A Resilient Algorithm for Power System Mode Estimation using Synchrophasors

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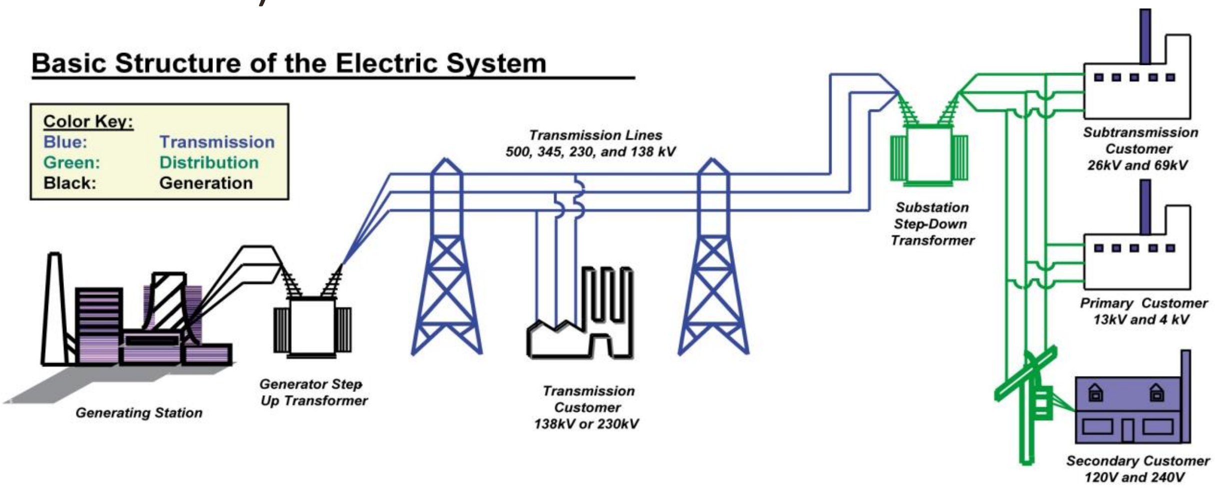
Outline

- Introduction
- Background and Problem
  - Prony Algorithm
  - Standard ADMM
  - False Data Injection
- Related Work
- Our Proposed Method
- Evaluation
- Analytical Intuition
- Conclusion

Power System

Large synchronous distributed system of interconnected electrical components used for generation, transmission and distribution of electric power

- Generators
- Transmission (and distribution) lines
- Transformers
- Substations



Basic structure of Power System*

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* Image Source: http://www2.econ.iastate.edu

Stability In Power Systems

Introduction

- The ability of operating an AC power network with:
  - All generators in synchronism and
  - Retaining synchronism even after a large disturbance

- Faults can lead to instability in power systems

- Instability problems in power systems can lead to brownouts or in extreme cases blackouts

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Northeast Blackout – August 2003

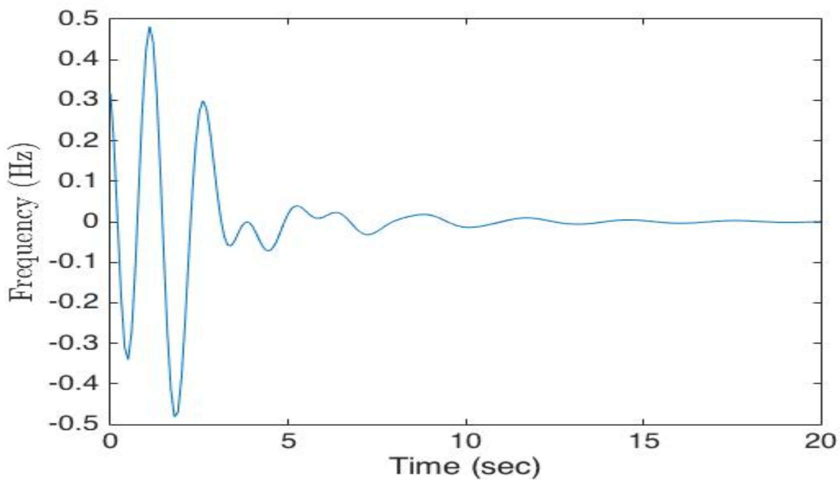
- Impacted 50 million people
- Estimated loss: $4-$10 billion
- At least 2 deaths in New York city attributed to the blackout

Northeast Blackout Map*

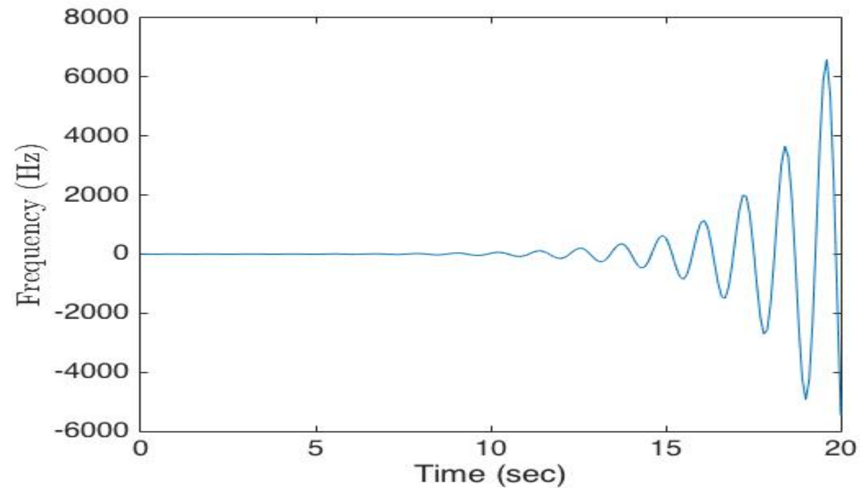
*Image Source: http://naturalhistory.si.edu/exhibits

