U.S. National Committee

STATE ESTIMATION IN DISTRIBUTION SYSTEMS

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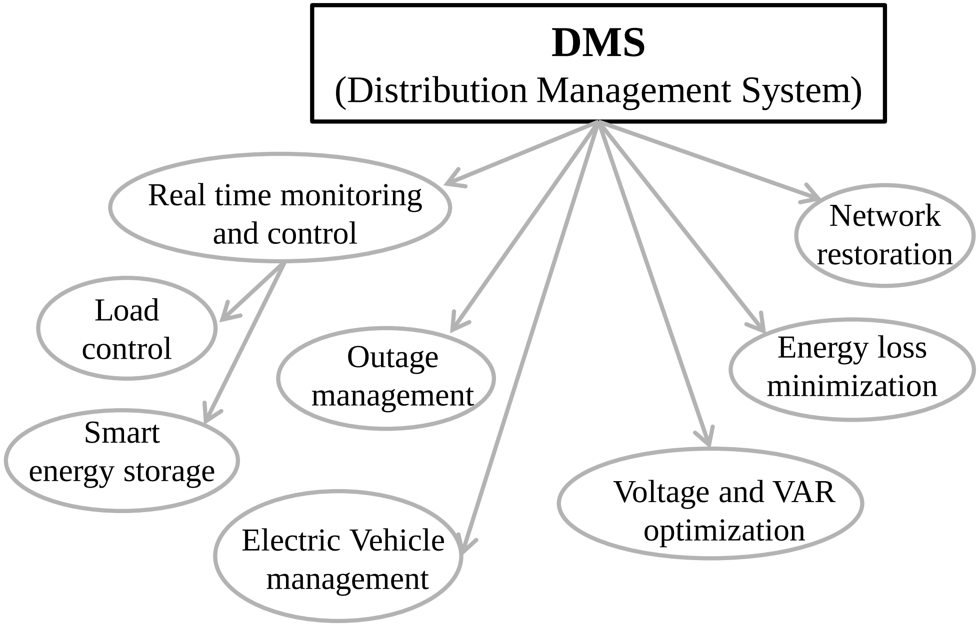
What has been done…

We developed and tested a State Estimation approach for Distribution Systems, as well as a sensitivity analysis to test the robustness of the method

…has multiple applications



DMS

(Distribution Management System)

Real time monitoring and control

Load control

Smart energy storage

Outage management

Electric Vehicle management

Voltage and VAR optimization

Energy loss minimization

Network restoration

Outline

- Smart Distribution Systems
- Challenges in Distribution Systems
- State Estimation Overview
- Use of WLS for State Estimation
- WLS State Estimation in Distribution Systems
- Case Study – IEEE 34-Bus Test System
  - Numerical results
  - Sensitivity analysis
  - Sensitivity analysis results
- Conclusions

Smart Distribution Systems

Renewable energy resources

Distributed Generation

Smart Meters (PMUs, AMI)

Smart Grid

Quality of service

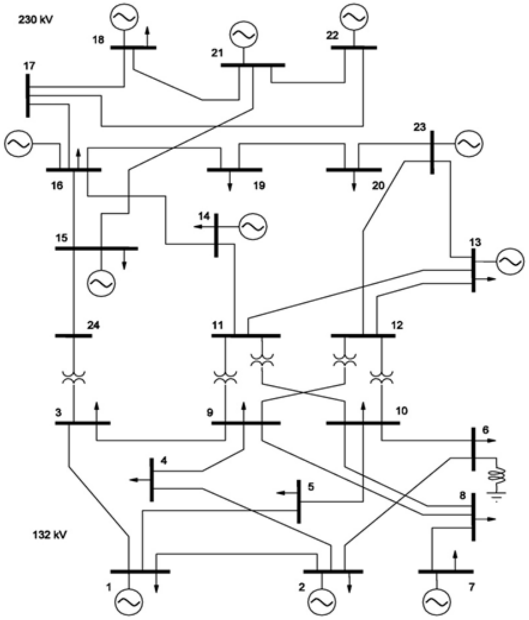
Reliability

State Estimation (SE):
Provides State of the Grid in real-time for **monitoring** and **control**:

