SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy

ENERGISE Webinar:

Solar to the Max: Innovations in Distribution Grid Planning and Operations

Robust Distributed State Estimator for Interconnected Transmission and Distribution Networks

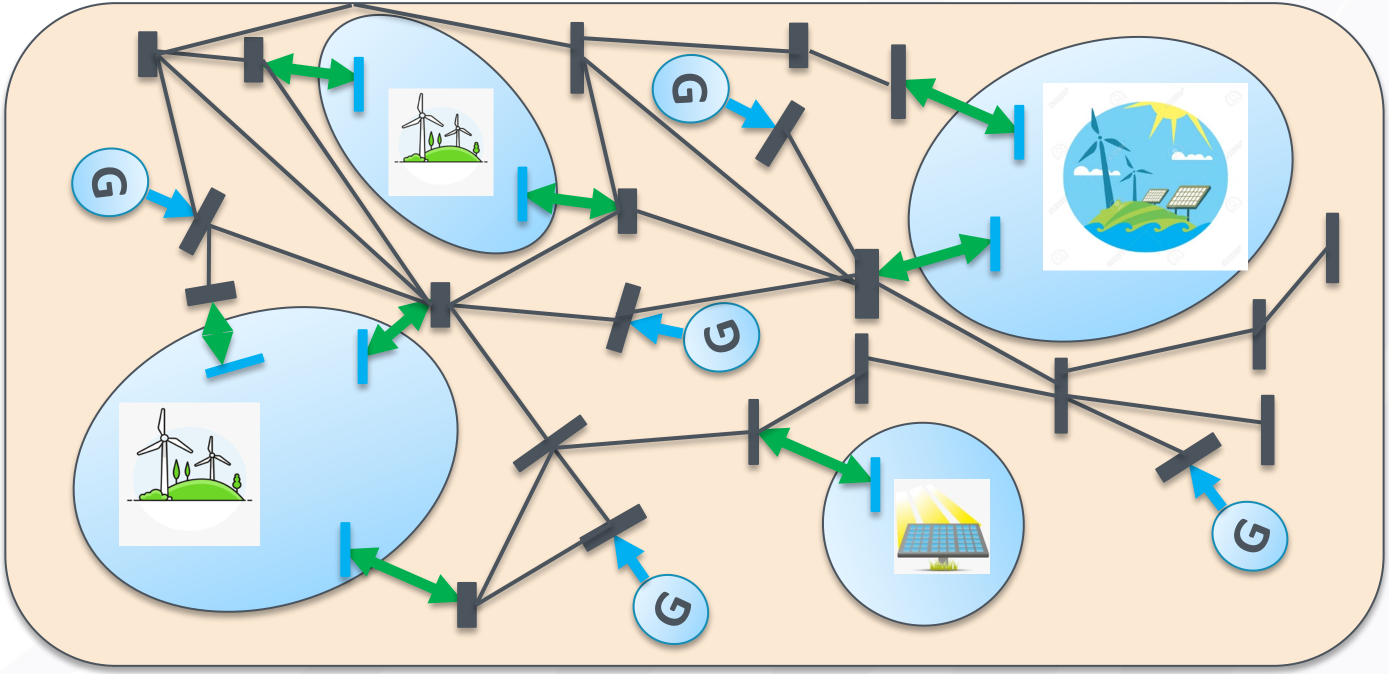
Northeastern University

DE-EE0008005

June 25, 2021

Principal Investigator: Ali Abur (NEU); Sub-contractor: Jianzhong Tong (PJM)
Other Contributors: Andre Langner, David Kelle, Ramtin Khalili (PhD students @NEU)

The goal: develop a state estimator for monitoring transmission and distribution systems simultaneously.



TRANSMISSION SYSTEMS

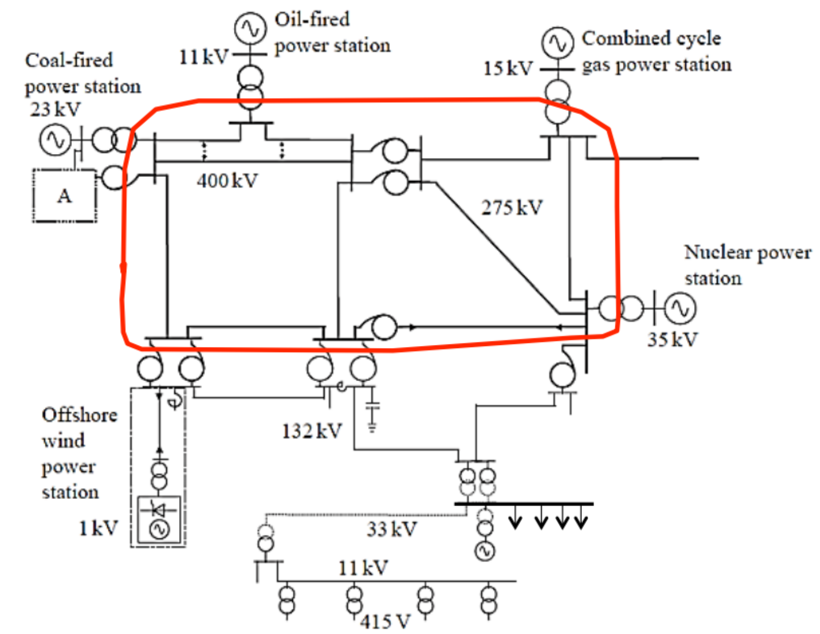
Established real-time monitoring and control practices

SCADA measurements

Monitored by SE introduced by Schweppe in 1970

Balanced operation, + seq. model

Transmission Systems (230 – 750 kV)



DISTRIBUTION SYSTEMS

Radial / Meshed networks

Lack of real-time measurements

Distribution Management Systems (DMS)

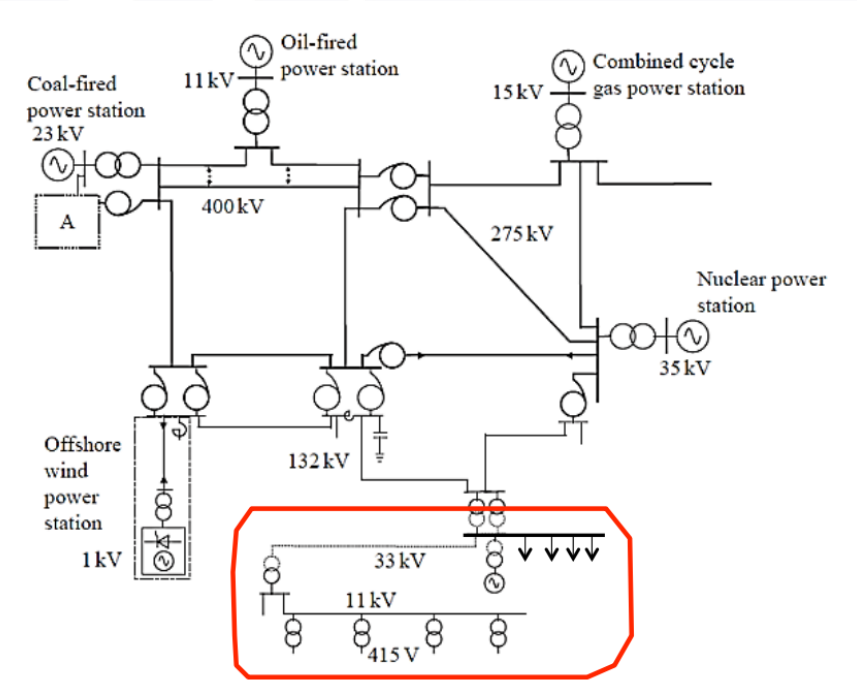
Smart Grids

Distributed Generation (DG)

Advanced Measurement Infrastructure (AMI)

Advanced DMS

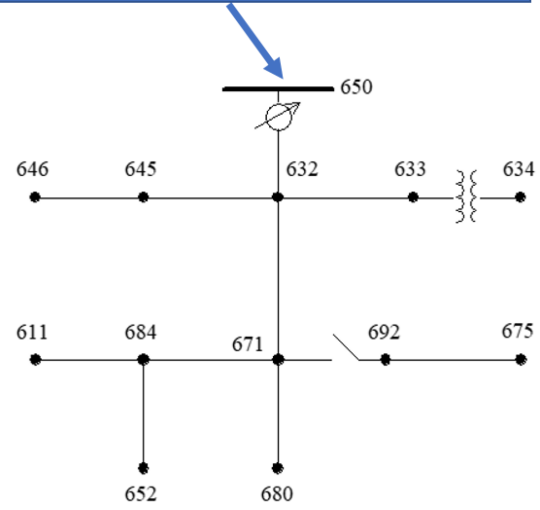
Distribution Systems (13 - 33 kV)



- Challenges / Innovations:
  - **3-Phase SE formulation / Choice of a reference**
  - **Unbalanced operation / Mixed-phase SE**
  - System size / Scalable solution
  - Uneven areas / Optimal system partitioning
  - Bad measurements / Robust estimator

CHOICE OF A REFERENCE BUS

$$\theta^{a}_{650} = 0^{o} \; \theta^{b}_{650} = -120^{o} \; \theta^{c}_{650} = 120^{o}$$