Inter-Area Oscillation Modes

- In the presence of a fault, two or more coherent groups of generators may start swinging against each other leading to frequency *oscillations*
- It is important to detect unstable oscillations and take corrective action



Stable Power Oscillations



Unstable Power Oscillations

Oscillation Mode Detection Approaches

Introduction

	Model-Based Methods	Measurements-Methods
Time Efficiency	✗	✓
Scalability	✗	✓
On-line	✗	✓
Accuracy	✓	✗
Topology Independency	✗	✓

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Prony Algorithm [Hauer 1990]

Background and Problem

- Prony algorithm is a popular measurement-based method
- Consider a power system with m synchronous generators
- Assume that each synchronous generator is modeled by a second-order swing equation
- $[y_i(t_0), \dots, y_i(t_n)]$ is a set of measurements provided by i^{th} Phasor Measurement Units at time t

$$y_i(t) = \sum_{k=1}^{2m} r_{i,k} e^{\sigma_k + j\Omega_k} + r'_{i,k} e^{\sigma_k - j\Omega_k}$$

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Prony Algorithm

- Goal: To estimate damping factors(σ_k) and , frequencies (Ω_k) of oscillation modes
- Finds coefficient vector $\vec{a}$:

$$\underbrace{\begin{bmatrix} y_i(t_0+nT) \\ y_i(t_0+(n+1)T) \\ \vdots \\ y_i(t_0+(n+l)T) \end{bmatrix}}_{\vec{c}} = \underbrace{\begin{bmatrix} y_i(t_0+(n-1)T) & y_i(t_0+(n-1)T) & \cdots & y_i(t_0) \\ y_i(t_0+nT) & y_i(t_0+(n-2)T) & \cdots & y_i(t_0+T) \\ \vdots & \vdots & \vdots & \vdots \\ y_i(t_0+(n+l-1)T) & y_i(t_0+(n+l-2)T) & \cdots & y_i(t_0+lT) \end{bmatrix}}_{H} \underbrace{\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix}}_{\vec{a}}$$

- Obtains the roots $Z_1, \ldots, Z_n$ of discrete-time characteristic polynomial equation

$$Z^n + a_n Z^{n-1} + a_{n-1} Z^{n-2} + \cdots + a_1 = 0$$

$$\sigma_i \pm \Omega_i = \frac{\log Z_i}{T}$$

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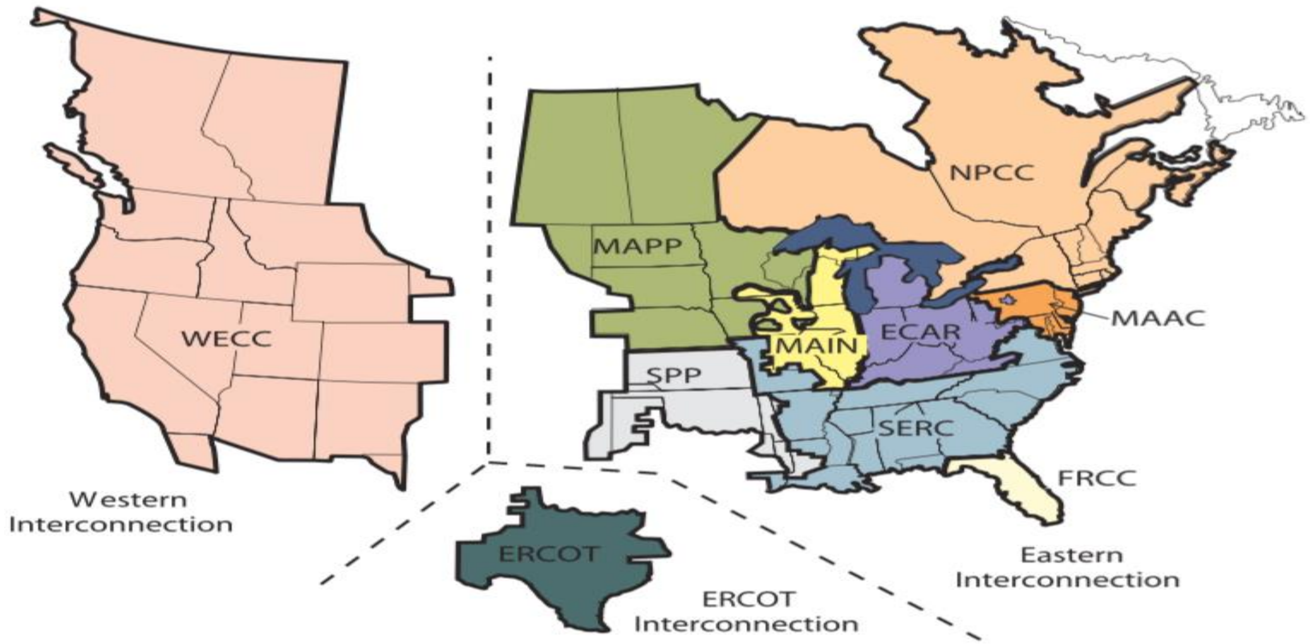
Power Grid: A Large Distributed Network

Background and Problem

- Power systems are usually divided into multiple areas of control



North American Interconnections*

*Image source: [Andersson (2005)]

Power Grid: A Large Distributed Network

Background and Problem

- Power systems are usually divided into multiple areas of control
- Using Alternating Direction Method of Multipliers (ADMM) to implement Prony Algorithm in a distributed fashion [Wei 2013]:
  - Local objective function of i^{th} area: $(f_i(a) = \|H_i a - C_i\|)$
  - Goal: to find a solution for:

$$\min_{a} \sum_{i=1}^{N} \|H_i a_i - C_i\|$$
$$s.t \;\; a_i - z = 0$$

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Standard ADMM (S-ADMM)[Nabavi 2015]

