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Distribution System State Estimator

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Workshop on

Challenges for Distribution Planning, Operational and Real-time Planning Analytics

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U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Robust Distributed State Estimator for Interconnected Transmission and Distribution Networks

Northeastern University

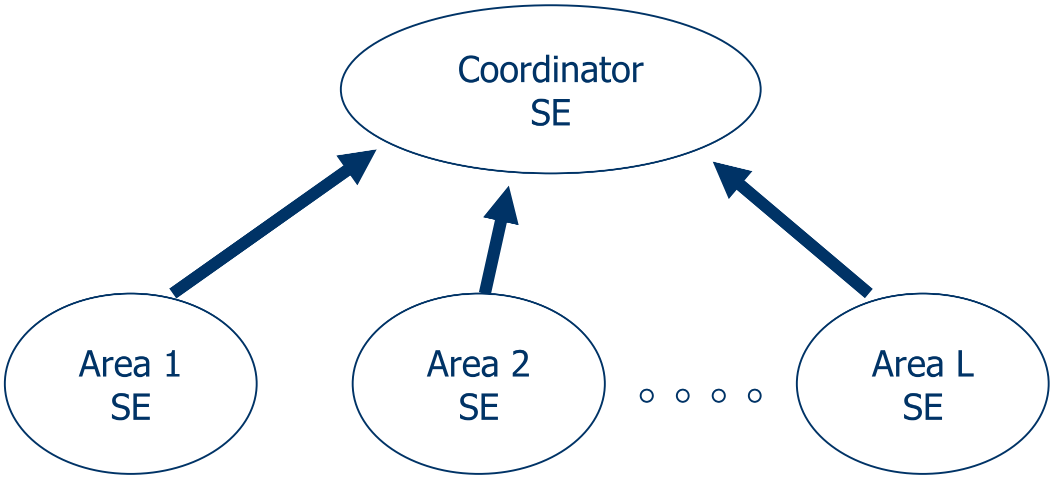
May 16, 2019

Motivation

- Computational burden: finding a scalable solution which will remain viable as the network size increases.
- Robustness: maintain the ability to detect and remove bad data, thus provide an unbiased state estimate both for the distribution and transmission system states.
- Stitching the transmission and distribution system real-time models, by combined estimation of transmission and distribution system states.

Multi-area SE

- Each area SE estimates its own state.
- Coordinator SE
  - merges the solutions, and
  - processes bad data for boundary measurements.



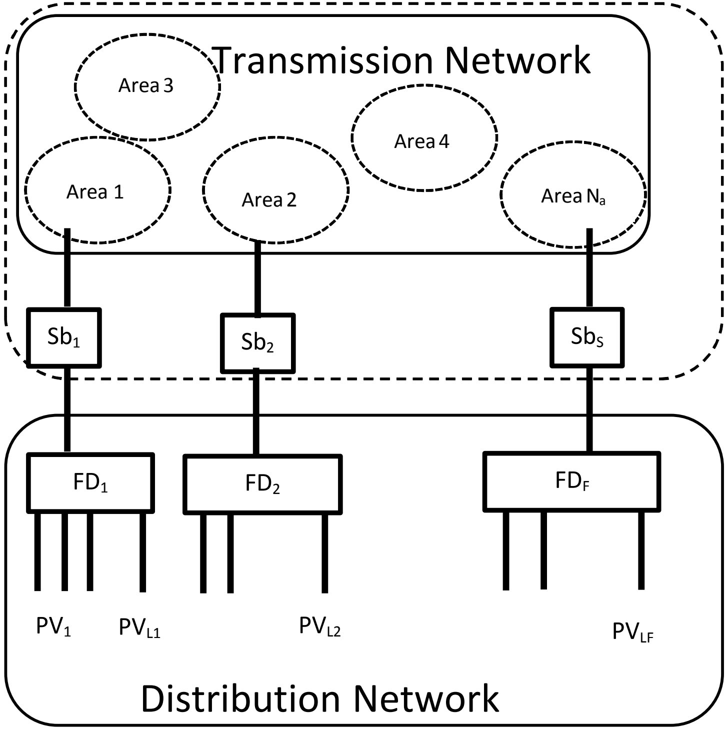
Properties

- No boundary measurements are discarded.
- All detectable / identifiable bad data are detected and identified.
- PMU measurements are effectively used, but not required for this scheme to work.
- Areas do not share network data (internal system details) or intermediate iteration results. They only provide boundary network model and measurements and their estimated states to the coordinator.
- Applicable to both single phase [positive seq.] and three-phase SE, areas representing either transmission control areas or distribution system feeders which may or may not be configured radially.

Robustness

- Conventional WLS SE followed by the largest normalized residual (LNR) – Plan to use a recently developed technique which drastically increases the computational speed of LNR test for very large scale systems.
- Alternative LAV SE: Plan to use a recently developed multi-copy multi-partition approach to address the scalability issue while maintaining robustness against bad data.