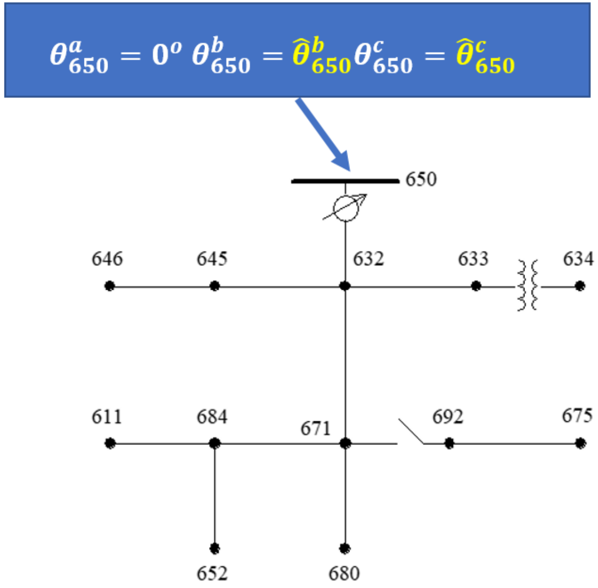


DEFAULT PRACTICE:
Approach I

Assume a balanced voltage bus exists

Set the phase angles to 0, 120,-120

Approach II: USE OF A SINGLE-PHASE REFERENCE



Approach II

Fix only one phase angle

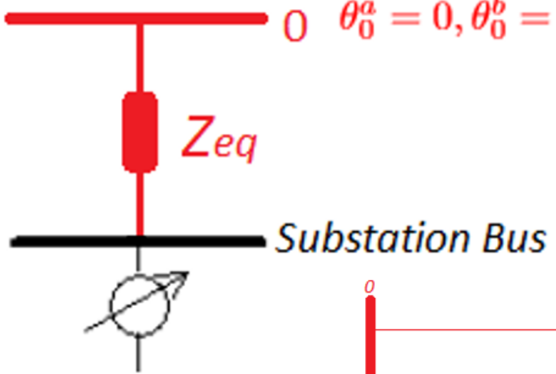
Estimate the rest of the phases

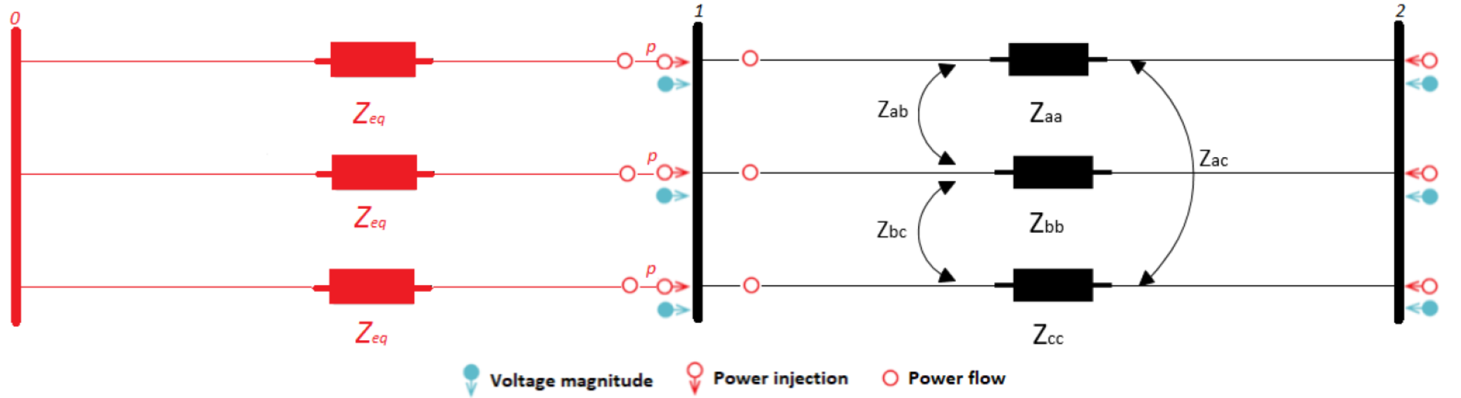
Approach III: USE OF 3-PHASE BALANCED VIRTUAL BUS

Andre L. Langner and A. Abur, "Formulation of Three-Phase State Estimation Problem Using a Virtual Reference," *IEEE Transactions on Power Systems*, vol. 36, no. 1, pp. 214-223, Jan. 2021.

