Event Detection Using Phasor Angle Measurements

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Motivation

- Four of the six major North American blackouts were due in part to a lack of situational awareness
- One crucial part of situational awareness is knowledge of device statuses, both locally and over the wide area
- Detecting and identifying significant switching events on the system will help operators understand and react to problems on the grid

(Some) Quantities That Can Be Used for Wide Area Event Detection

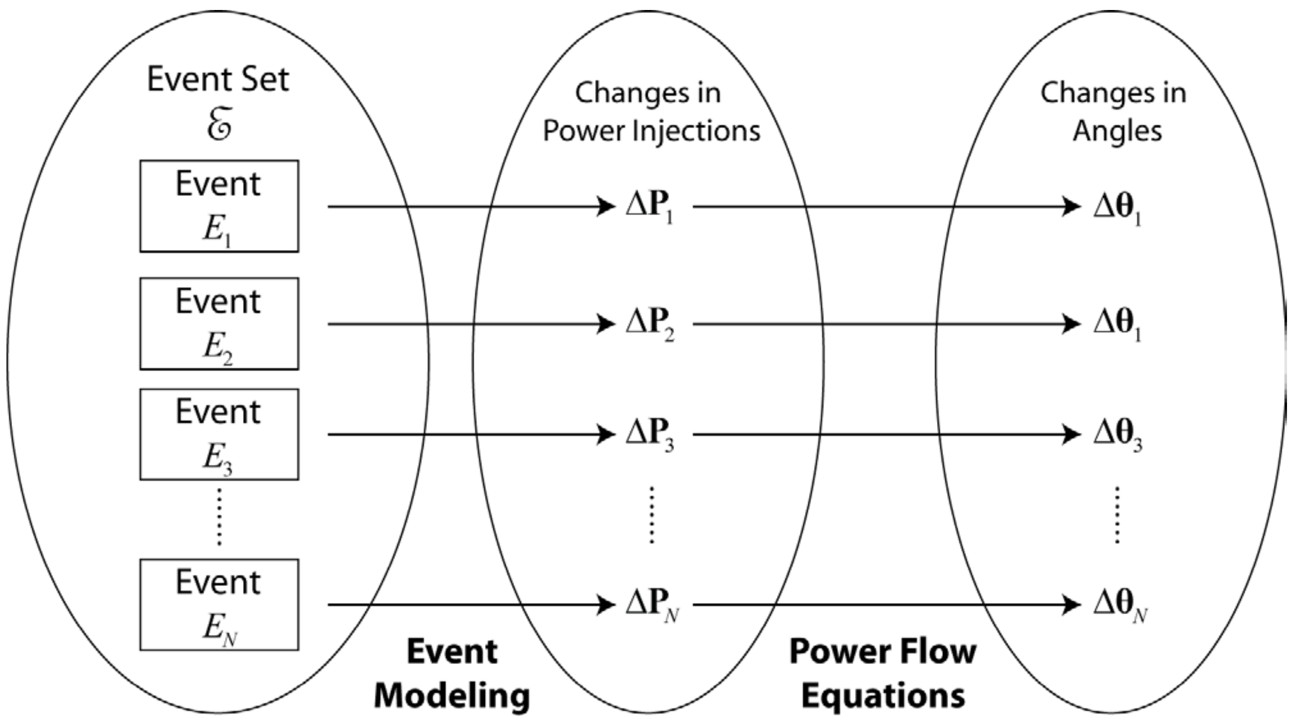
- Line impedances & ratings (from study cases)
- Pre-event, wide area topology information (from the NERC System Data Exchange)
- Wide area measurements (from PMUs and FNET devices)

Using this Data to Detect Events

- The basic premise of the event detection algorithm is to match observed measurements with the expected measurements due to an event
- Research thus far has focused on PMU-measured changes in steady state angle changes and involves two steps:
    1. Mapping candidate events to angle changes
    2. Finding the event which best matches the observed angle changes

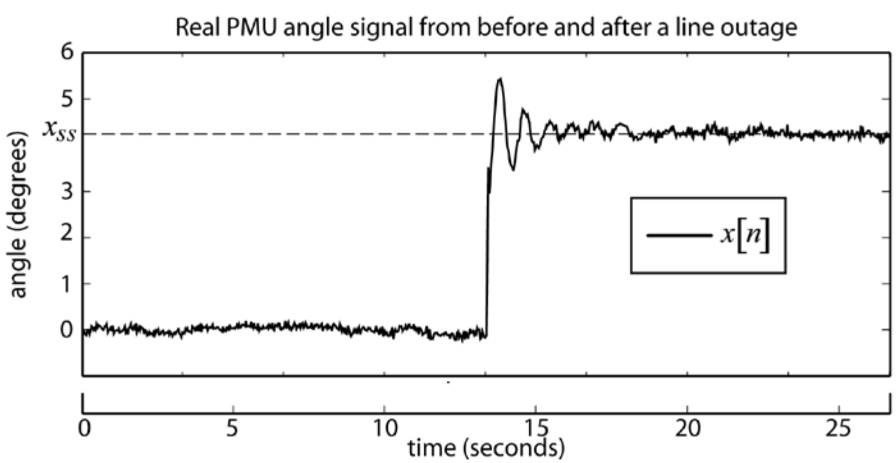
Step One: Mapping Candidate Events to Angle Changes