Project Architecture



Two-level Multi-Area Transmission SE

Combining T&D SE Solutions

Two-level Multiple Distribution Feeder SE with Solar PV

Measurements

- SCADA measurements
  - Active/Reactive power injections
  - Active/Reactive power flows
  - Voltage magnitude measurements
- Generated from OpenDSS
  - Three-phase power flow program
  - Developed by EPRI

EPRI
ELECTRIC POWER
RESEARCH INSTITUTE

Weighted Least Squares Formulation

$$\min_{r_i} \sum_{i=1}^{m} W_{ii} r_i^2$$

$$\text{s.t.} \quad z_i = h_i(x) + r_i, \quad i = 1, \ldots, m.$$

Not Robust Against Bad Data, requires BD processing

$$r_i^N = \frac{| r_i |}{\sqrt{\Omega_{ii}}}, \quad i = 1, \ldots, m.$$

$$\Omega = R - H(H^T R^{-1} H)^{-1} H^T$$

$$r_i^N \geq 3, \quad i = 1, \ldots, m.$$

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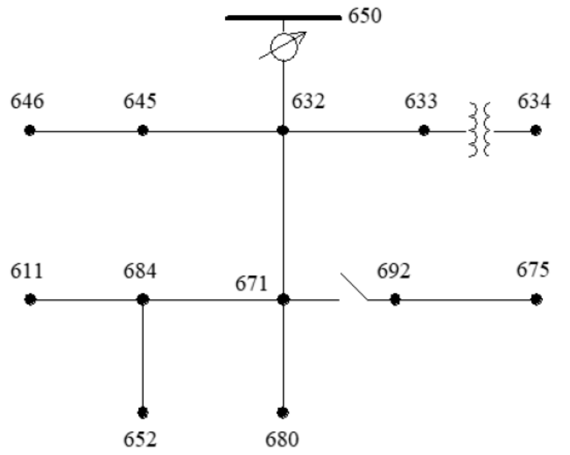
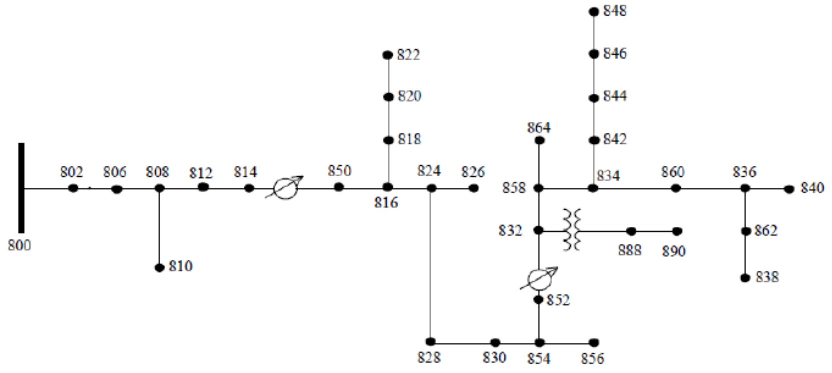
Distribution State Estimation

- IEEE Test Feeders
  - 13 node feeder
  - 34 node feeder





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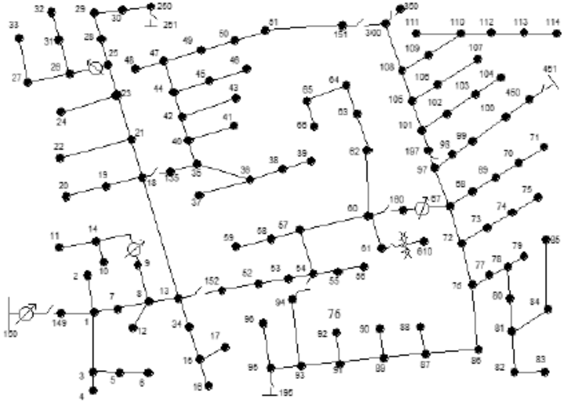
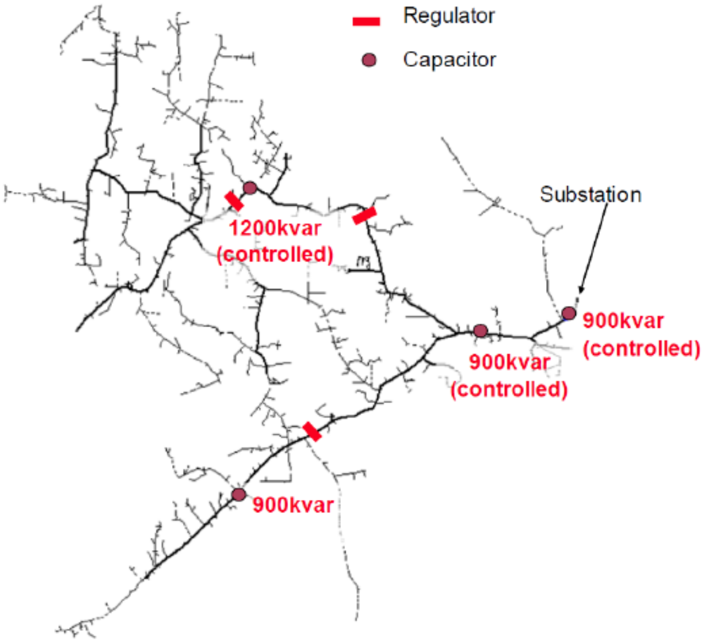
Distribution State Estimation

