Real-time Data Analytics for Energy Cyber-Physical Systems

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Introduction

- The goal of this research is to improve system understanding and situational awareness in power grids.
- Unexpected natural disasters and attacks can make transmission lines inoperative.
- The proposed work will provide a collection of algorithmic solutions to improve model estimation, and provide the control center with the ability to detect minor events and take appropriate control actions before they develop into major blackouts.
- This research focuses on line outage detection and state estimation.

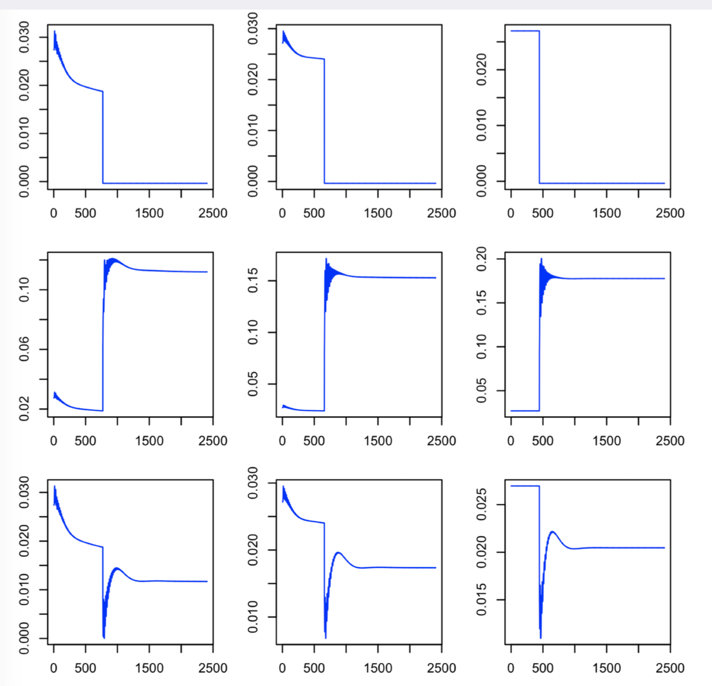
Line Outage Detection and Identification

- The active power transfer from bus i to bus j

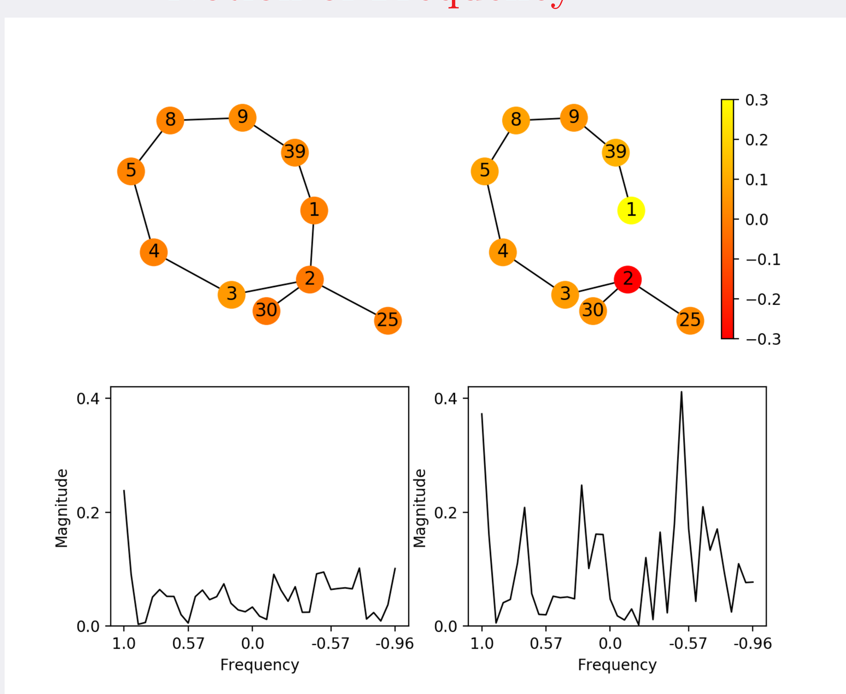
$$P_{ij} = |V_i||V_j| \left(G_{ij} cos(\theta_i - \theta_j) + B_{ij} sin(\theta_i - \theta_j)\right)$$

- Line outage causes disruption on P_{ij}
- Observed disruption on PMU data $\rightsquigarrow$ Classification on PMU data $\rightsquigarrow$ Line outage identification
- Classification algorithms: Graph Convolutional Neural Networks

Observed Data



Notion of Frequency



GCN Spatial Filter

- Input signal $\boldsymbol{x} \in \mathcal{R}^N$
- The normalized adjacency matrix $\tilde{A} \in \mathcal{R}^{N^2}$
- The spatial filter

$$w(\tilde{A}) = \sum_{i=0}^{H} w_i \tilde{A}^i$$

- The output feature from the convolutional layer

$$\boldsymbol{y} = \sum_{i=0}^{H} (w_i \tilde{A}^i) \boldsymbol{x}$$

GCN Spectral Filter

- The eigen-decomposition of $\tilde{A}$

$$\tilde{A} = \mathbf{V} \mathbf{\Lambda} \mathbf{V}^{-1}$$

- The spectral filter

$$w(\mathbf{\Lambda}) = \sum_{h=0}^{H} w_h \mathbf{\Lambda}^h$$

- The output feature

$$\widehat{\boldsymbol{y}}^g = \sum_{k=1}^{K} w^{k,g}(\mathbf{\Lambda}) \widehat{\boldsymbol{x}}^k$$

