FLiER: Practical Topology Error Correction Using Sparse PMUs

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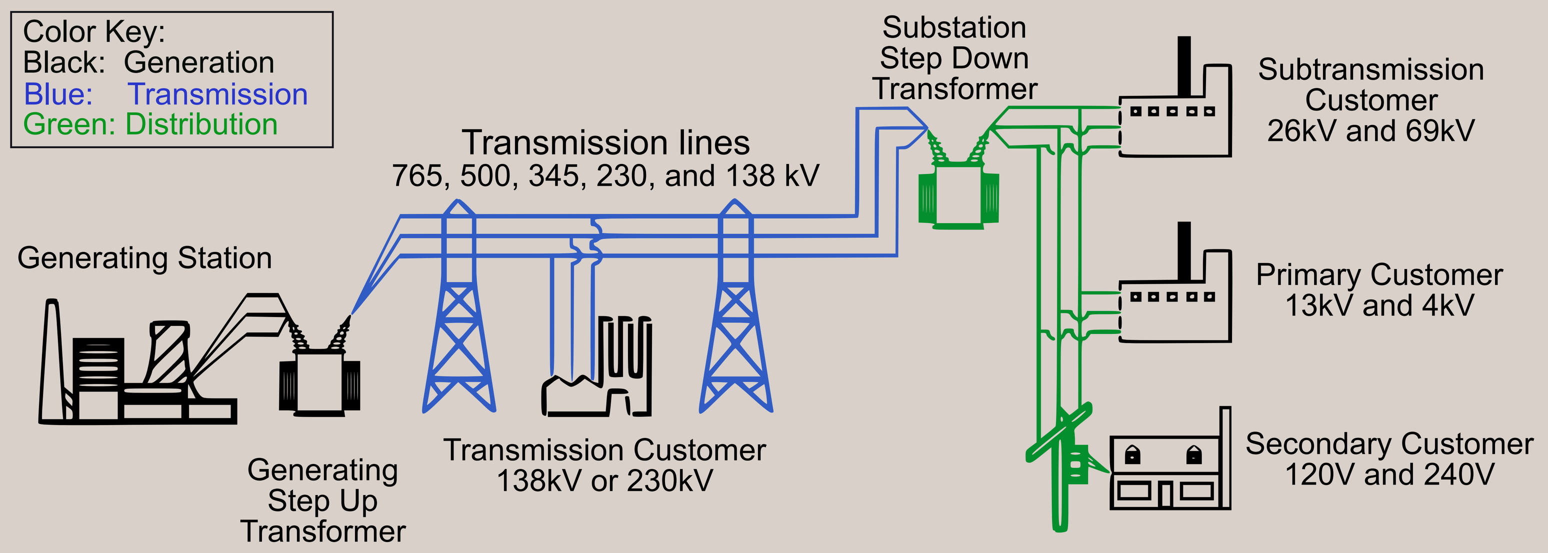
The Biggest Machine in the World: US Power Grid



- 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 v:

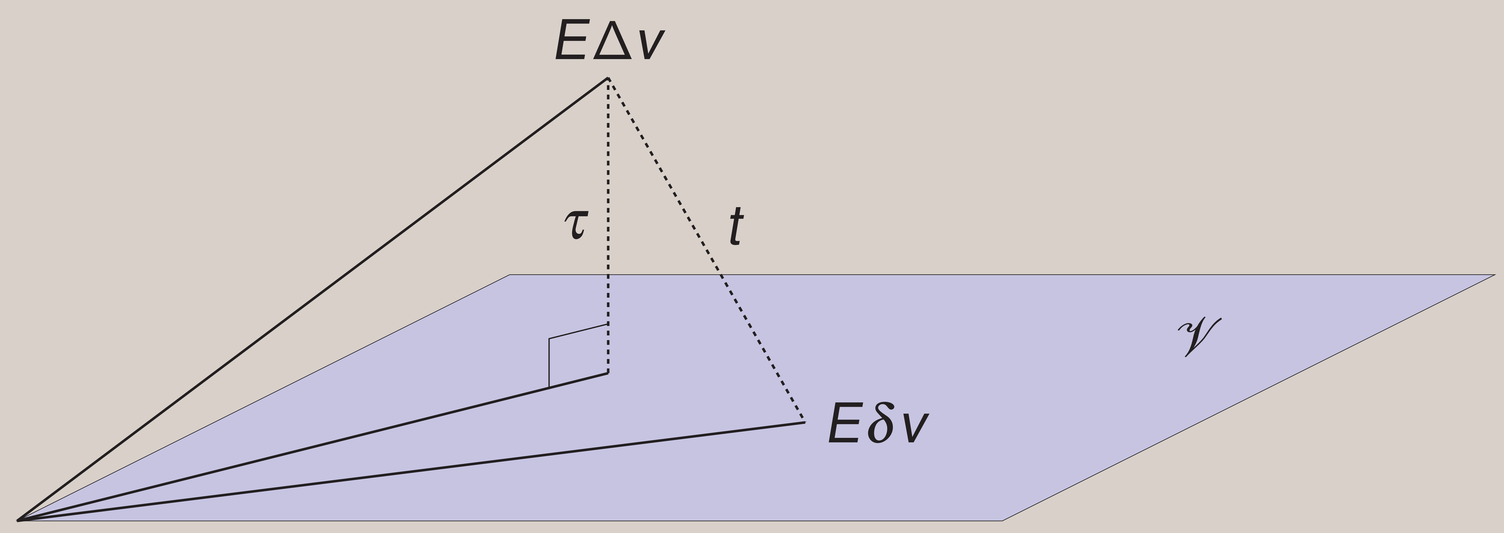
$$(J + A)\,\delta v \approx -H(v; \Delta Y)$$

where

$$J = \frac{\partial H(v;Y)}{\partial v} \qquad A = \frac{\partial H(v;\Delta Y)}{\partial v}$$

- A is *sparse*: A_{kl} 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-Morrison-Woodbury)
- Cost per fingerprint: a few linear solves with a factored matrix