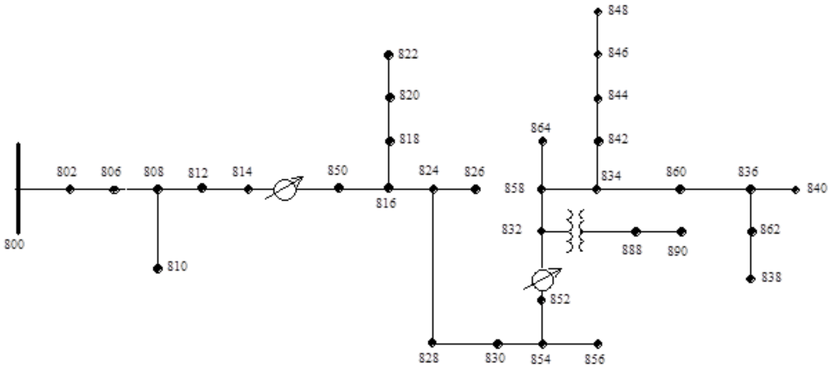
- Online contingency analysis
- Bad data detection
- Power Flow Optimization

Challenges in Distribution Systems

Transmission System vs Distribution System



IEEE 24 Bus Test System

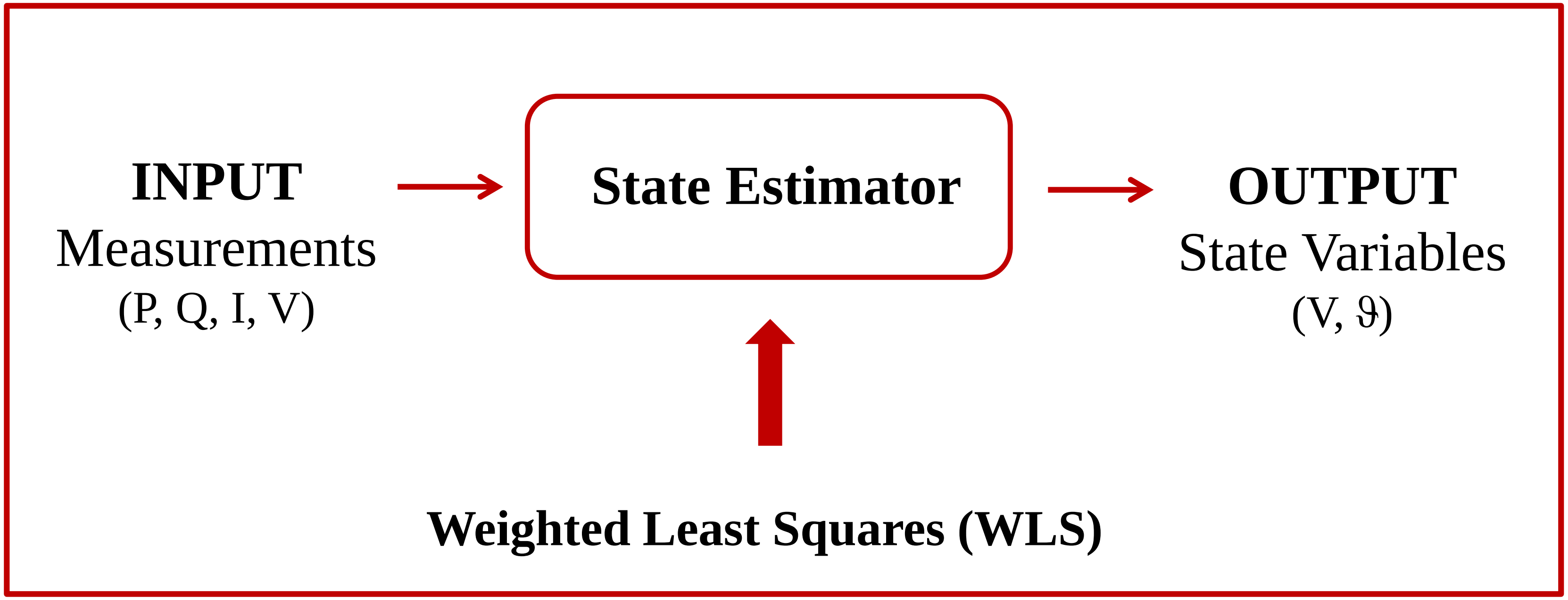


IEEE 34 Bus Test System

Meshed topology
Uni-directional power flows
Balanced lines and loads

Radial topology
Bi-directional power flows
Unbalanced lines and loads

State Estimation Overview



INPUT
Measurements
(P, Q, I, V)

State Estimator

OUTPUT
State Variables
(V, ϑ)

Weighted Least Squares (WLS)

Advantages

- Overdetermined System
- Performs well in presence of noise

Disadvantages

- Fails to reject bad data
- Sensitive to initial point

Observability → pseudo-measurements

Use of WLS for State Estimation (1/2)