Background and Problem

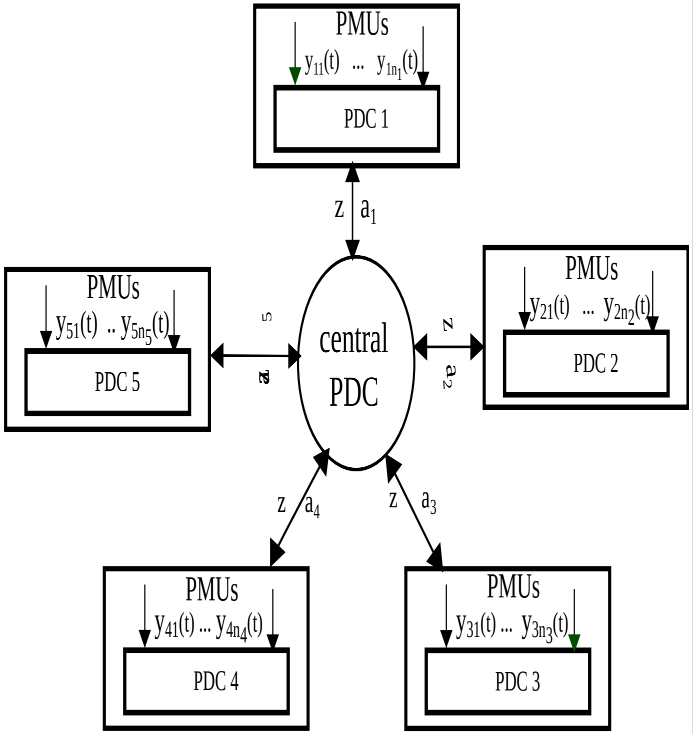
Local Phasor Data Concentrator (PDC):

- Gathers measurements to create Henkel matrix H_i and vector C_i

Disadvantage: S-ADMM is not robust against false data injection

Compromised areas can send corrupted data to mislead other areas or disrupt convergence

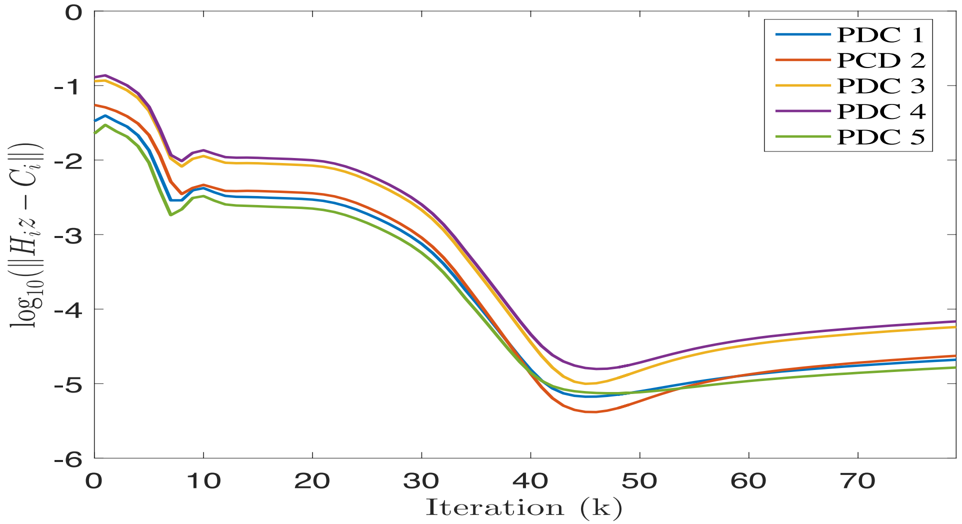
- Computes the global optimal estimate vale (z^{k+1}) and shares it with local PDCs



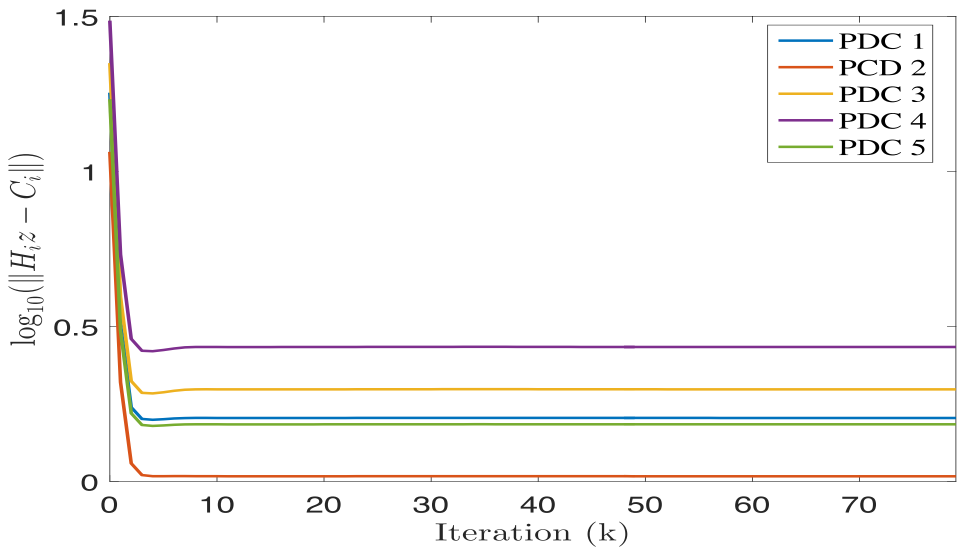
Impact of False Data Injection on Convergence

Background and Problem

Without Attack



With Attack



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Potential Adversary Goals

- Disrupting the mode estimation by preventing convergence :
  - Random Value Attack
- Driving the estimate away from the real modes (potentially to desired modes)
  - Desired Value Attack
- Remaining Undetected
  - Periodic Attack

