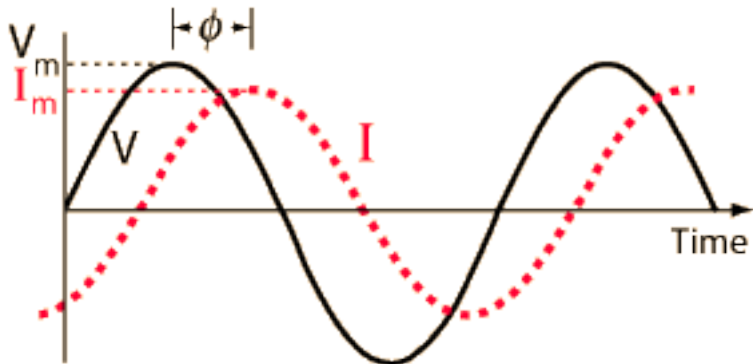


# Fast Fingerprints for Power System Events

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## Reminder: AC Power



Voltages

$$V(t) = \sqrt{2} V_{\text{avg}} \cos(\omega t)$$

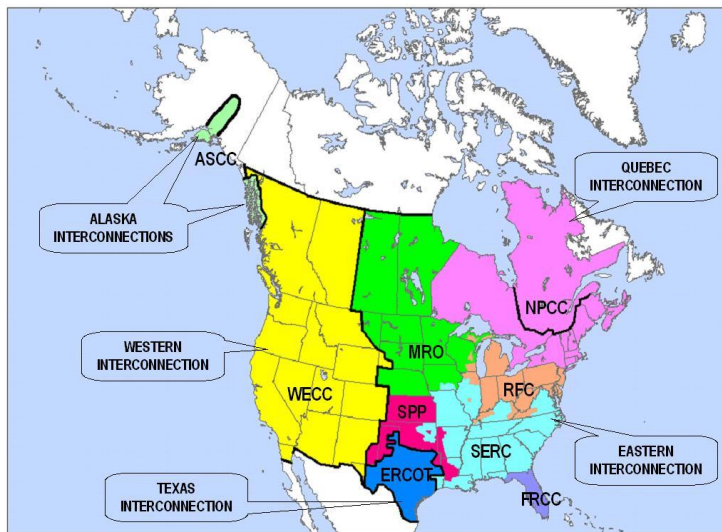
Currents

$$I(t) = \sqrt{2} I_{\text{avg}} \cos(\omega t + \phi)$$

Power

$$P_{\text{avg}} = V_{\text{avg}} I_{\text{avg}} \cos \phi$$

# Biggest Machine(s) in the World



# SCADA: Supervisory Control and Data Acquisition

- Non-synchronized measurements every 2–10 seconds
- Report digital status and power flows
- Complete observability in transmission grid
- Voltages/currents inferred from power flows (state estimation)
- *Topology estimation* co-evolved with state estimation

# Synchrophasors / Phasor Measurement Units (PMUs)

- GPS-synchronized measurements and 10-30 reports per second
- Directly report voltage and current angles/magnitudes
- Really now coming into their own
  - First commercial PMU in 1992
  - Funding from American Recovery and Reinvestment Act of 2008
  - Now enough for *partial* observability in most places
- We're still figuring out what to do with them!
  - Model free system identification approaches (PMU only)
  - Dynamic state estimation / data fusion (PMUs + SCADA)
  - Today: topology update estimation from PMUs + SCADA

# Best of Both Worlds

- Combine *model-driven* state estimates with PMU observations
- Goal: Identify system (topology change) events (line outages, substation change, generator trips, ...)
- Idea: Match PMU measurements  $E\Delta v$  to model predictions  $\delta v_c$ 
  - Need predictions for many possible changes  $c$ !
  - Each  $\delta v_c$  depends on current state – constantly changing.
- How can we do this fast?

# Power Flow Basics

Abstract power flow equation

$$H(v; Y) - s = 0$$

In polar form:

$$\begin{bmatrix} H_\ell \\ H_{n+\ell} \end{bmatrix} = \sum_{h=1}^n |v_\ell| |v_h| \begin{bmatrix} g_{\ell h} & b_{\ell h} \\ -b_{\ell h} & g_{\ell h} \end{bmatrix} \begin{bmatrix} \cos(\theta_{\ell h}) \\ \sin(\theta_{\ell h}) \end{bmatrix},$$

with  $\theta_{\ell h} = \theta_\ell - \theta_h$  and

$$s = [P_1 \quad \cdots \quad P_n \quad Q_1 \quad \cdots \quad Q_n]^T.$$

# Power Flows and PMUs

Power flow equation

$$H(v; Y) - s = 0$$

- Measure  $E v$  via PMUs ( $E \in \{0, 1\}^{m \times n}$ ).
- Suppose  $E v$  shifts to  $E v' = E v + E \Delta v$ .
- Goal: Map  $E \Delta v$  to change in topology (e.g.  $\Delta Y$ ).



