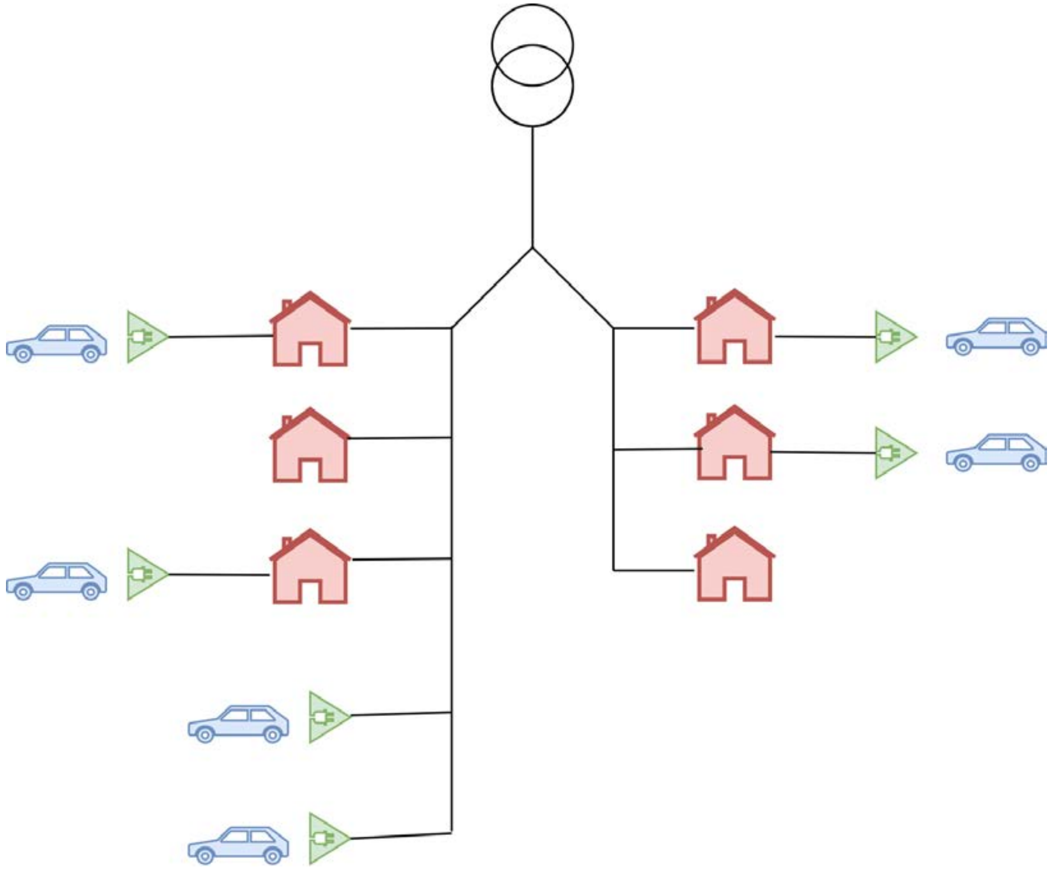

Grid State Estimation in Swarm Grids

Research Project

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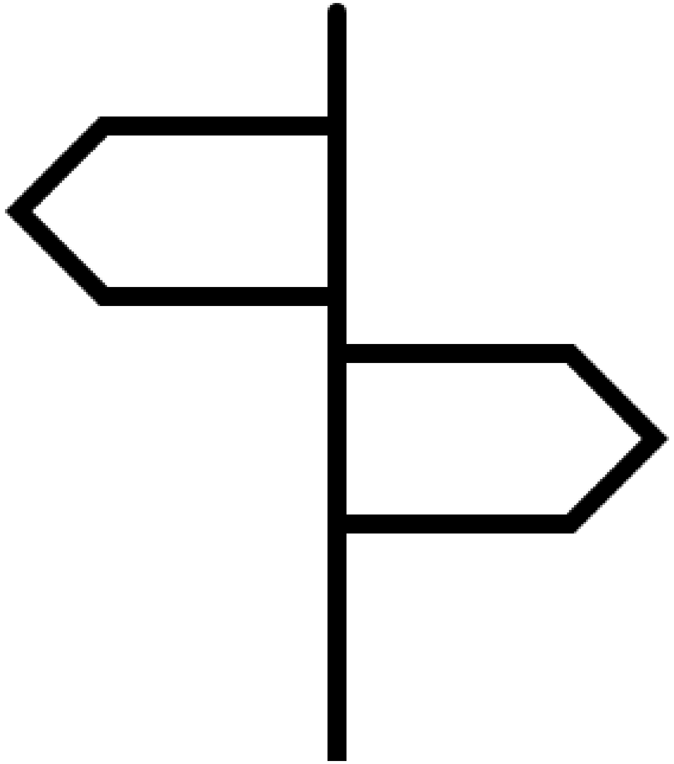