- ✓ **Weighted Least Squares:**

$$\boxed{z = h(x) + e}$$

$\boldsymbol{z}$:measurement vector

$\boldsymbol{x}$:state variables vector

$\boldsymbol{e}$:measurement errors (Gaussian distribution)

$\boldsymbol{h}(\boldsymbol{x})$:measurement function

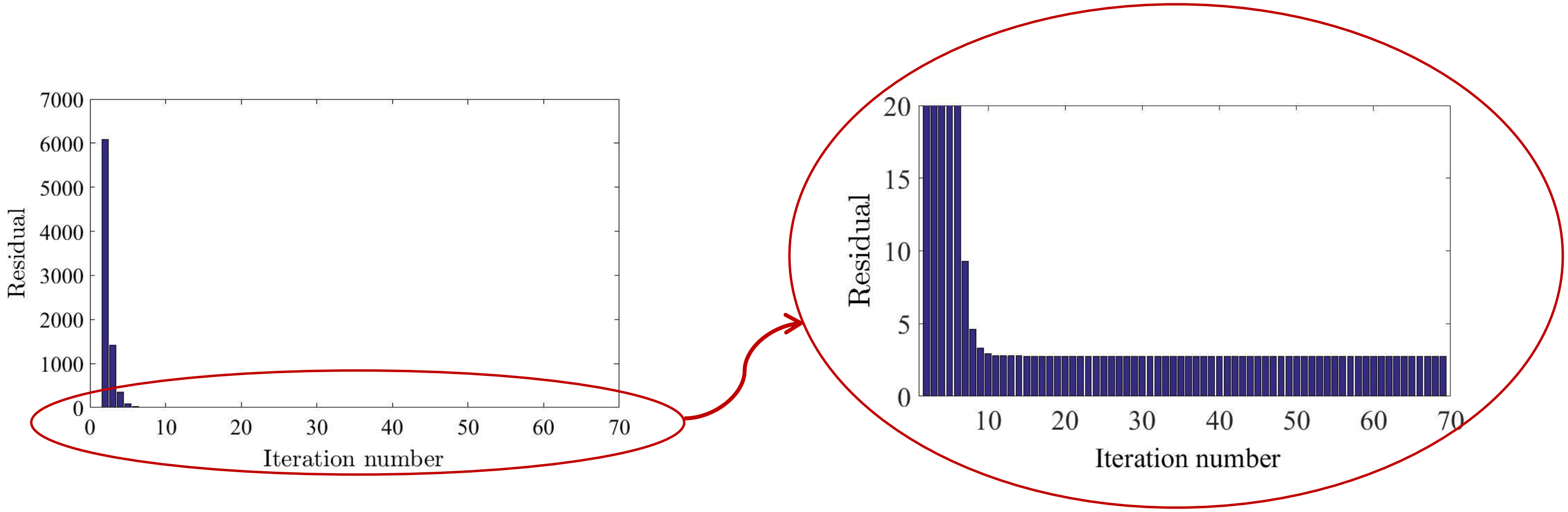
$$\boxed{r = z - h(x)}$$

$\boldsymbol{r}$:residual error

$\boldsymbol{W}$:penalty factor of measurements

Optimization problem:

$$\min_{x} J(x) = [z - h(x)]^{T} W [z - h(x)] \longrightarrow \left| \begin{array}{l} H^{T}(x) W [z - h(x)] = 0 \\ H(x) = \dfrac{\partial h(x)}{\partial x} \end{array} \right.$$



Use of WLS for State Estimation (2/2)

✓ **Iterative** Process:

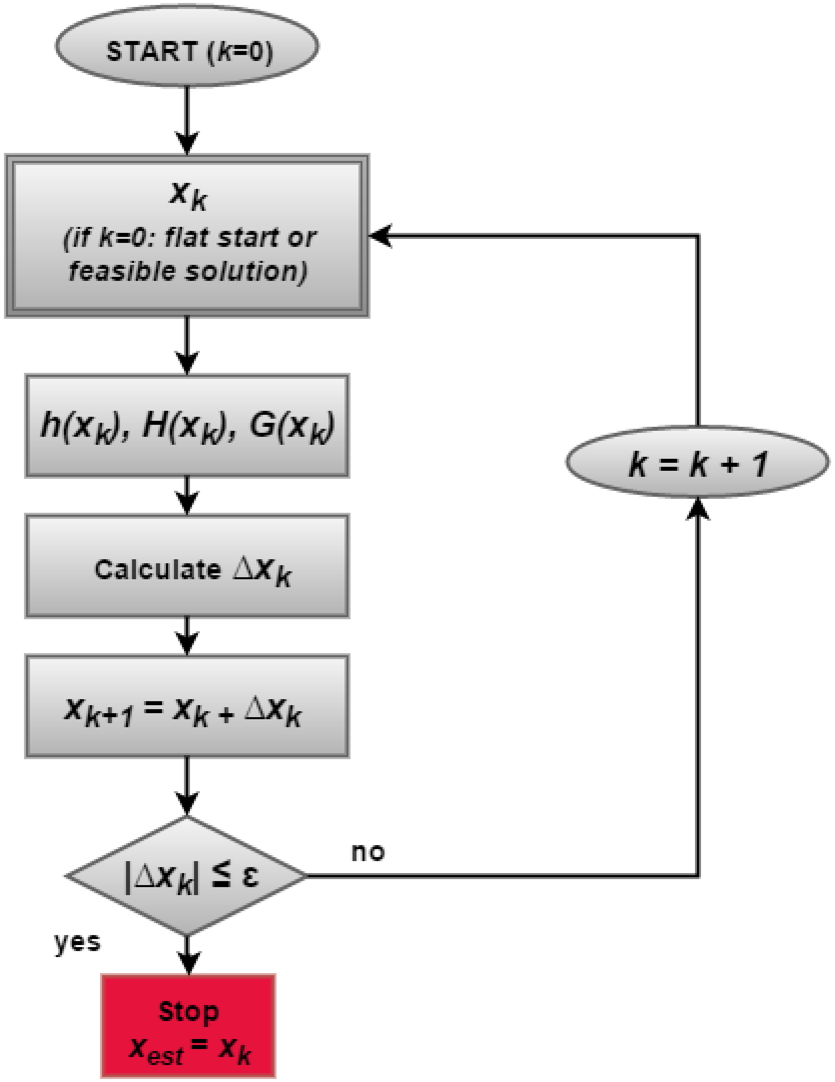
$$\boxed{x_{k+1} = x_k + \Delta x_k}$$

given that the increment Δx_k is given by

$$[G(x_k)]\Delta x_k = H^T(x_k)W[z - h(x_k)]$$

where

$$G(x) = H^T(x)WH(x)$$



WLS State Estimation in Distribution Systems

Measurements and State Variables vectors

$$z = \left[{P^f}^T, {Q^f}^T, {I_l}^T, {V_m}^T, P^T, Q^T, {P_L}^T, {Q_L}^T\right]^T \qquad x = \left[{V_m}^T, \theta^T\right]^T$$

Jacobian Matrix of the State Equations

$$H(x) = \begin{bmatrix} \frac{\partial P^T}{\partial V} & \frac{\partial Q^T}{\partial V} & \frac{\partial {I_l}^T}{\partial V} & \frac{\partial {V_m}^T}{\partial V} & \frac{\partial P^T}{\partial V} & \frac{\partial Q^T}{\partial V} & \frac{\partial {P_L}^T}{\partial V} & \frac{\partial {Q_L}^T}{\partial V} \\ \frac{\partial P^T}{\partial \theta} & \frac{\partial Q^T}{\partial \theta} & \frac{\partial {I_l}^T}{\partial \theta} & \frac{\partial {V_m}^T}{\partial \theta} & \frac{\partial P^T}{\partial \theta} & \frac{\partial Q^T}{\partial \theta} & \frac{\partial {P_L}^T}{\partial \theta} & \frac{\partial {Q_L}^T}{\partial \theta} \end{bmatrix}^T$$

Penalty factors matrix

$$W_{ii} = \left\{ \begin{matrix} 1 & \text{For the forecasted load} \\ 10 & \text{For the actual measurements} \end{matrix} \right.$$