Accelerated Convergence for State Estimation

- State estimation in power systems is a graph-structured optimization problem
- Propose a decentralized architecture for solving graph-structured optimization problems
- Idea: use overlapping subdomains to promote and accelerate convergence

Graph-Structured Optimization Problem

- Consider an optimization problem defined on a graph $G(V, E)$ with $|V| = n, |E| = m$:

$$\min_{x,u} \ \frac{1}{2} x^T Q x - f^T x + \frac{1}{2} u^T R u + \frac{1}{2} v^T S v$$
$$s.t. \quad Ax = u, \ Bx = v$$

where $Q, R, A \in \mathbb{R}^{n \times n}, B \in \mathbb{R}^{m \times n}, S \in \mathbb{R}^{m \times m}, x, u \in \mathbb{R}^n, v \in \mathbb{R}^m$.

- Equivalent quadratic program:

$$\min_{x} \ \frac{1}{2} x^T (Q + A^T R A + B^T S B) x - f^T x \Longrightarrow \ \min_{x} \ \frac{1}{2} x^T H x - f^T x$$

- Solution exists and is unique by solving a linear system: $Hx = f$

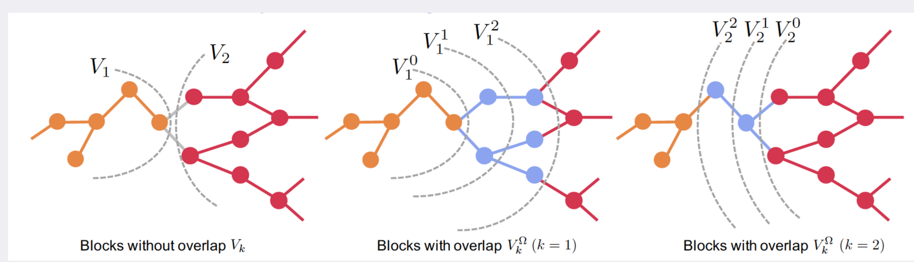
Decentralized Scheme to Solve $Hx = f$

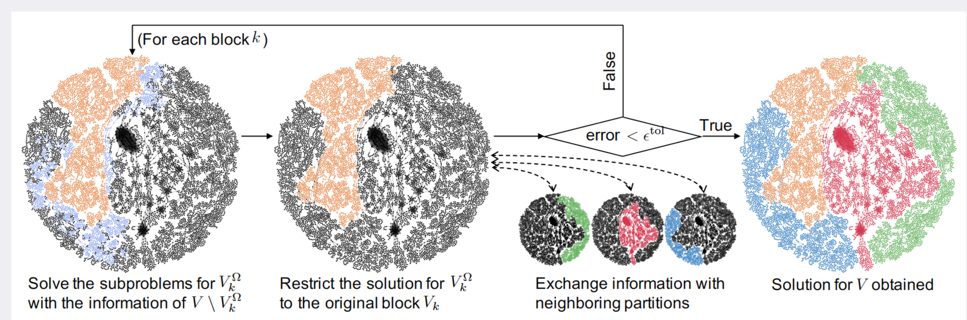
- Partition V into subdomains $\{V_k\}$; Define overlapping region: $V_k^{\Omega} = \{i \in V | d_G(i, V_k) \leq \Omega\}$
- Solving $Hx = f$ in a decentralized manner:
- at any iteration, only the subset of x in the overlapping region is updated

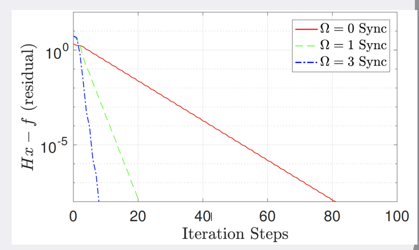
$$(H_k^{\Omega})\{x\}_{V_k^{\Omega}} = \left(-H_{-k}^{\Omega}\{x^{(t)}\}_{V \setminus V_k^{\Omega}} + f_k^{\Omega}\right) \quad (1)$$

- after solving (1) the solution is restricted to V_k

$$x_k^{(t+1)} = \left\{(H_k^{\Omega})^{-1}(-H_{-k}^{\Omega}\{x^{(t)}\}_{V \setminus V_k^{\Omega}} + f_k^{\Omega})\right\}_{V_k} \quad (2)$$







Convergence

- Convergence rate

$$\rho \leq \frac{R}{\lambda_{min}} \left(\frac{\lambda_{max} - \lambda_{min}}{\lambda_{max} + \lambda_{min}}\right)^{\Omega}$$

- Convergence rate improves with larger overlap Ω; the computational cost for the subdomain problems increases with Ω.