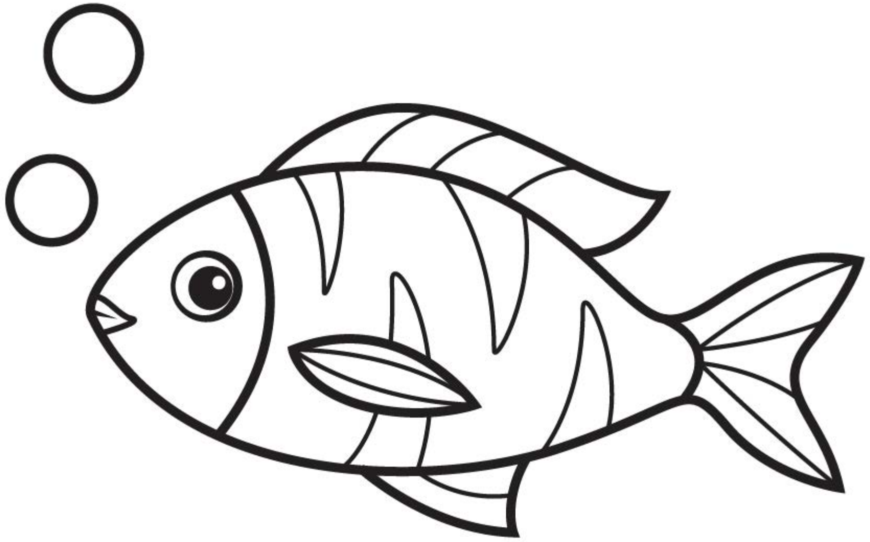
Content

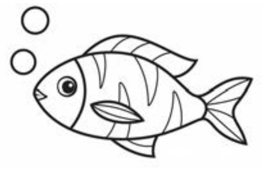
- Swarm Grid
- State Estimation
  - in Literature
  - Algorithm
  - Worst Case Analysis
  - Results
- Outlook