$\boldsymbol{P^f}$ Forecasted real injection

$\boldsymbol{Q^f}$: Forecasted reactive injection

$\boldsymbol{I_l}$ **:** Line current measurements

$\boldsymbol{V_m}$ **:** Voltage magnitudes

$\boldsymbol{\theta_m}$ **:** Voltage angles

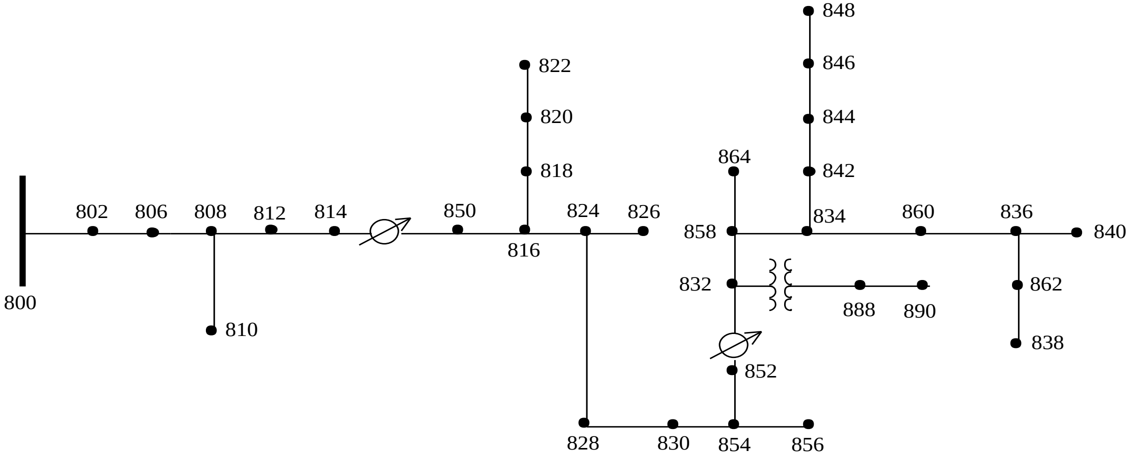
$\boldsymbol{P_L}$**:** Real bus withdrawals at load nodes

$\boldsymbol{Q_L}$: Reactive bus withdrawals at load nodes

$\boldsymbol{P}$**:** Real bus injections at generator nodes

$\boldsymbol{Q}$: Reactive bus injections

Case Study – IEEE 34-Bus Test System



24.9 kV
Radial feeder
Some single-phase laterals
but mostly 3-phase

Scenario 1 set of measurements:

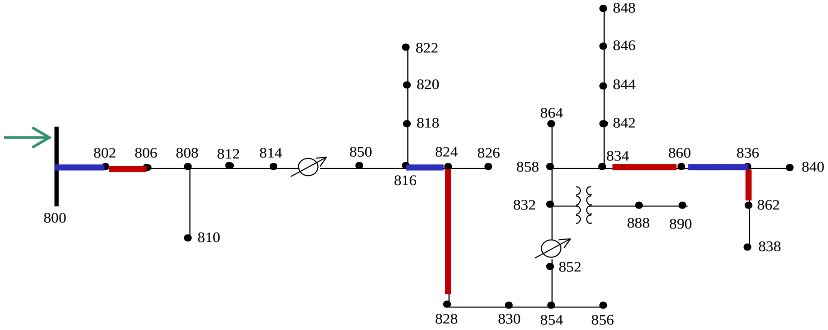
- Forecasted load with 10% of perturbation
- Power injection measurement at substation
- Power flow of lines 802-806, 824-828, 834-860, 836-862
- Line current of lines 800-802, 816-824, 860-836

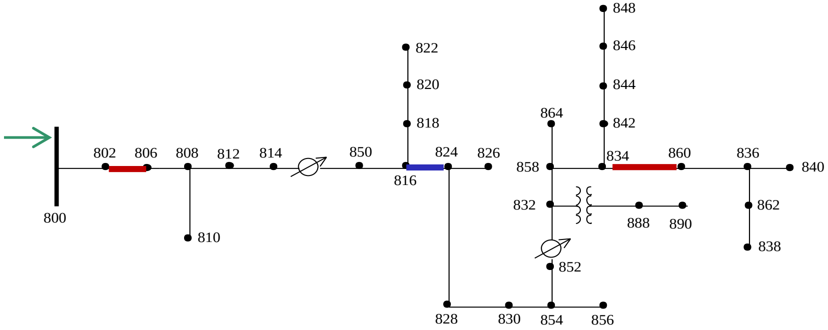
Scenario 2 set of measurements:

- Forecasted load with 10% of perturbation
- Power injection measurement at substation
- Power flow measurements of lines 802-806, 834-860
- Line current measurements of line 816-824

→ We test the performance of the State Estimator in two different scenarios, including different quantity of measurements each time.

Case Study – Numerical results





Scenario 1

- Algorithm converged in **69** iterations
- Residual for the last iteration:

$$r = z - h(x) = \mathbf{2.7494}$$

- Maximum difference between estimated and actual voltage magnitude value is **0.09 pu**

Scenario 2

- Algorithm converged in **67** iterations
- Residual for the last iteration:

$$r = z - h(x) = \mathbf{2.5293}$$

- Maximum difference between estimated and actual voltage magnitude value is **0.095 pu**

✓ Results are very similar in both cases.