# Breaker, Breaker!

More detailed: *breaker-level* formulation

$$\begin{aligned} H(v; Y) + C\lambda - s &= 0 \\ C^T v &= b \end{aligned}$$

Equations in  $C^T v = b$  have the form

$$\begin{array}{ll} v_i - v_j = 0 & \text{Equal voltage on bus sections} \\ v_i = b_k & \text{Specified voltage at PV node} \end{array}$$

Can eliminate constraints if desired – but we don't want to!

# Breaker, Breaker!

Breaker-level formulation

$$\begin{aligned} H(v; Y) + C\lambda - s &= 0 \\ C^T v &= b \end{aligned}$$

Notation:

$$x = \begin{bmatrix} v \\ \lambda \end{bmatrix}, \quad A = \begin{bmatrix} \frac{\partial H}{\partial v}(v; Y) & C \\ C^T & 0 \end{bmatrix}, \quad \bar{E} = [E \quad 0].$$

# Augmented Systems

Consider several possible topology changes:

- Breaker closes in a substation (bus merge)
- Breaker opens in a substation (bus split)
- Load or generator trip
- Line trip

Write each as an *augmented* power flow system.

## Example: Breaker Opening

Add a multiplier to “delete” previous constraint in  $C$ :

$$H(v'; Y) + C\lambda' - s = 0$$

$$C^T v' + F\gamma - b = 0$$

$$F^T \lambda' = 0$$

where  $F \in \{0, 1\}^{n \times 2}$  indicates voltage for “breakaway” segment.

## Example: Line Trip

After trip  $Y' = Y + \Delta Y$ .  $H$  linear in  $Y$ , so:

$$H(v'; Y) + Uw + C\lambda' - s = 0$$

$$C^T v' - b = 0$$

$$w - U^T H(v'; \Delta Y) = 0$$

where  $U \in \{0, 1\}^{n \times 4}$  indicates equations for end-point buses.<sup>1</sup>

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<sup>1</sup>Can actually use three rather than four slack variables – see [paper](#) 

## Strawman Method 0

For each possible topology update (and base case):

- Compute predicted change  $\Delta v^{\text{pred}}$
- Compute mismatch  $\mu = \ell(E\Delta v^{\text{pred}} - E\Delta v)$

Report (mismatch, update) pairs in descending order by mismatch.

Problem: Too many possible updates!

# Fast Fingerprints

*Post-update* systems linearized about *pre-update* state look like:

$$\begin{bmatrix} A & U \\ V^T & D \end{bmatrix} \begin{bmatrix} \delta x \\ \gamma \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$$

For each possible update, estimate change to be  $\bar{E}\delta x$ .

- Core matrix  $A$  does not change with updates – factor *once*
- Border matrix and RHS do depend on updates
- Solve bordered systems via a few solves with  $A$

# Strawman Method 1

- Save factorization of core matrix  $A$
- For each possible topology update (and base case):
  - Get linearized predicted change  $\delta v^{\text{pred}}$
  - Compute mismatch  $\mu = \ell(E\delta v^{\text{pred}} - E\Delta v)$
- Report (mismatch, update) pairs in descending order by mismatch.

Problem: Too many possible updates! And maybe approximation error?



# Filtering

Care about some loss  $\ell(E\delta x - E\Delta x)$ , where

$$\begin{bmatrix} A & U \\ V^T & D \end{bmatrix} \begin{bmatrix} \delta x \\ \gamma \end{bmatrix} = \begin{bmatrix} d_1 \\ d_2 \end{bmatrix}$$

Rewrite as

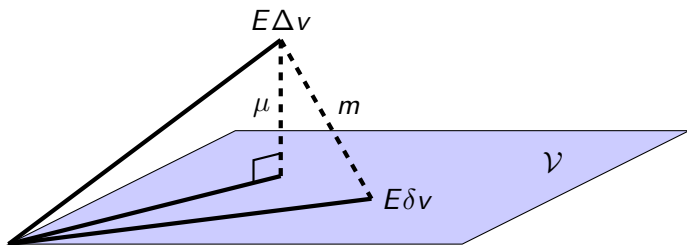
$$E\delta v = \bar{E}A^{-1}(d_1 - U\gamma)$$

and

$U$  narrow and *sparse*  $\implies$

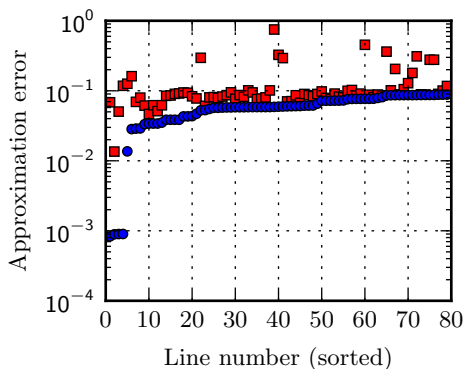
$(\bar{E}A^{-1})U$  involves only a few columns of  $\bar{E}A^{-1}$