Related Work

- Round-Robin ADMM[Liao 2016]
  - Central PDC updates the global optimal estimate value by using a local optimal estimate value from only one area in each iteration ($z^{k+1} = a_i^{k+1}$)
  - Central PDC removes the local optimal estimate which causes the most change in global optimal
- D-ADMM[Nabavi 2015]
  - Fully distributed version of S-ADMM
  - Areas send their local optima estimate values to each other
  - Each area uses its objective function to detect compromised area
- CON:
  - They need two runs: one for compromised area detection and one for mode estimation
  - Not robust against periodic attack

Our Contributions

Our Proposed Method

- Unlike previous methods that localize the false data, our approach aims to tolerate the false data

- Our approach needs only one run to estimate oscillation modes

- We considered different attack scenarios to evaluate our methods

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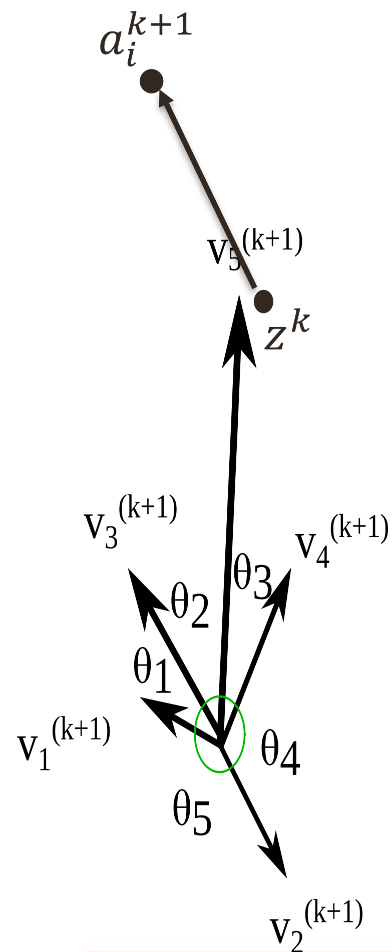
Fault Tolerance Approach

Our Proposed Method

- Central PDC will identify outlier and remove it from $z^{(k+1)}$ calculation
- Direction of $v_i^{(k+1)} = a_i^{(k+1)} - z^k$ points to the location of optimal value from view of area *i*
- Dissimilarity matrix $(M_{dis}(i,j))$ keeps the angle between v_i^{k+1} and v_j^{k+1}
- To resist against periodic attacks, central PDC has a local memory with size W to track attacker.

$$M_{dis} = \begin{bmatrix} 0 & \theta_5 & \theta_1 & \theta_1+\theta_2+\theta_3 & \theta_1+\theta_2 \\ \theta_5 & 0 & \theta_4+\theta_2+\theta_3 & \theta_4 & \theta_4+\theta_3 \\ \theta_1 & \theta_4+\theta_2+\theta_3 & 0 & \theta_2+\theta_3 & \theta_2 \\ \theta_1+\theta_2+\theta_3 & \theta_4 & \theta_2+\theta_3 & 0 & \theta_3 \\ \theta_1+\theta_2 & \theta_4+\theta_3 & \theta_2 & \theta_3 & 0 \end{bmatrix}$$

1	2	4	2	5	2	3



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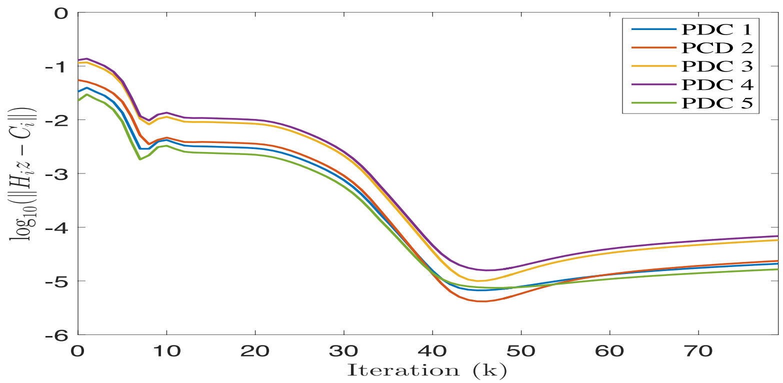
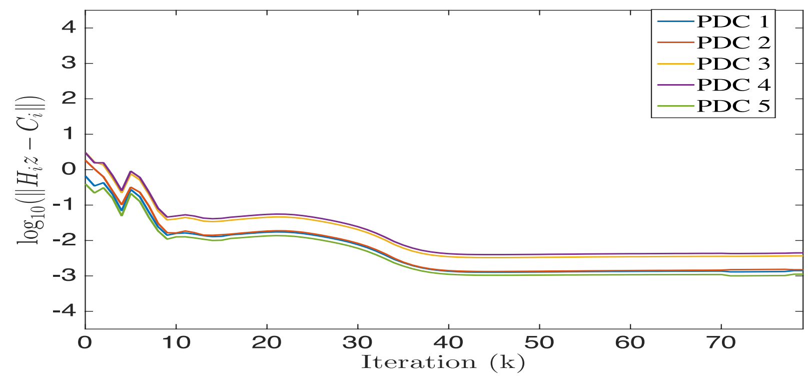
Fault Tolerance Approach's Impact on Convergence