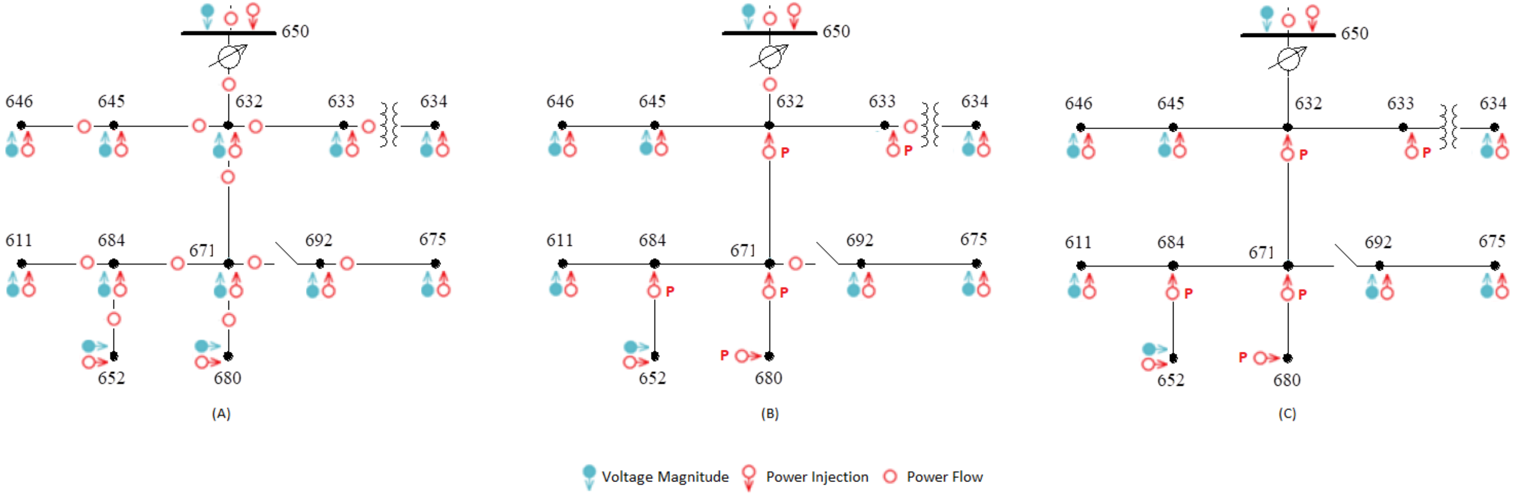
- IEEE Test Feeders
  - 123 node feeder
  - 8500 node feeder





Distribution State Estimation

- Results
  - Measurement scenarios



Distribution State Estimation

- Results
  - MSE values
  - Diagonal of inverse of Gain matrix

Perfect Measurements

Scenarios	V	θ	Combined
Case A	1.6125×10^{-7}	1.2403×10^{-6}	8.8437×10^{-7}
Case B	7.6933×10^{-6}	2.6239×10^{-5}	1.9335×10^{-5}
Case C	6.5733×10^{-6}	5.0437×10^{-5}	3.5966×10^{-5}

Gaussian Noise

Scenarios	V	θ	Combined
Case A	7.5934×10^{-4}	4.859×10^{-3}	3.4829×10^{-3}
Case B	1.7352×10^{-3}	7.8424×10^{-3}	5.7013×10^{-3}
Case C	1.7767×10^{-3}	9.7926×10^{-3}	7.0580×10^{-3}

Diagonal of G^{-1}

Scenarios	Average	Maximum
Case A	3.2902×10^{-4}	4.6×10^{-3}
Case B	3.3896×10^{-4}	5.2×10^{-3}
Case C	6.6890×10^{-4}	1.2×10^{-2}

