Dynamic Power System Line Outage Detection and Localization

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Background

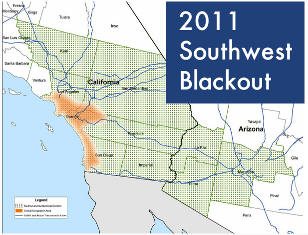
- Critical infrastructure
- Complex dynamic system
- Wide-area monitoring, protection and control

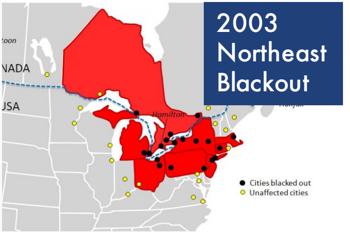
Research Problem

Real-time power system line outage detection and localization using sensor data.

Why do we need to do it? Infrastructure resilience.

Why *Line Outage* detection and localization?





2.7 million customers affected

44 million customers affected

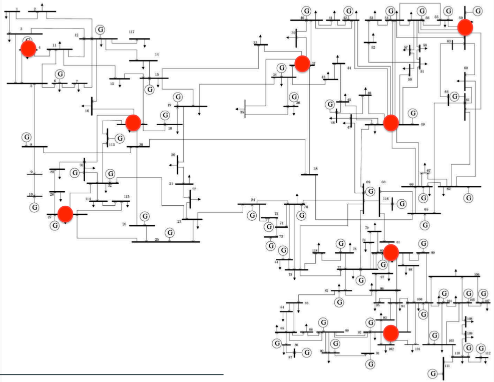
Critical Reason

Systems operators were unaware of the loss of key transmission lines.

Why can we do it? Enabling technology.

Phasor Measurement Unit (PMU): sensor installed on a bus[1].

1. GPS time-synchronized
2. High sampling rate (30 samples/sec)
3. Measures total current and voltage on a bus



[1] Busbar, a station in the power system where electrical lines are connected to.

Problem

Given the need to improve operators' real-time situational awareness and the potential of PMU technology:

Research Problem

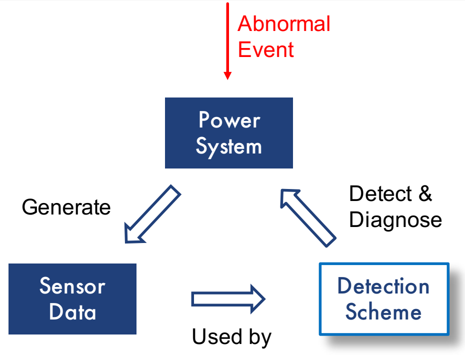
Develop a scheme that can detect and locate power system line outage in real time.

1. **Detection**: When a line is tripped, we want to detect it as fast as possible.
2. **Localization**: When detected, we want to locate the tripped line accurately.

Framework of line outage detection

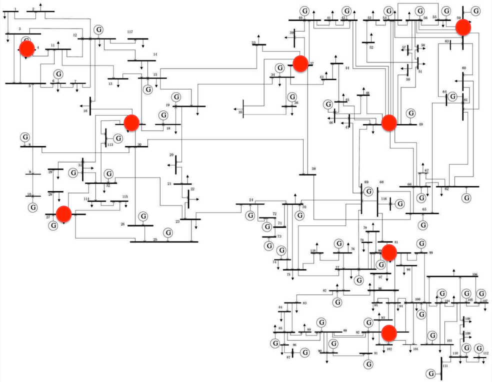
1. We know: normal topology (Y) and line parameters (g, b).
2. Sensor measures: Bus voltage phasor ($|V|, \theta$).
3. Output: detection alarm & tripped line number.

Like a doctor tries to detect a disease early.



Challenges

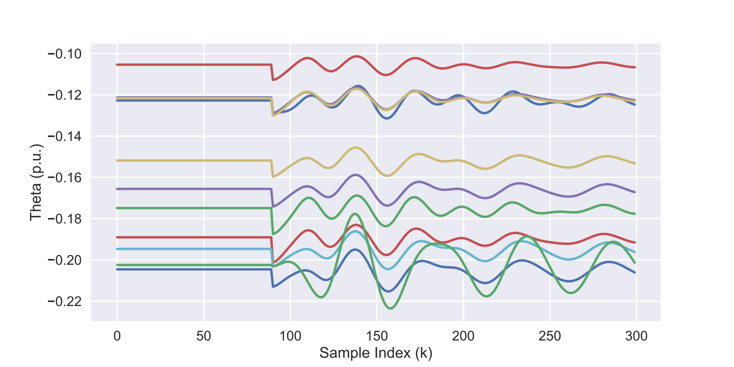
1. Economic constraint: Not every bus has a PMU.
   - Outages are not directly observable.
   - From limited information to localization is very hard.