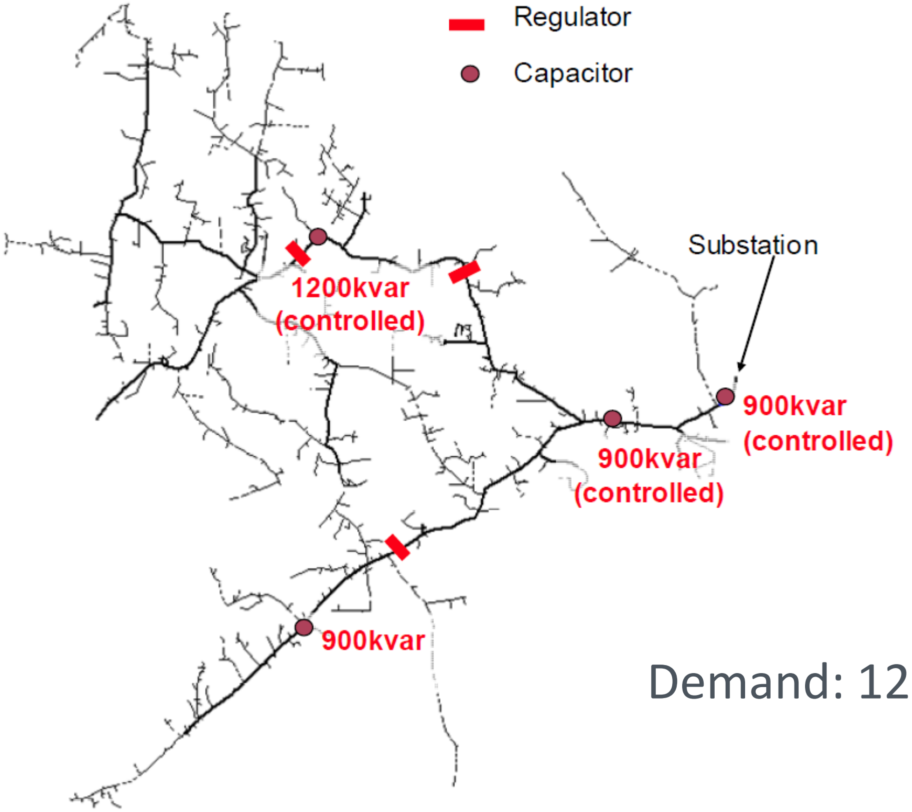
$$V_0^a = V_0^b = V_0^c$$

$$\theta_0^a = 0, \theta_0^b = -120, \theta_0^c = 120$$





8500 NODE DISTRIBUTION SYSTEM



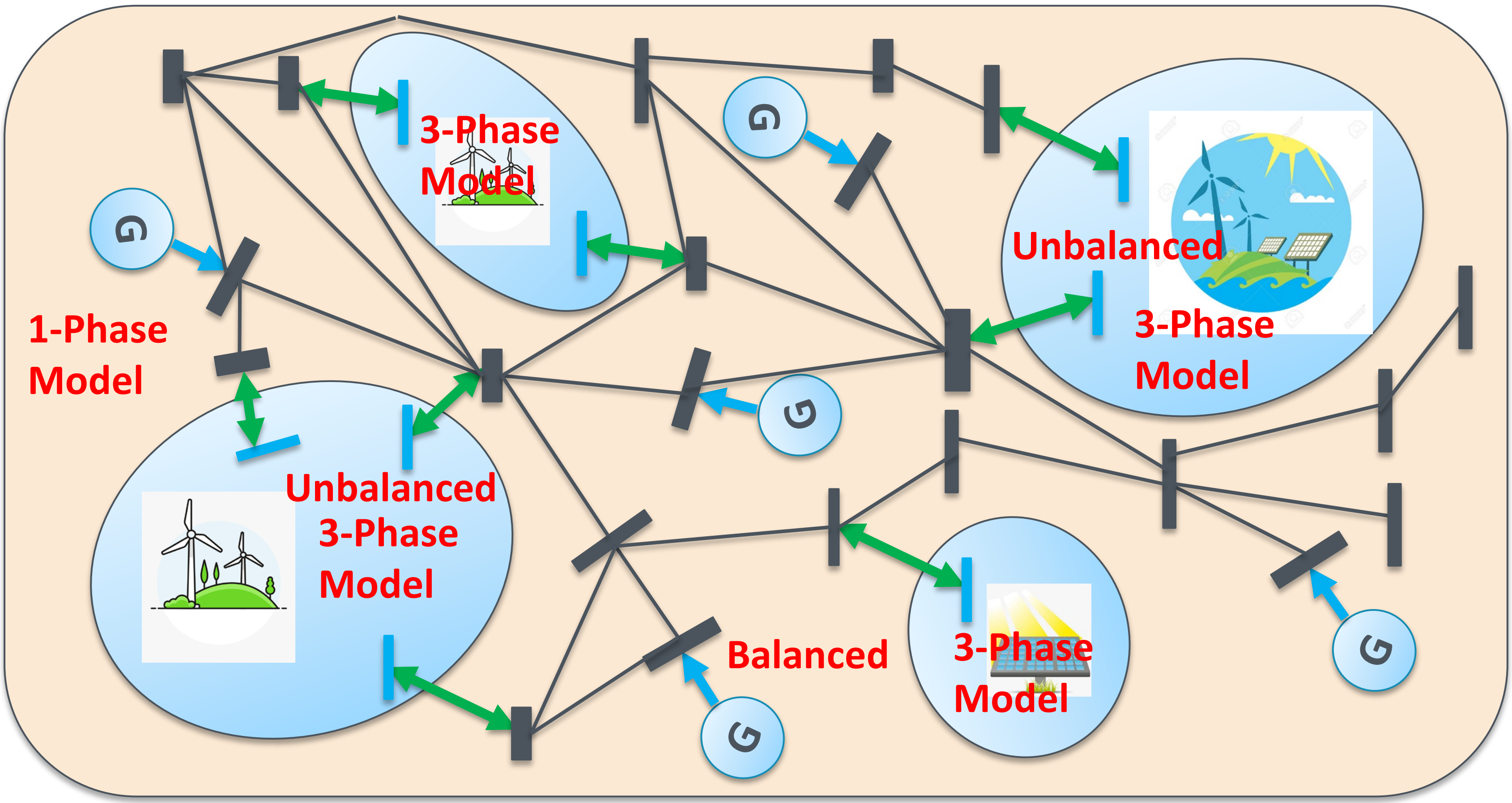
Demand: 12.04 MW and 1.44 MVAr

IEEE 8500-NODE DISTRIBUTION SYSTEM

True States	App. I	App. II	App. III
$-2.8597°$	$-2.8597°$	$-2.8597°$	$-2.8626°$
$-122.7995°$	$-122.8597°$	$15.7623°$	$-122.8008°$
$117.1093°$	$117.1403°$	$292.0141°$	$117.1023°$

App.	No Iterations	J-index	Processing Time (s)
I	9	0.0644	26.1323
II	14	0.0609	39.8192
III	9	0.0507	29.4274

- Challenges / Innovations:
  - 3-Phase SE formulation / Choice of a reference
  - **Unbalanced operation / Mixed-phase SE**
  - System size / Scalable solution
  - Uneven areas / Optimal system partitioning
  - Bad measurements / Robust estimator

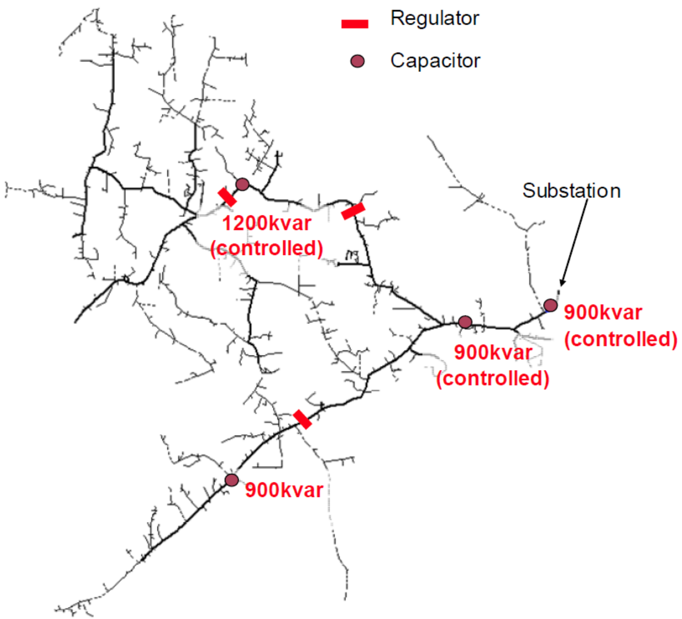


MODELING CHALLENGES: Mixed-phase line sections; Unbalanced DS

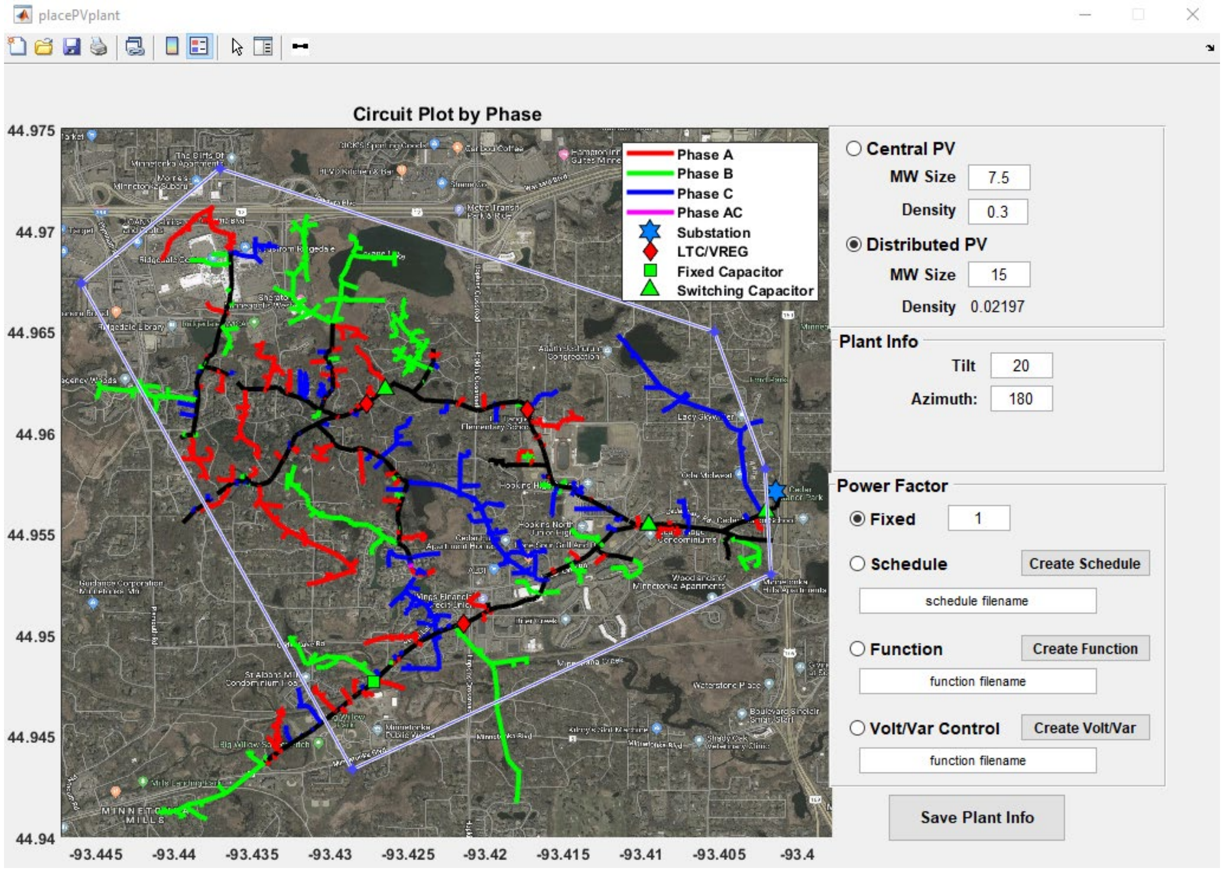
Network Data and Measurements

8500 Node System

- GridPV was used to insert solar PVs in the feeder
- Many different scenarios are simulated
- Validation for accuracy and bad data detection



Example Scenario Solar PVs : 15 MW



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State Estimation Results

MSE Values - Scenario 1

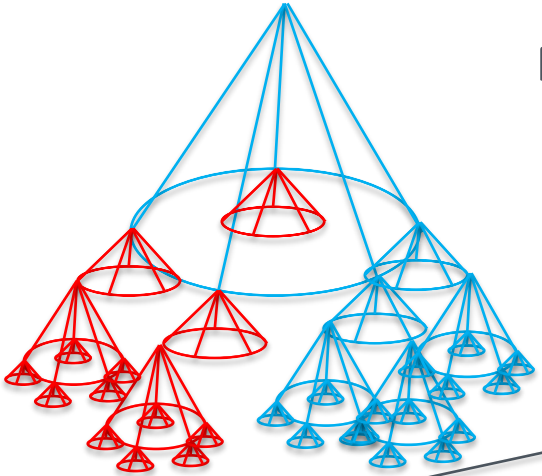
Case	V	θ	Combined
Perfect Meas.	2.84×10^{-29}	6.99×10^{-20}	3.49×10^{-20}
Gaussian Noise	2.71×10^{-11}	3.34×10^{-5}	1.67×10^{-5}