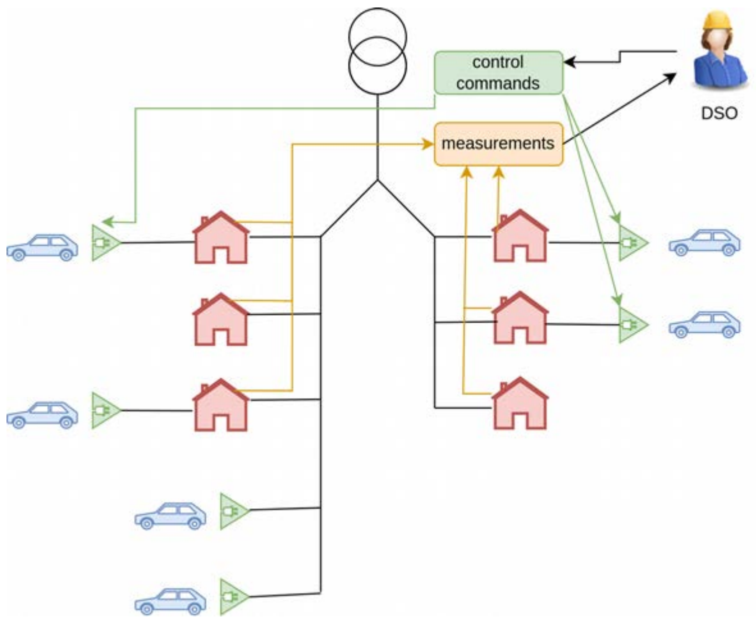
Swarm Grid



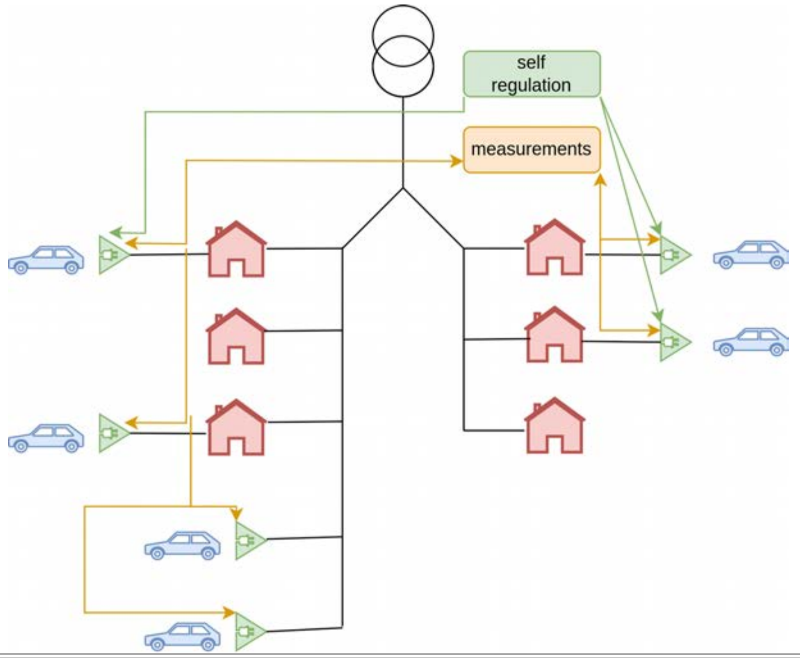
Swarm Grid

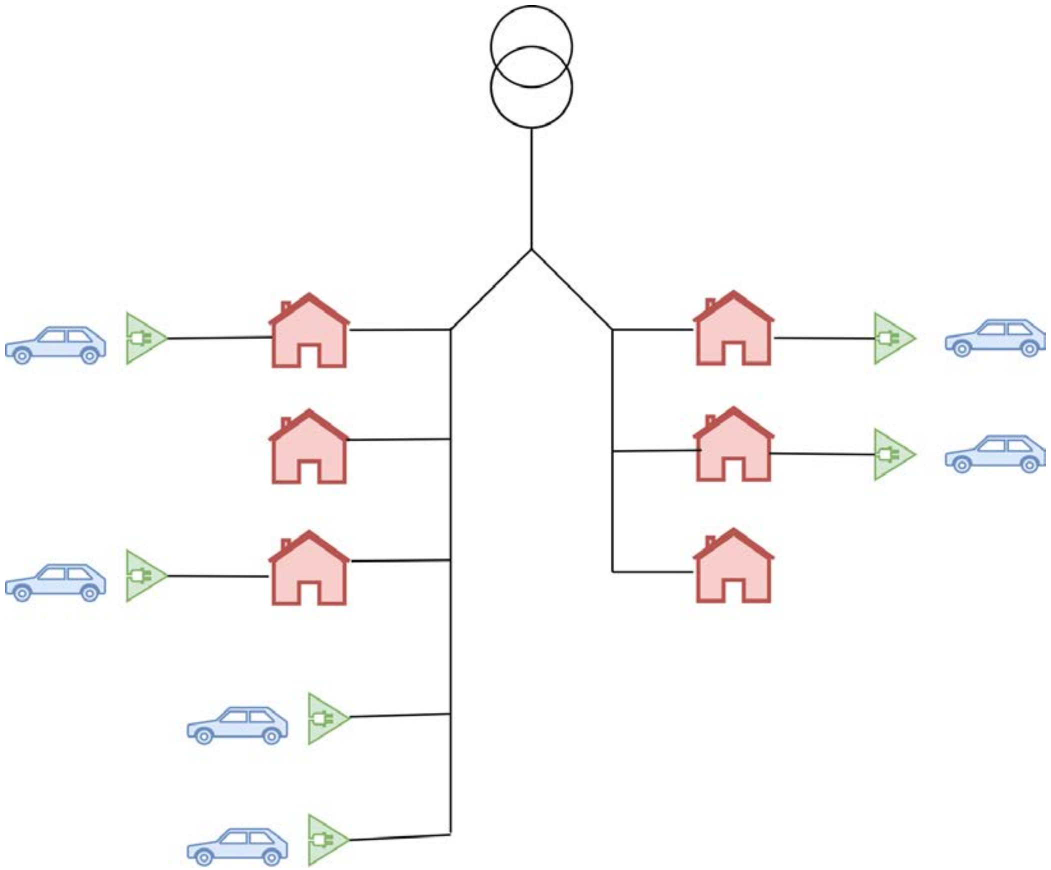


- Central Instance
  - Gathers measurements
  - Calculates network state
  - Sends control commands



- Swarm Grid Nodes
  - act independently
  - don’t rely on centralized instance
  - share information