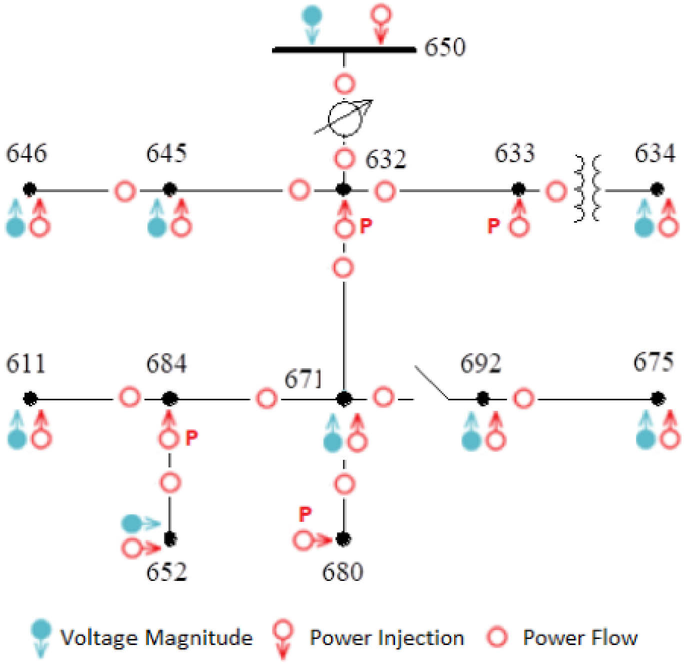
Bad Data Processing

- LNR test
  - 1. Solve WLS and form residual vector
  - 2. Compute the normalized residuals
  - 3. Find k such that r_k^N is the largest one
  - 4. If $r_k^N > c$, k is suspected of BD; usually $c = 3$
  - 5. Eliminate or correct k-th measurement and go back to 1
- Correction of BD
  - $z_i \approx z_i^{bad} - \frac{R_{ii}}{\boldsymbol{\Omega}_{ii}} r_i^{bad}$

IEEE 13-Node Feeder

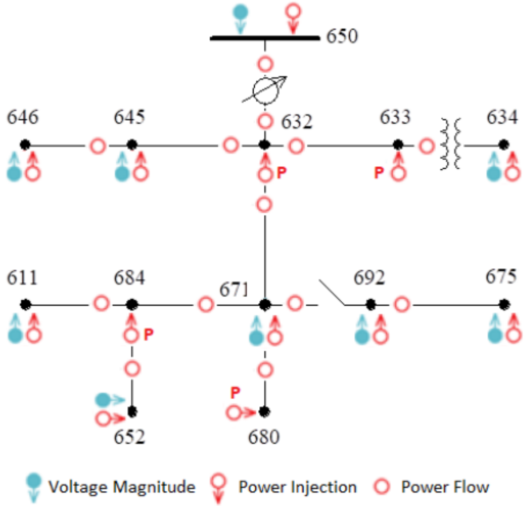
- Perfect and noisy measurements
- Different magnitudes of errors
  - 20, 25, 30, and 50 σ
  - σ: standard deviation

Parameter	Value
σ_{inj}	0.001
σ_{flow}	0.001
σ_{v}	0.001
$\sigma^{p}_{\text{nullInj}}$	0.0001
tolerance	10^{-4}
Iteration Limit	30



IEEE 13-Node Feeder with Bad Data

- Detection and correction results



BD magnitude (σ)	BD detected	Perc. (%)
20	136	97.84
25	136	97.84
30	139	100
50	139	100

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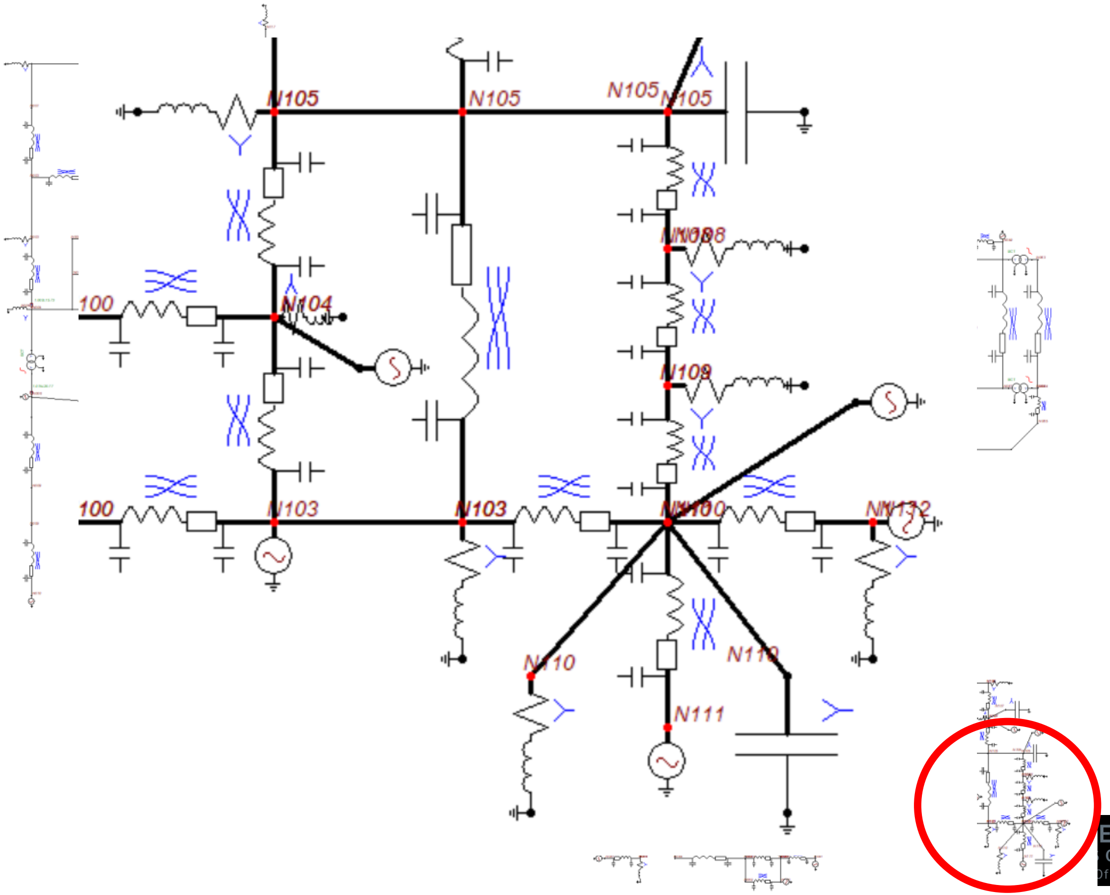
Least Absolute Value Formulation