IEEE 118 bus test system

Challenges

2. Physical modeling: How to model a dynamic non-linear system?
   - Low signal-to-noise ratio: seek direction from physical model.
   - Transients: non-negligible system dynamics are present.



State of the art

- Many do not allow limited PMUs nor support localization.
- Very few consider system transients.

	Allow limited PMUs	Consider transients	Support localization	Support other events
Xie2014	√	X	X	√
Rafferty2016	X	X	√	√
Hosur2019	X	X	X	√
Ardakanian2017, 19	X	X	√	√
Jamei2016, 17	√	√	X	√
Chen2014, 16	√	X	√	X
Rovatsos2017	√	√[2]	√	X
Our method	√	√	√	X

[2] Not a systematic approach.

How to detect line outage?

Power grid has N buses connected by L transmission lines.

- p_i: net real power at bus i.
- θ_i: voltage phase angle at bus i.

Physical Model (to provide direction)

Based on full alternate-current (AC) power flow model, we obtain:

$$\Delta\boldsymbol{\theta} = J(\boldsymbol{\theta})\Delta p$$

Statistical Model (to provide speed)

After a line outage at ℓ , the distribution of $\boldsymbol{\Delta\theta}$ changes:

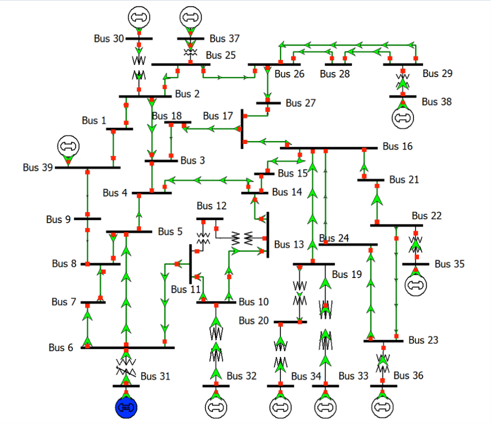
$$\mathcal{N}\left(0, J(\boldsymbol{\theta})_0 \boldsymbol{\Sigma} J(\boldsymbol{\theta})_0^T\right) \to \mathcal{N}\left(0, J(\boldsymbol{\theta})_\ell \boldsymbol{\Sigma} J(\boldsymbol{\theta})_\ell^T\right)$$

detected by a change detection scheme.

Numerical Results

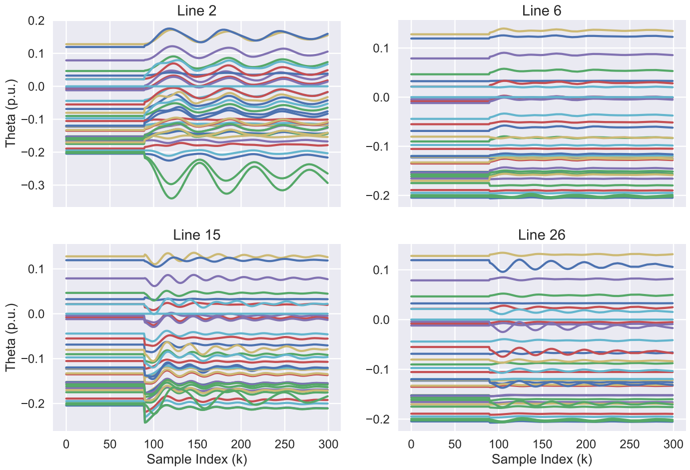
Simulation setup: outage of IEEE 39 bus system

- Duration: 10 seconds (300 samples)
- Outage time: 3rd second (90th sample)
- Detection threshold $C = 18.43$ with $ARL_0 = 24$ hours and $N = 39$.

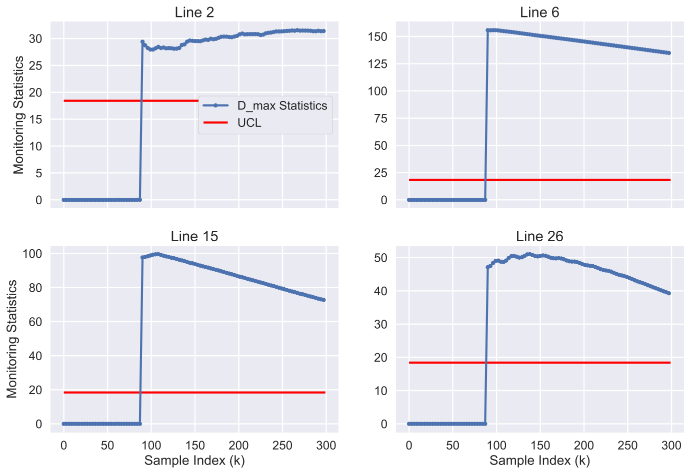


Detection - full PMU deployment

Comparison for four line outages with weak signals.