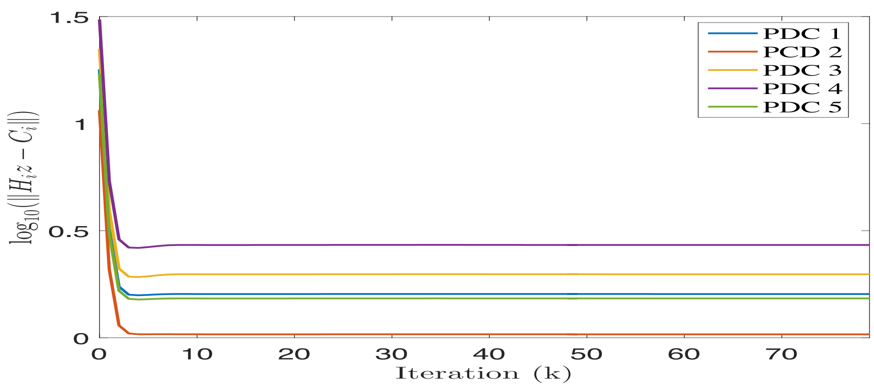
Our Proposed Method



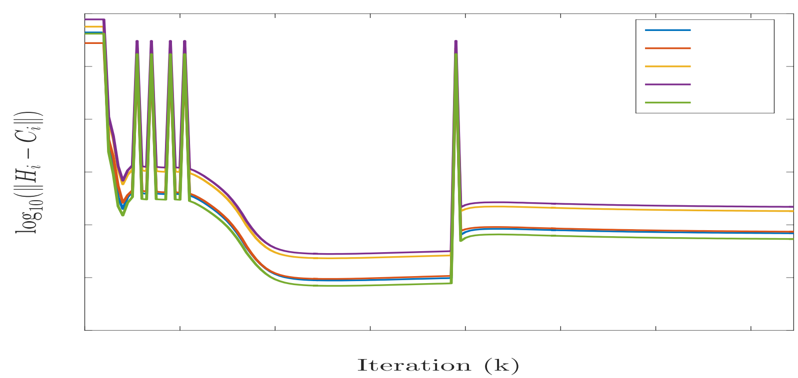
Without Attack and No Tolerance Approach



No Attack and With Using Attack Tolerance Approach



With Attack and Without Tolerance Approach



With Attack and With Using Attack Tolerance Approach

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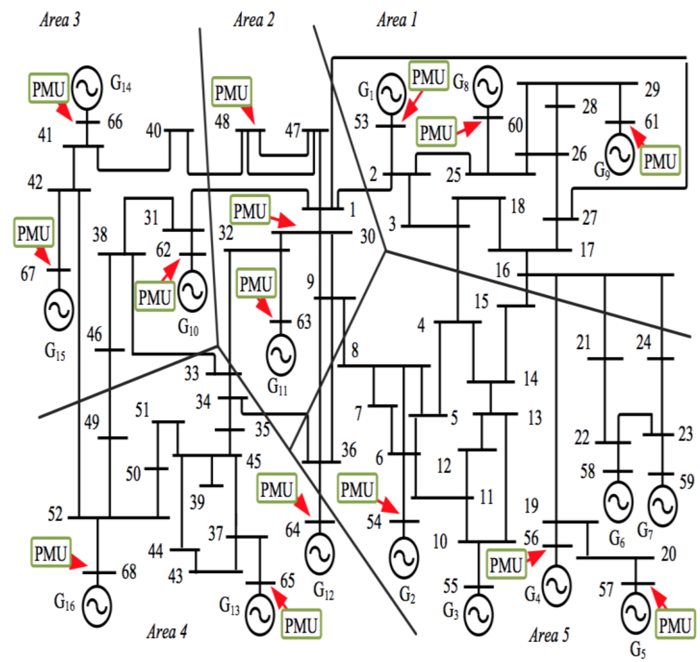
Evaluation

- IEEE 68-bus power system divided into 5 areas
- Generated measurements using Power System Toolbox (PST)
- Generators in this model are 6^{th} order
  - Many of modes have small residues
  - Inter-area oscillation modes have small frequency
  - Therefore, we consider about 40 modes



