Exploring Power System State Estimation Divergence via Synthetic Measurement Data Creation

- Efforts Led by IEEE Task Force on Standard Test Cases for Power System State Estimation

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Panel on Power System Synthetic Data Generation and Sharing
Room 440, IEEE PES GM 2024, Seattle, WA, USA
10:00 AM -12:00 PM, July 25, 2024

Binghamton University
State University of New York

Collaborators and Sponsors of Presented Work

Collaborators (sorted by their last names)

- ❑Shahrokh Akhlaghi (Ulteig Engineers Inc.)
- ❑Renke Huang, Zhenyu Huang, Shaobu Wang, et al. (PNNL)
- ❑ Yuzhang Lin (New York University)
- ❑Da Meng, Shuai Lu (EnerMod)
- ❑Greg Welch (University of Central Florida)
- ❑Junbo Zhao (Mississippi State University)

Sponsors (sorted by their names)

- ❑DOE Advanced Grid Modeling program
- ❑NSF CAREER grant no. #1845523

Outlines

- **Background**
- Creation of Challenging Cases to SSE
- Challenges from Time-Skew Problems
- Summary of Findings and Future Work

SCADA/EMS Systems

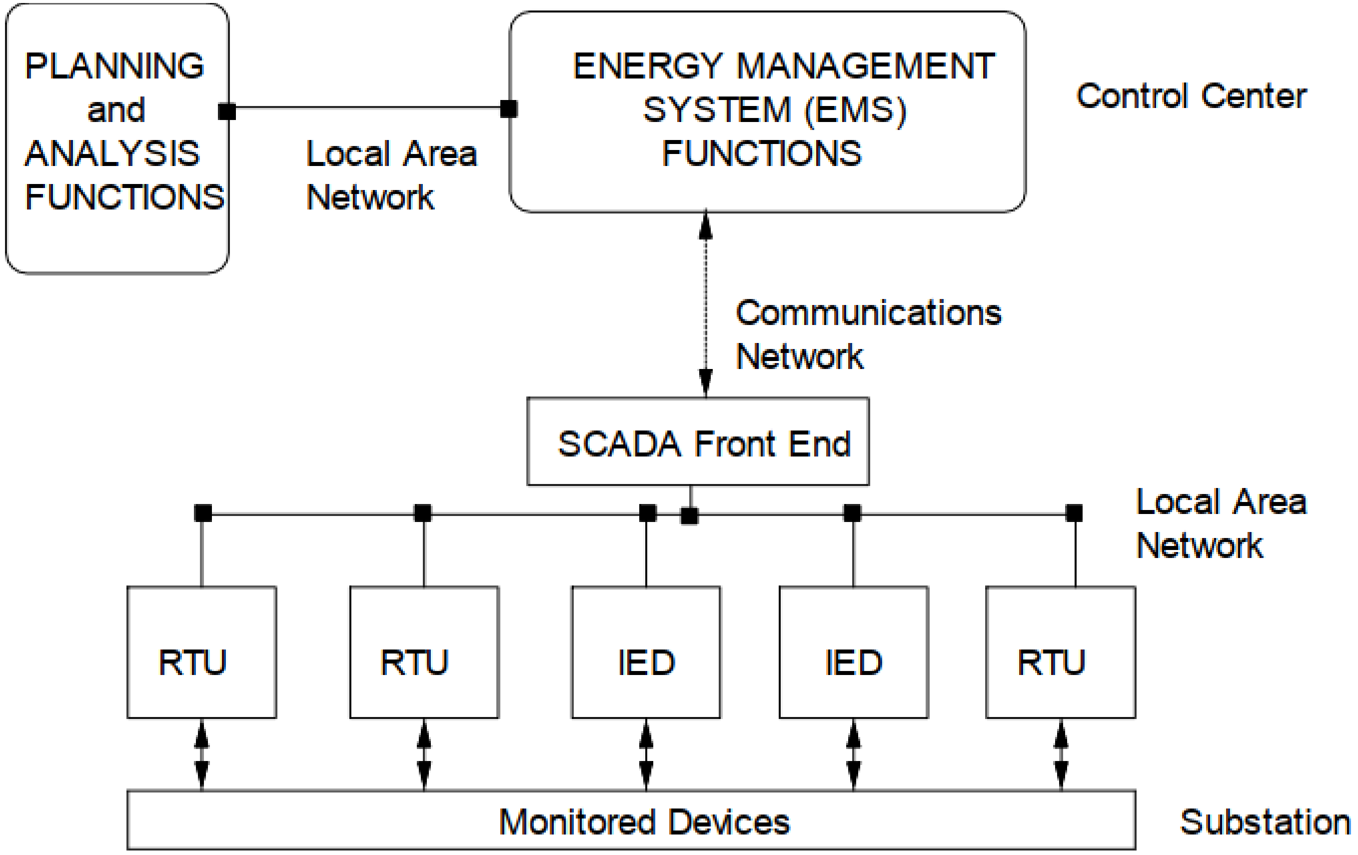
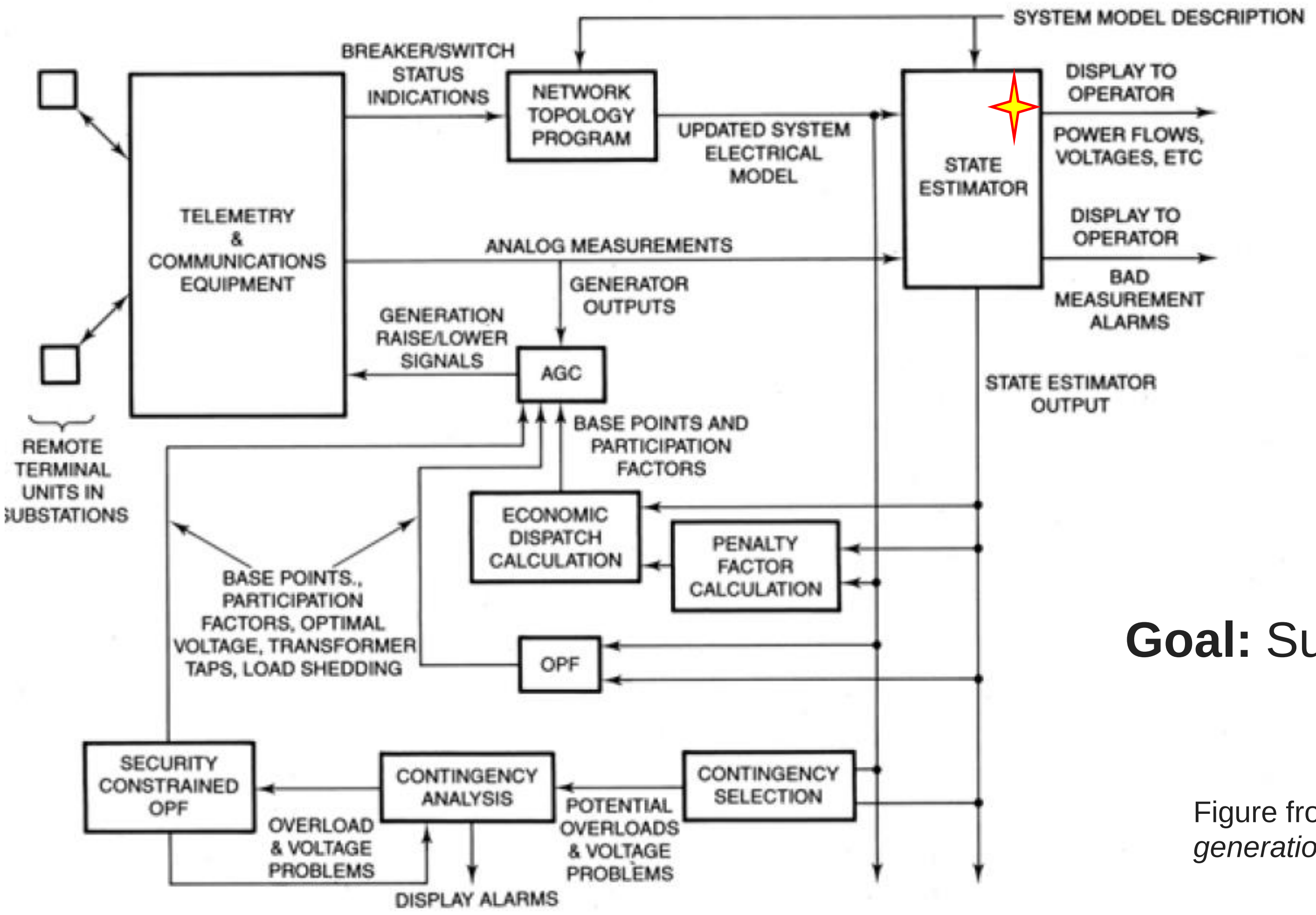


Figure from Abur, Ali, and Antonio Gomez Exposito. *Power system state estimation: theory and implementation*. CRC press, 2004.

Critical Role of State Estimation in Power System Operations



Inputs:
- Measurement Data
- Power Flow Models

Outputs:
- Estimated States
- Improved Models

Goal: Support well-informed decision making.