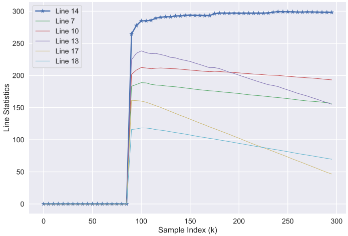


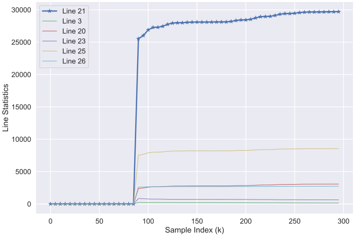
Dynamic scheme: Zero detection delay

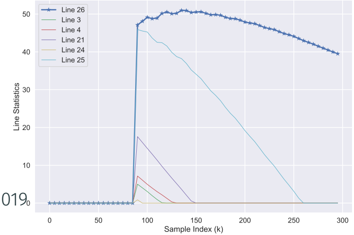


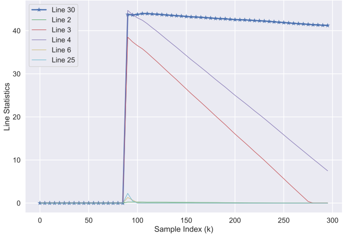
Localization - full PMU deployment

Identify tripped line by $\arg \max_{\ell=1,\dots,L} W_\ell[k]$.



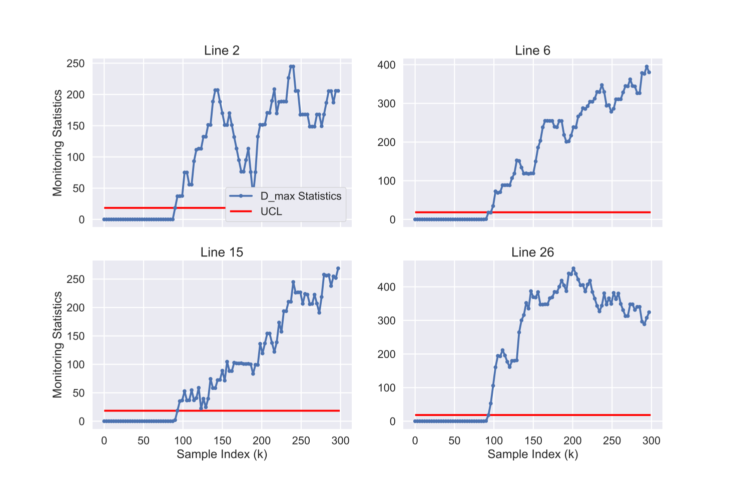






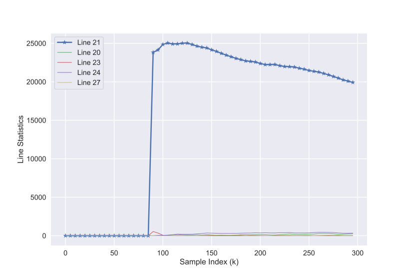
Detection - limited PMU deployment, 15 PMUs

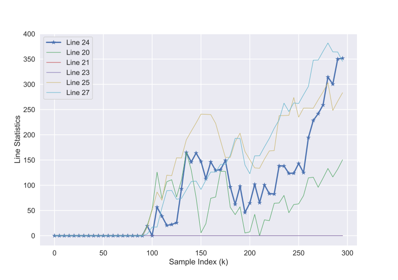
Randomly placed on 39 bus system: Detection delays (< 10 samples) are observed for outages at line 2, 6, 15 and 26.

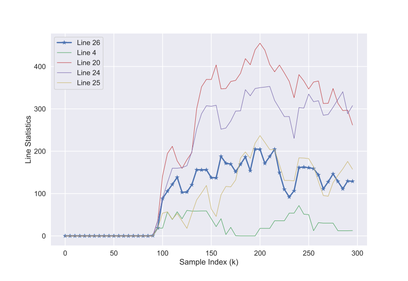


Localization - limited PMU deployment, 15 PMUs

Localization performance is affected by limited deployment.