## Partial Predictions



- Find subspace  $\mathcal{V}_c$  containing predictions  $E\delta v_c$
- Bound: subspace distance  $\mu(c) \leq \text{mismatch } m(c)$
- Sort events by ascending  $\mu(c)$
- Check  $c_1, \dots, c_k$  until  $\mu(c_{k+1}) \leq \min_{1 \leq j \leq k} m(c_j)$

## Filter Effectiveness (IEEE 57-bus, line trips only)



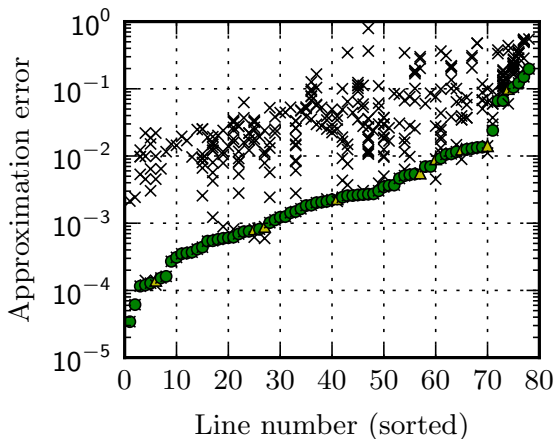
Blue squares are filter scores, red squares are actual mismatches.

# But is it right?

## Test scenarios (IEEE 57-bus network)

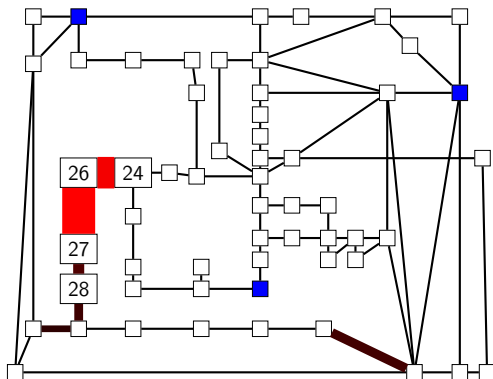
- Three PMU deployments: everywhere, sparse, and single
- With no noise or Gaussian noise ( $\sigma = 0.0017$ )
  - Consistent with largest phase angle error allowed by the synchrophasor standard (0.1 degree)
- Will show behavior with bad data later

## Line Failure Diagnosis (sparse, no noise)



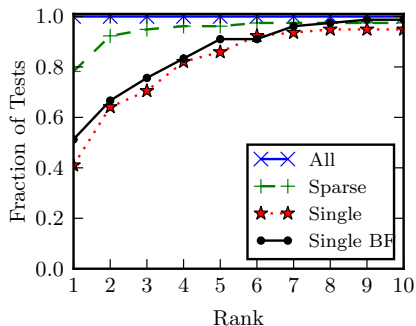
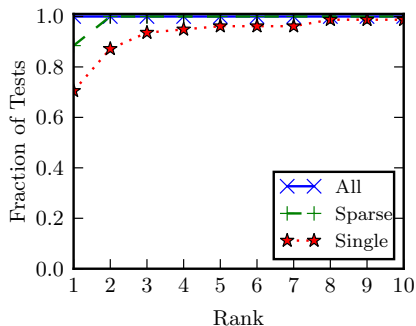
Green/yellow: scores for correctly/incorrectly diagnosed tripped lines.  
Black crosses: scores for other lines.

## Example: Hard Case in IEEE 57-bus

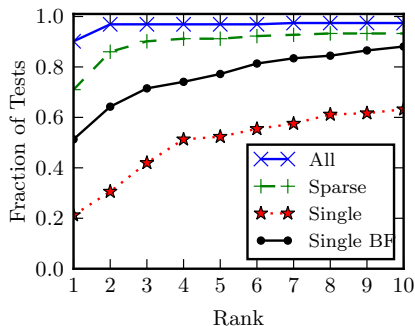
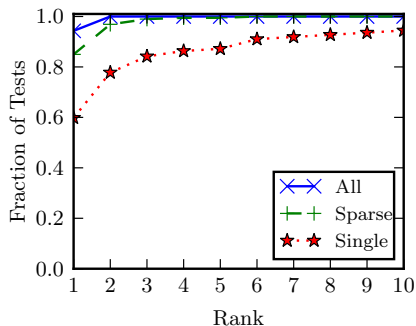


(24,26) tripped, (26,27) chosen. Color/thickness by mismatch<sup>-1/2</sup>.  
PMU locations are highlighted in blue.