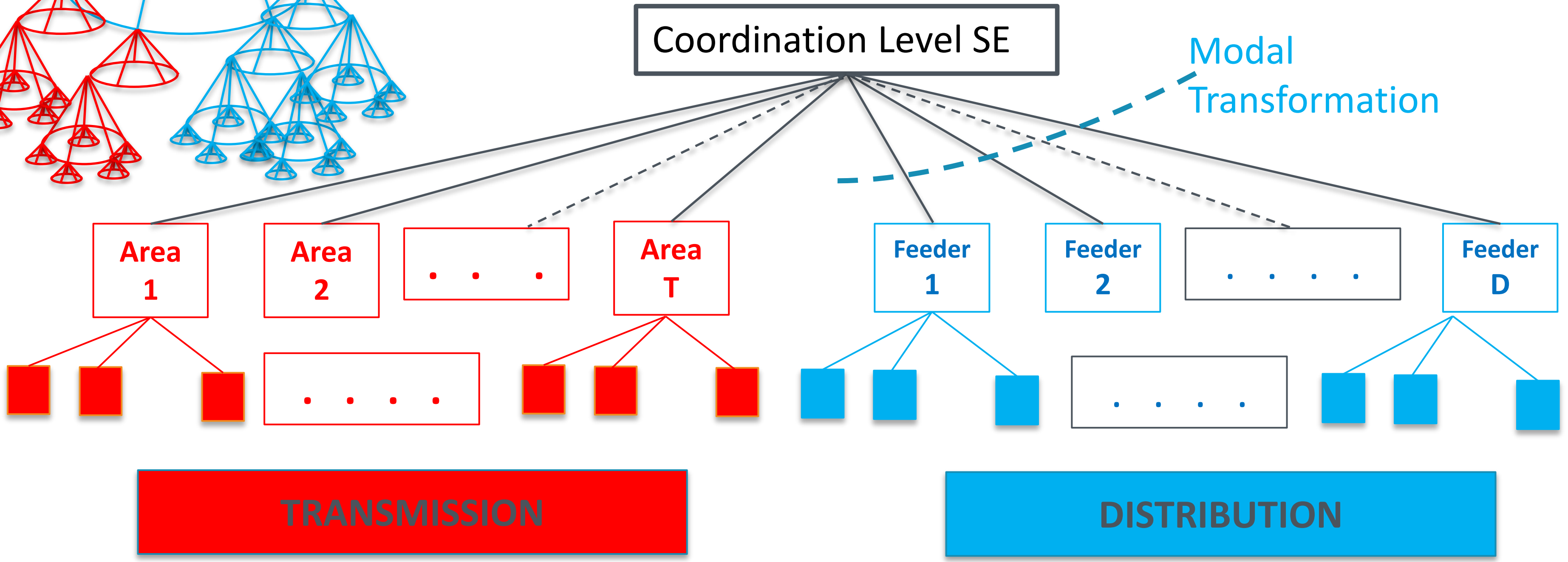
J-index, Convergence, and mean of diag. of G inverse - Scenario 1

Case	J	Iterations	mean($diag(G^{-1})$)
Perfect Meas.	5.83×10^{-13}	4	0.0018
Gaussian Noise	37.98	5	0.0018

- Challenges / Innovations:
  - 3-Phase SE formulation / Choice of a reference
  - **Unbalanced operation / Mixed-phase SE**
  - **System size / Scalable solution**
  - Uneven areas / Optimal system partitioning
  - Bad measurements / Robust estimator

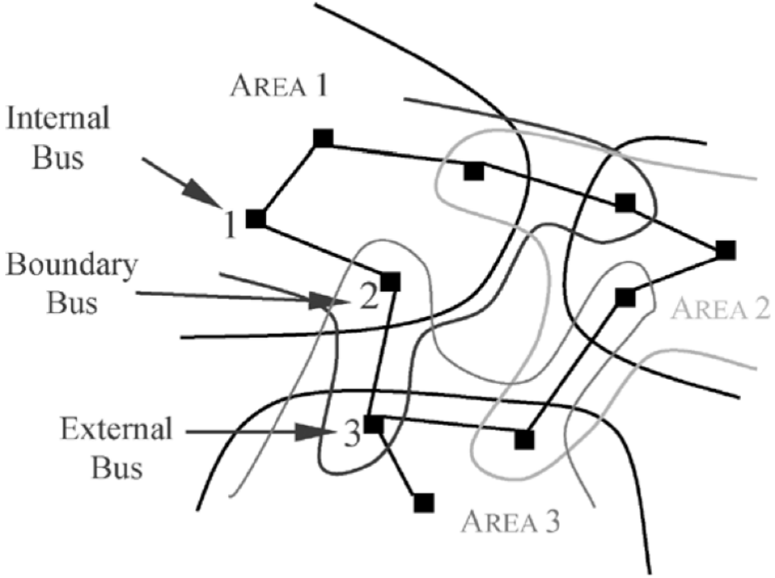
Multi-Area Hierarchical Computational Model





Multi-area State Estimation

Zhao and Abur (2005) Multiarea State Estimation Using Synchronized Phasor Measurements



Partition the network into non-overlapping areas

Identification of buses:

- Internal
- Boundary
- External

Two-Level Computation Framework

Ren and Abur (2018) Obtaining Partial Solutions for Divergent State Estimation Problems in Large Power Systems

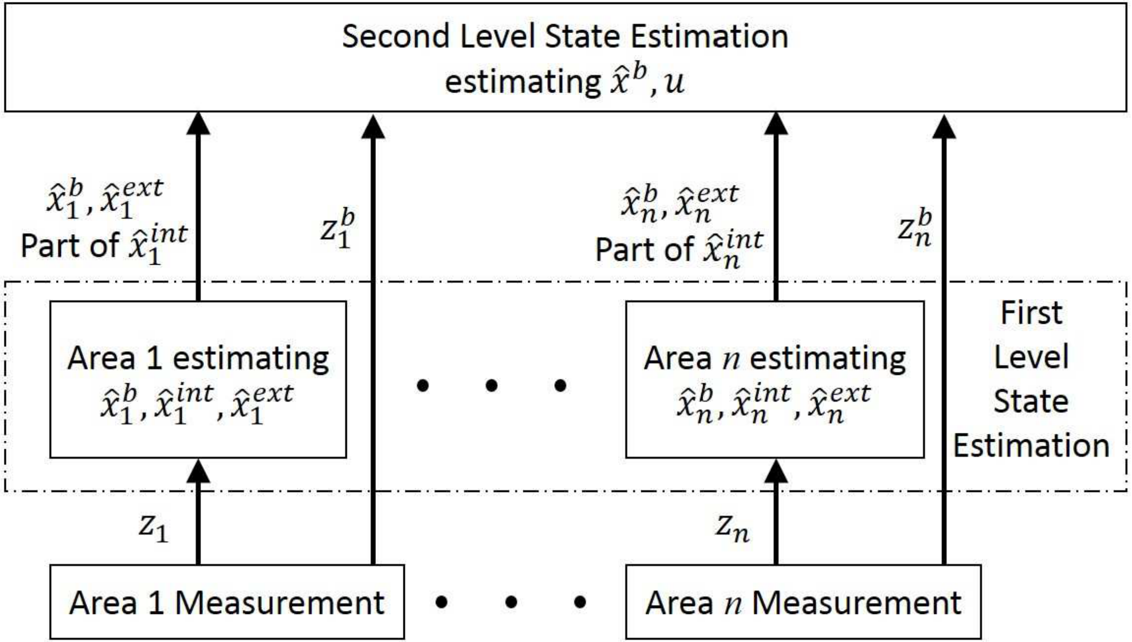
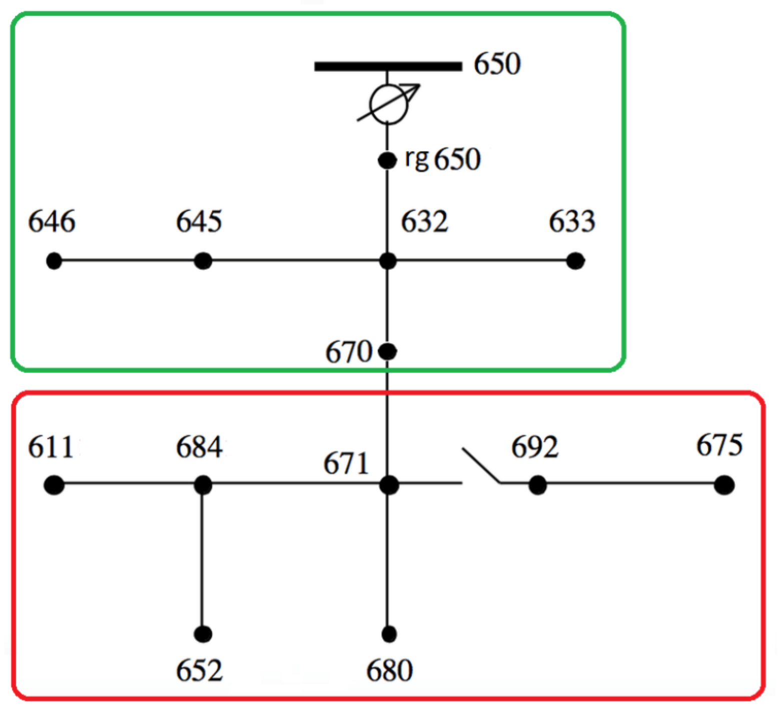