  - share computing power

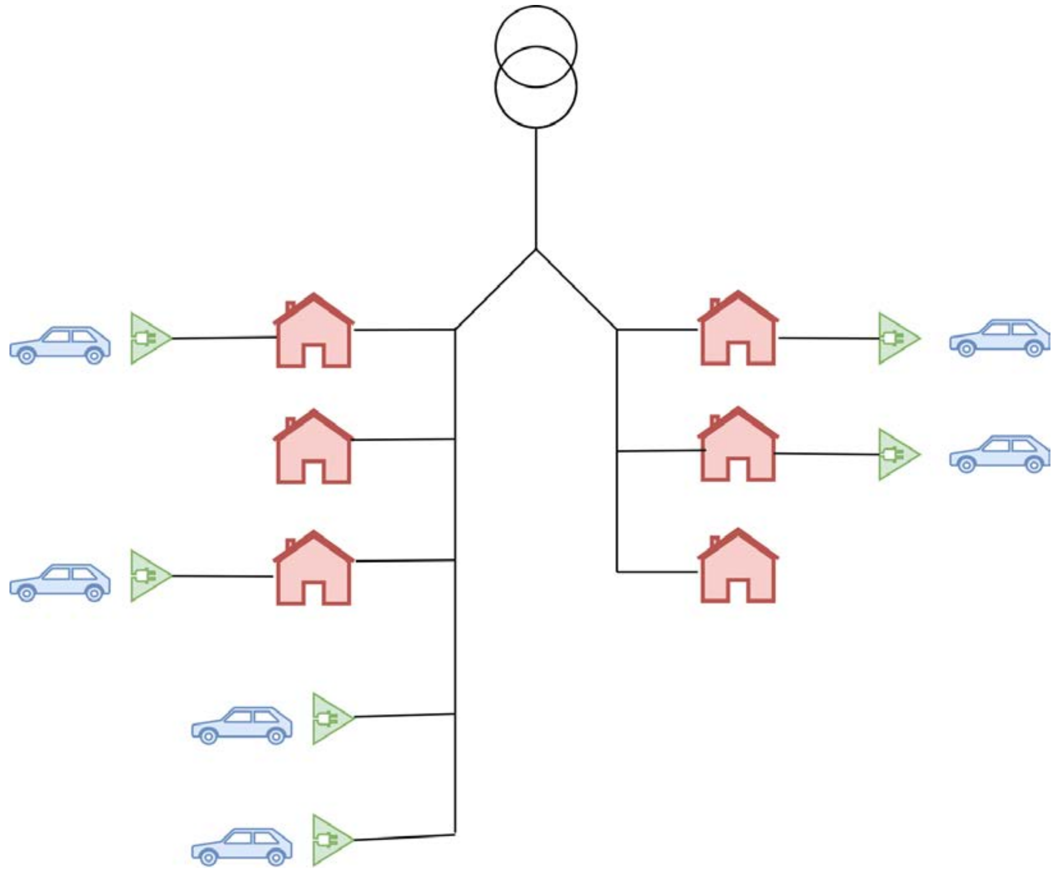




State Estimation

State Estimation

- Distribution System State Estimation (DSSE)
- Assumption:
  - Only some data is available
- Goal:
  - Estimate missing data
- Purpose:
  - **Prevent voltage limit violations**
  - Create load profiles
  - Localize faults
  - Outage Handling
  - Loss Monitoring



