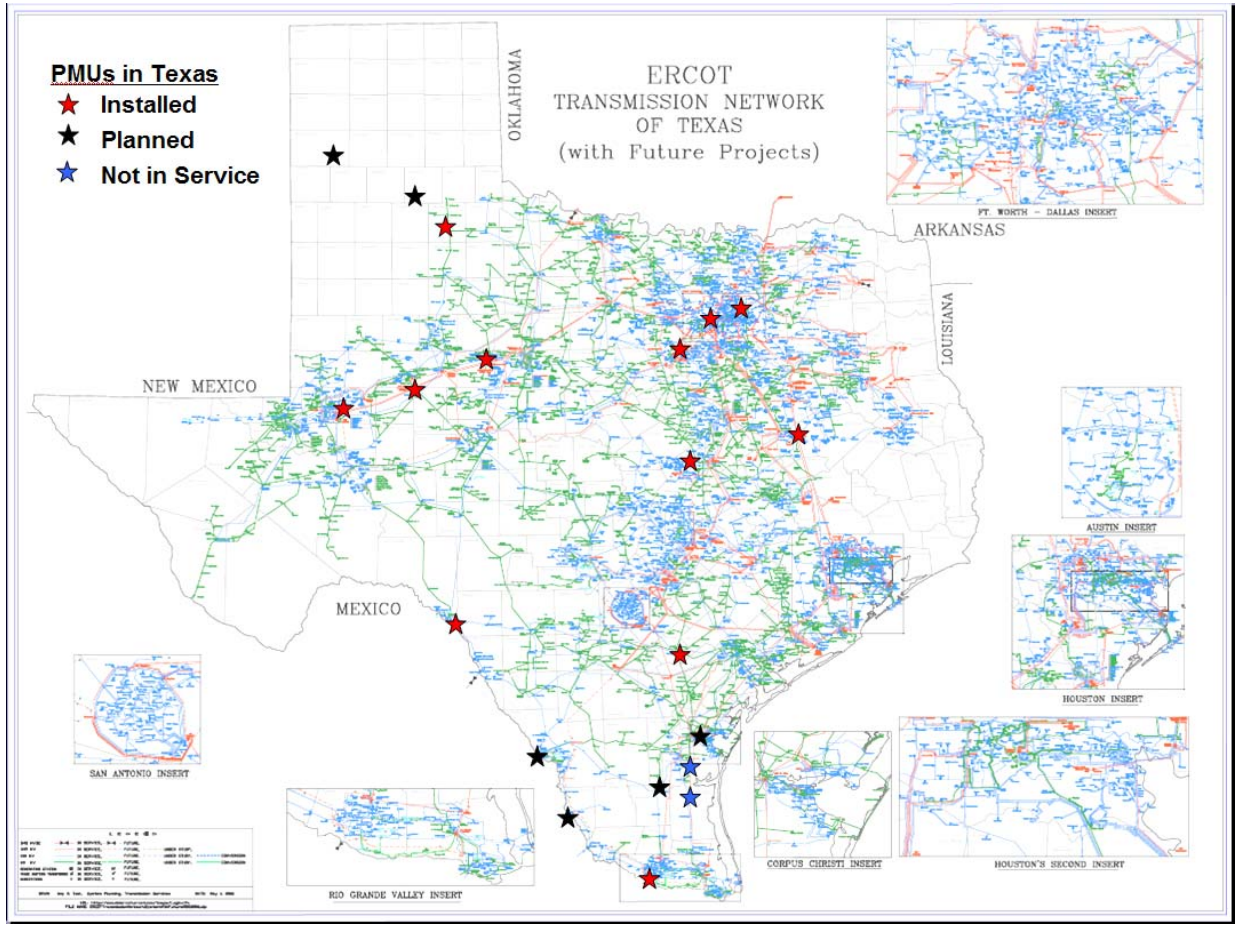
- Eastern Interconnection Phasor Project (EIPP):



Source: EIPP

PMU Deployment Status

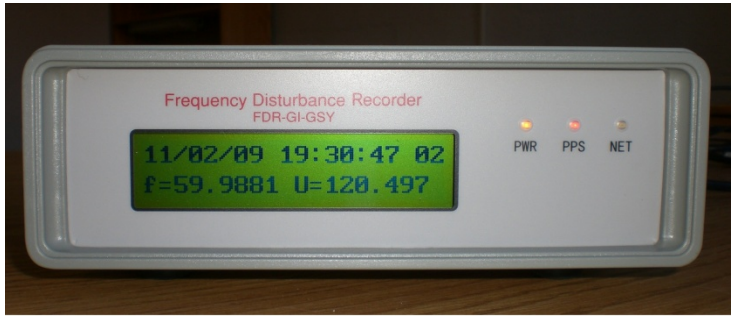
- CCET Discovery Across Texas Project:



Source: CCET

PMU Deployment Status

- FNET (Frequency Monitoring Network) Project:
  - University of Tennessee
  - Virginia Tech
- They use a special type of PMU:
  - Frequency Disturbance Recorder (FDR)