Figure from Wood, Allen J., Bruce F. Wollenberg, and Gerald B. Sheblé. *Power generation, operation, and control*. John Wiley & Sons, 2013.

Problem Statement

Functions of a State Estimator:

- Monitors operating conditions (variables) of a power grid in a control center
- Supports real-time operations (e.g., ED, OPF)

Challenges:

- Noise and even bad data in measurements (Inaccuracy)
- Limited number of direct measurements (limited scope)

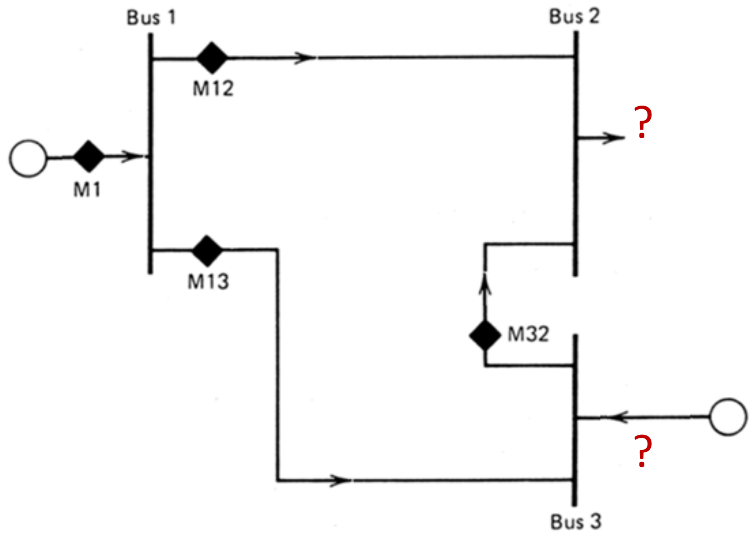


Figure from Wood, Allen J., Bruce F. Wollenberg, and Gerald B. Sheblé. *Power generation, operation, and control*. John Wiley & Sons, 2013.

Classical Solutions: SSE

Static State Estimation (SSE)

- Estimate x , $bus\ voltage\ phasors$
- By integrating
  - SCADA/PMU measurements: z
  - Power flow models $z = h(x) + r$
- To
  - Filter out noise using spatial redundancy
  - Estimate variables that are not measured

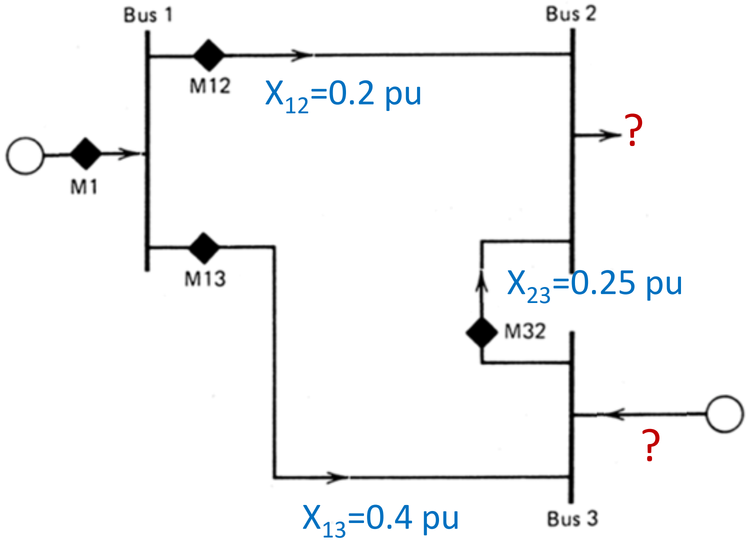


Figure from Wood, Allen J., Bruce F. Wollenberg, and Gerald B. Sheblé. *Power generation, operation, and control*. John Wiley & Sons, 2013.

Example Algorithms

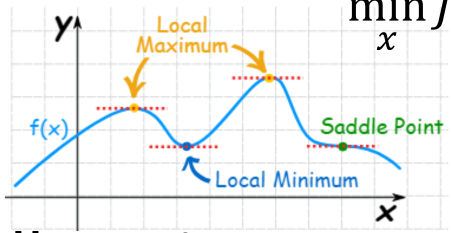
- Weighted least squares (WLS)
- Least absolute values (LAV)

$$\min_x J(x) = [z - h(x)]^{\mathrm{T}} R^{-1} [z - h(x)]$$

$$\min_x J(x) = \sum_{i=1}^{m} \frac{1}{\sqrt{R_{ii}}} |z_i - h_i(x)|$$

Challenges to Conventional SSE

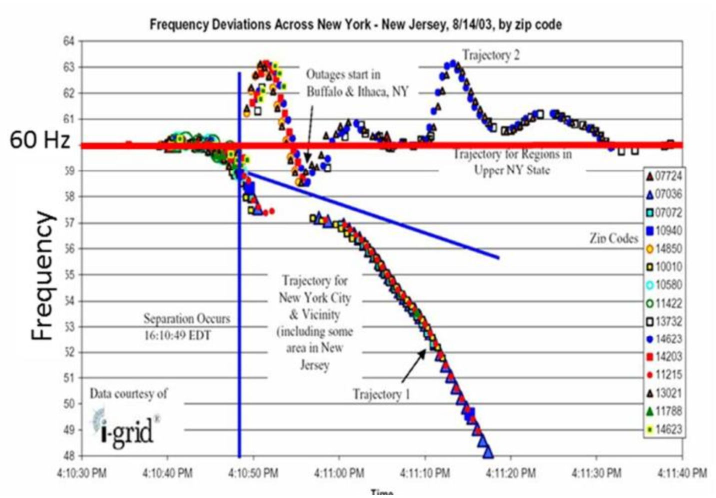
$$\min_{x} J(x) = [z - h(x)]^{\mathrm{T}} R^{-1} [z - h(x)]$$

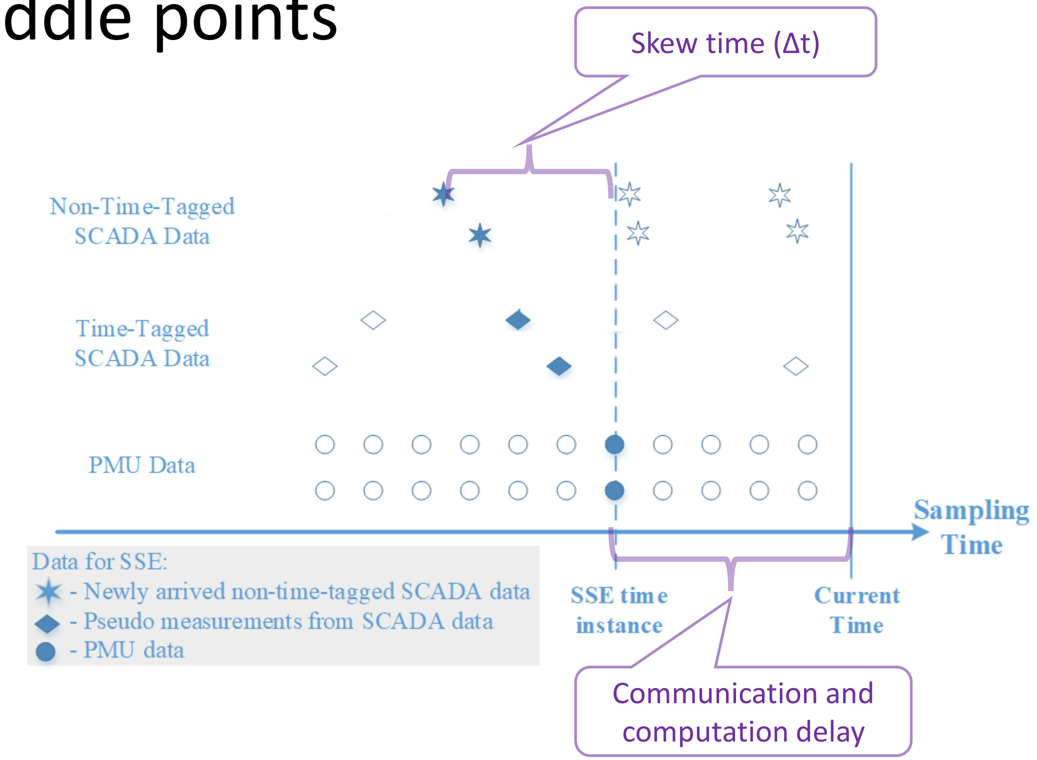


Divergence caused by

- time-skewed measurements,
- local minimums, maximums, and saddle points

Significant frequency deviations from the nominal 60 Hz during the August 14, 2003 Northeast Blackout [1]





[1] Z. Huang, N. Zhou, R. Diao, S. Wang, S. Elbert, D. Meng and S. Lu, "Capturing real-time power system dynamics: Opportunities and challenges," in 2015 IEEE Power & Energy Society General Meeting, Denver, CO, USA, 2015.