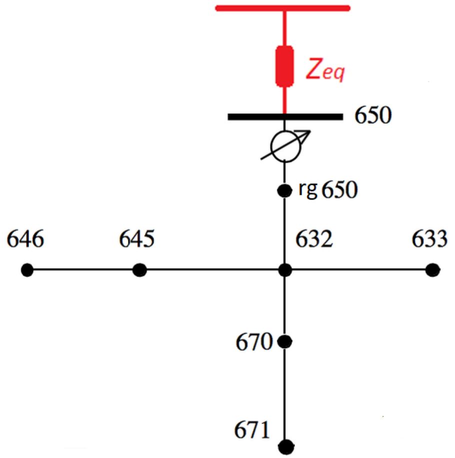
Illustration on a Distribution System

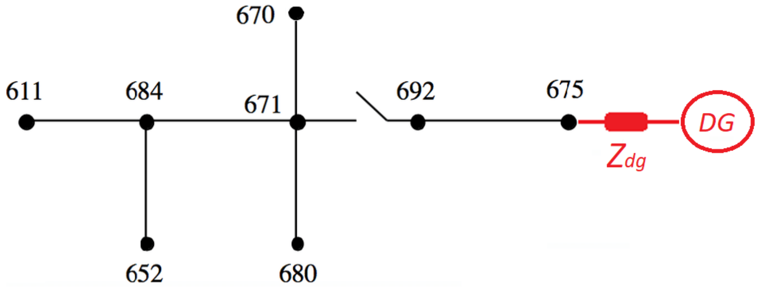
- Multi-phase Solution
- Scalable to large networks
- Parallel processing



IEEE 13-node test feeder

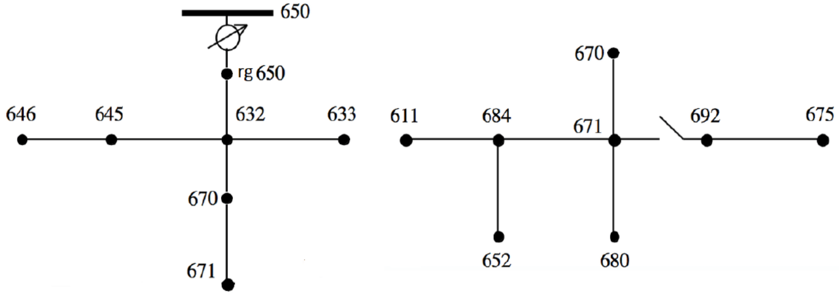
Use of a Virtual Bus



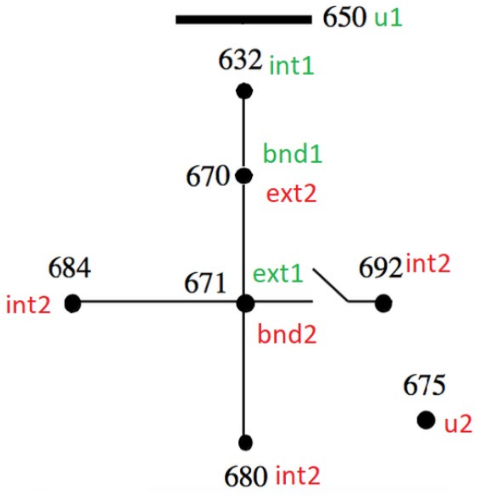


Two-stage Solution

Stage 1 – Individual areas



Stage 2 – Coordination



PJM Transmission Model Details

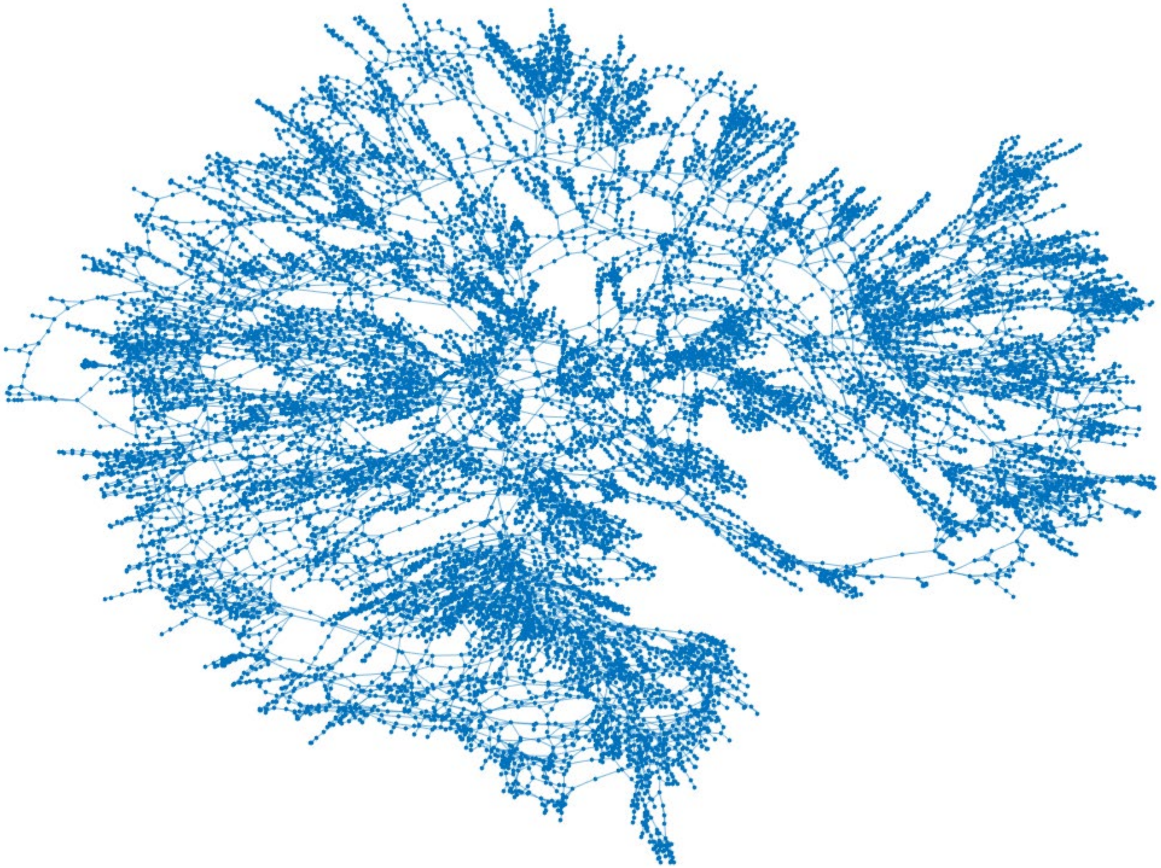
System Overview

Component	Number
buses:	14207
loads:	7598
on	7598
off	0
fixed	7594
dispatchable	4
generators:	2574
on	1001
off	1573
shunt elements:	1238
branches:	19248
areas:	2

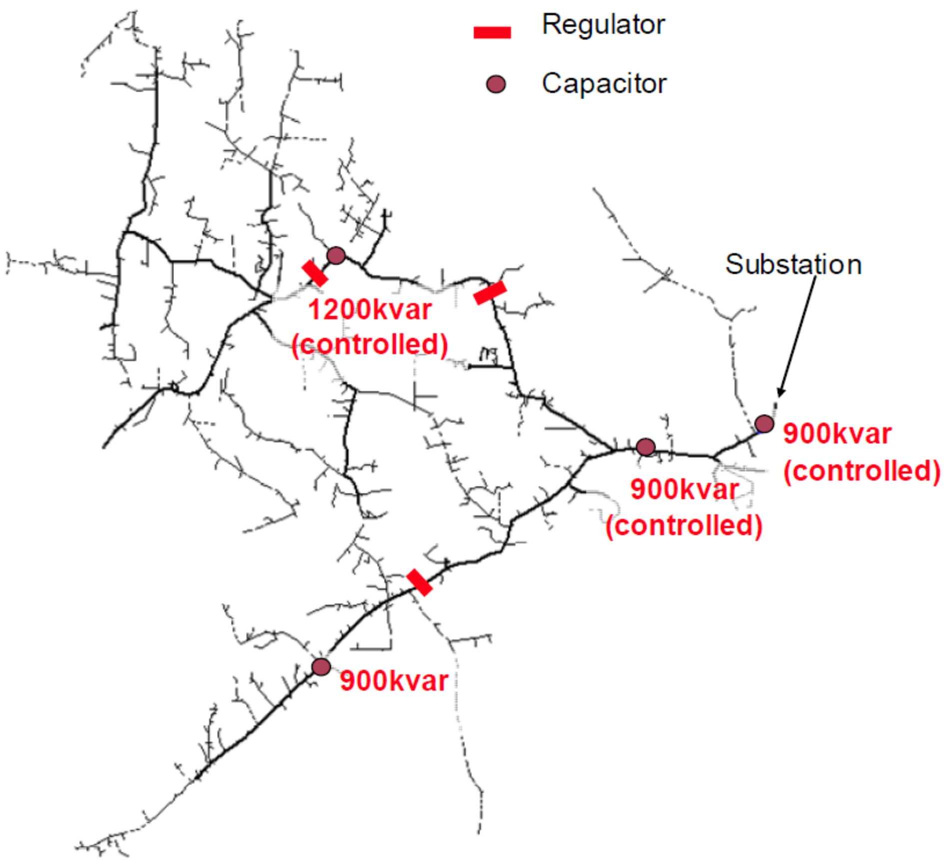
Generation and Loads

Type	Active (MW)	Reactive (MVAr)
total dispatched loads:	217431.8	36528.6
fixed	217405.7	36600.6
dispatchable	26.1	−72.0
total curtailed loads:	0	292.0
total nominal loads:	217431.8	36820.6
on	217431.8	36820.6
off	0	0
fixed	217405.7	36600.6
dispatchable	26.1	220.0
on	26.1	220.0
off	0	0
total dispatched generation:	222850.5	17898.2