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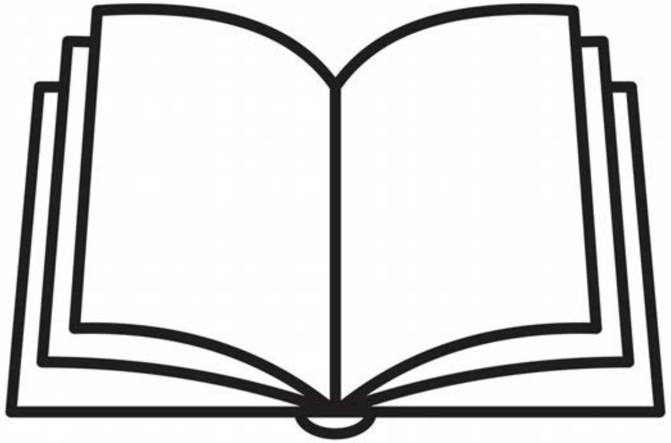

Literature

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State Estimation

in Literature (Wäresch 2018, Brandalik 2020)

- Low Voltage Systems are operated asymmetrically
  - Absolute value of line currents is not identical
  - Phase shift and voltages are different from symmetrical operation
  - Thus: Calculation using simplified symmetrical system is not possible (prone to errors)
- Solution: Split up into three symmetrical components
  - Positive sequence component (index 1)
  - Negative sequence component (index 2)
  - Zero sequence component (index 0)

in this research project

- Simplified symmetrical system
  - Accepting errors

$$\underline{Y}_{L123} = \begin{bmatrix} \underline{Y}_{L1L1} & \underline{Y}_{L1L2} & \underline{Y}_{L1L3} \\ \underline{Y}_{L2L1} & \underline{Y}_{L2L2} & \underline{Y}_{L2L3} \\ \underline{Y}_{L3L1} & \underline{Y}_{L3L2} & \underline{Y}_{L3L3} \end{bmatrix}$$

Three – phase admittance matrix

$$\underline{a} = e^{j\,120^\circ}$$

Complex AC operator

$$\underline{T} = \frac{1}{3} \cdot \begin{bmatrix} 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \\ 1 & 1 & 1 \end{bmatrix}$$

transformational matrix

$$\underline{Y}_{120} = \underline{T} \cdot \underline{Y}_{L123} \cdot \underline{T}^{-1}$$

State Estimation Algorithms

Model-based	**Forecasting-Aided**	**Data-driven**
A single set of measurement data	*Recursive updates of state estimation*	*Trained on existing data*
Weighted Least Squares	Kalman-based Filters	ANN / DNN
Least Absolute Value	Extended Kalman Filters	Physics aware neural networks (aware of structure of distribution network)
Least Trimmed Squares	Unscented Kalman Filters	
Least Median of Squares		
Generalized Maximum Likelihood		