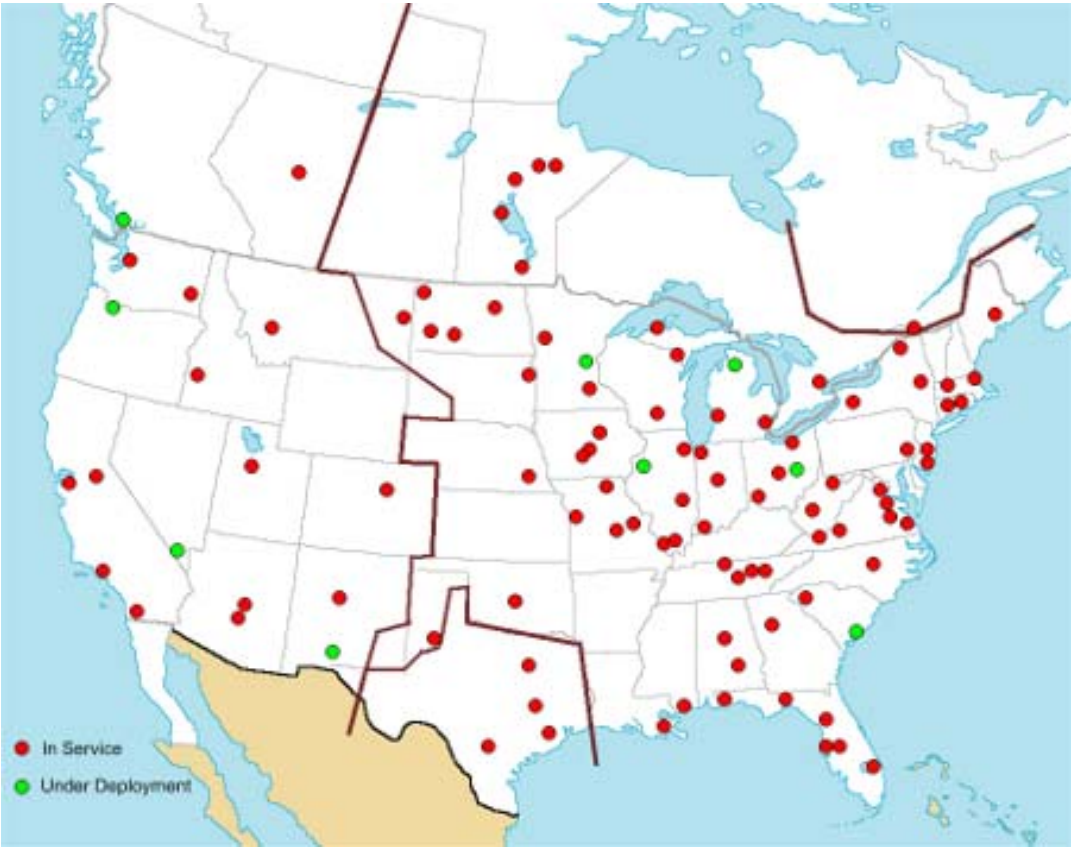


PMU Deployment Status

- FDR measures
  - Measure frequency, phase angle, and voltage
    - Of the power system at ordinary 120 V outlets
- It is a single phase PMU.
- FDRs send data to the FNET servers over the Internet.
- Video: www.youtube.com/watch?v=9Vt2OlVoBJc (From 0:40)

PMU Deployment Status

- Locations of current FDRs installed:



PMU Deployment Status

- They have monitored frequency at some recent events:
  - Visualization of the Eastern Interconnection power system frequency before, during, and after a generator trip at the John Amos plant in Nitro, West Virginia. (8/6/2007).
  - Video: http://www.youtube.com/watch?v=f0rdFy1f4t4
- They have also simulated some other major events:
  - Blackout of 2003 (8/14/2003).
  - Video: http://www.youtube.com/watch?v=eBucg1tX2Q4

PMU Deployment Status

- Link to FNET website:
  - http://www.tntech.edu/cesr/fnet
  - http://fnetpublic.utk.edu/
- Link to more captured events:
  - http://fnetpublic.utk.edu/sample_events.html
- Link to more simulations:
  - http://www.youtube.com/PowerITLabUTK

References

- North American Electric Reliability Council, "Technical Analysis of the August 14, 2003, Blackout: What Happened, Why, and What Did We Learn?", Report to the NERC Board of Trustees by the NERC Steering Group, July 2004. http://www.nerc.com/docs /docs/blackout/NERC_Final_Blackout_Report_07_13_04.pdf.

- M. Vaiman, M. Vaiman, S. Maslennikov, E. Litvinov, and X. Luo, "Calculation and Visualization of Power System Stability Margin Based on PMU Measurements", in Proc. of IEEE Smart Grid Communications Conference (Smart Grid Comm'10), Gaithersburg, MD, October 2010.

References

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- A. Chakrabortty and C. F. Martin, "Optimal measurement allocation for parametric model identification of electrical networks", IEICE Transactions on Nonlinear Theory and Its Applications, vol. 2, no. 3, pp. 302-319, 2010.