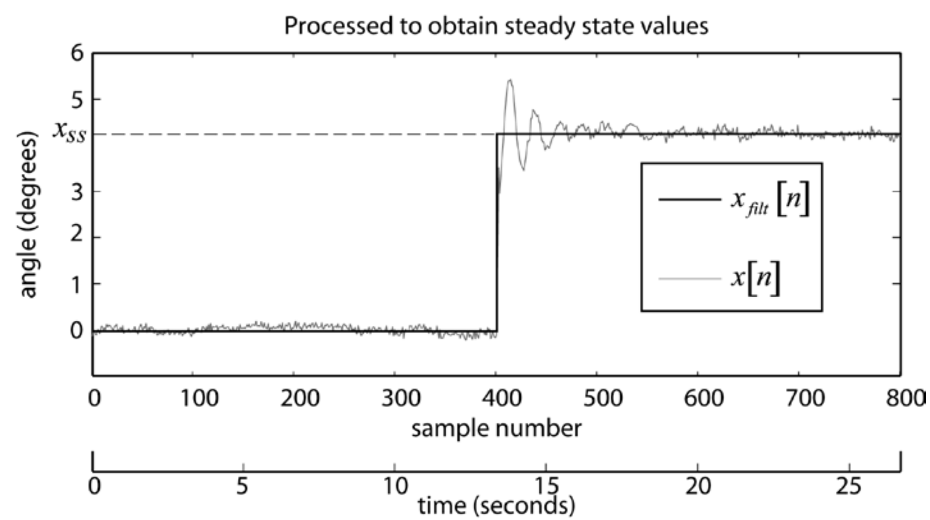
- Given a particular event, we can predict what the changes in angles will be using the (in this case, dc) power flow equations:



Step Two: Finding the Event Which Best Matches Observed Angle Changes

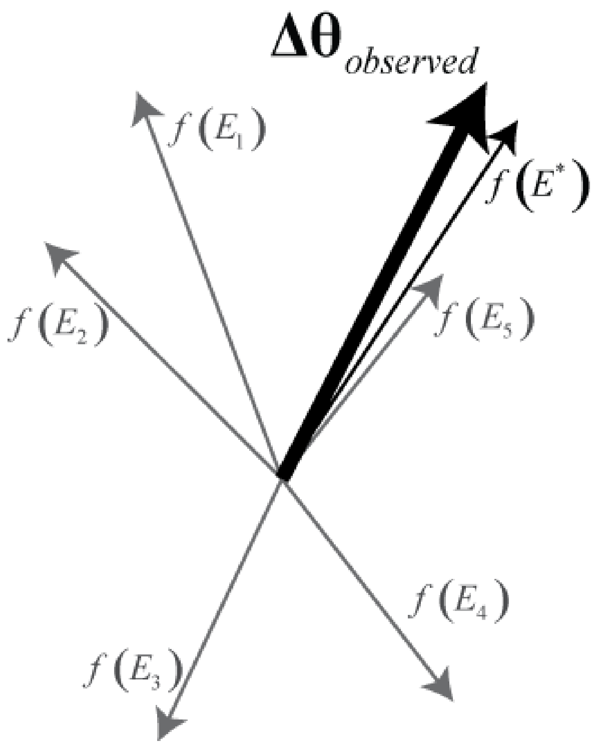
- First, need to determine the change in steady-state angles on the system
  - Filtering to eliminate oscillations
  - Edge detection





Step Two: Finding the Event Which Best Matches Observed Angle Changes (cont'd)

- Next, solve the problem of matching the observed angles against the possible events:



$$E^* = \arg\min_{E \in \mathcal{E}} \left\| \Delta\boldsymbol{\theta}_{observed} - \mathbf{f}(E) \right\|$$

$$\Delta\boldsymbol{\theta}_{observed} \in \mathbb{R}^K$$

$$\mathbf{f} : \mathcal{E} \to \mathbb{R}^K$$

Single Line Outages

- Pre-outage flow is unknown, so this must be estimated as well:

$$\text{line outaged } l^* = \arg\min_{l \in \{1,2,\ldots,L\}} \left(\min_{P_l} \left\| \Delta\boldsymbol{\theta}_{observed} - deltaAngles_l \left(P_l \right) \right\| \right)$$