✓ The method results in a **feasible solution** for the estimate of the state variables

Case Study – Sensitivity analysis

Motivation: Test the robustness of the algorithm and sensitivity to bad quality input data.

Relative error of voltage magnitudes at each bus →

$$\boxed{\text{Error} = \frac{V_{estimate} - V_{actual}}{V_{actual}} \times 100\%}$$

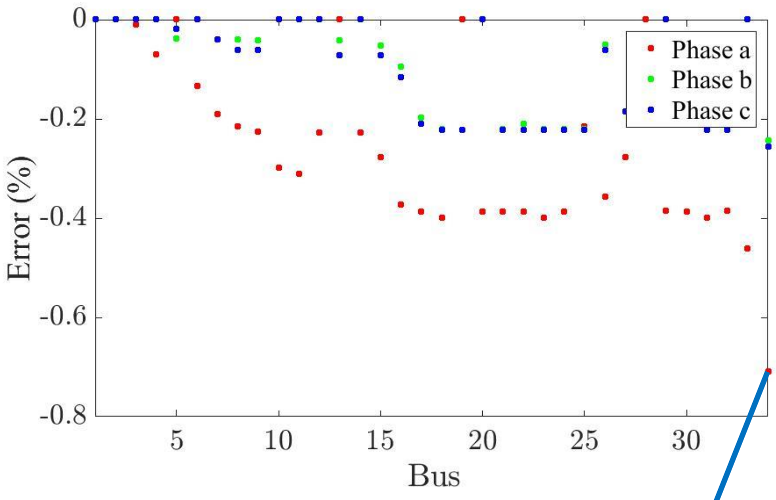
Simulation of bad quality data recreated in 4 different cases:

- **Case 1:** Increased the line power flow measurements by 2.5%
- **Case 2:** Increased the line power flow measurements by 10%
- **Case 3:** Increased the power flow and line current measurements by 2.5%
- **Case 4:** Increased the power flow and line current measurements by 10%

Case Study – Sensitivity analysis results (1/4)

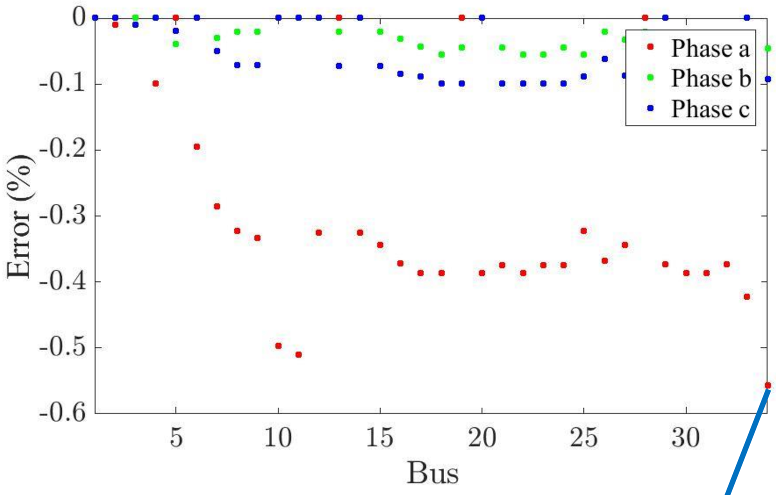
Case 1: Increased the line power flow measurements by 2.5%

- Voltage magnitude error for Scenario 1



Max. Error = -0.71%

- Voltage magnitude error for Scenario 2

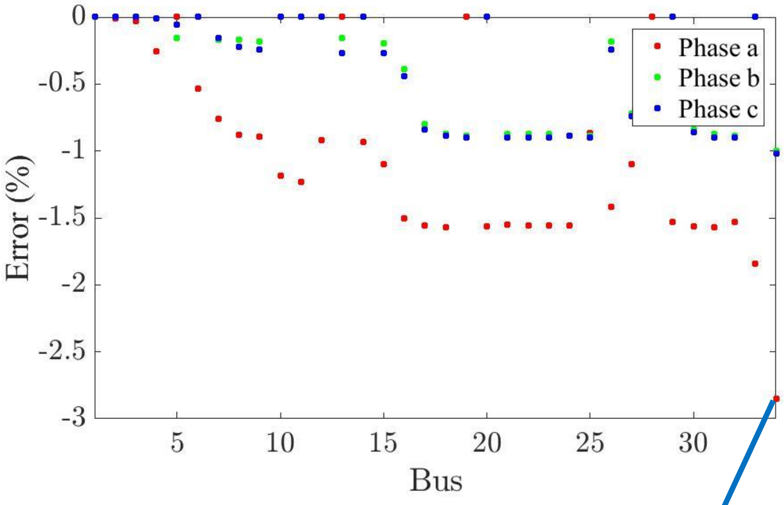


Max. Error = -0.56%

Case Study – Sensitivity analysis results (2/4)