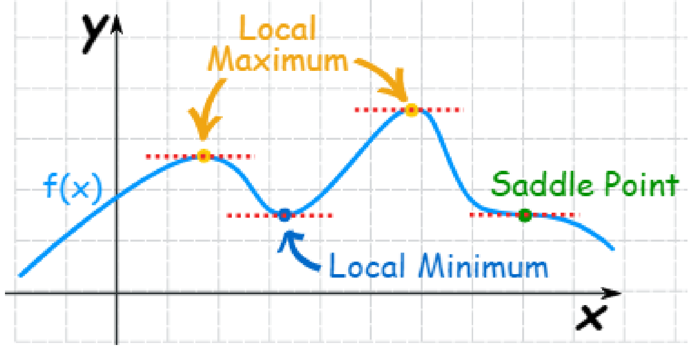
Normal Equations Solutions

Objective function

$$x_{MLE} = \underset{x}{\arg\min}\{J(x) \triangleq [z - h(\boldsymbol{x})]^{\mathrm{T}} R^{-1} [z - h(\boldsymbol{x})]\}$$

Necessary conditions

$$g(x) = \frac{\partial J(x)}{\partial x} \overset{\text{set}}{\longrightarrow} 0$$

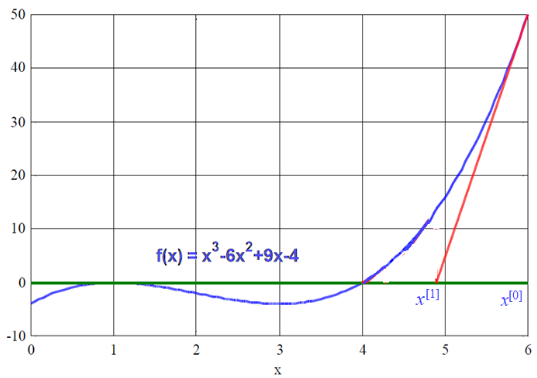


Normal Equation from Newton Method

$$\Delta x^k = \left[\frac{\partial g(x)}{\partial x}\right]^{-1} [0 - g(x)\,]$$

$$\approx \left[H^T\left(x^k\right) R^{-1} H\left(x^k\right)\right]^{-1} H^T\left(x^k\right) R^{-1} \left(z - h\left(x^k\right)\right)$$

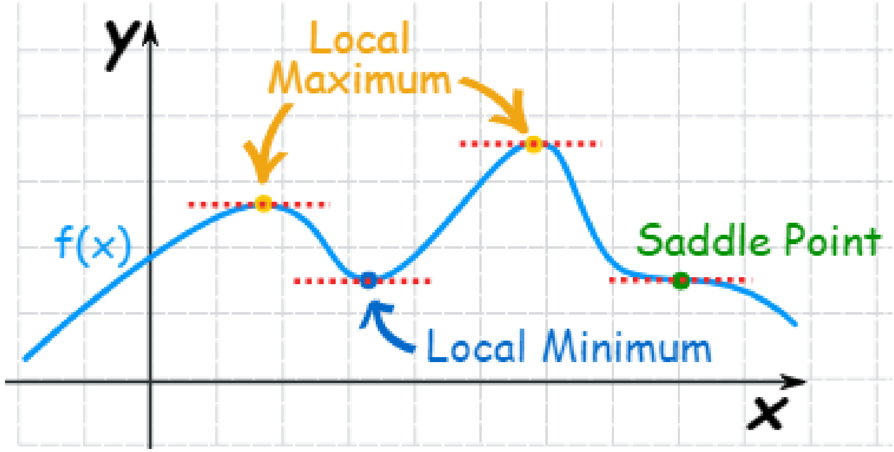
$$\frac{\partial g(x)}{\partial x} = H^T\left(x^k\right) R^{-1} H\left(x^k\right) + 2^{nd} \ order \ derivative$$

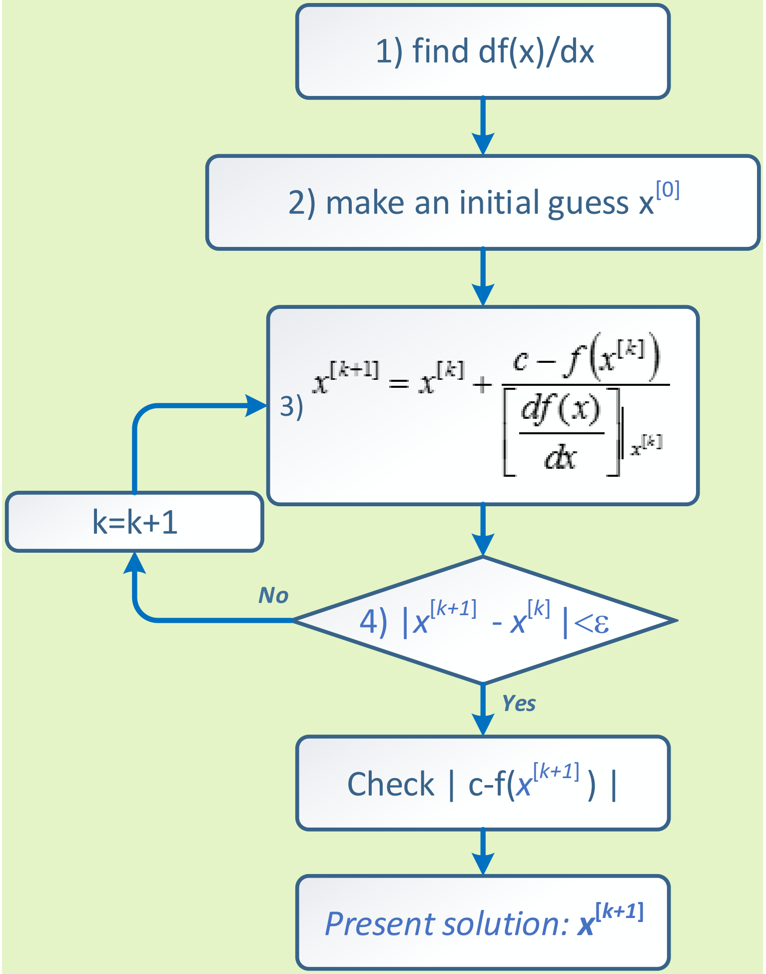


Divergence

Converge to local instead of global min

Increased J(x)





Outlines

- Background
- **Creation of Challenging Cases to SSE**
- Challenges from Time-Skew Problems
- Summary of Findings and Future Work

Factors that may Trigger Divergence of SSE

(1) Initial values of the states far away from the true value [Weng 2012][Gou 2023]

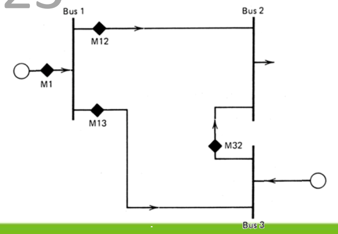
(2) Presence of numerous **bus power injection measurements** tends to make the normal equations method increasingly unstable. [Gu 1983]

(3) An injection flow measurement associated with a large number of branches [Gou 2023]

(4) Very heavy weights for modeling very accurate virtual measurements (such as zero injections) [Abur 2004][Gou 2023]

(5) A long line and a short line at the same bus, i.e., lines with significantly different impedances [Abood 2017] [Tripathy 1982][Gou 2023]

(6) Bad data that cannot be effectively rejected by the WLS algorithm [Gou 2023



A. Divergent Case through Changing Operational Points

Base case:

- ❑IEEE 57-bus model with low redundancy measurements

Approach:

- ❑Change the true voltage magnitudes of bus 36:38 by increasing them to 1.3*

Divergent cases:

- ❑B0057s_033.mat
- ❑B0057s_data_033.csv
- ❑B0057s_header_033.csv
- ❑state_zn33_divergent.mat (stores true states)