PJM Transmission System: ~16K substations



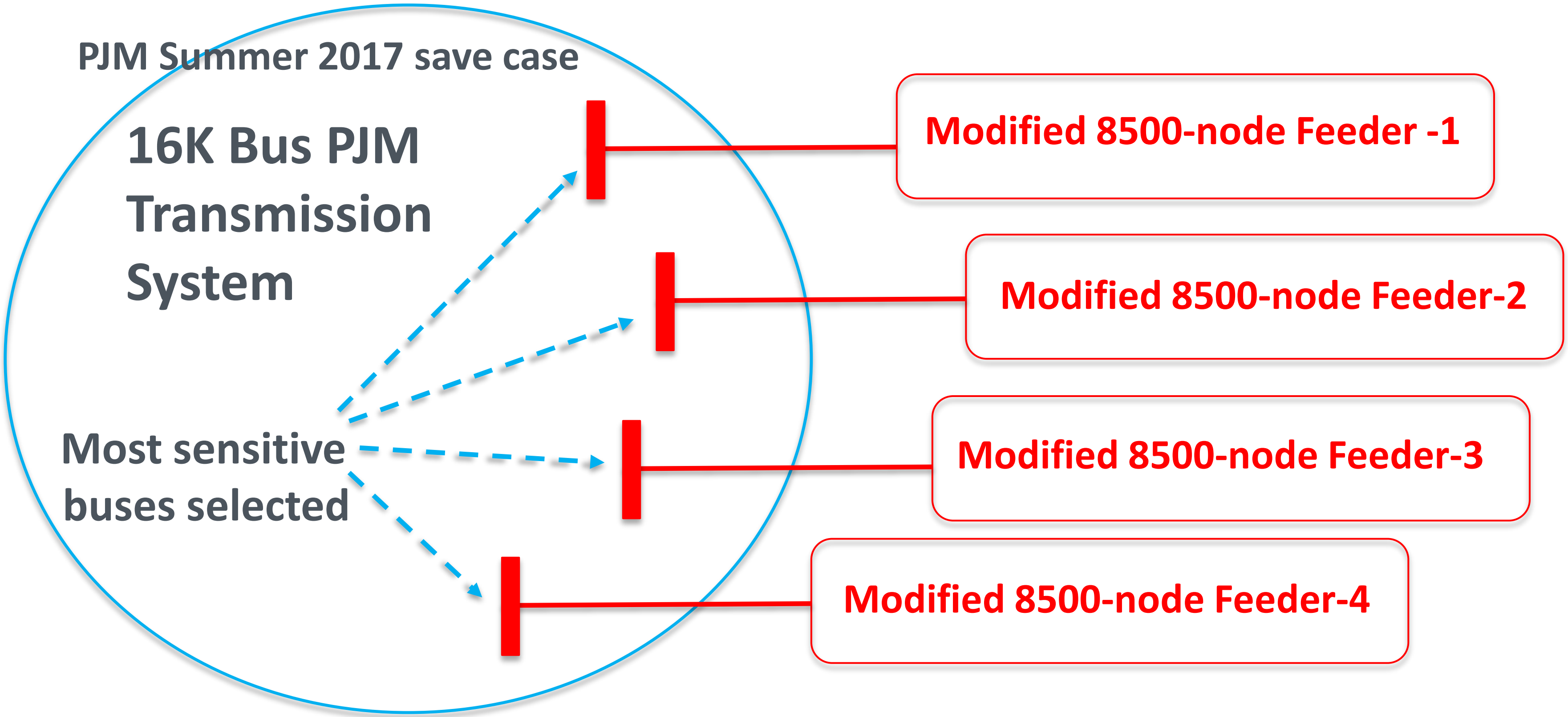
Distribution System



8500 node feeder

GridPV was used to insert solar PVs in the feeder

Large-scale Testing Configuration



Results

Only the first three areas are shown

Table 22: Level 1 MAT SE MSE Values (Error-Free)

SE	V	θ	Combined
Area 1	2.659×10^{-12}	1.256×10^{-12}	2.084×10^{-12}
Area 2	2.055×10^{-10}	1.553×10^{-10}	1.823×10^{-10}
Area 3	6.525×10^{-11}	7.189×10^{-11}	6.860×10^{-11}

Table 23: Level 2 SE Convergence (Error-Free)

SE	J	Iterations
Area 1	1.351×10^{-12}	15
Area 2	1.559×10^{-8}	4
Area 3	2.065×10^{-9}	5

Results

Table 25: Level 2 SE MSE Values (Error-Free)

SE	V	θ	Combined
MAT Coordinator	2.634×10^{-10}	2.479×10^{-10}	2.558×10^{-10}
MDF (Feeder I)	1.211×10^{-7}	1.865×10^{-6}	9.929×10^{-7}
MDF (Feeder II)	5.77×10^{-8}	4.762×10^{-7}	2.67×10^{-7}
MDF (Feeder III)	2.964×10^{-6}	8.653×10^{-5}	4.475×10^{-5}
MDF (Feeder IV)	6.912×10^{-9}	2.622×10^{-7}	1.311×10^{-7}

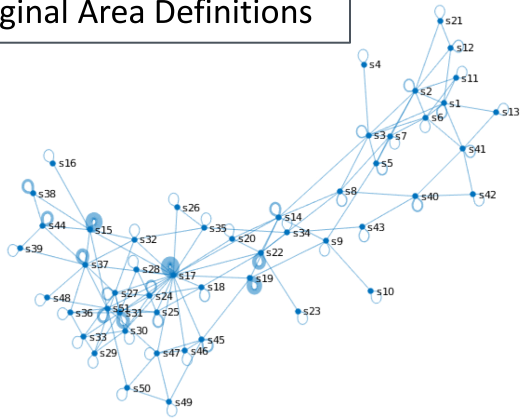
Table 26: Level 2 SE Convergence (Error-Free)

SE	J	Iterations
MAT Coordinator	7.735×10^{-15}	15
MDF (Feeder I)	1.804×10^{-4}	4
MDF (Feeder II)	7.062×10^{-8}	5
MDF (Feeder III)	1.402×10^{-4}	4
MDF (Feeder IV)	1.676×10^{-5}	4

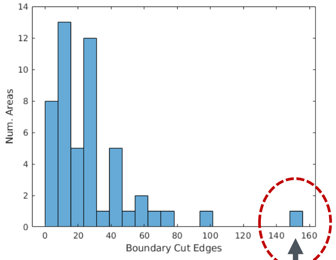
- Challenges / Innovations:
  - 3-Phase SE formulation / Choice of a reference
  - **Unbalanced operation / Mixed-phase SE**
  - **System size / Scalable solution**
  - **Uneven areas / Optimal system partitioning**
  - Bad measurements / Robust estimator

Partitioning Results

Case 1: Original Area Definitions

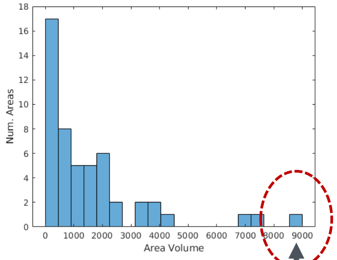


Boundary Branches



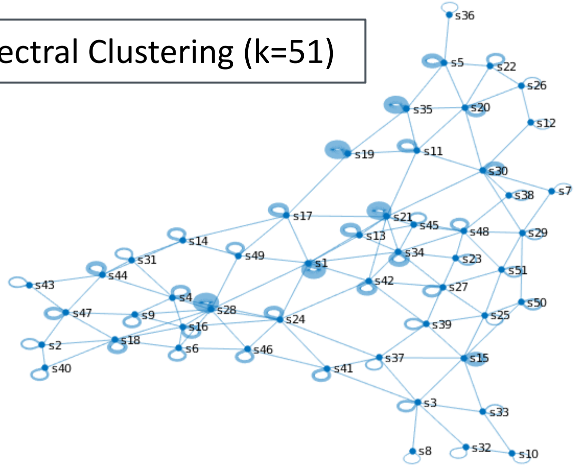
150

Internal Branches

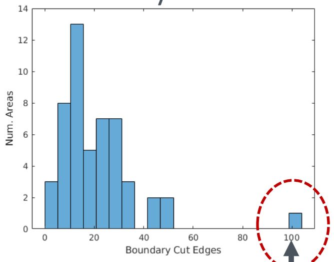


9000

Case 2: Spectral Clustering (k=51)