- Single line outages are modeled as power injections at the line terminals, as is done in defining line outage distribution factors (LODFs)

Single Line Outage Modeling Details

- Using the dc load flow equations, we can express the expected angle changes as a scalar-vector multiplication:

$$\boldsymbol{\Delta\theta} = \mathbf{B}^{-1}\boldsymbol{\Delta}\mathbf{P} \qquad \tilde{P}_l = \frac{P_l}{1 - PTDF_{l,l_{from}-l_{to}}} \qquad \mathbf{K} = \begin{bmatrix} \mathbf{I}_{K\times K} & \mathbf{0}_{K\times(N-K)} \end{bmatrix}$$

$$\begin{aligned} \boldsymbol{\Delta\theta}_{calc,l}^{\tilde{P}_l} &= \mathbf{K}\mathbf{B}^{-1} \begin{bmatrix} 0 \\ \tilde{P}_l \\ -\tilde{P}_l \\ 0 \end{bmatrix} \begin{array}{l} \\ \leftarrow l_{to} \\ \leftarrow l_{from} \\ \\ \end{array} \\ &= \tilde{P}_l \boldsymbol{\Delta}\tilde{\boldsymbol{\theta}}_{calc,l} \end{aligned}$$

$$\text{line outaged } l^* = \underset{l\in\{1,2,\ldots,L\}}{\arg\min} \left(\min_{\tilde{P}_l} \left\| \boldsymbol{\Delta\theta}_{observed} - \tilde{P}_l \boldsymbol{\Delta}\tilde{\boldsymbol{\theta}}_{calc,l} \right\| \right)$$

Single Line Outage Modeling Details (cont'd)

- A different form of the problem is obtained after some manipulation:

$$\text{line outaged } l^* = \arg\min_{l \in \{1,2,\ldots,L\}} \left(- \frac{\left(\Delta\boldsymbol{\theta}_{observed} \cdot \Delta\tilde{\boldsymbol{\theta}}_{calc,l} \right)^2}{\left[\left(\Delta\boldsymbol{\theta}_{observed} \cdot \Delta\boldsymbol{\theta}_{observed} \right) \left(\Delta\tilde{\boldsymbol{\theta}}_{calc,l} \cdot \Delta\tilde{\boldsymbol{\theta}}_{calc,l} \right) \right]} \right)$$

$$= \arg\max_{l \in \{1,2,\ldots,L\}} \left| \left(\frac{\Delta\boldsymbol{\theta}_{observed}}{\left\| \Delta\boldsymbol{\theta}_{observed} \right\|} \right) \cdot \left(\frac{\Delta\tilde{\boldsymbol{\theta}}_{calc,l}}{\left\| \Delta\tilde{\boldsymbol{\theta}}_{calc,l} \right\|} \right) \right|$$

- Because arbitrary scaling is allowed on the expected angle change vector, the direction of the two vectors is all that really matters

Example: Single Line Outage in TVA's System

- Based on actual PMU measurements obtained during a 500 kV line outage; pre-outage topology information taken from state estimator
- With only 7 (out of 7000) angles measured, correct line is detected and the pre-outage flow is estimated with 1% error
- Removing angle measurement closest to line, still detect correct line outage and still estimate pre-outage flow with 1% error

Double Line Outages

- Pre-outage flows are unknown on both lines, so there are two unknown flows to estimate:

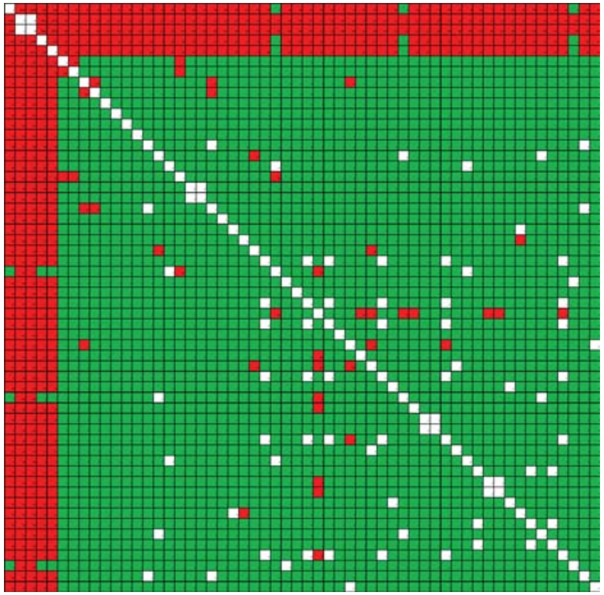
$$\text{lines outaged } \{l_1^*, l_2^*\} =$$

$$\underset{\{l_1,l_2\}\in\{1,2,\ldots,L\}\times\{1,2,\ldots,L\}}{\arg\min} \left(\min_{P_{l,1},P_{l,2}} \left\| \Delta\boldsymbol{\theta}_{observed} - deltaAngles_{l_1,l_2}\left(P_{l,1}, P_{l,2}\right) \right\| \right)$$