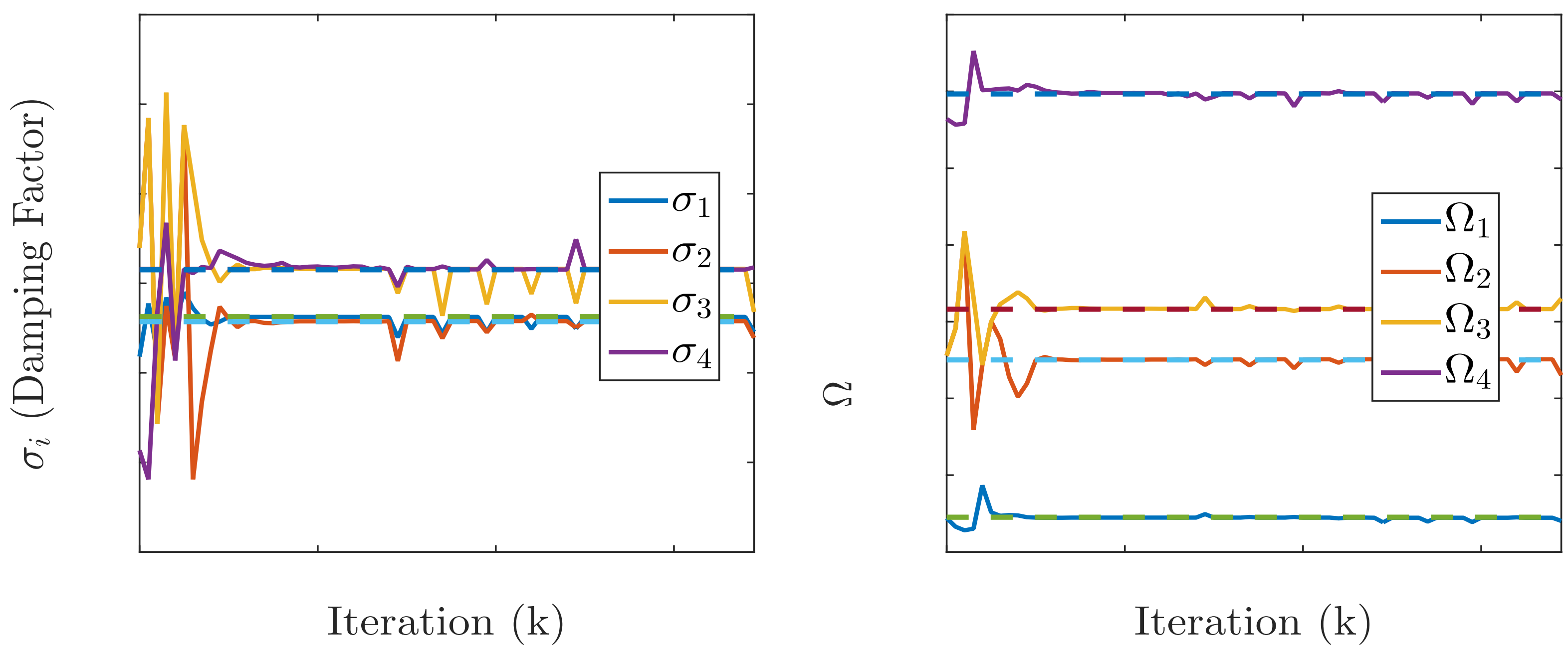
IEEE 68-bus*

*Image Source: [Nabavi 2015]

Evaluation (Cont.)

Evaluation

Different Attack Scenarios



Periodic Desired Value Attack

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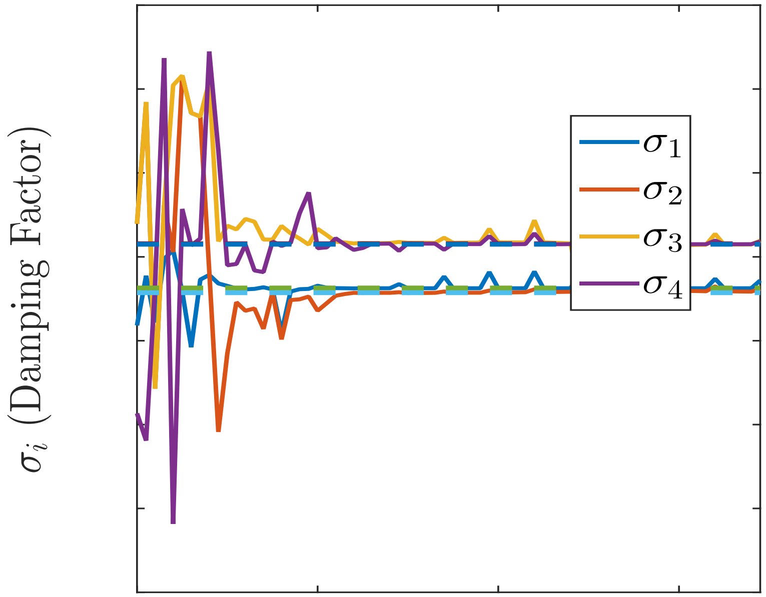
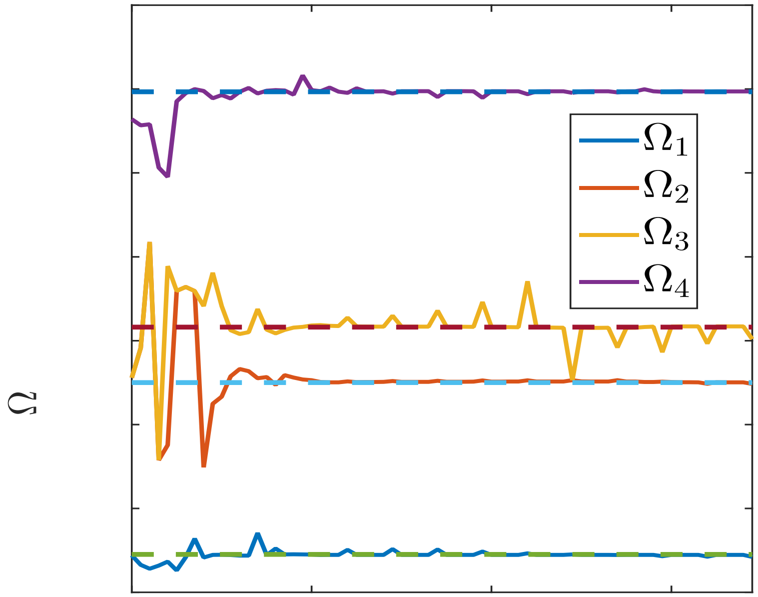
Evaluation (Cont.)