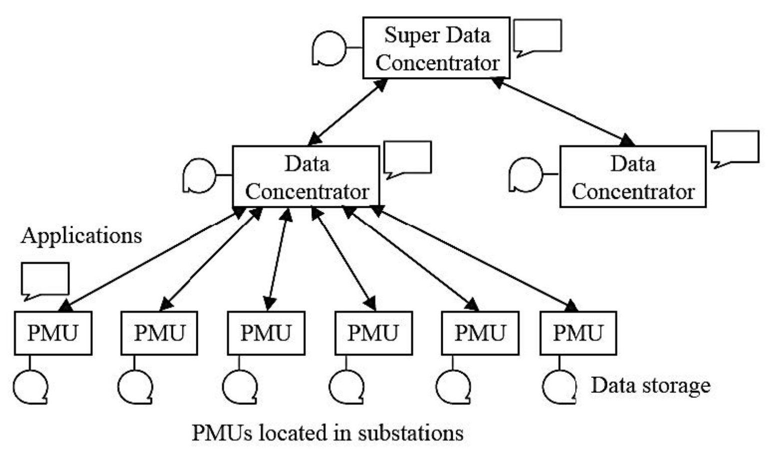


Questions?

Backup Slides

PMU network

A typical PMU network in power grid.



State of the art

Data-driven: No power system-specific modeling

- *Xie et al.(2014)*: PCA + Monitor approximation error
- *Rafferty et al.(2016)*: SW-PCA[3] + Monitor T^2 and Q statistics
- *Hosur & Duan (2019)*: LTI system identification + Monitor approximation error

Hybrid: Power system model is considered

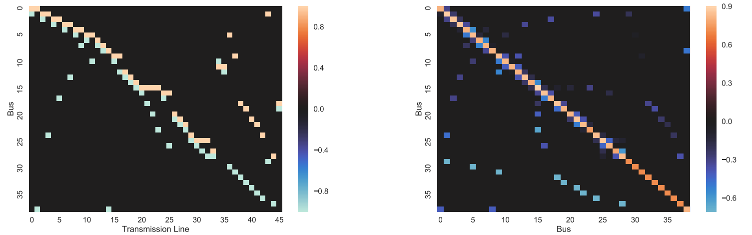
1. *Ardakanian et al.(2017, 2019)*: Ohm's Law + Recover admittance matrix (Y) by lasso
2. *Jamei et al.(2016, 2017)*: Ohm's Law + Monitor approximation error
3. *Chen et al.(2014, 2016)*: DC power flow model + GLR procedure
4. *Rovatsos et al.(2017)*: Governor power flow model + GLR procedure

[3] SW-PCA: Sliding window PCA, LTI: Linear time-invariant, DC: Direct current, GLR: Generalized likelihood ratio.

Bus incidence matrix (A) and admittance matrix (Y) are related by $Y = AyA^{\top}$ where y is the vector with line admittance, e.g.:

$$A = \begin{bmatrix} 1 & 0 & -1 \\ -1 & 1 & 0 \\ 0 & -1 & 1 \end{bmatrix}.$$

The admittance matrix encodes both the sparse connection and line parameters[4] information of the system.



[4] Scaled between -1 and 1.

Full AC power flow equation

Power flows in a power grid can be summarized in the following two equations:

$$
\begin{aligned}
p_i &= \sum_{k=1}^{N} |V_i||V_k| \left[g_{ik} \cos(\theta_i - \theta_k) + b_{ik} \sin(\theta_i - \theta_k) \right], \\
q_i &= \sum_{k=1}^{N} |V_i||V_k| \left[g_{ik} \sin(\theta_i - \theta_k) - b_{ik} \cos(\theta_i - \theta_k) \right],
\end{aligned}
$$

where $i = 1, \ldots, N$ represents the bus number. Symbols: real power (p), reactive power (q), voltage magnitude ($|V|$) and voltage phase angle (θ), g_{ik} and b_{ik} are the conductance and susceptance of the line connecting bus i and k, $y_{ik} = g_{ik} + jb_{ik}$.

Real power equation

Using $Y_{ik} = g_{ik} + jb_{ik} = y_{ik}\cos(\alpha_{ik})$:

$$
\begin{aligned}
p_i &= |V_i| \sum_{k=1}^{N} |V_k| y_{ik} \cos(\theta_i - \theta_k - \alpha_{ik}), \\
&= |V_i| \sum_{k=1}^{N} \left\{ |V_k| y_{ik} \cos\alpha_{ik} \cos(\theta_i - \theta_k) + |V_k| y_{ik} \sin\alpha_{ik} \sin(\theta_i - \theta_k) \right\}, \\
&= |V_i| \cos\theta_i \sum_{k=1}^{N} |V_k| y_{ik} \cos\theta_k \cos\alpha_{ik} + |V_i| \sin\theta_i \sum_{k=1}^{N} |V_k| y_{ik} \sin\theta_k \cos\alpha_{ik} \\
&\quad + |V_i| \sin\theta_i \sum_{k=1}^{N} |V_k| y_{ik} \cos\theta_k \sin\alpha_{ik} - |V_i| \cos\theta_i \sum_{k=1}^{N} |V_k| y_{ik} \sin\theta_k \sin\alpha_{ik},
\end{aligned}
$$

where $i = 1, \ldots, N$.

