Less Data, More Resilient

Optimal Placement of Limited PMUs for Transmission Line Outage Detection and Identification

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Background

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

Research Problem

Optimal location of sensors for real-time power system line outage detection and identification.

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- Critical infrastructure
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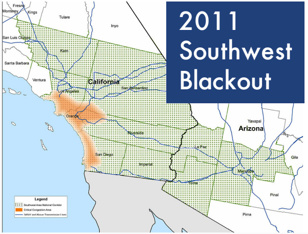
Research Problem

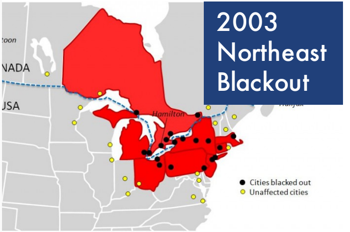
Optimal location of sensors for real-time power system line outage detection and identification.

Parallel $\rightarrow$ COVID-19 desease outbreak

Why do we need to do it? Infrastructure resilience.

Why *Line Outage* detection and localization?





2.7 million customers affected

44 million customers affected

One Common Factor

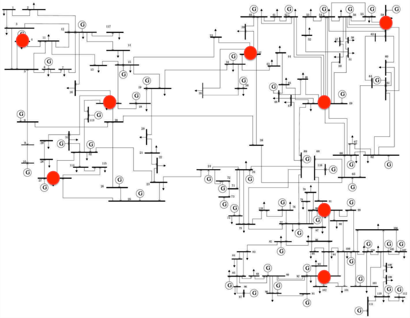
Systems operators were unaware of the loss of key transmission lines.

Parallel $\rightarrow$ Undetected initial cases could develop into clusters.

Why can we do it? Enabling technology.

Phasor Measurement Unit (PMU): sensor installed on a bus (substation).

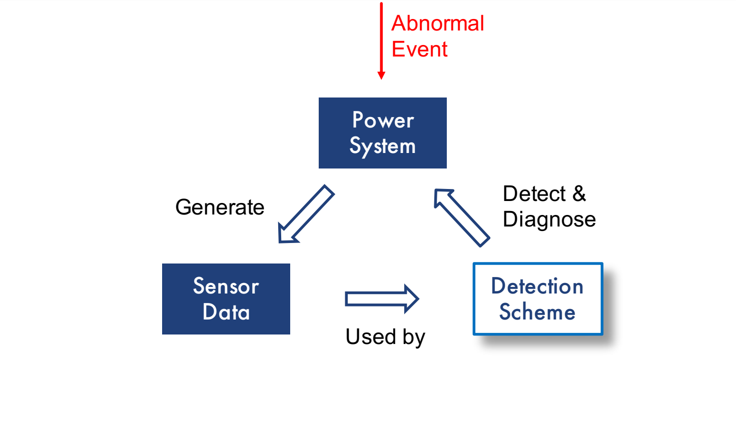
1. GPS time-synchronized
2. High sampling rate (30 samples/sec)
3. Measures current and voltage on a bus



Parallel → Public health resources for detecting COVID-19.

Detection Framework

Framework of line outage detection

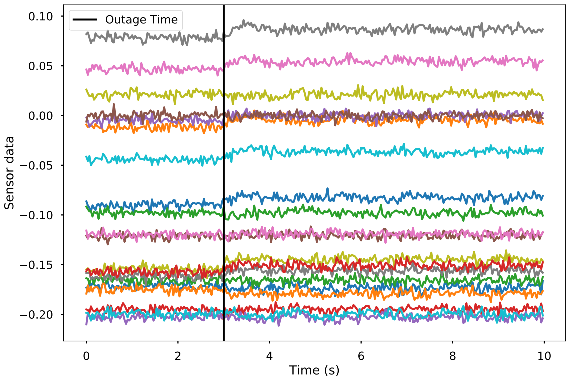


Parallel → COVID-19 patients are detected and isolated through various public health interventions.

Challenges

Challenge 1: Weak signals

- Large network, small disturbance
- Low signal-to-noise ratio



Parallel $\rightarrow$ Asymptomatic patients, incubation period, mostly mild symptoms

Challenge 2: Incomplete signals

- Not every bus is equipped with a sensor.
- From limited observations to localization is very hard.

Figure 1: Limited PMU Deployment

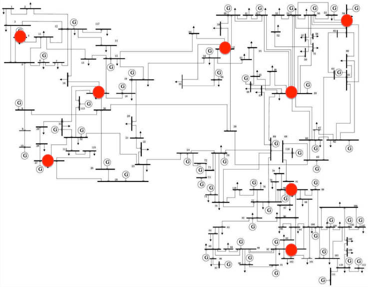
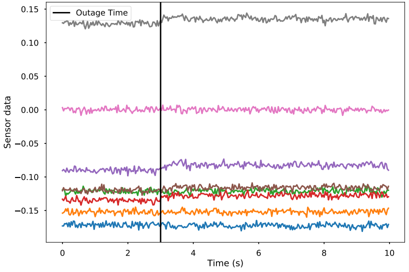


Figure 2: Patial System Observation



Parallel → Limited testing means we only see some infected patients.