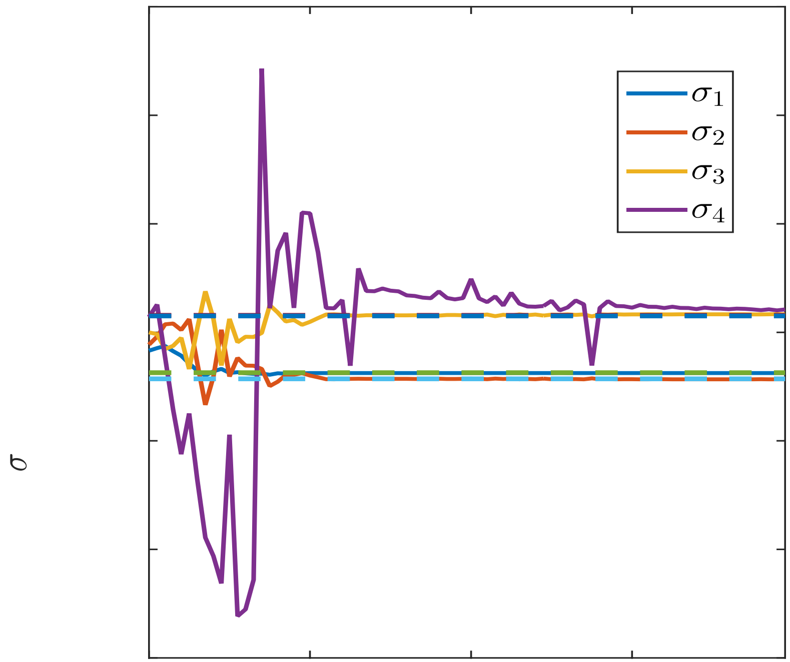
Different Attack Scenarios

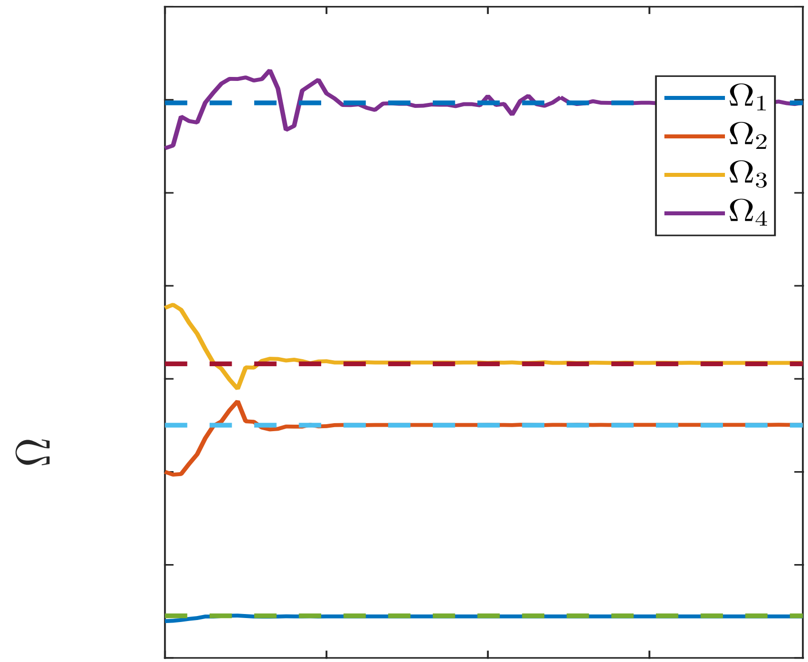




Periodic Random Value Attack

Evaluation (Cont.)





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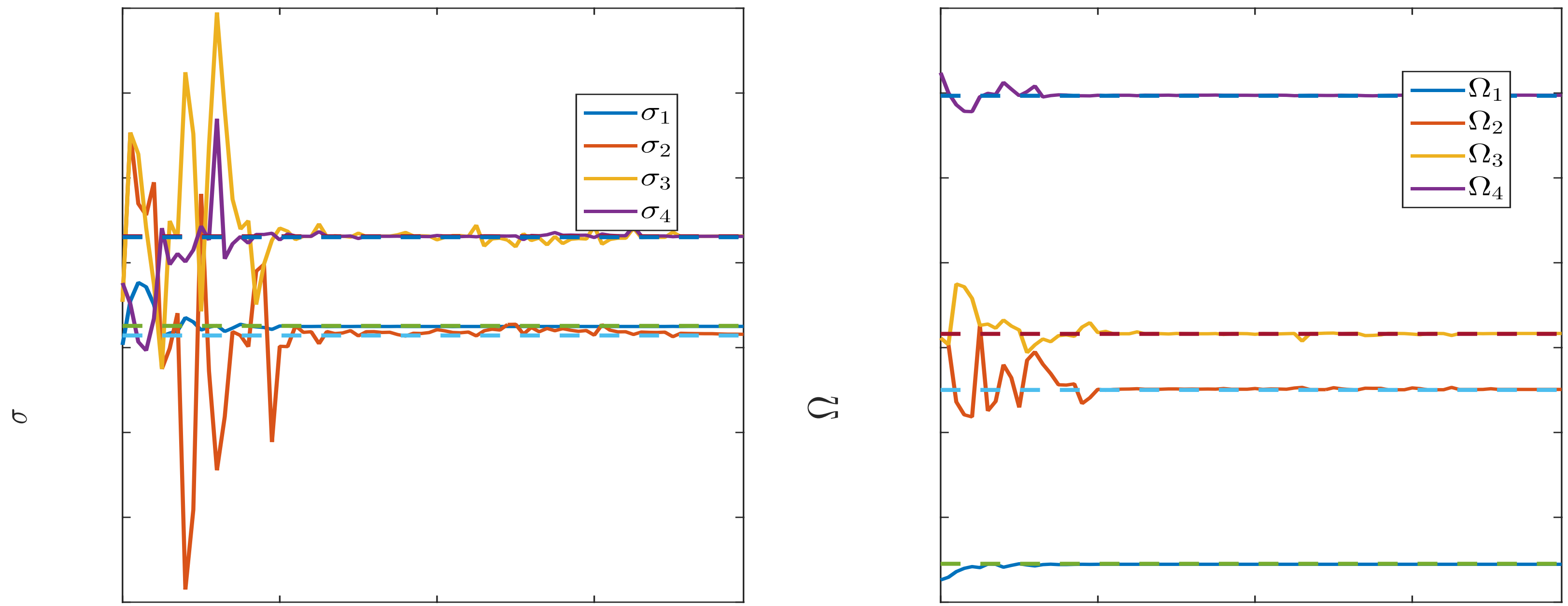
Evaluation (Cont.)