Real power equation

Let $V = |V|$ to simplify the terms. Define the following:
$x_1 = [V_1 \cos\theta_1, \ldots, V_n \cos\theta_n]^T$, $x_2 = [V_1 \sin\theta_1, \ldots, V_n \sin\theta_n]^T$, and

$$Y_1 = \begin{bmatrix} y_{11}\cos\alpha_{11} & \ldots & y_{1n}\cos\alpha_{1n} \\ \vdots & \ddots & \vdots \\ y_{n1}\cos\alpha_{n1} & \ldots & y_{nn}\cos\alpha_{nn} \end{bmatrix},$$

$$Y_2 = \begin{bmatrix} y_{11}\sin\alpha_{11} & \ldots & y_{1n}\sin\alpha_{1n} \\ \vdots & \ddots & \vdots \\ y_{n1}\sin\alpha_{n1} & \ldots & y_{nn}\sin\alpha_{nn} \end{bmatrix},$$

where y_{ij} and α_{ij} corresponds to the ijth component of the network admittance matrix, $\circ$ is the Hadamard product. Using the defined terms, write the real power equation in matrix form:

$$p = x_1 \circ (Y_1 x_1) + x_2 \circ (Y_1 x_2) + x_2 \circ (Y_2 x_1) x_1 \circ (Y_2 x_2).$$

Small signal model

Take derivative w.r.t t on both sides of the previous equation to get:

$$\begin{aligned}
\frac{\partial p}{\partial t} \quad = \quad & Y_1 x_1 \circ \frac{\partial x_1}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t} + (x_1 \cdot \mathbf{1}^\top \circ Y_1) \frac{\partial x_1}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t} \\
& + Y_1 x_2 \circ \frac{\partial x_2}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t} + (x_2 \cdot \mathbf{1}^\top \circ Y_1) \frac{\partial x_2}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t} \\
& + Y_2 x_1 \circ \frac{\partial x_2}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t} + (x_2 \cdot \mathbf{1}^\top \circ Y_2) \frac{\partial x_2}{\partial t \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t} \\
& - Y_2 x_2 \circ \frac{\partial x_1}{\partial \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t} - (x_1 \cdot \mathbf{1}^\top \circ Y_2) \frac{\partial x_2}{\partial t \boldsymbol{\theta}} \frac{\partial \boldsymbol{\theta}}{\partial t},
\end{aligned}$$

where $\mathbf{1}$ is a column vector of 1s. Rearrange to get

$$\frac{\partial p}{\partial t} = J(\boldsymbol{\theta}) \frac{\partial \boldsymbol{\theta}}{\partial t}, \tag{1}$$

where the Jacobian matrix is

$$\begin{aligned}
J(\boldsymbol{\theta}) \quad = \quad & \left[\operatorname{diag}(Y_1 x_1) + x_1 \mathbf{1}^T \circ Y_1 - \operatorname{diag}(Y_2 x_2) + x_2 \mathbf{1}^T \circ Y_2\right] \frac{\partial x_1}{\partial \boldsymbol{\theta}} \\
& + \left[\operatorname{diag}(Y_1 x_2) + x_2 \mathbf{1}^T \circ Y_1 + \operatorname{diag}(Y_2 x_1) - x_1 \mathbf{1}^T \circ Y_2\right] \frac{\partial x_2}{\partial \boldsymbol{\theta}}.
\end{aligned}$$

Detection scheme: Generalized likelihood ratio procedure

Task: Detect the distribution change as fast as possible using streaming data $\{\Delta\boldsymbol{\theta}[k]\}_{k\geq 1}$.

Monitor: Monitoring statistics for each possible line outage $\ell = 1, \ldots, L$:

$$W_\ell[k] = \max\left\{0, W_\ell[k-1] + \ln\frac{F_\ell(\Delta\boldsymbol{\theta}[k])}{F_0(\Delta\boldsymbol{\theta}[k])}\right\}.$$

Decide: Stop when their maximum crosses the threshold:

$$\tau_{\max} = \inf\left\{k \geq 1 : \max_{\ell=1,\ldots,L} W_\ell[k] > C\right\}.$$

C can be approximated by $\log(ARL_0 \times N)$[5] to satisfy certain false alarm rate constraint.