$$\min_{r} C^T \cdot |r|$$
$$Z = h(\hat{x}) + r$$
$$Z_e = h_e(\hat{x})$$

- Robust against measurement errors
- Easily incorporates equality constraints

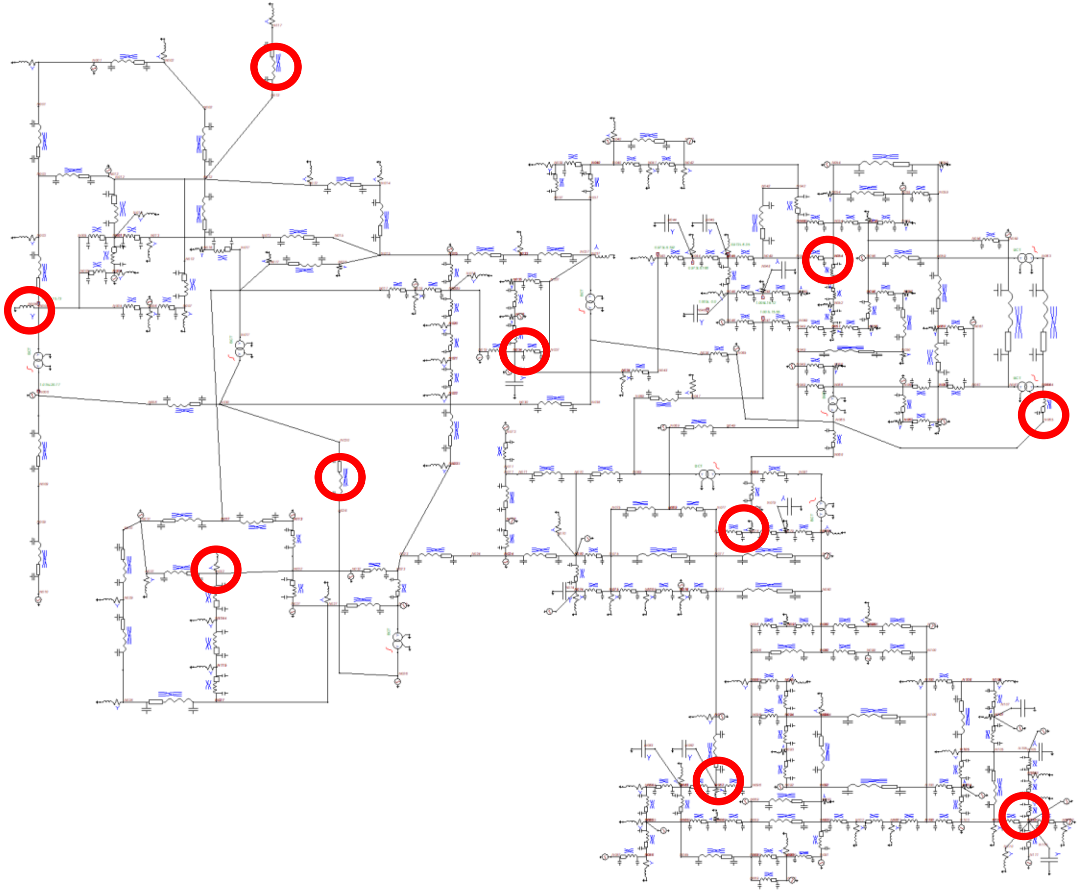
Simulations

3-Phase Model
IEEE 118 Bus Test
System

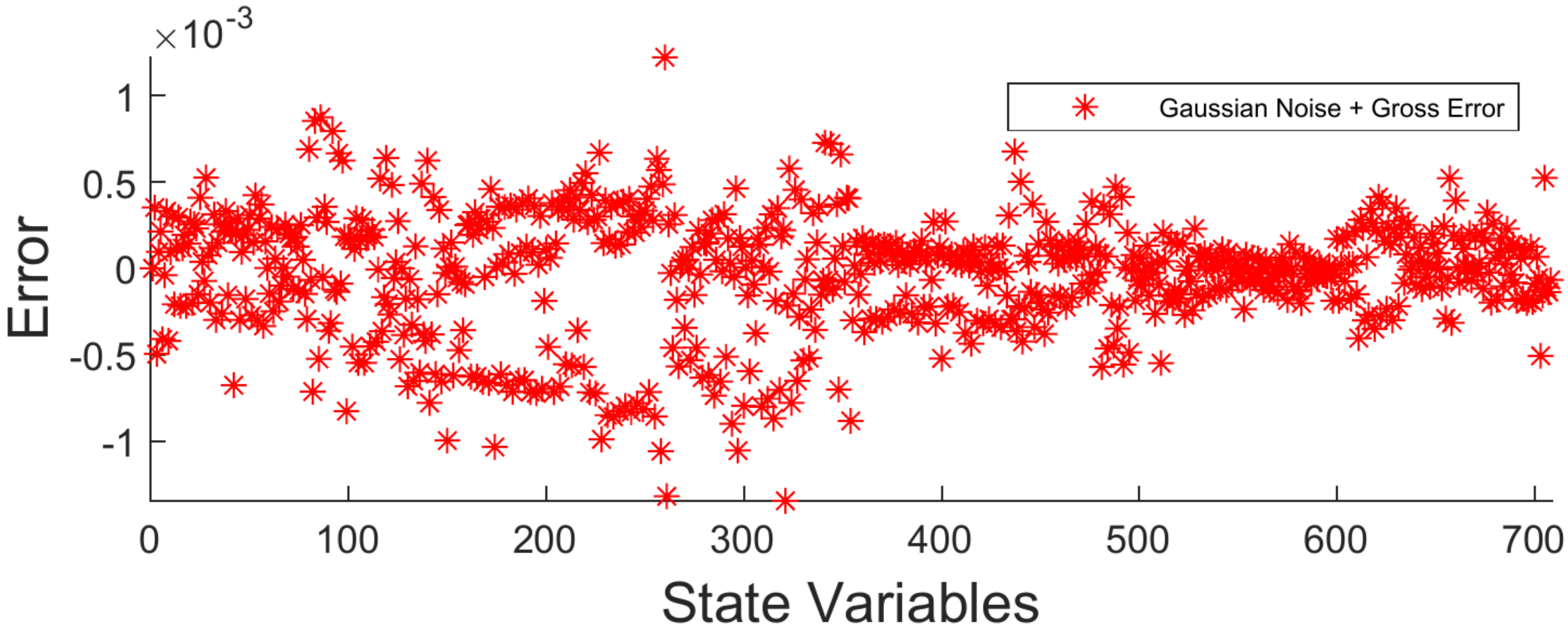


Simulation Results – Noise + Gross Errors

Measurement	Bus From	Bus To	Phase	Error
P_flow	14	15	A	1 pu
P_flow	69	47	B	1 pu
P_flow	89	85	A	1 pu
Q_flow	8	30	C	1 pu
Q_flow	32	113	B	1 pu
Q_flow	47	46	A	1 pu
P_Inj	-	103	C	1 pu
Q_Inj	-	10	B	1 pu
V_mag	-	2	A	1 pu
P_flow	12	117	B	phase swap
P_flow	12	117	C	phase swap



Simulation Results – Noise + Gross Errors



Simulation Results – Noise + Gross Errors

Gross Error Added

Measurement	Bus From	Bus To	Phase	Error
P_flow	14	15	A	1 pu
P_flow	69	47	B	1 pu
P_flow	89	85	A	1 pu
Q_flow	8	30	C	1 pu
Q_flow	32	113	B	1 pu
Q_flow	47	46	A	1 pu
P_Inj	-	103	C	1 pu
Q_Inj	-	10	B	1 pu
V_mag	-	2	A	1 pu
P_flow	12	117	B	phase swap
P_flow	12	117	C	phase swap

Simulation Results

Type	Bus From	Bus To	Estimated	Measured	Residues
P_flow	14	15	-0.0065	0.9925	0.9991
P_flow	69	47	0.2958	1.2947	0.9989
P_flow	89	85	0.3617	1.3600	0.9983
P_inj	0	103	0.0856	1.0889	1.0032
Q_flow	8	30	0.1506	1.1518	1.0012
Q_flow	32	113	-0.0865	0.9129	0.9994
Q_flow	47	46	-0.0041	0.9960	1.0001
Q_inj	0	10	-0.2568	0.7406	0.9975
V_mag	0	2	0.6875	1.6883	1.0008
P_flow	12	117	0.1114	0.0949	0.0165
P_flow	12	117	0.0959	0.1118	0.0159