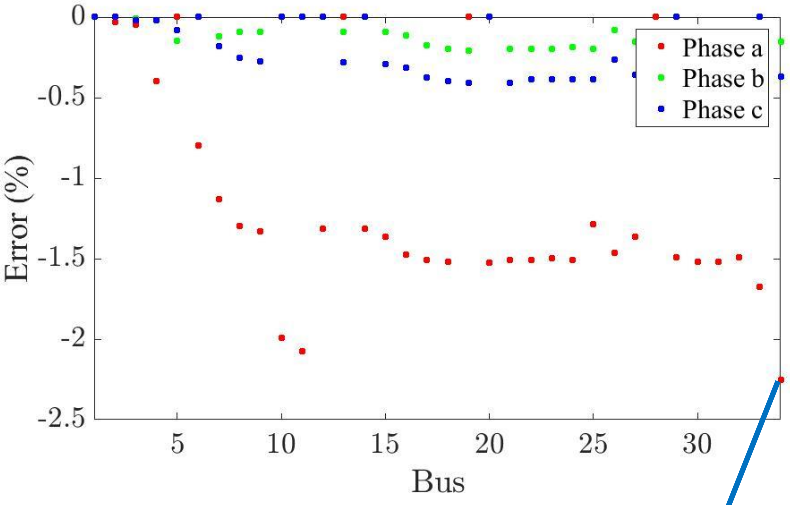
Case 2: Increased the line power flow measurements by 10%

- Voltage magnitude error for Scenario 1



Max. Error = -2.85%

- Voltage magnitude error for Scenario 2

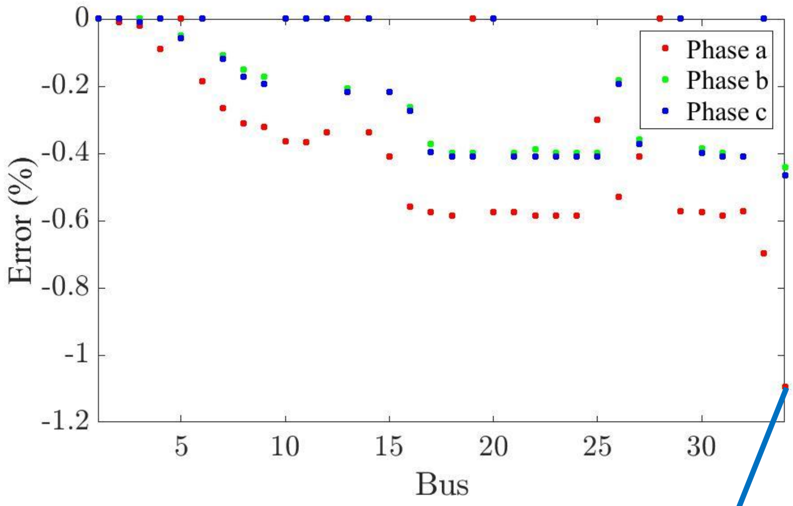


Max. Error = -2.26%

Case Study – Sensitivity analysis results (3/4)

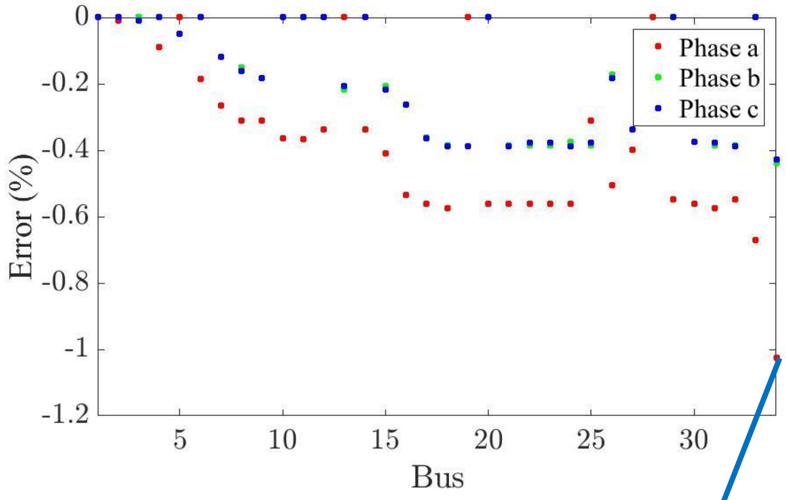
Case 3: Increased the line power flow and line current measurements by 2.5%