Methodology

Methodology

Tackling challenges

- Incomplete signals → Given a limited number of PMUs, find their optimal location.

Key Idea

Optimal PMU placement (OPP) problem can be formulated as a combinatorial optimization problem solved by meta-heuristic genetic algorithm.

Performance[1]

1. Most outages can be detected.
2. Many outages are located with above 90% accuracy.

[1] PMUs installed on 50% of the substations.

Approach: Detection scheme as the foundation

Physical Model

Based on full AC power flow model, we obtain:

$$\Delta\boldsymbol{\theta} = \boldsymbol{J}(\boldsymbol{\theta})_0 \Delta\boldsymbol{p}$$

$\boldsymbol{\theta}$: voltage phase angle; $\boldsymbol{p}$: active power

Statistical Model

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

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

detected by a change detection scheme.

However, $\boldsymbol{J}$ is not accurately determined with limited PMUs.

Approach: Formulating OPP problem

Quantify the discrepancy

$$\delta_{\text{limited}} = \int_{\boldsymbol{\theta}} \left| \|\boldsymbol{J}\|_{\mathrm{F}} - \|\boldsymbol{J}_{\text{limited}}\|_{\mathrm{F}} \right| dH(\boldsymbol{\theta}) \,, \tag{1}$$

F is the Frobenius norm.

Given a fixed number of PMUs, n_p, the OPP problem can be written as

$$\begin{aligned} \min_{S(n_p)} \quad & \delta_{S(n_p)} \\ \text{s.t.} \quad & S(n_p) = [x_1, \ldots, x_N] \\ & x_i \in \{0, 1\}, i = 1, \ldots, N \\ & \sum_{i=1}^{N} x_i = n_p \end{aligned} \tag{2}$$

Solved by genetic algorithm: more effective than random search, more efficient than exhaustive search.

Simulation study

Simulation setup

- 35 different line outages in IEEE 39-bus test system
- PMUs are installed on 20 selected buses
- GA related: the mutation probability of 0.2, index shuffling probability of 0.05, tournament of size 3

Placement Strategy	Placement (Bus)
Scattered	1, 2, 5, 7, 9, 11, 13, 14, 16, 17, 19, 21, 23, 24, 26, 27, 30, 32, 34, 37
Tree-based	2-5, 7-9, 11-19, 21, 26-28
Degree-based	1-8, 10, 11, 13, 14, 16, 17, 19, 22, 23, 25, 26, 29
GA-generated	2-5, 8, 10-12, 14-18, 21-25, 27, 35

Simulation study results: GA-generated placement

The optimal placement found by GA is similar to that of tree-based, but:

- Loop is present
- Disconnected graph is present

Figure 3: GA-generated

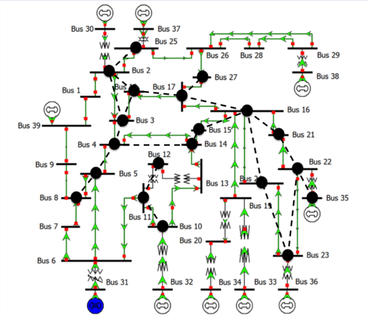
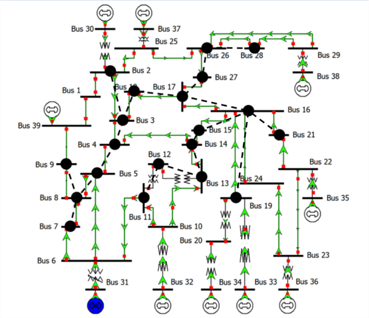


Figure 4: Tree-based



Simulation study results: Localization accuracy

Heat map showing the localization accuracy comparison of the GA-generated placement and full PMU placement.

Figure 5: GA-generated placement

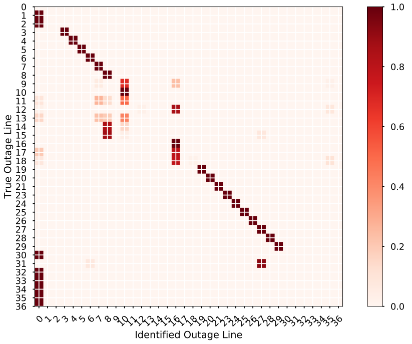
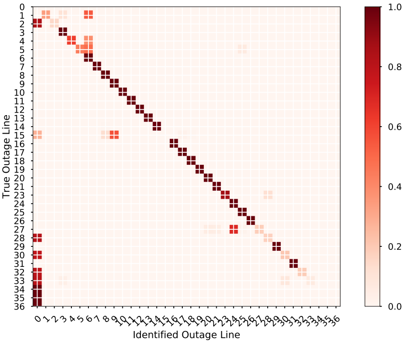


Figure 6: Full PMU placement



Heat map showing the localization accuracy comparison of the GA-generated placement and full PMU placement.