[5] ARL_0: Number of samples before a false alarm is triggered.

GLR procedure

The log-likelihood ratio can be computed by:

$$\ln \frac{F_\ell(\Delta\boldsymbol{\theta}[k])}{F_0(\Delta\boldsymbol{\theta}[k])} = \frac{1}{2}\left[\ln\!\left(|\boldsymbol{\Sigma}_0||\boldsymbol{\Sigma}_\ell|^{-1}\right) + \Delta\boldsymbol{\theta}[k]^\top \boldsymbol{\Sigma}_0^{-1}\Delta\boldsymbol{\theta}[k] - \Delta\boldsymbol{\theta}[k]^\top \boldsymbol{\Sigma}_\ell^{-1}\Delta\boldsymbol{\theta}[k]\right],$$

where $\boldsymbol{\Sigma}_0 = \sigma^2(J_0^\top J_0)^{-1}$ and $\boldsymbol{\Sigma}_\ell = \sigma^2(J_\ell^\top J_\ell)^{-1}$.

Projection through eigen-decompostion: $(J_0^\top J_0)^{-1} \approx \boldsymbol{G^q}_0 \boldsymbol{L^q}_0^{-1} \boldsymbol{G^q}_0^\top$, by keeping the largest q eigenvalues and eigenvectors.

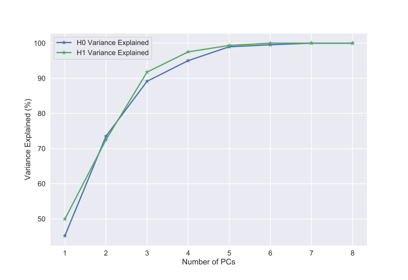
Drop the superscript q. Let $X_0 = \boldsymbol{G}_0^\top \Delta\boldsymbol{\theta}$ and $X_\ell = \boldsymbol{G}_\ell^\top \Delta\boldsymbol{\theta}$. Then:

$$\begin{aligned}
\ln\left[\frac{F_\ell(X_\ell[k])}{F_0(X_0[k])}\right] &= \tfrac{1}{2}\left[\ln\!\left(|\boldsymbol{\Sigma}_0||\boldsymbol{\Sigma}_\ell|^{-1}\right) + X_0[k]^\top \boldsymbol{\Sigma}_0^{-1} X_0[k] - X_\ell[k]^\top \boldsymbol{\Sigma}_\ell^{-1} X_\ell[k]\right],\\
&= \tfrac{1}{2}\left[\ln|\boldsymbol{L}_\ell| - \ln|\boldsymbol{L}_0| + \tfrac{1}{\sigma^2}\left(X_0[k]^\top \boldsymbol{L}_0 X_0[k] - X_\ell[k]^\top \boldsymbol{L}_\ell X_\ell[k]\right)\right].
\end{aligned}$$

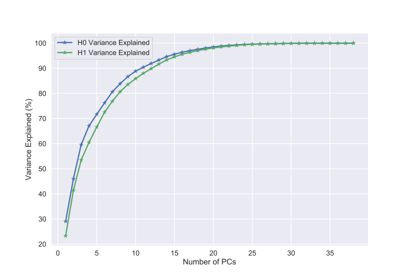
Dimensionality reduction

Cumulative variance can be explained by a few PCs for both IEEE test systems via $J^\top J = GLG^\top$.

For 39 bus system, 9 PCs are retained.



