FLiER: Practical Topology Error Correction Using Sparse PMUs

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The Biggest Machine in the World: US Power Grid

- Many threats: lightning, line overheating, de-synchronization, ...
- Reliable diagnostics help operators respond
  ▶ Input: Models + sensor data (SCADA and PMUs)
  ▶ Output: Computed state estimates
- Our work: a new approach to diagnosing line failures quickly

Monitoring Systems

- SCADA
  ▶ Non-synchronized measurements every 2–4 seconds
  ▶ Useful for reporting power flows (vs voltage phasors)
  ▶ Complete observability in transmission grid
  ▶ Voltage and currents are inferred from power flows (state estimation)
- Syncrophasors / Phasor Measurement Units (PMUs)
  ▶ Directly report voltage and current angles and magnitudes
  ▶ Synchronized measurements at 30–60 samples / second
  ▶ Partial observability in most places

Steady-State Power Flow Equations

\[ H(v; Y) = s \]

- \( v \) is a vector of voltage magnitudes and angles
- \( s \) is a vector of real/reactive power
- \( Y \) is the system admittance matrix
- \( H \) is linear in \( Y \), nonlinear in \( v \)

PMU Line Failure Diagnosis

- Complete network state estimate initially known
- Line fails shortly after state estimate
  ▶ Assumption 1: Supply / demand remain roughly fixed
  ▶ Assumption 2: Only one line fails (for now)
- PMUs measure part of voltage change \( E\Delta v \)
- Goal: Find failed line from \( E\Delta v \)
- Approach: Compare \( E\Delta v \) to simulated failure “fingerprints”
  ▶ One power flow solve per candidate — expensive!

Trick 1: Fast Linear Approximation

Let \( Y = Y + \Delta Y \) = post-failure admittance. Linearize about old \( v \):

\[ (J + A) \delta v = -H(v; \Delta Y) \]

where

\[ J = \frac{\partial H(v; Y)}{\partial v}, \quad A = \frac{\partial H(v; \Delta Y)}{\partial v} \]

- \( A \) is sparse: \( A_{ij} \) nonzero only if \( (k, l) \) adjacent to failed line
- \( A \) is low rank, total rank is at most 3
  ▶ Apply \( (J + A)^{-1} \) quickly given factorization of \( J \)
  (Sherman-Morris-Woodbury)
- Cost per fingerprint: a few linear solves with a factored matrix

Trick 2: Filtering through Subspace Bounds

\[ E\Delta v \]

\[ E\Delta v \text{ belongs to } \gamma \text{ a 3D space spanned by columns of } EJ^{-1} \]

\[ t \equiv ||E\Delta v - E\delta v|| \leq \tau \equiv \min_{w \in \gamma} ||E\Delta v - w||. \]

- Computing \( \tau \) is much cheaper than computing \( t \)
  ▶ \( EJ^{-1} \) involves \# sensors solves with \( J \)
  ▶ \( \tau \) for any line is cheap once \( EJ^{-1} \) formed
  ▶ \( t \) for each line requires a few linear solves.

FLiER: Fingerprint Linear Estimation Routine for Line Failures

- Compute \( EJ^{-1} \)
- Compute \( \tau_k \) for each line \((k, l)\)
- Sort lines by ascending \( \tau_k \)
  ▶ \( f_{\min} = \infty \)
  ▶ For each line \((k, l)\) in order
    ▶ If \( \tau_k > f_{\min} \), return line
    ▶ Compute \( t_k \)
    ▶ If \( t_k < f_{\min} \) then update \( f_{\min} \), set line = \((k, l)\)

Results: Accuracy and Filter Effectiveness

- Left: 77 line failure tests on IEEE 57-bus network
  ▶ Three PMUs used for measurement
  ▶ 68 lines correctly identified (green dots)
  ▶ 9 lines misdiagnosed, but among three lowest scores (triangles)
  ▶ Black dots indicate other computed \( t \) values
- Right: Effectiveness of filter with PMUs on 1, 3, or all nodes

Results: An Identification Failure

IEEE 57-bus network
PMUs at blue nodes

Line (24,26) fails
Line (26,27) diagnosed
Thickness \( \propto t^{-1/2} \)
Not right, but close!

For More

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