- Double line outages are modeled as power injections at the two lines' terminals, an extension of single line outage modeling

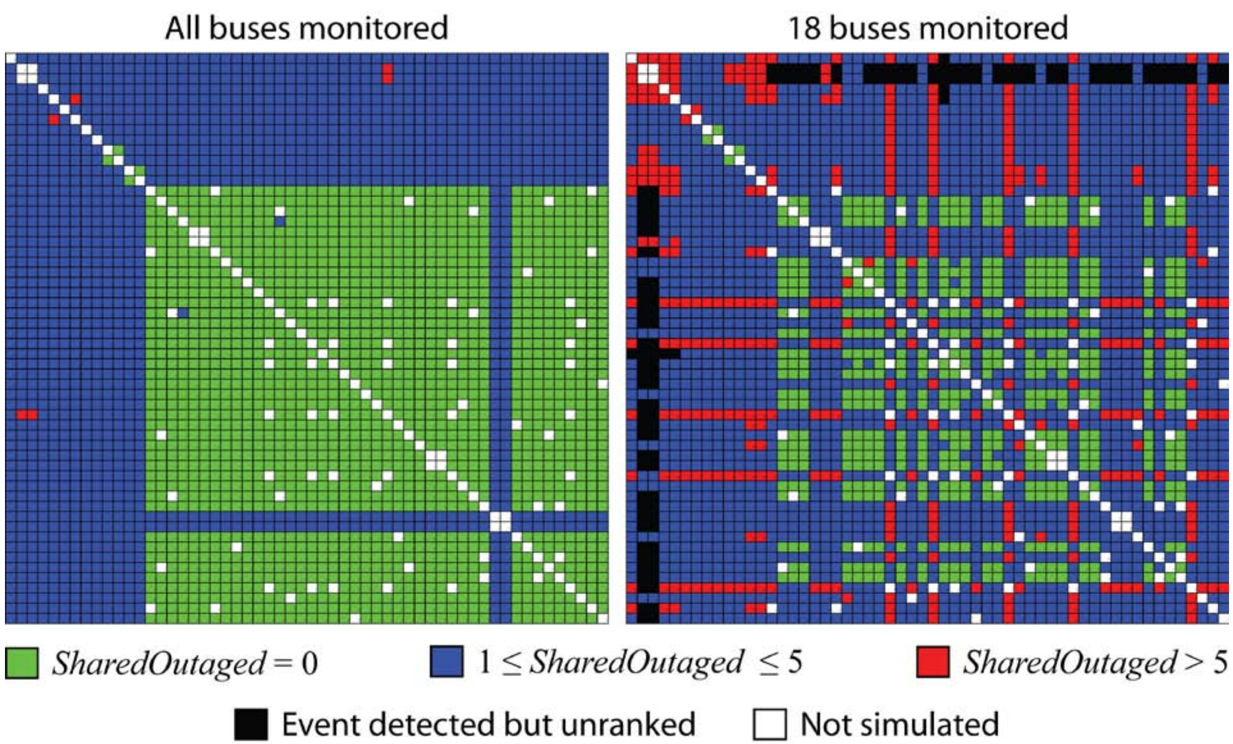
Example: Double Line Outages, 37 Bus Study System, Full PMU Coverage

- Test results based on time domain simulation of 1504 double line outages
- Green = correctly ranked, Red = incorrectly ranked
- Problem rows/columns (255 out of 273 misranked outages) are due to high R/X ratio (1.82) lines



Example: Double Line Outages, 37 Bus Study System, Half PMU Coverage

- Very similar results to full PMU coverage in terms of outage ranking
- The primary difference is in differentiation between different double line outages



Conclusions

- Can detect events based on sparse PMU measurements using currently available data
- Including additional data (e.g., line ratings) can make a significant difference in detection accuracy
- Improvements in detection and differentiation between events can be made with incremental PMU deployment

Future Work

- Incorporation of additional information (e.g., voltage magnitudes, FNET devices, local data)
- Placement of new measurement devices
- Better filtering
- More testing with real data

Questions?