Figure 7: GA-generated placement

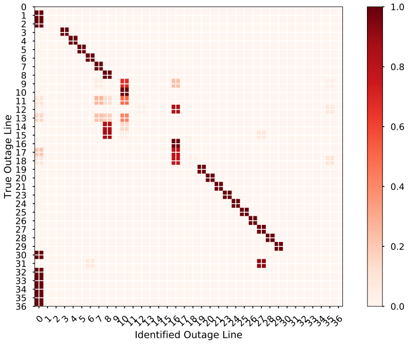
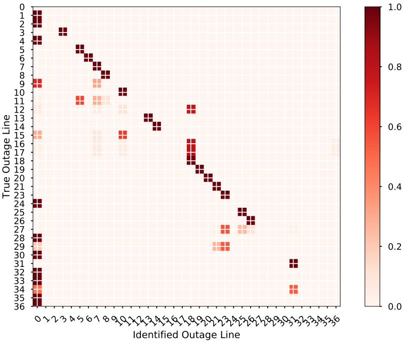


Figure 8: Tree-based placement



Summary

Summary

Problem

Formulate an optimal PMU placement problem to improve line outage detection & localization accuracy.

Challenges

Weak and incomplete signals.

Key idea

Based on a detection scheme, OPP is formulated as a combinatorial optimization problem solved by meta-heuristic algorithm.

For more details, discuss with me or refer to our papers:

1. Yang, X., Chen, N., & Zhai, C. (2020). Optimal placement of limited PMUs for transmission line outage detection and identification. *PMAPS*
2. Yang, X., Chen, N., & Zhai, C. (2020). A control chart approach to power system line outage detection under transient dynamics. *IEEE Transactions on Power Systems*.

Thank you for listening!
Questions?

Backup Slides

State of the art in first work

Data-driven: No power system-specific modeling

- *Xie et al.(2014)*: PCA + Monitor approximation error
- *Rafferty et al.(2016)*: SW-PCA[2] + 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

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

AC power flow model

Given a power network where N buses are connected by L power lines, AC power flow model describes the relationship between net active power (P), net reactive power (Q), nodal voltage magnitude (V), and voltage phase angle (θ) governed by Kirchhoff's circuit laws:

$$\mathrm{P}_m = \mathrm{V}_m \sum_{n=1}^{N} \mathrm{V}_n \mathrm{Y}_{mn} \cos(\theta_m - \theta_n - \alpha_{mn}) \,,$$

$$\mathrm{Q}_m = \mathrm{V}_m \sum_{n=1}^{N} \mathrm{V}_n \mathrm{Y}_{mn} \sin(\theta_m - \theta_n - \alpha_{mn}) \,,$$

for bus $m = 1, 2, \ldots, N$. Y_{mn} is the magnitude of the $(m, n)_{th}$ element of the bus admittance matrix $\boldsymbol{Y}$ when the complex admittance is written in the exponential form, i.e.,

$$\mathrm{Y}_{mn} e^{j\alpha_{mn}} = G_{mn} + jB_{mn} \,.$$

Linear time-variant relationship

The small-signal time-variant model describing the relationship between active power mismatches and the changes in voltage angles is

$$\frac{\partial \mathbf{P}}{\partial t} \approx \mathbf{J}_1(\boldsymbol{\theta}) \frac{\partial \boldsymbol{\theta}}{\partial t}\,.$$

The off-diagonal and diagonal elements of the $\mathbf{J}$ matrix can be derived as:

$$\frac{\partial \mathsf{P}_m}{\partial \theta_n} = \mathsf{V}_m \mathsf{V}_n \mathsf{Y}_{mn} \sin\left(\theta_m - \theta_n - \alpha_{mn}\right)\,, m \neq n\,,$$

$$\frac{\partial \mathsf{P}_m}{\partial \theta_m} = -\sum_{\substack{n=1\\ n\neq m}}^{N} \mathsf{V}_m \mathsf{V}_n \mathsf{Y}_{mn} \sin\left(\theta_m - \theta_n - \alpha_{mn}\right)\,.$$

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 $\ell = 1, \ldots, L$:

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

Decide: Stop when their maximum crosses the threshold:

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

C can be approximated by $\log(ARL_0 \times N)$[3] to satisfy certain false alarm rate constraint.

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

First work: Comparison with other methods

		Mean Time to False Alarm (day)			
Line	Scheme	1/24	2	7	30
26	DC - full	9.9908	9.9908	9.9908	9.9908
	DC - limited	–	–	–	–
	Ohm's Law - limited	2.8150	3.0963	3.1406	3.9333
	AC - limited	0.1001	0.1005	0.3300	0.3489
27	DC - full	4.5398	4.5398	4.5398	4.5398
	DC - limited	–	–	–	–
	Ohm's Law - limited	3.3044	3.5000	3.6900	3.8630
	AC - limited	0.0012	0.0012	0.0026	0.0039
34	DC - full	0.1801	0.1801	0.1801	0.1801
	DC - limited	–	–	–	–
	Ohm's Law - limited	1.5811	2.9250	3.2014	3.6788
	AC - limited	0.0879	0.0879	0.1558	0.4994