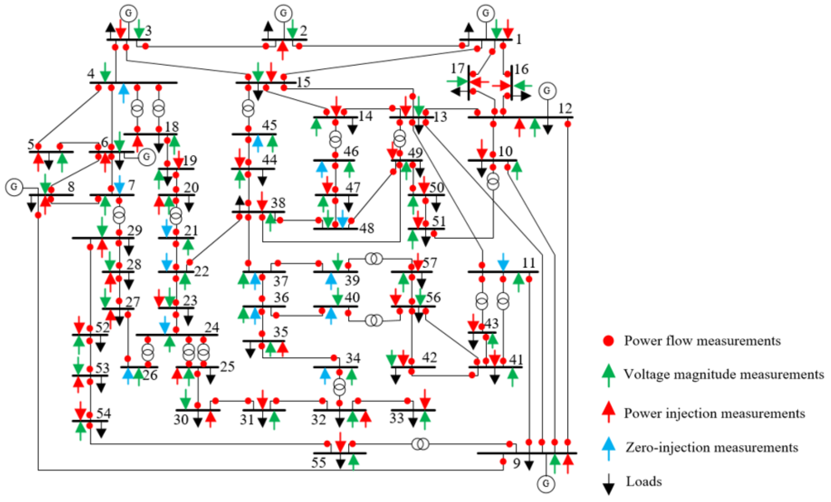
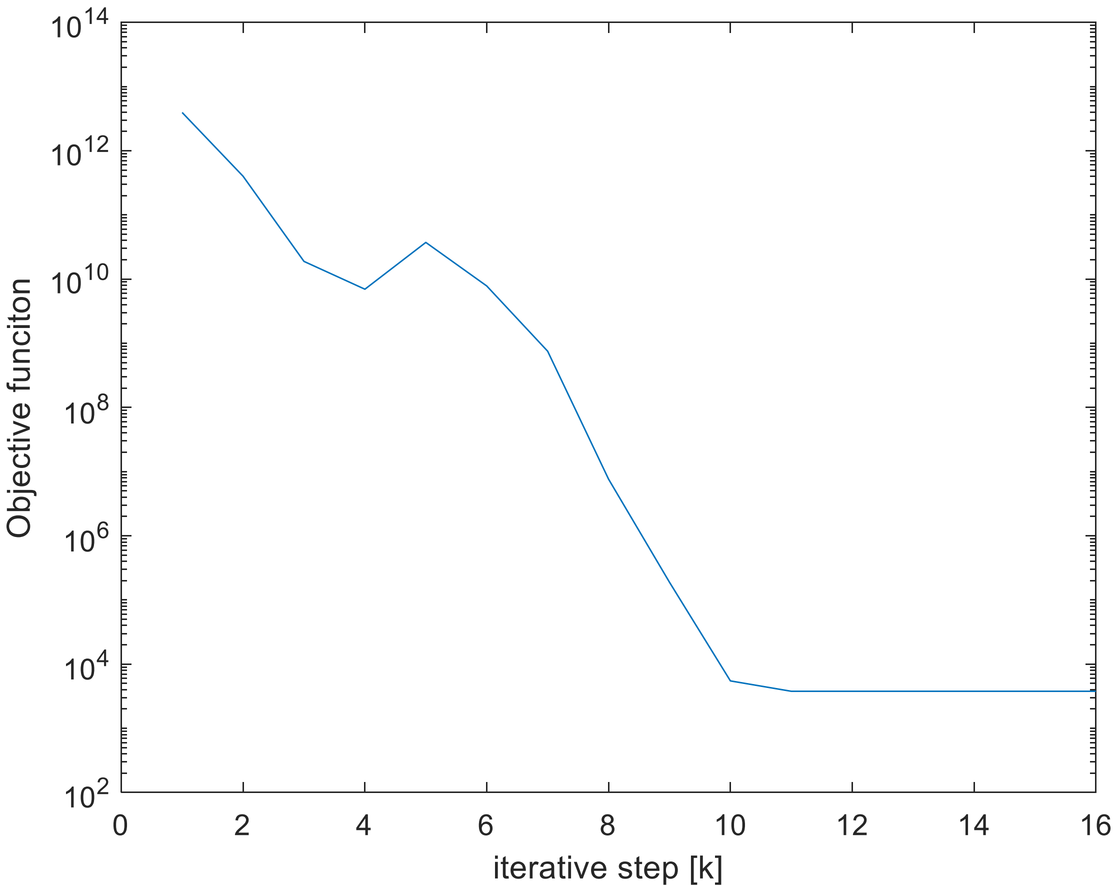
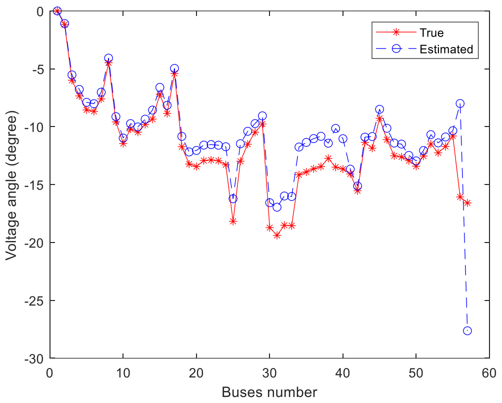


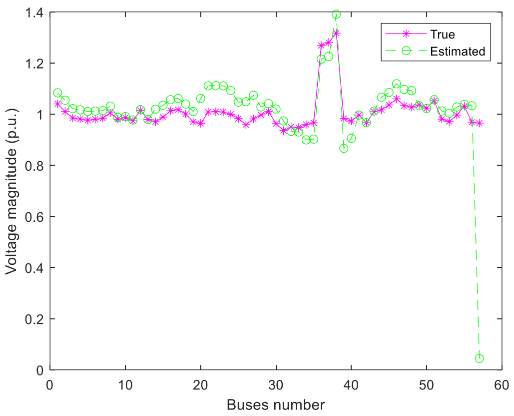
Fig. 1. IEEE 57-bus test system measured by pure SCADA measurements.

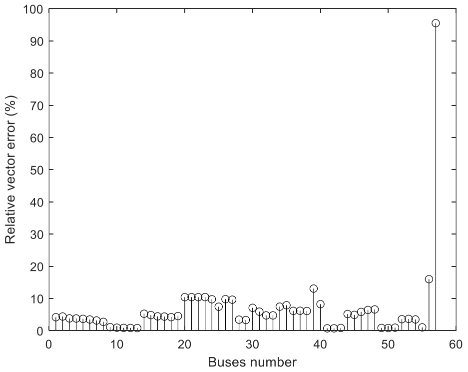
Task Force on Standard Test Cases for Power System State Estimation, “Standard Test Cases for Static and Dynamic State Estimation in Power Systems,” Section 4.3 IEEE 59-bus Test System, by Dr. Yuzhang Lin

Case A. WLS State Estimation Results









- Converged to a local minimum point

B. Divergent Case through Changing Operational Points and Using Only Bus Injection Measurements

Base case:

- ❑IEEE 57-bus model with high redundancy measurements

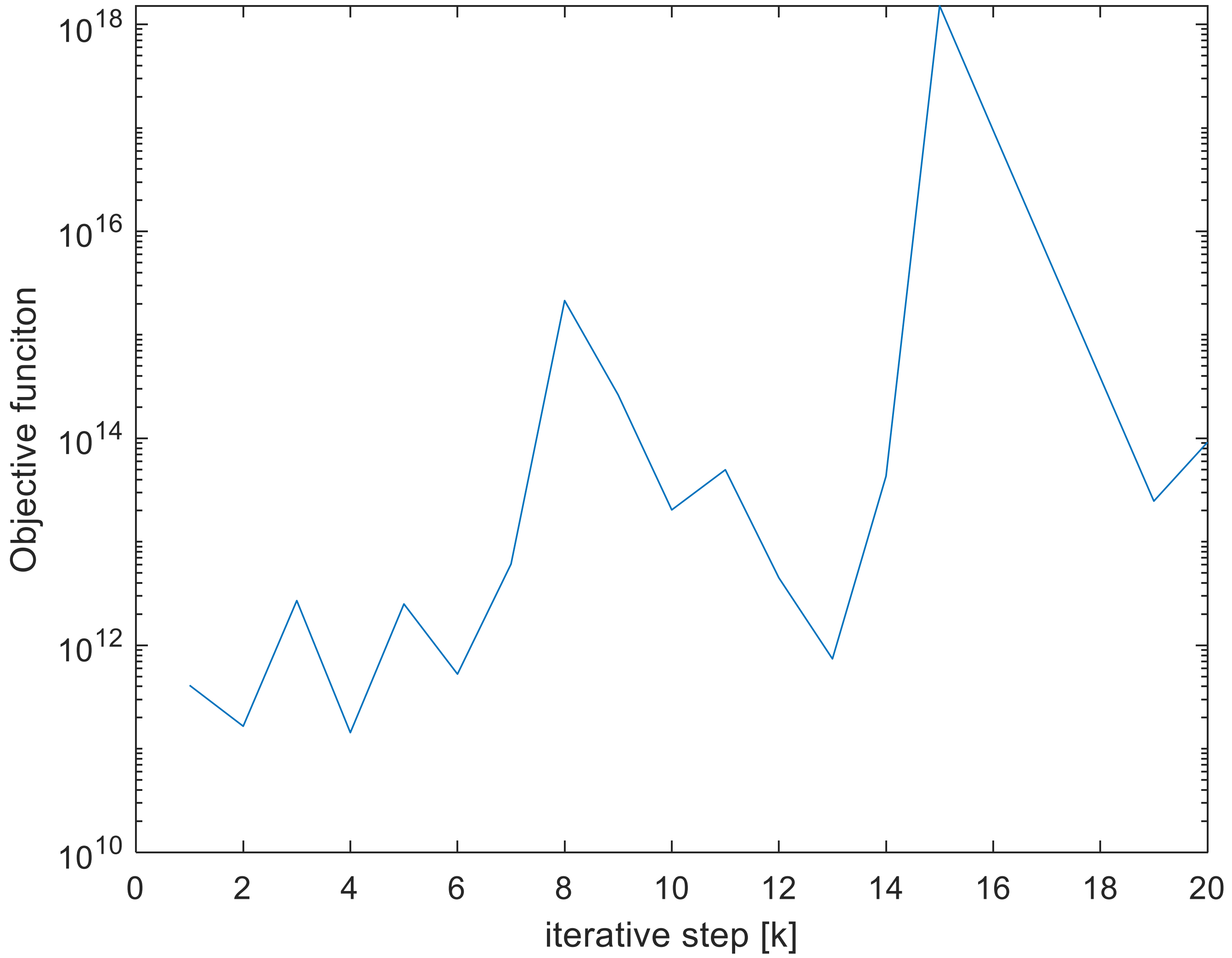
Approach:

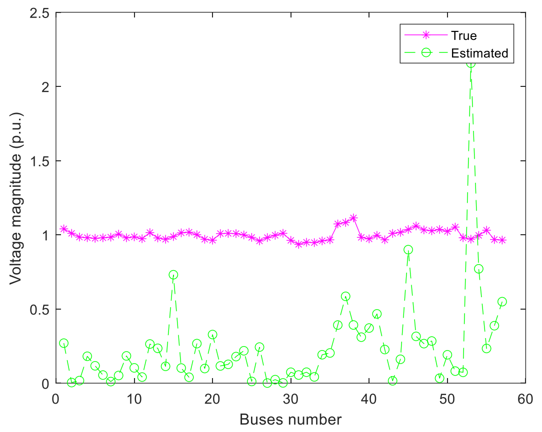
- ❑Change the true voltage magnitudes of bus 36:38 by increasing them to 1.1*
- ❑Change the measurements by including only bus power injection.

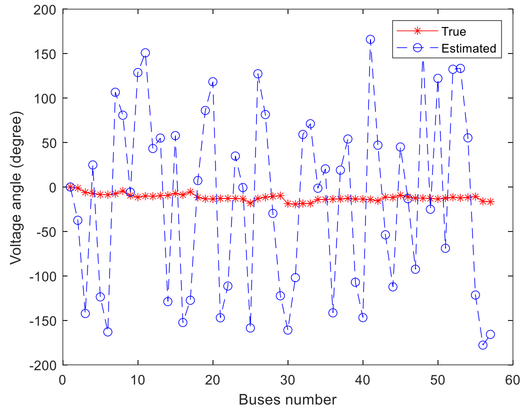
Divergent cases:

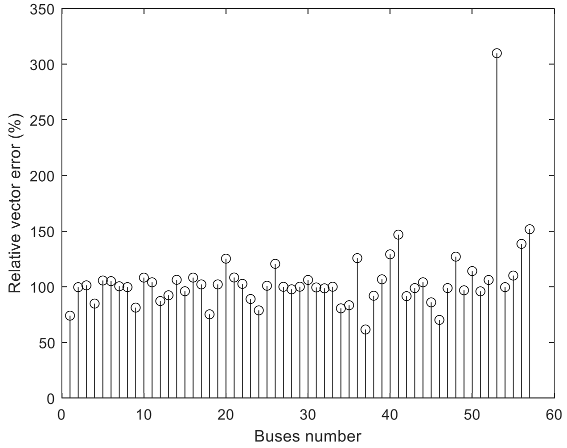
- ❑B0057s_022.mat
- ❑B0057s_data_022.csv
- ❑B0057s_header_022.csv
- ❑state_zn22_divergent.mat (stores true states)

Case B. WLS State Estimation Results









- Diverged

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(6) **Bad data** that cannot be effectively rejected by the WLS algorithm [Gou 2023

C. Divergent Cases by Putting Very Heavy Weights on the Virtual Measurement of Net Zero Injection

Base case:

- ❑IEEE 57-bus model with low redundancy measurements

Approach:

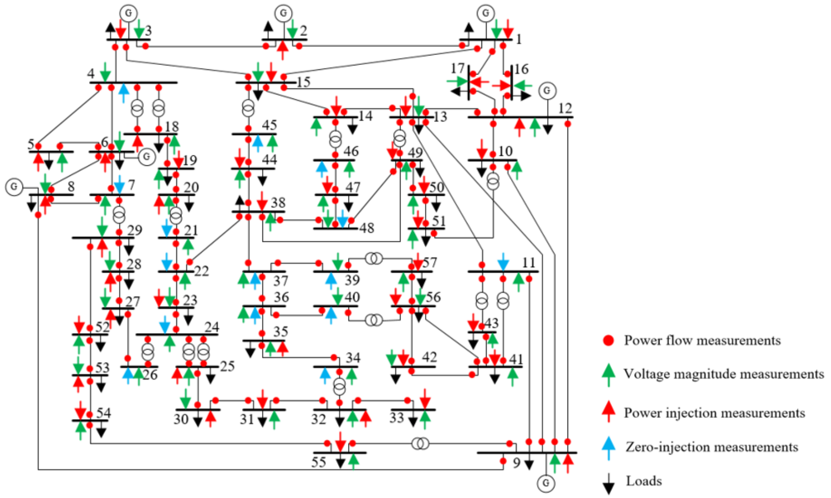
- ❑Change the weights on the 15*2 net zero injections (P_i,Q_i) by decreasing their standard deviations m from 1e-5 to **1e-11**

Setup: 491 measurements

- ❑57 Vmag
- ❑57 Pi, 57 Qi 160 Pij, 160 Qij

Divergent cases:

- ❑B0057s_044.mat
- ❑B0057s_data_044.csv
- ❑B0057s_header_044.csv
- ❑state_zn44_divergent.mat (stores true states)



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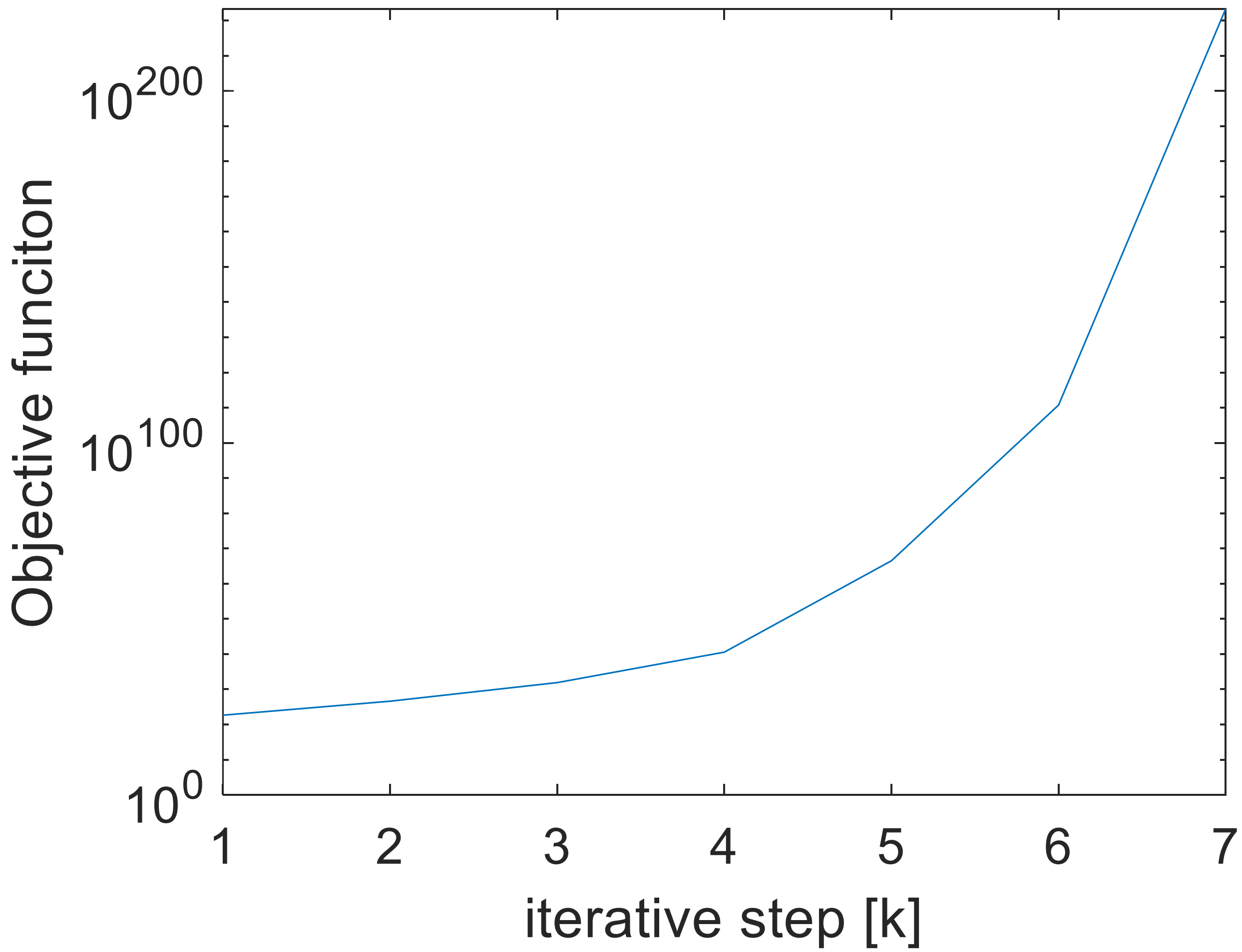
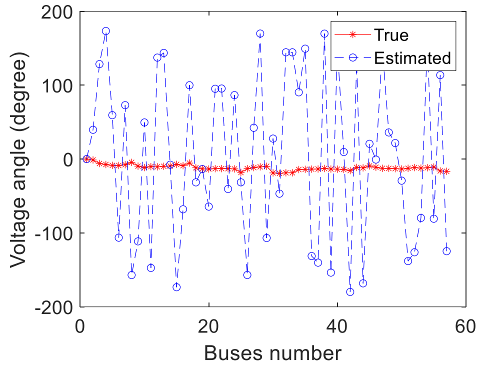
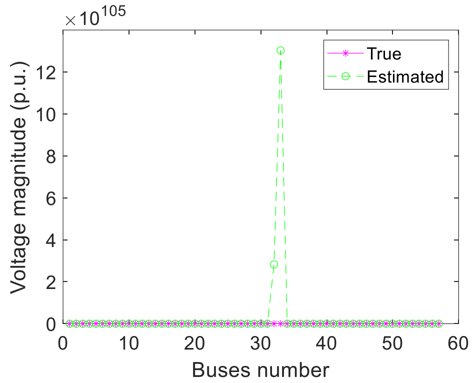
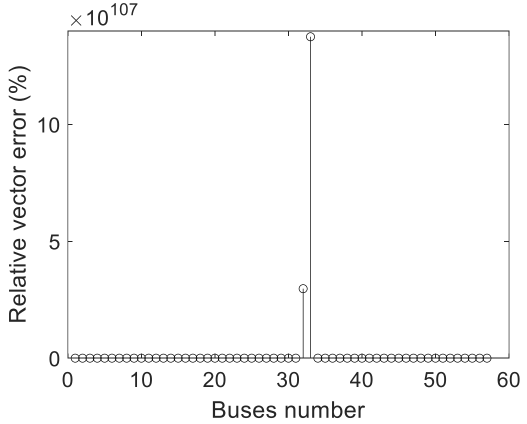
Case C. WLS State Estimation Results