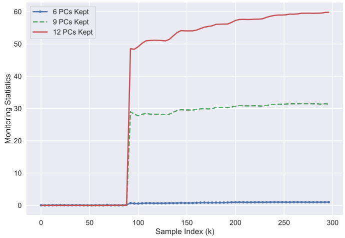
IEEE 9 Bus System

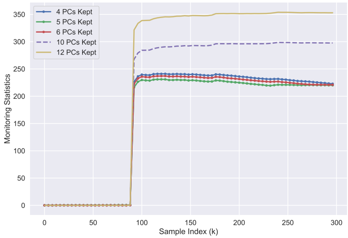


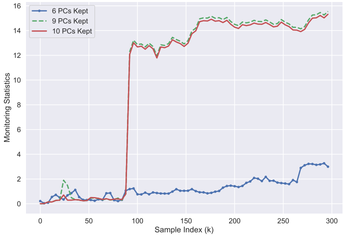
IEEE 39 Bus System

Effect of dimensionality reduction: 39 bus system

Line 2, Line 14 and Line 34

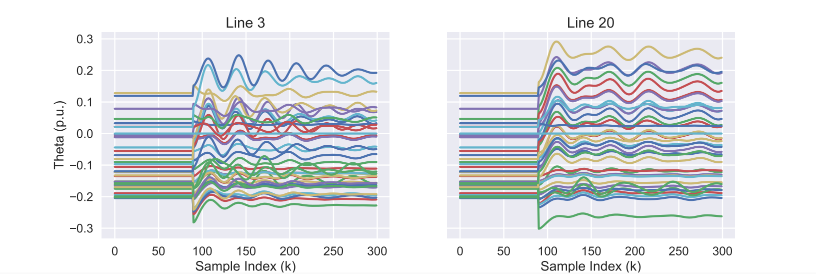




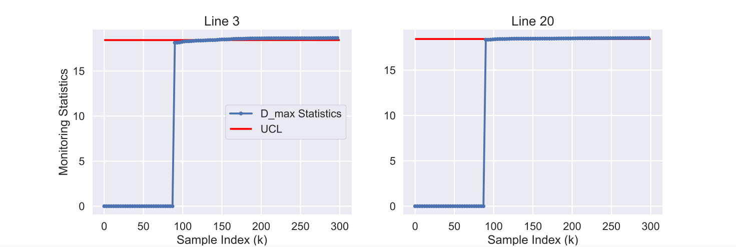


Detection - 39 bus system, strong signals

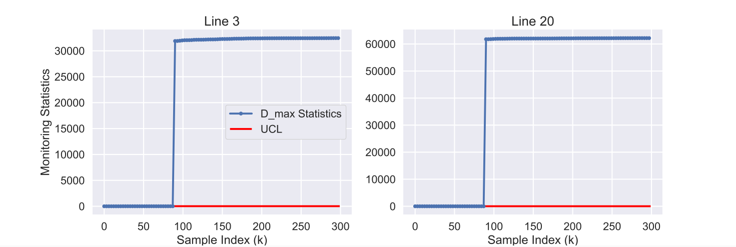
Comparison for two line outages with strong signals.



Detection - 39 bus system, strong signals



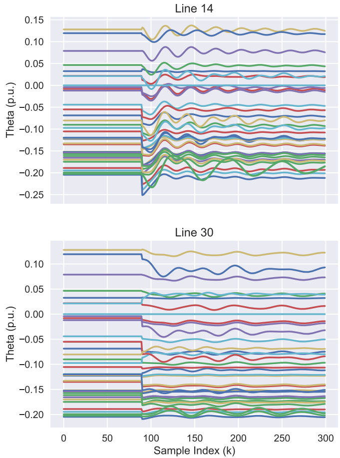
Static scheme: 50 samples and 11 samples of detection delay.



Dynamic scheme: zero detection delay.

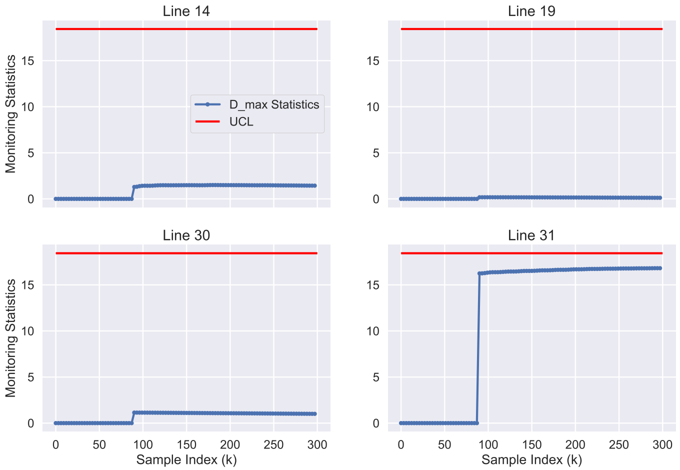
Detection - full PMU deployment

Comparison for four line outages with weak signals.