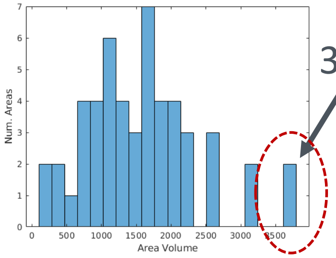


Boundary Branches



100

Internal Branches



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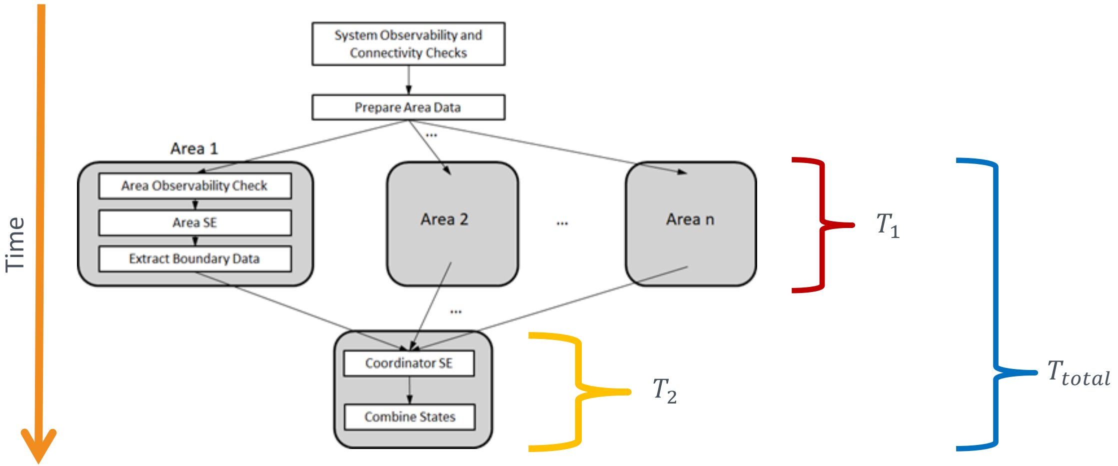
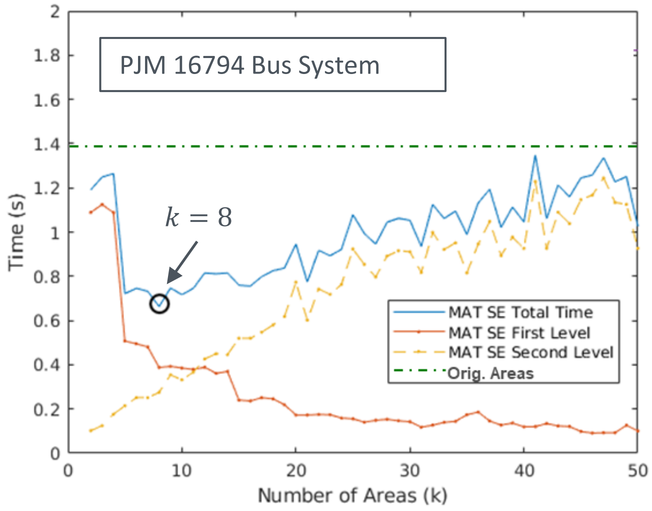
Timing Results

David Kelle and A. Abur, “Improving performance of multi-area state estimation using spectral clustering,” *Proceedings of the 51st North American Power Symposium*, 2019.

Multi-Area State Estimation Algorithm Structure



Execution Time



		Partition Results		Computation Time		
Case	k	$\sum r_j$	ϕ	T_1	T_2	T_{total}
Case 1	51	–	7.5465	0.2767	1.0841	1.3608
Case 2	51	12.0575	2.2864	0.1277	0.8658	0.9936
Case 3	8	1.6261	–	0.3876	0.2754	0.6630

- Challenges / Innovations:
  - 3-Phase SE formulation / Choice of a reference
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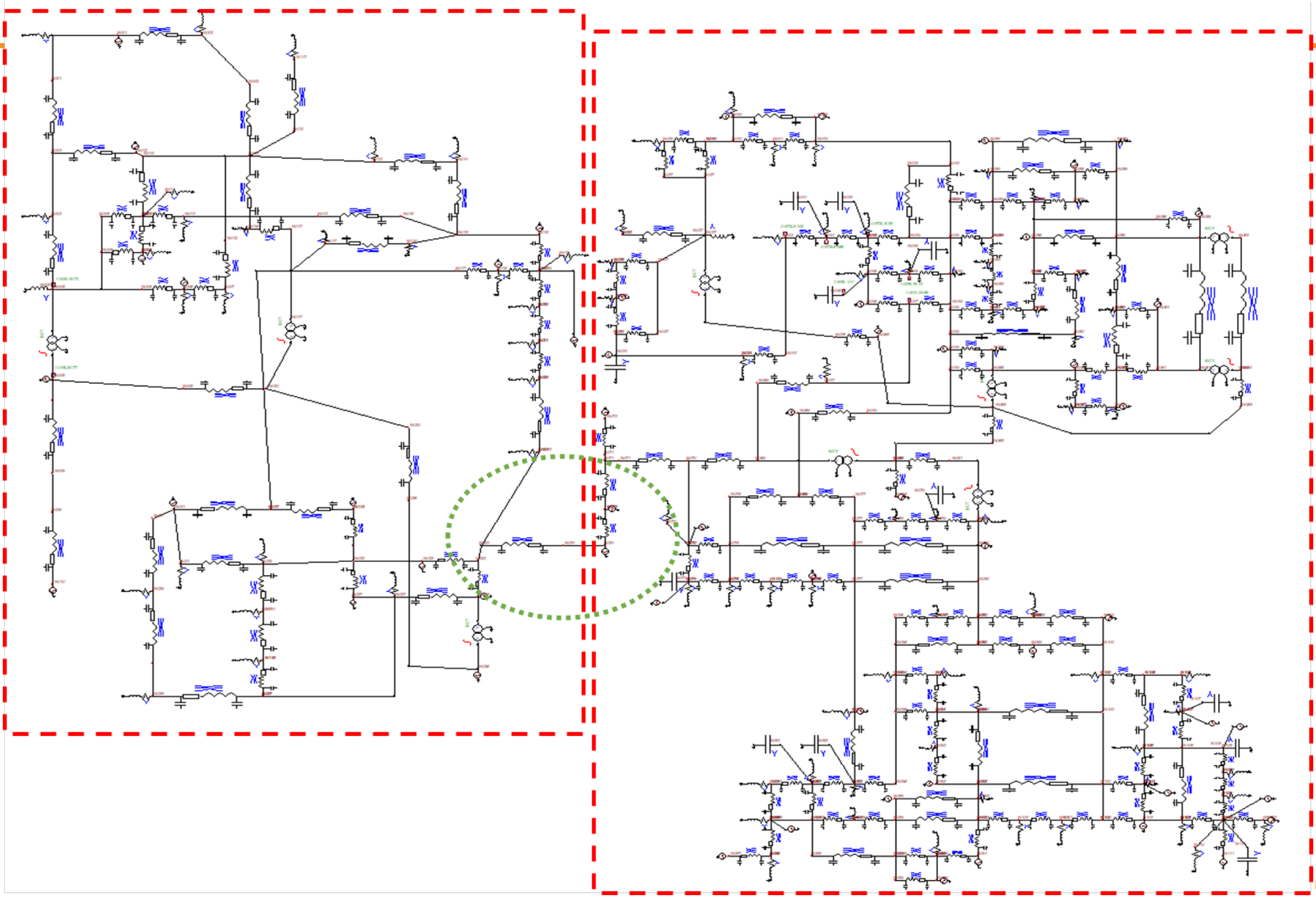
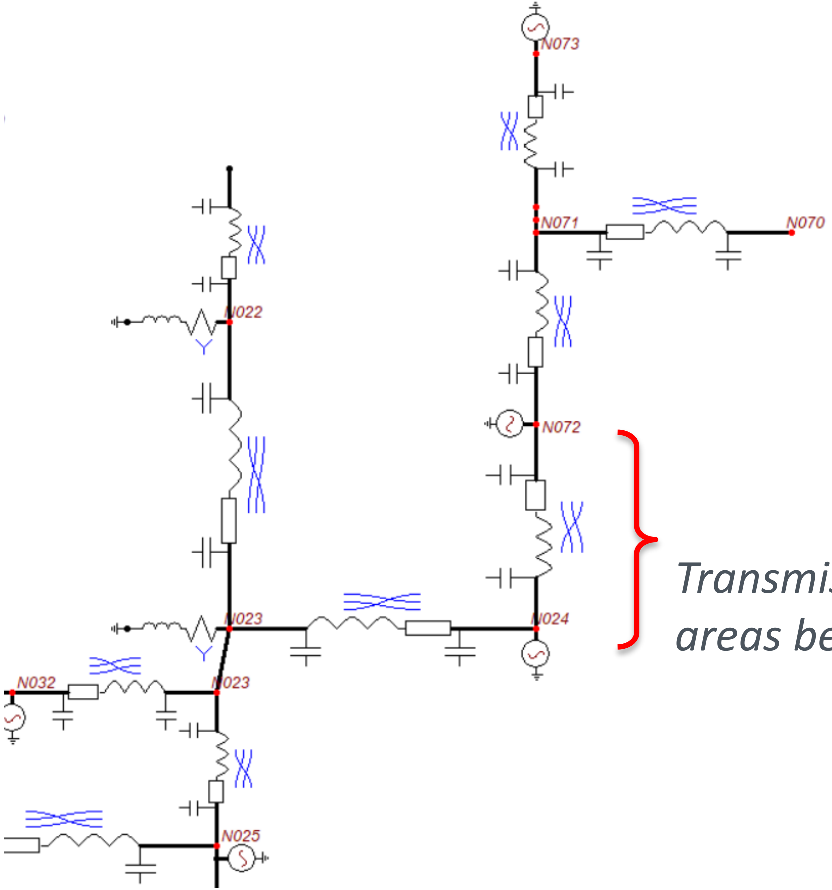
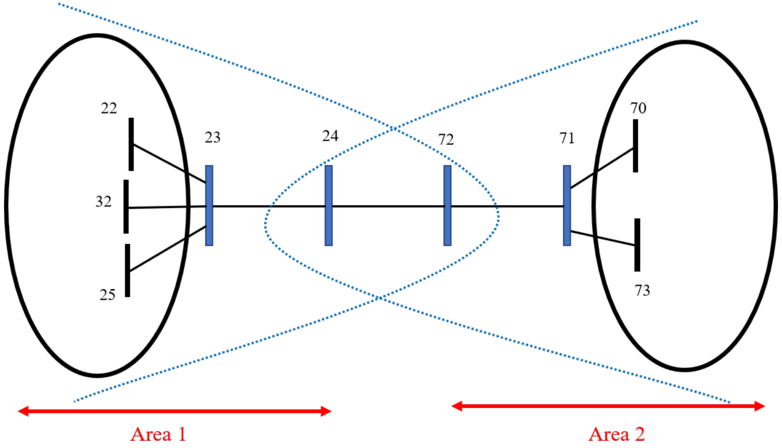
  - **Bad measurements / Robust estimator**