- Diverged

D. Divergent Case through Shortening a Transmission Line

Base case:

- ❑IEEE 57-bus model with low redundancy measurements

Approach:

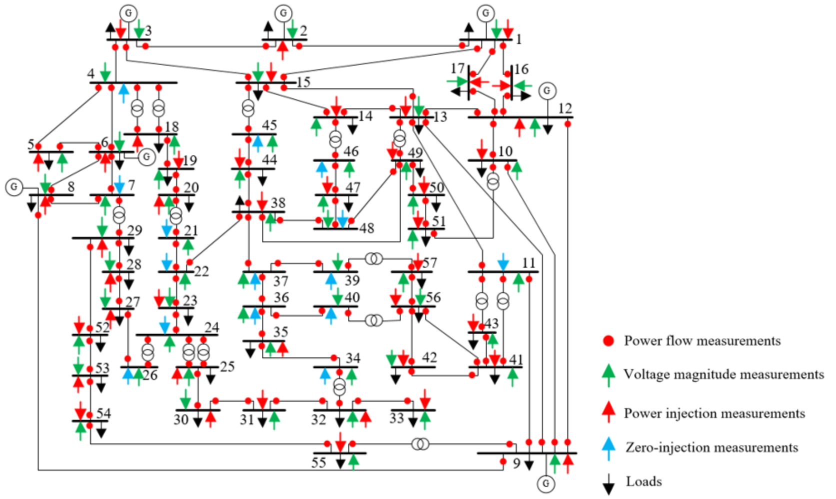
- ❑*Make the shortest line (line 33) shorter* by changing its impedance to 1e-16*original impedance.

Setup: 171 measurements

- ❑57 Vmag
- ❑57 Pi, 57 Qi

Divergent cases:

- ❑B0057s_055.mat
- ❑B0057s_data_055.csv
- ❑B0057s_header_055.csv
- ❑state_zn55_divergent.mat (stores true states)



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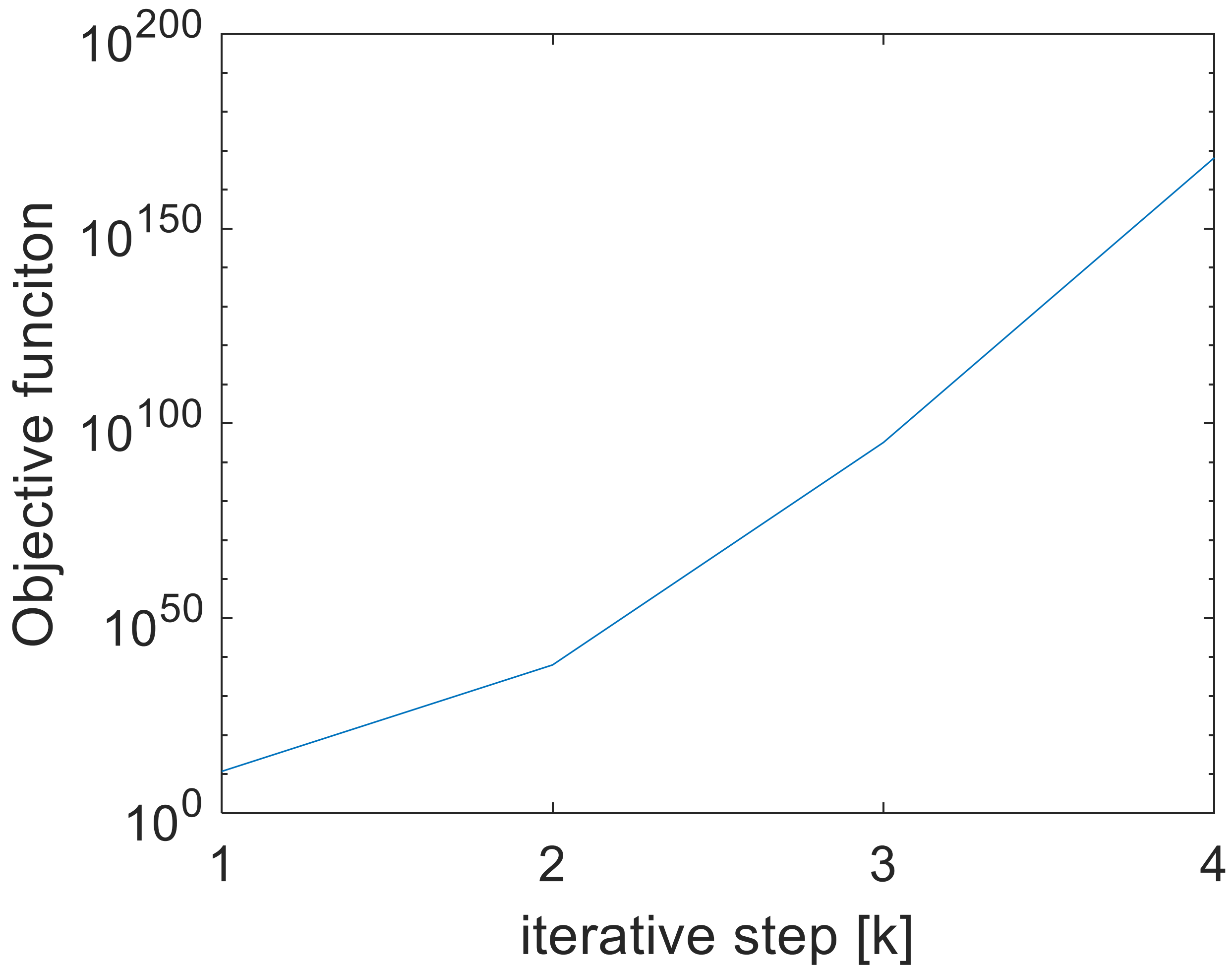