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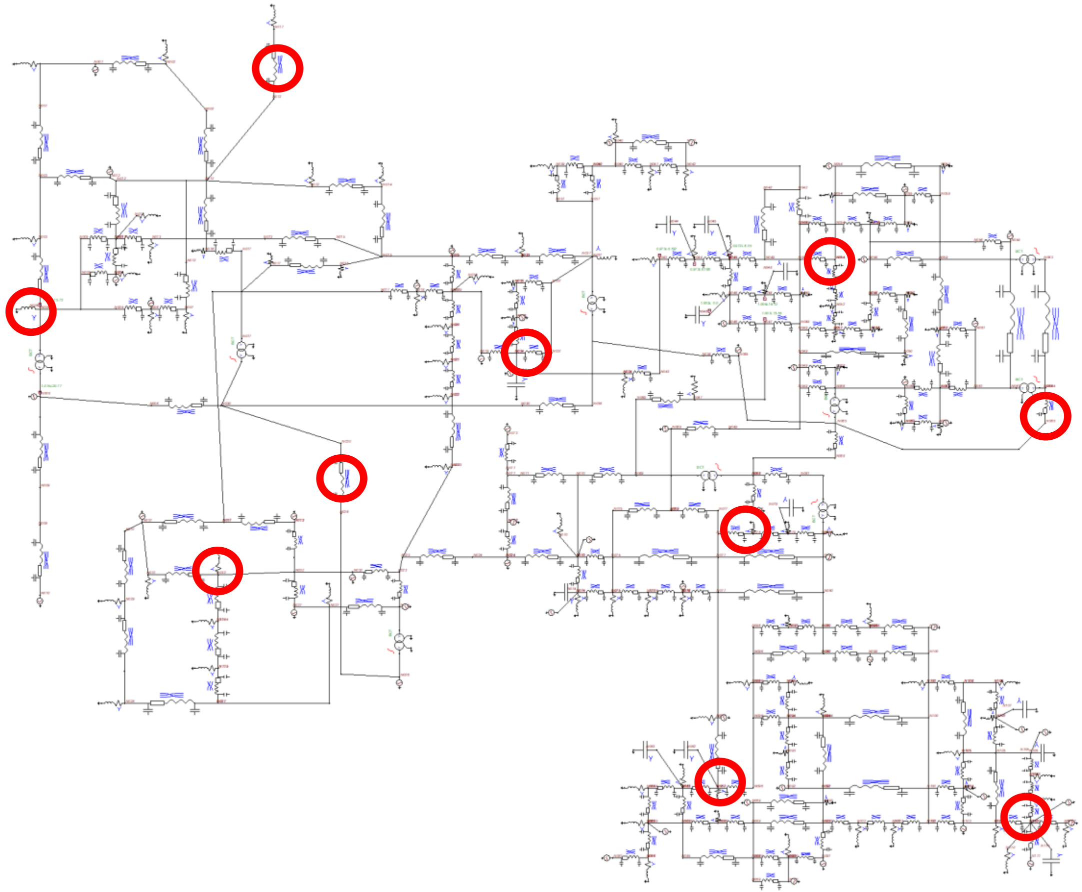
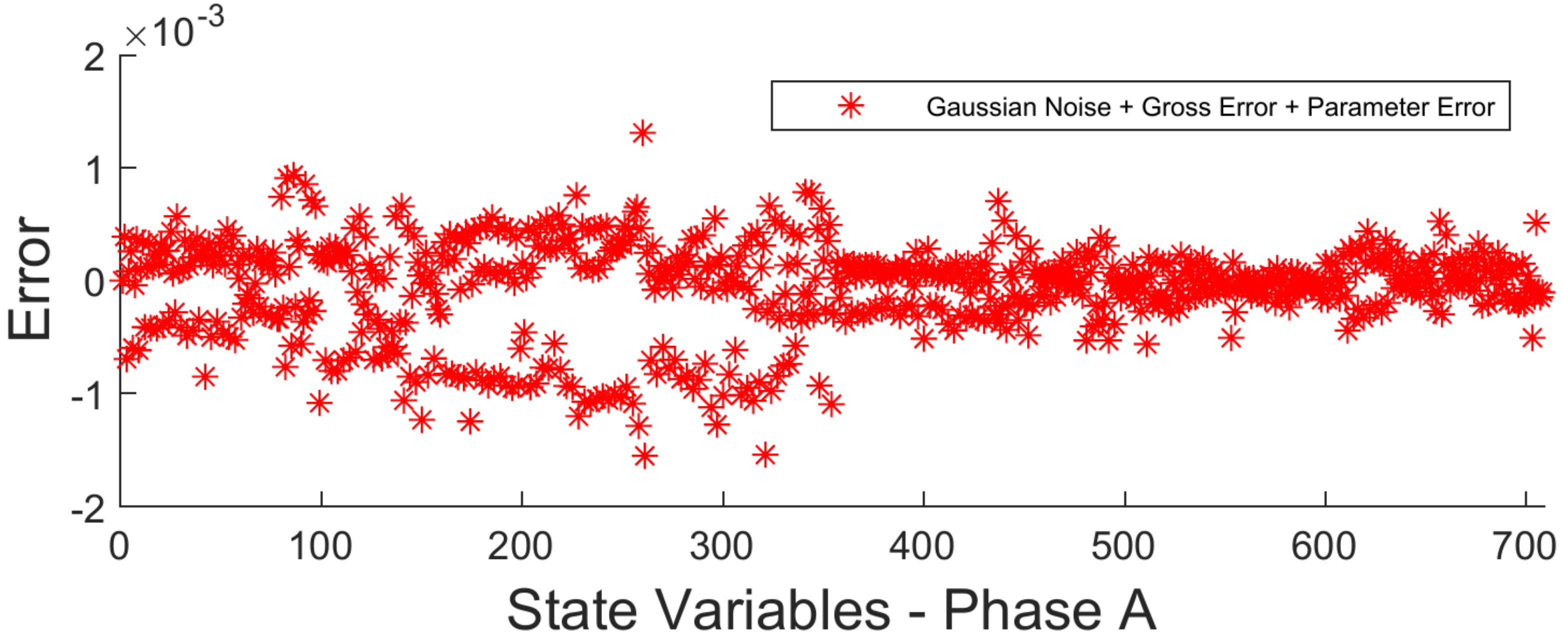
Simulation Results – Noise + Gross Errors + Bad Parameters