Detailed 3-Phase Model Using ATP



Boundary Configuration





Transmission Line that connects two areas between buses 24 and 72

Bad Data Testing

- Gross errors placed in the following locations:
  - Case 1: Interior of the transmission system (P_{23})
  - Case 2: Inner boundary of the transmission system (P_{24})
  - Case 3: Interior of the distribution system (P_{70})
  - Case 4: Inner boundary of the distribution system (P_{72})

Bad Data Results

Case 1:

Table 13: Bad Data Analysis Results: Case 1 – Area $\mathcal{G}_{(1,1)}$

	Original		Iteration 1	
Meas.	z_i	r_i^N	z_i	r_i^N
P_{23}	-0.02869	20.03	0.0503	0.001077
$P_{23,24}$	0.08247	19.90	–	0.0003111
$P_{23,25}$	-1.625	8.938	–	0.0003164
$P_{23,32}$	0.9308	8.022	–	0.0002817
$P_{22,23}$	-0.5328	6.084	–	0.0002382

BD Detected !

Bad Data Results

Case 2:

Table 14: Bad Data Analysis Results: Case 2 – MAT SE, Area $\mathcal{G}_{(1,1)}$

Meas.	Original z_i	Original r_i^N
P_{24}	-0.02708	1.798
Q_{24}	-0.1242	1.798
$\|V_{72}\|$	0.9800	1.798
$Q_{23,24}$	0.1090	0.5893
$Q_{8,30}$	0.2780	0.2514

Missed BD !

Table 15: Bad Data Analysis Results: Case 2 – Level 3 Coordinator

Meas.	Original z_i	Original r_i^N	Iteration 1 z_i	Iteration 1 r_i^N
P_{24}	-0.02708	20.03	-0.06711	0.01259
P_{72}	-0.1205	20.03	–	0.01259
$P_{23,24}$	0.08246	20.03	–	0.01259
$P_{71,72}$	0.1061	20.03	–	0.01259
$Q_{23,24}$	0.1089	11.95	–	0.007204

BD Detected !

Bad Data Results

Case 3:

Table 16: Bad Data Analysis Results: Case 3 – MDF SE, Area $\mathcal{G}_2$

Measurement	z_i	r_i^N
P_{70}^a	-0.7579	22.595
$P_{70,71}^a$	0.1739	9.241
$P_{71,70}^a$	-0.1735	9.132
$P_{69,70}^a$	1.0888	6.102
P_{74}^a	-0.6796	5.703

BD Detected !

Bad Data Results

Case 4:

Table 17: Bad Data Analysis Results: Case 4 – MDF SE, Area $\mathcal{G}_2$

Measurement	z_i	r_i^N
P_{72}^a	-0.1165	0.463
-	-	0.323
-	-	0.251

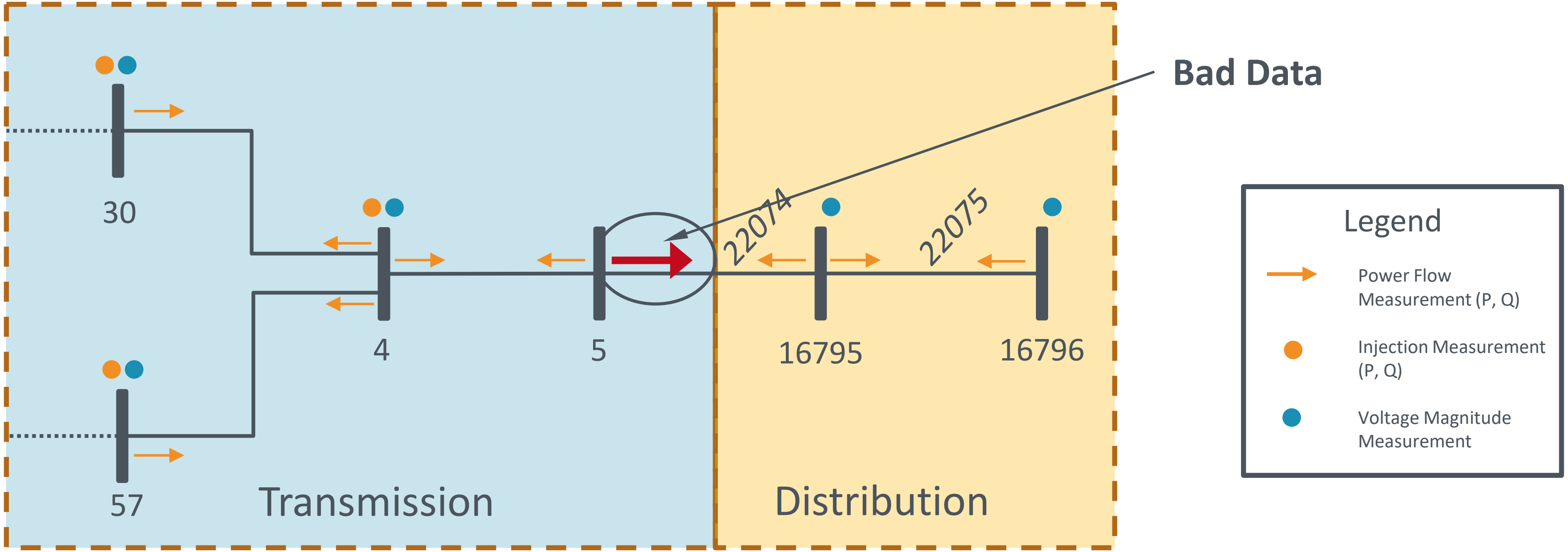
Missed BD !

Table 18: Bad Data Analysis Results: Case 4 – Level 3 Coordinator

	Original		Iteration 1	
Meas.	z_i	r_i^N	z_i	r_i^N
P_{72}	-0.08047	23.12	-0.1205	0.01215
P_{24}	-0.06708	23.12	–	0.01215
$P_{24,23}$	0.1061	8.777	–	0.006597
$P_{23,24}$	0.08246	8.755	–	0.004615
$P_{71,72}$	-0.08214	8.725	–	0.004595

BD Detected !

Large System: Gross error on the boundary



Bad Data Location	Level 1	Level 2	Level 3	Final MSE
$P_{5,16795}$	Not Detected	–	Corrected	1.92×10^{-7}

First Workshop at NEU – May 7, 2019 / NEU Campus

7 external speakers

- PNNL (2)
- NREL (2)
- U. California-R (1)
- ANL (1)
- ISO-NE (1)

3 NEU speakers

24 attendees

All presentations are posted on workshop web page: http://www1.ece.neu.edu/~abur/NEU_workshop/wkshop1.html

Final Workshop at PJM – Changed to Virtual

- Date: October 30, 2020
- Location: virtual
- NEU speakers (3)
- External speakers (4):
  - National Renewable Energy Laboratory, Colorado (2)
  - Pacific Northwest National Laboratory, Washington (1)
  - University of California-Riverside (1)

- All presentations are posted on workshop web page:

http://www1.ece.neu.edu/~abur/NEU_workshop/wkshop2.html

Contributions

- A combined transmission and distribution system state estimator is developed. The estimator is scalable to very large-scale grids and can detect, identify and remove bad data.

- Some of the useful byproducts of the project include a novel formulation of multiphase state estimation using virtual reference buses, a decoupled modal domain state estimation, and an efficient partitioning algorithm for large scale power grids for improved multiarea state estimation.

- The developed combined state estimator is successfully implemented and tested using the large 16Kbus PJM transmission system and four copies of the IEEE 8500-node test feeders.