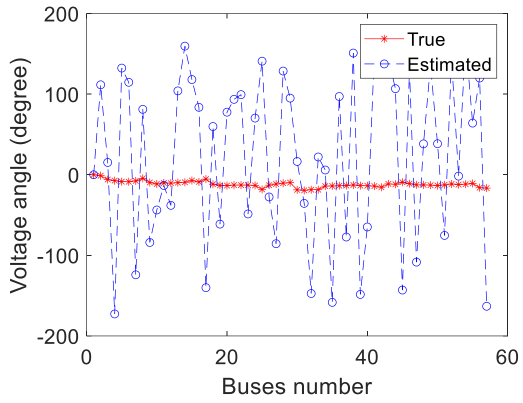

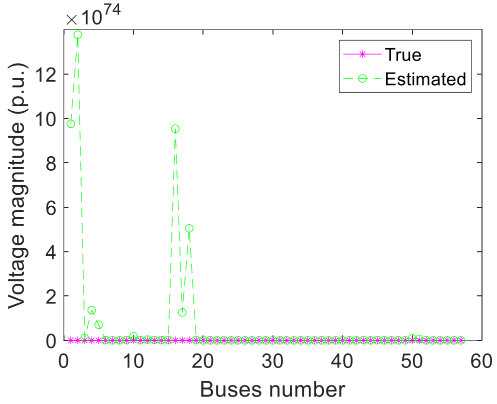

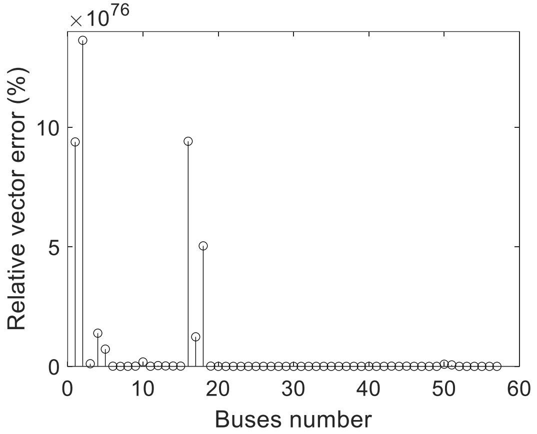

- Diverged

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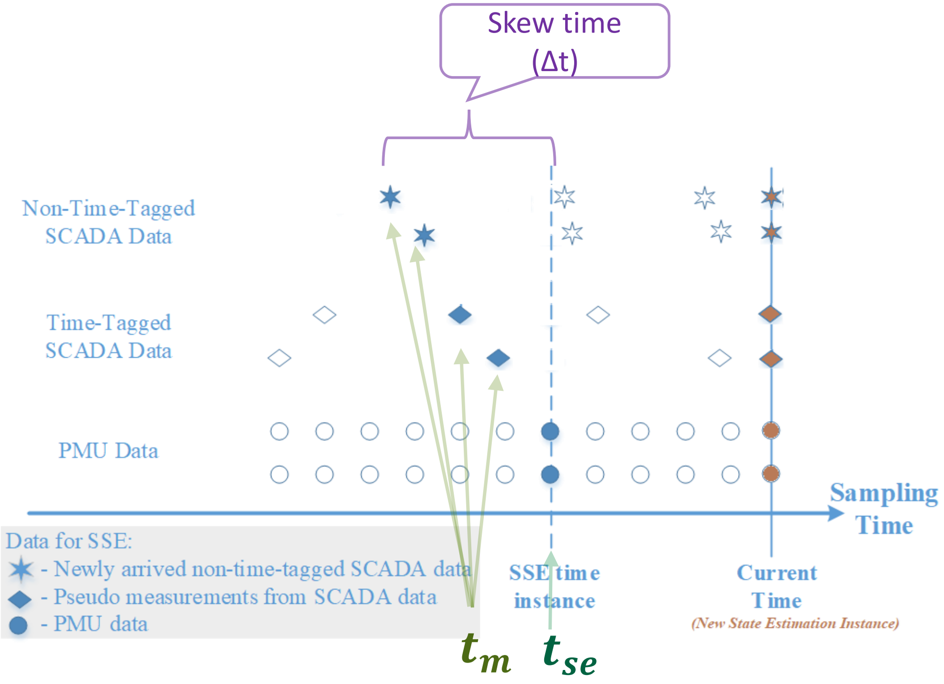
Problem Definition of SSE and its Time-Skew Problem

- **Ideal SSE:** Assume a snapshot of measurements at $\boldsymbol{t_{se}}$

$$\widehat{\boldsymbol{x}}_{t_{se}} = \boldsymbol{arg}\min_{\boldsymbol{x}_{t_{se}}} \left\{ \sum_{m=1}^{M} \frac{\left(\boldsymbol{z}_{m,t_{se}} - h_{m,t_{se}}\left(\boldsymbol{x}_{t_{se}}\right)\right)^2}{R_{mm}} \right\}$$



- **Actual SSE:** $\hat{z}_{m,t_{se}} = z_{m,t_m}$

$$\widehat{\boldsymbol{x}}_{t_{se},\Delta t} = \boldsymbol{arg}\min_{\boldsymbol{x}_{t_{se}}} \left\{ \sum_{m=1}^{M} \frac{\left(z_{m,t_m} - h_{m,t_{se}}\left(x_{t_{se}}\right)\right)^2}{R_{mm}} \right\}$$

$$t_m \in [\min(t_m), \min(t_m) + \Delta t]$$

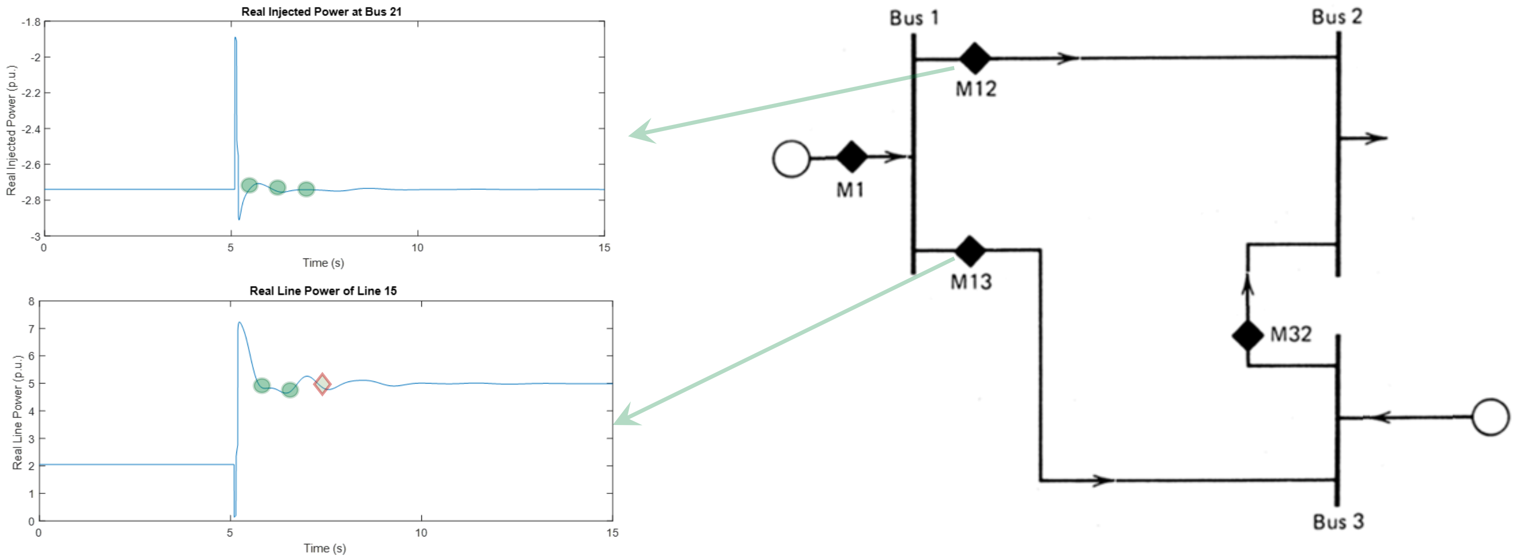
- Skew time:

$$\Delta t = t_{se} - \min_{m\in[1,M]}(t_m)$$

- Time skew errors:

$$\Delta z_{m,\Delta t} = z_{m,t_m} - z_{m,t_{se}}$$

Constructing Forecasting Models based on Spatial and Temporal Correlation



$$\hat{z}_{m,t_{se}} = \sum_{i=1}^{M} \sum_{k_i=0}^{K_i} z_{i,t_i-k_i} \beta_{i,t_i-k_i} + \beta_{m,0}$$

