Grid Event Fingerprints and PMUs

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Basic picture

- Direct state measurements (e.g. via PMU) at some buses
- Not enough for complete observability
  - Because of incomplete deployment in local grid
  - Because of interactions with neighboring parts of grid
- Goal: Check for fingerprint of significant events

Variations on a theme

- Steady state fingerprints (now)
  - Measurement: Change in steady-state voltage
  - Events considered: Failure of one or two lines
  - Fingerprints derived computationally
- Transient fingerprints (next)
  - Measurement: Time-aligned windowed PMU transient data
  - Events considered: Line failures, problems in neighbors?
  - Fingerprints derived from computation or recordings

Steady state fingerprints

Concrete case: fingerprint for line failures in the network

- State: complex bus voltage vector v
- Fast observation: subset of voltage vector Ev
- Fingerprint: change $E\delta v$

Question: Can we find a line failure (ΔY) that explains $E\delta v$?

Steady state fingerprint test

Line (i, j) fails, $Y \mapsto Y + \Delta Y_{ij}$. Power flow equations:

$$A_{ij}\delta v \quad = \quad (A + U_{ij} C U_{ij}^T)\delta v \quad = \quad b_{ij} + O(\|\delta v\|^2)$$

where $U_{ij} \in \mathbb{R}^{n \times 4}$ and $b_{ij} \in \mathbb{R}^n$ are simple functions of (i, j).

Linearize in δv to get fingerprint:

- Fingerprint: $E\delta v_{ij} = EA_{ij}^{-1} b_{ij}$.
- Fingerprint distance: $t_{ij} = \|E\delta v_{ij} - \delta v\|$

Computing t_{ij} may require two linear solves with A.

Fast filtering

Goal: Avoid a linear solve to compute each fingerprint distance.

Start with defining equation

$$(A + U_{ij} C U_{ij}^T)\delta v_{ij} = b_{ij}$$

Rewrite as

$$\delta v_{ij} = A^{-1} \left(b_{ij} - U_{ij} C U_{ij}^T \delta v_{ij} \right)$$

Bound

$$t_{ij} \equiv \|E\delta v_{ij} - E\delta v\| \quad \geq \quad s_{ij} \equiv \min_z \|EA^{-1}(b_{ij} - U_{ij} z) - E\delta v\|$$

Algorithm

Compute and store EA^{-1}.
Compute s_{ij} for all ij.
Order ij's by ascending s_{ij}.
for all transmission lines i, j **do**
  Keep track of $M :=$ smallest t_{ij} yet found.
  If $s_{ij} > M$, continue.
  Compute t_{ij}.
end for
Select smallest computed t_{ij}.

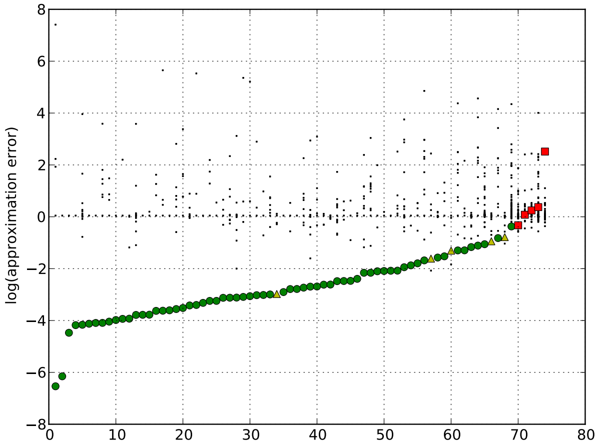
How Accurate Is It?

IEEE 57-Bus Test Network

# PMUs	% Correct	% In Top 3
1	77 %	81.2 %
3	86.5 %	93.2 %
Everywhere	94.6 %	94.6 %

Results with 3 PMUs

$$\log\left(\frac{\|E\delta v - E\delta v_{ij}\|}{\|E\delta v\|}\right)$$



Filter Results

No. of Buses that Get Past Filter

	IEEE 57-Bus Network	IEEE 118-Bus Network
# PMUs	3	7
Median	5.0	4.0
Mean	10.1	13.1
Stddev	15.2	29.4

Two Line Failures?

- Possible failure scales quadratically!
- IEEE 57 bus: 76 lines, 2850 pairs
- Can we narrow it down with fingerprints?

Empirical Observation

When lines i and j fail, change in voltage δv often looks like

$$\delta v = \delta v_i + \text{ other stuff},$$

where δv_i is voltage change if *just i failed*.

Two Lines: Current Approach

Start by guessing at one of the failed lines.

- Compute effects of single-line failures δv_i: cheap compared to testing all pairs!
- Let

$$M = \begin{bmatrix} | & | & & | \\ \delta v_1 & \delta v_2 & \cdots & \delta v_m \\ | & | & & | \end{bmatrix}$$

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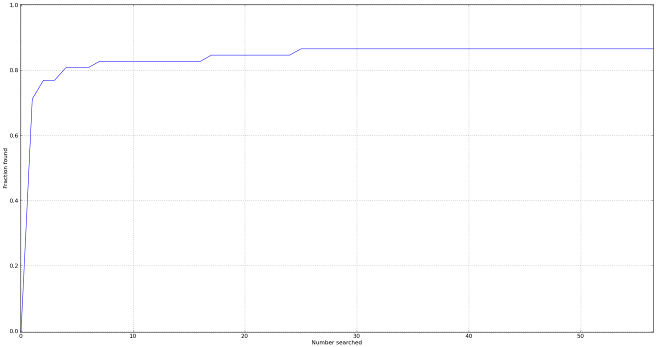
- Let
$$M = \begin{bmatrix} | & | & & | \\ \delta v_1 & \delta v_2 & \cdots & \delta v_m \\ | & | & & | \end{bmatrix}$$
- Solve
$$\min_x (E\delta v - Mx)^2 + \|x\|_1 \text{ for } x \in [0,1]^m$$
to guess at one failure.

Two Lines: Current Approach

- Resulting x scores each line in network with failure likelihood.
- Take most likely single line choices.
- For that choice, run **one-line algorithm** to get the second.
- Create a list of top scoring pairs.
- Check top 20 or 40 pairs exactly.

Two Lines: Initial Results (IEEE 57)



Top 3: 73%
Top 40: 80%

Future Directions

Fingerprints for Transient Analysis

- Transients travel through network.
- PMUs can observe transients, create a fingerprint.
- Use fingerprint to analyze transient.
  - Have I seen something like this before?
  - What is its likely effect?
  - How quickly will it transit to a neighboring operator?
- Goal: Fast lookup for data streaming from GridCloud