Evaluation



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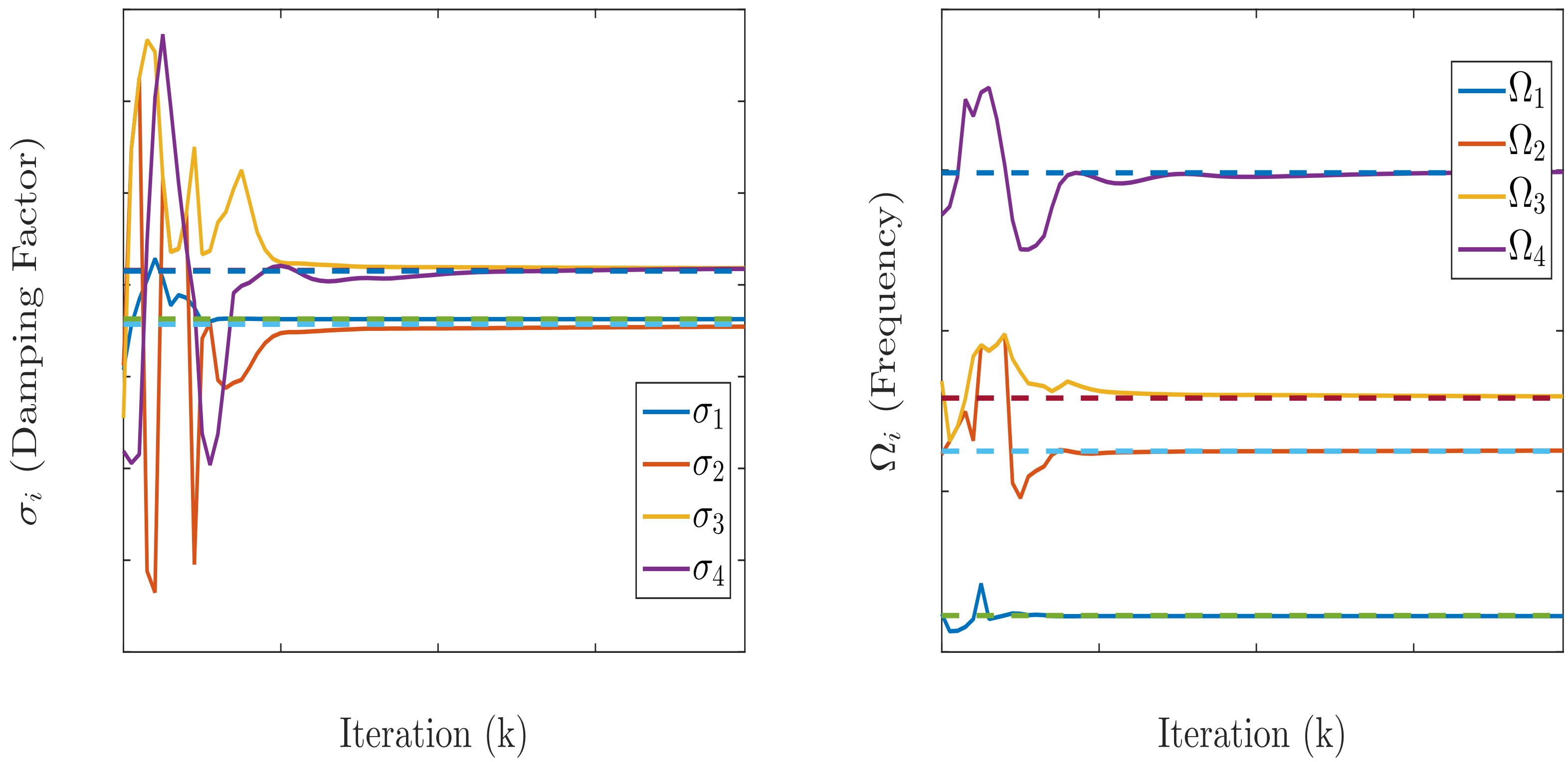
Evaluation (Cont.)

Evaluation



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Analytical Intuition

Evaluation

Theorem 2. Let $f_1(x)$ and $f_2(x)$ be convex functions with the same optimal value, i.e., $f_1(x_1^*) = f_2(x_2^*)$ and whose derivative exists at every point, then $\| x^{\varepsilon} - x_1^* \| \gg \varepsilon$, $\| x_1 - x_2^* \| \gg \varepsilon$ then $\cos\theta \approx 1$ where x_i^* is the optimal value at which $f_i(x)$ has its minimum value and θ is the angle between $f_1'(x)$ and $f_2'(x)$

Theorem 3. Let for all objective functions $\forall i \in S_i = \{x \mid \| x_i^* - x_j^* \| \leq \varepsilon\}$ [illegible] $\frac{f_2'(x)}{\|f_2'(x)\|}$ [illegible] $\frac{f_n'(x)}{\|f_n'(x)\|}$. Then false data by an intelligent attacker will be identified and dis-carded unless its $f_{bad}'(x)$ points to $\cup S_i$

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Conclusions

- We proposed a promising byzantine fault tolerant mode estimation method based on S-ADMM

- Our proposed method does not localize the attacker but can tolerate byzantine attackers

- Our proposed method works well under different attack scenarios

Future Directions

Conclusion

We plan to:

- Evaluate this approach further both empirically and analytically
- Provide a formal analysis of our approach and characterize its limitations
- Apply machine learning algorithms to partition areas into non-faulty and faulty areas

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Thanks

Q& A

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S-ADMM (Cont.)

Iteration *k:*

1. Local PDCs updating local optima

$$a_i^{(k+1)} = (H_i' H_i + \rho I)^{-1} \left(H_i' C_i - w_i^{(k)} + \rho z^{(k)}\right)$$

2. Central PDC compute the global optima:

$$z^{(k+1)} = \sum_{i=1}^{N} a_i^{(k+1)}$$

3. Local PDC update dual parameter

$$w_i^{(k+1)} = w_i^{(k)} + \rho(a_i^{(k)} - z^{(k+1)})$$