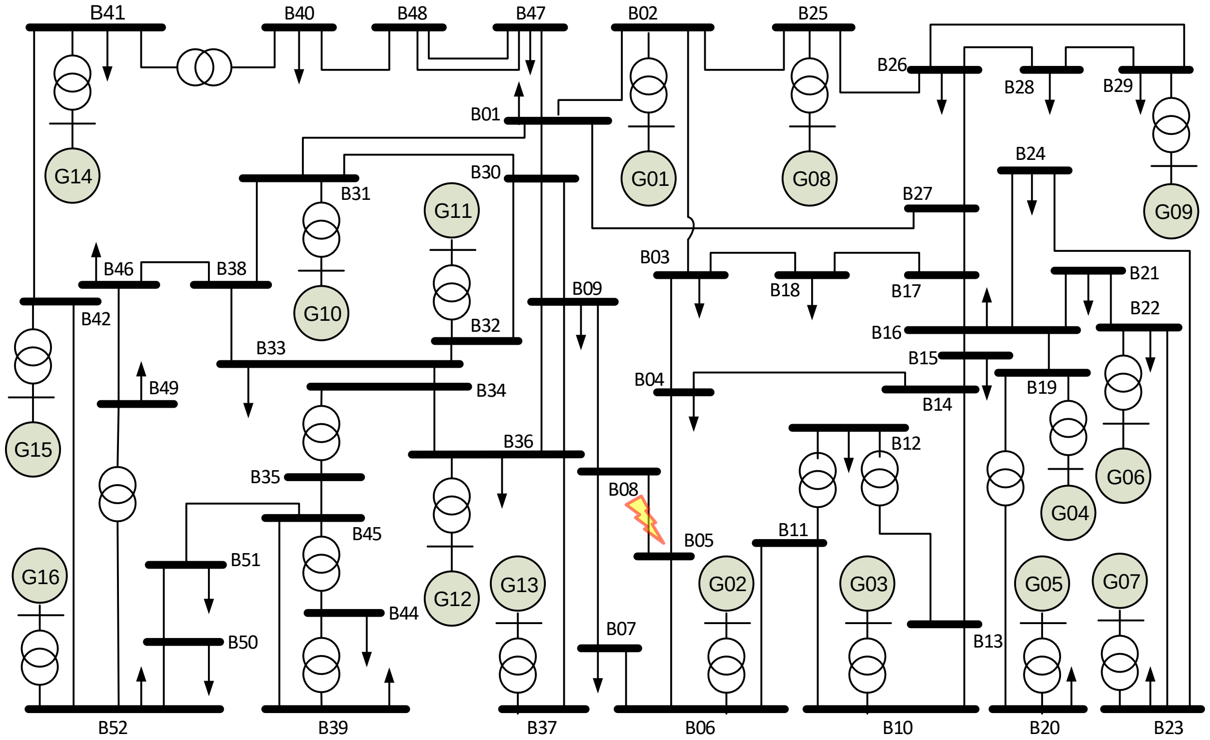
$$\hat{z}_{m,t_{se}} = F_m\left(z_{i,t_i-k_i} \middle| i = 1, 2, \cdots, M;\ k_i = 0, 1, \cdots, K_i\right)$$

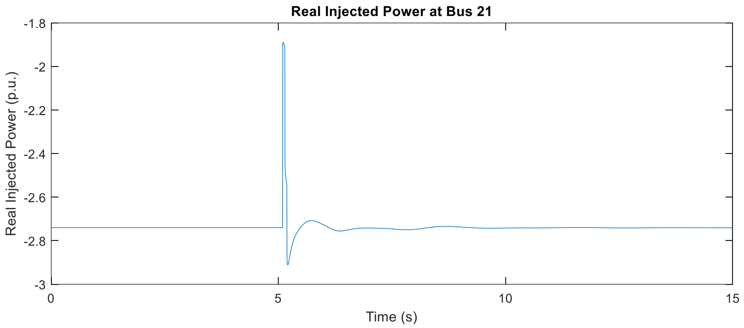
Simulation Setup

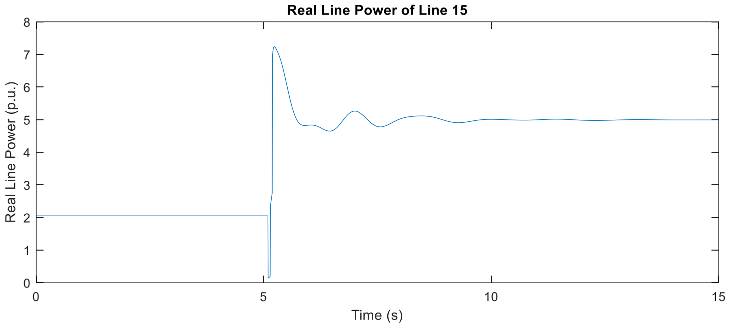
16-machine 68-bus system with PST

Fault between bus 5 and bus 8 at 5.1th second

Gaussian white noise: $\sigma = 3 \times 10^{-2}$ (100 Instances of MC)



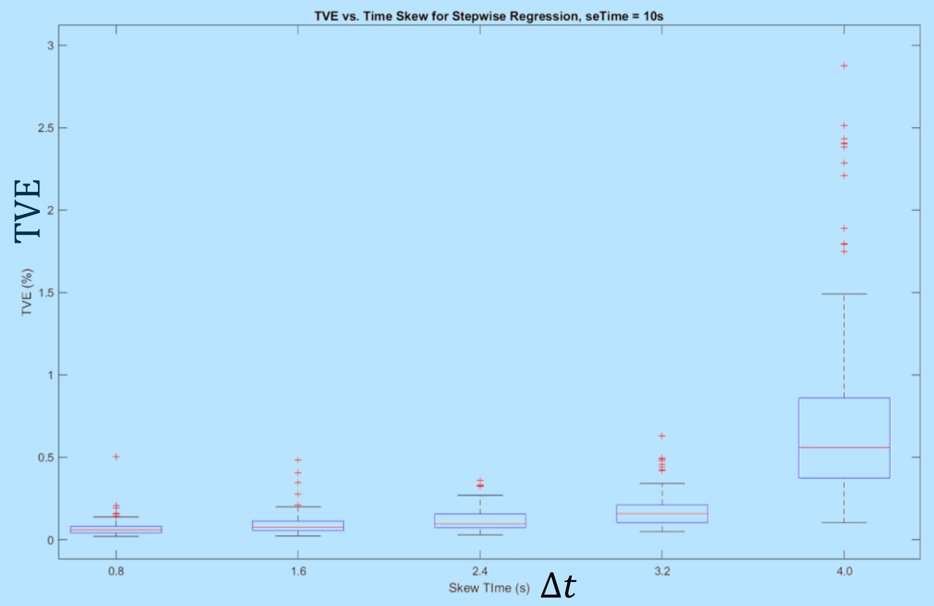




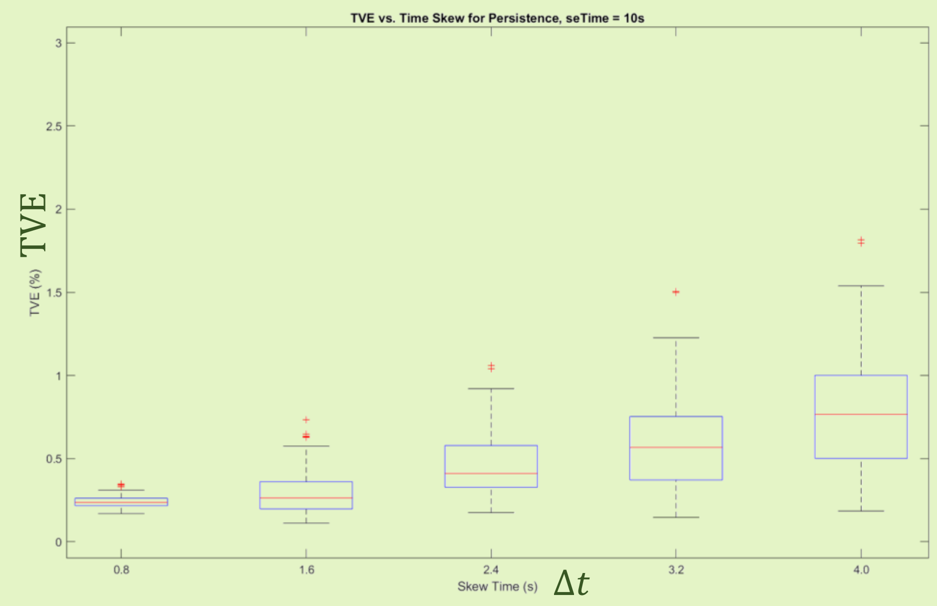
Estimation Accuracy w.r.t. to Δt

Estimation errors increase with Δt

Forecasting-Aided method is more accurate than persistence model



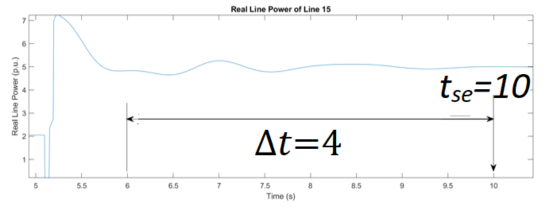
Forecasting aided method



persistence model

$$TVE_{t_{se}} = \frac{\sum_{i=1}^{n} \left| \hat{V}_{i,t_{se}} \angle \hat{\theta}_{i,t_{se}} - V_{i,t_{se}} \angle \theta_{i,t_{se}} \right|}{\sum_{i=1}^{n} \left| V_{i,t_{se}} \angle \theta_{i,t_{se}} \right|}$$

$$t_{se} = 10s$$



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6. Summary of Findings

- SSE formulated as **an optimization problem**, solved iteratively using numerical methods
- **Ill-conditioning of the gain matrix G** contributes to numerical instability and potential divergence.
- **Contributing factors:**
  - Heavy weights on virtual measurements.
  - Presence of both very short and long lines at the same bus.
  - Measurement sets dominated by bus injection measurements.
  - Initial state values significantly deviating from true values.
  - Ineffective bad data rejection.
  - Large systems with many state variables and low redundancy.
  - Time-skew errors during large variations and topology changes

On-going Efforts and Works

Comprehensive Report:

- Title: "Standard Test Cases for Static and Dynamic State Estimation in Power Systems.“
- Published by **IEEE Task Force on Standard Test Cases for Power System State Estimation**.

Data Accessibility:

- Test case data will be made publicly available.
- Data formatted using IEEE standard format and other convenient format

Questions or Comments?

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