- Voltage magnitude error for Scenario 1



Max. Error = -1.09%

- Voltage magnitude error for Scenario 2

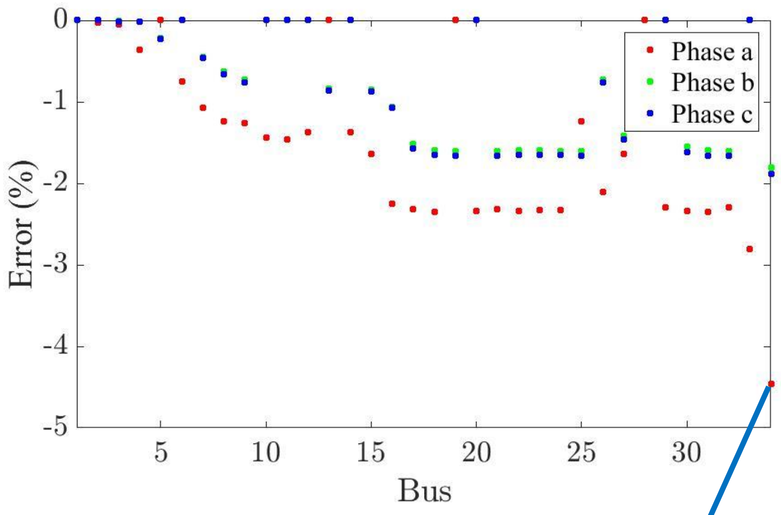


Max. Error = -1.03%

Case Study – Sensitivity analysis results (4/4)

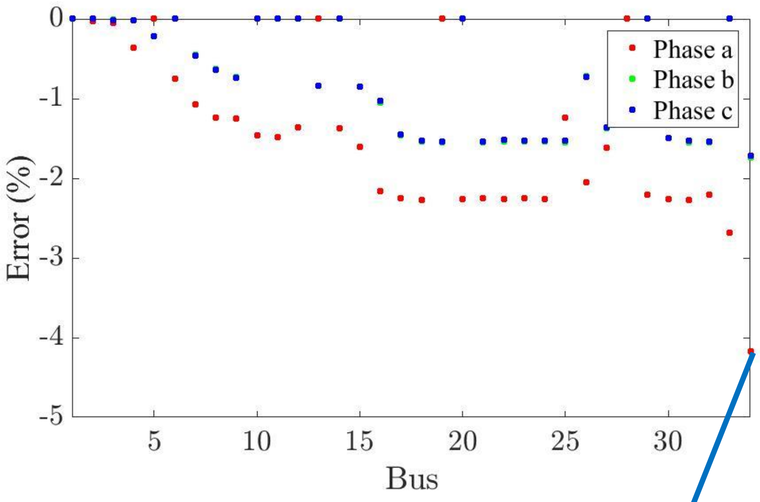
Case 4: Increased the line power flow and line current measurements by 10%

- Voltage magnitude error for Scenario 1



Max. Error = -4.46%

- Voltage magnitude error for Scenario 2



Max. Error = -4.17%

Summary of Sensitivity analysis results

- Absolute error in the results:

Error Introduced	**Scenario**	**+2.5%**	**+10%**
Power Flow Measurements	1	0.71%	2.85%
	2	0.56%	2.26%
Power Flow and Current Measurements	1	1.09%	4.46%
	2	1.03%	4.17%

Conclusions

- SE is a powerful tool that has been traditionally used in Transmission Systems. Its application for Distribution Systems is feasible today and would enhance grid operation and planning.
- The traditional approach to this method, the WLS algorithm, can be implemented to Distribution Systems taking into account the specific characteristics of these systems.
- The tool created based on WLS algorithm showed encouraging results when applied to different Scenarios of the IEEE 34 Bus Test System.
- This algorithm is robust and still present good results under the “bad quality data” simulation.
- Application to a real feeder is currently under study, as well as other possible approaches to the State Estimation problem.

Thank you!