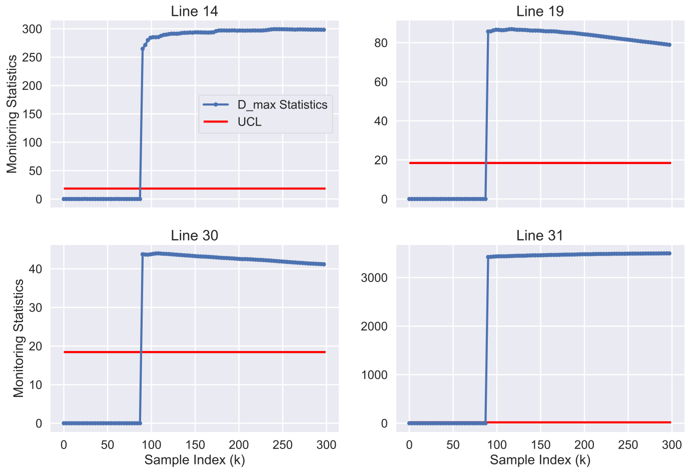
Detection - full PMU deployment

Static scheme: Missed detection



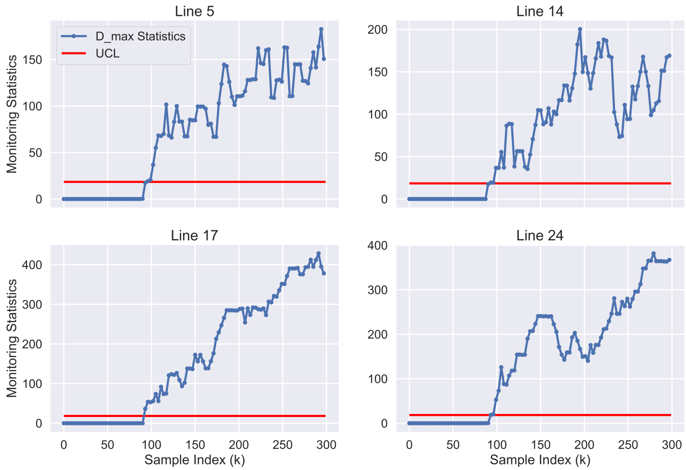
Detection - full PMU deployment

Dynamic scheme: Zero detection delay



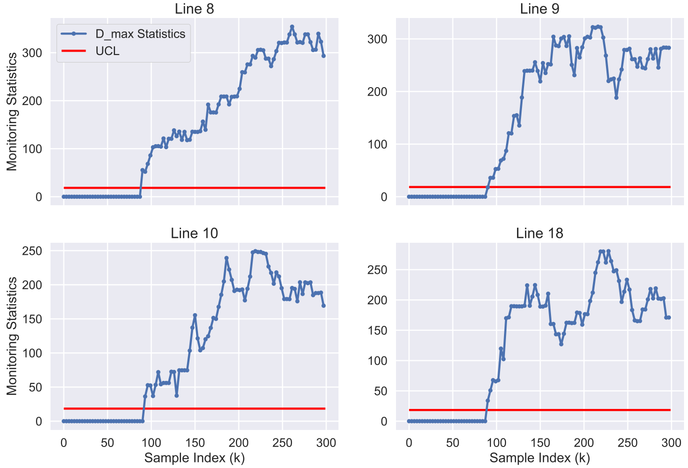
Detection - limited PMU deployment, 15 PMUs

Randomly placed on 39 bus system: Detection delays (< 10 samples) are observed for outages at line 5, 14, 17 and 24.



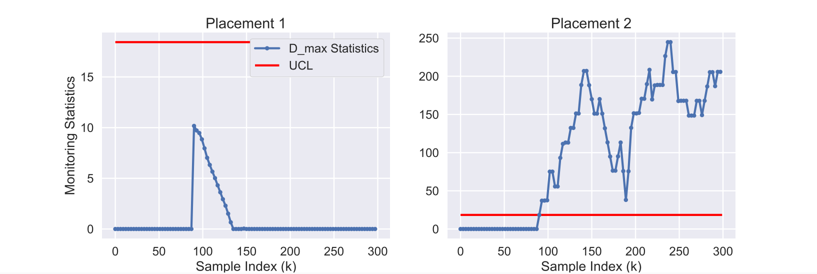
Detection - limited PMU deployment, 15 PMUs

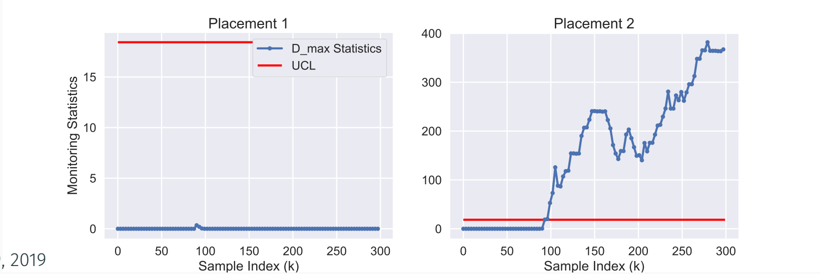
Randomly placed on 39 bus system: Detection delays ($<$ 10 samples) are observed for outages at line 8, 9, 10 and 18.



Comparison - Placement 1: first 15, Placement 2: random

Outage at line 2 and line 24:





References i