Simulation Results – Noise + Gross Errors + Bad Parameters

Bus From	Bus To	Phase	R	X	B	R	X	B	R	X	B
			A	A	A	B	B	B	C	C	C
62	**67**	A	0.05050	0.16652	0.01976	0.02020	0.06661	-0.00564	0.02020	0.06661	-0.00564
62	**67**	B	0.02020	0.06661	-0.00564	0.05050	0.16652	0.01976	0.02020	0.06661	-0.00564
62	**67**	C	0.02020	0.06661	-0.00564	0.02020	0.06661	-0.00564	0.05050	0.16652	0.01976

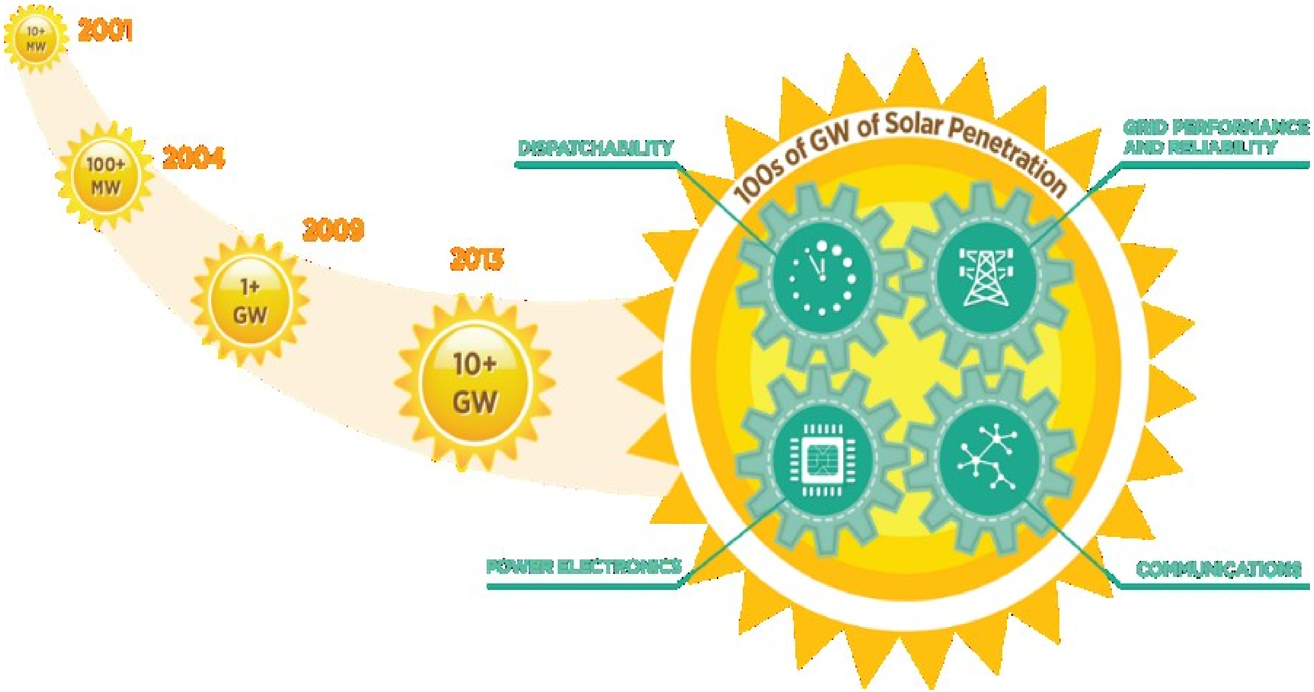
Simulation Results – Noise + Gross Errors + Bad Parameters



Conclusion

- WLS and LAV based DSE are implemented and tested.
- Large numbers of bad data favors LAV implementation.
- Future work:
  - Implement cases with distributed solar PVs
  - Combine DSE and TSE
  - Implement both as multi-area distributed SE

Questions?



10+ MW
2001
100+ MW
2004
1+ GW
2009
10+ GW
2013
100s of GW of Solar Penetration
DISPATCHABILITY
GRID PERFORMANCE AND RELIABILITY
POWER ELECTRONICS
COMMUNICATIONS