# IEEE 57-bus: Line Failures

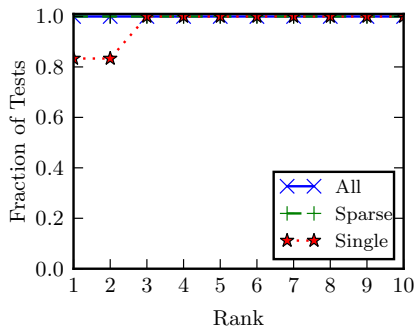
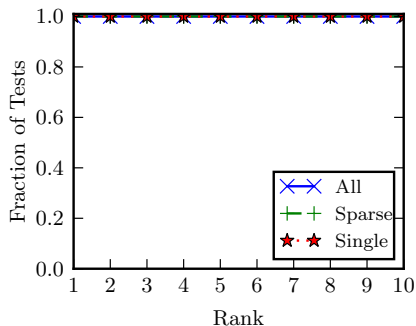


# IEEE 57-bus: Substation Reconfigurations

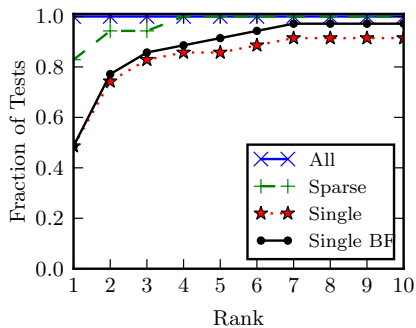
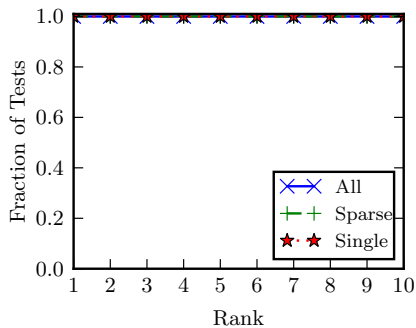




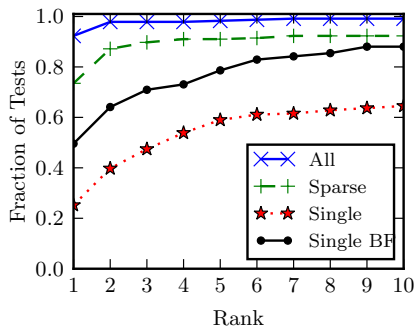
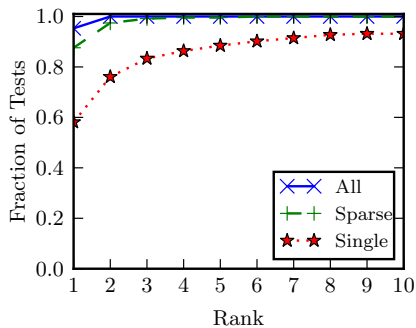
# IEEE 57-bus: Generator Trips



# IEEE 57-bus: Load Trips



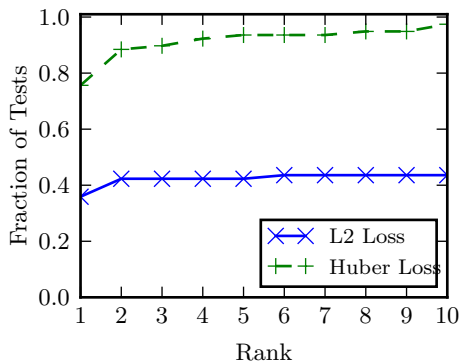
# IEEE 57-bus: All Contingencies



# Bad Data Robustness via Huber

- Experiments so far reflect  $\ell^2$  loss.
- With outliers/bad data: use a more robust loss!
- We use Huber with scale parameter  $1.365 \cdot 0.0017$ .

## IEEE 57-bus: All Contingencies



One PMU delivers 5 degree errors (sparse PMU deployment) + Gaussian noise on all readings.

## Ongoing Related Efforts

- Spectroscopic event identification (Eric Lee, Nate Rogalskyj)
  - Goal: Identify state from ringdown/ambient oscillations
  - Approach: Residual + bound generation similar to FLIER
- SECURED: Synthetic regulating reserves (Eaton, CMU, ANL, LLNL)
  - Goal: Reduce regulating reserve req'ts to offset VER
  - Approach: Fast distribution-level coordinated demand response
- GridCloud (Birman, WSU)
  - Goal: Fast, reliable cloud infrastructure to communicate PMU data
  - Approach: Replication for performance and reliability

# Acknowledgements



FLiER: Practical Topology Update Detection Using Sparse PMUs.  
Ponce and Bindel, arXiv:1409.6644