Trick 2: Filtering through Subspace Bounds

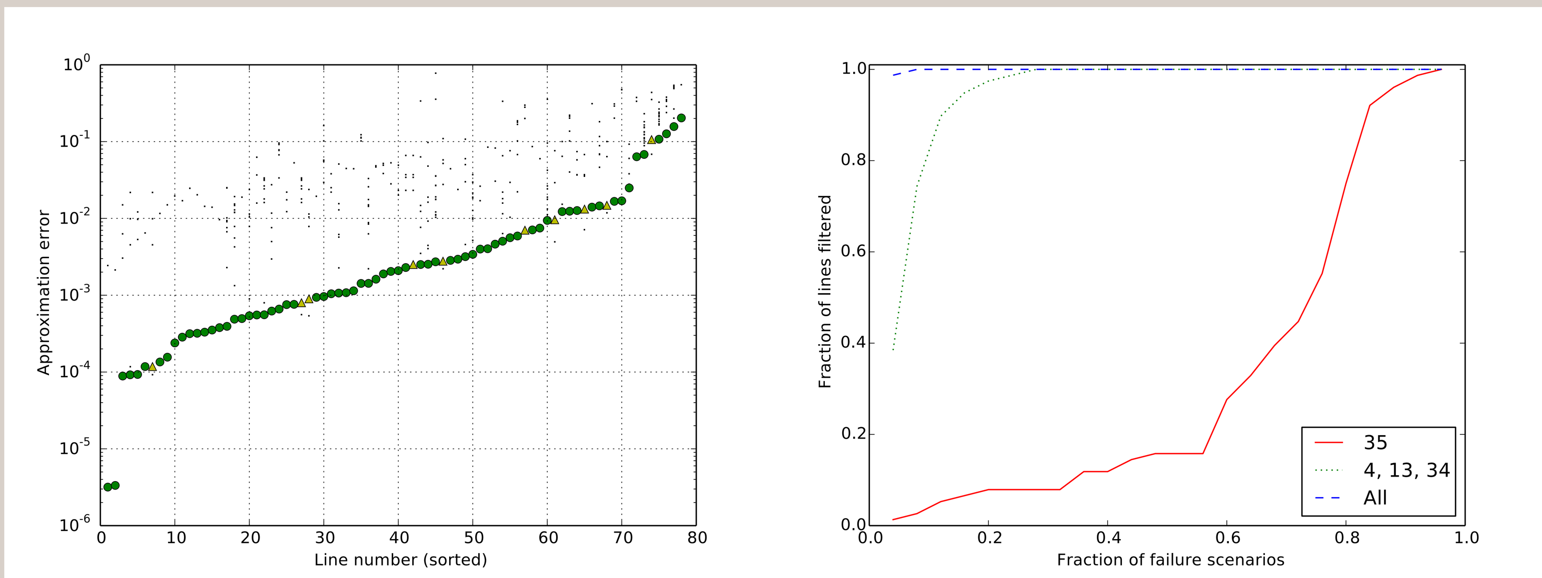


- $E\delta v$ belongs to $\mathscr{V}$ a 3D space spanned by columns of EJ^{-1}
  $\implies \quad t \equiv \|E\Delta v - E\delta v\| \quad \leq \quad \tau \equiv \min_{w \in \mathscr{V}} \|E\Delta v - w\|$.
- Computing τ is much cheaper than computing t
  - EJ^{-1} involves # sensors solves with J
  - τ 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

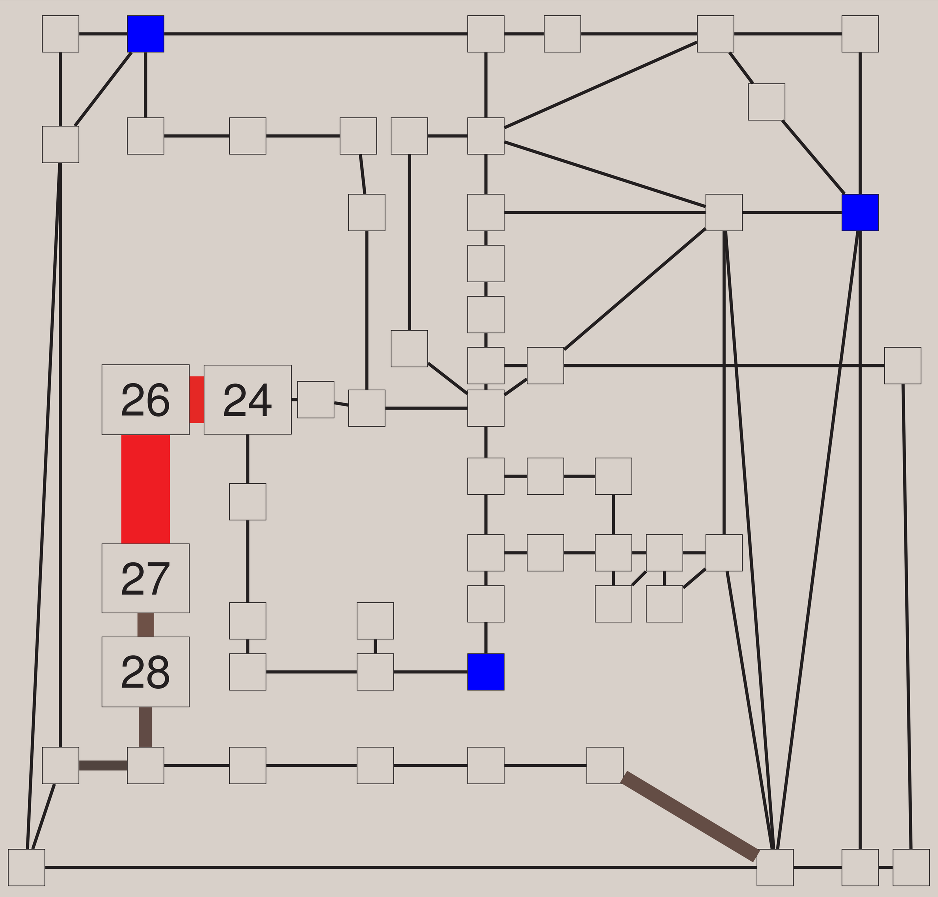
- Compute EJ^{-1}
- Compute $\tau_{k\ell}$ for each line (k, ℓ)
- Sort lines by ascending $\tau_{k\ell}$
- $t_{\min} = \infty$
- For each line (k, ℓ) in order
  - If $\tau_{k\ell} > t_{\min}$, return `line`
  - Compute $t_{k\ell}$
  - If $t_{k\ell} < t_{\min}$ then update $t_{\min}$, set `line` = (k, 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 indicated 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

Colin Ponce and David Bindel
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