State Estimation

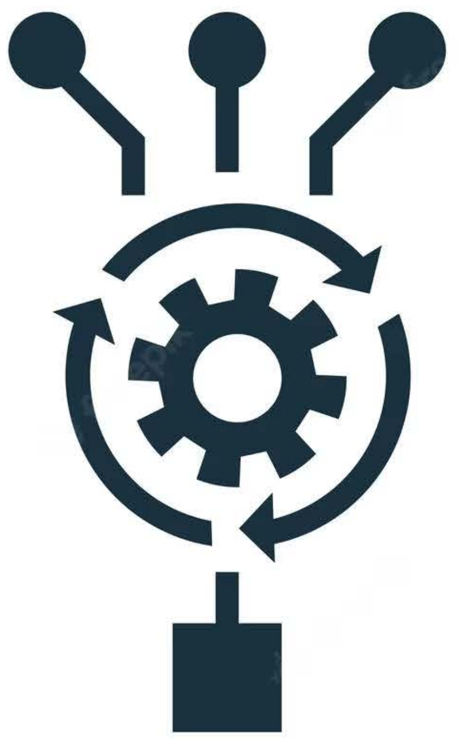
Literature

- In model-based algorithms
  - One fully known state vector
  - If values are unknown:
    filled with replacement values
    - Virtual measurements
    - Pseudo measurements
    - Historical data
- In data-driven & forecasting-aided algorithms
  - Historical data
  - Fresh measurements

Bad Data Detection

- Measurement data may be flawed
- Obvious wrong data needs to be removed before state estimation
- Additional available measurement data is helpful!

Model-based	Data-driven
L^2-Norm	Linear regression
Largest normalised residual	Support Vector machine
Chi-square test	ANN, CNN
	Margin Setting Algorithm
	K-Means Clustering

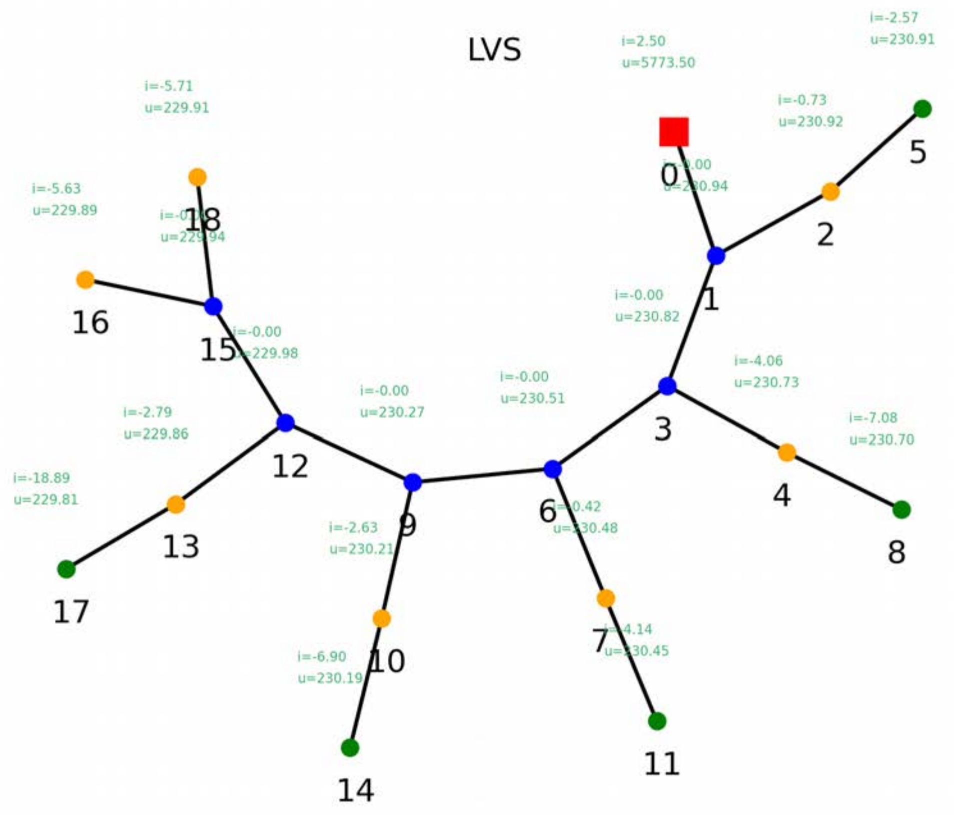


Algorithm

State Estimation

Starting Assumptions

- Network topology is known
  - Through topology estimation
  - Through manual input
- Nodal admittance matrix is available
- Measurement data is partially available
- Radial Network Topology
  - Meshes will be dealt with later
- Phase shift is known
  - Definition of a slack node (usually Transformer)



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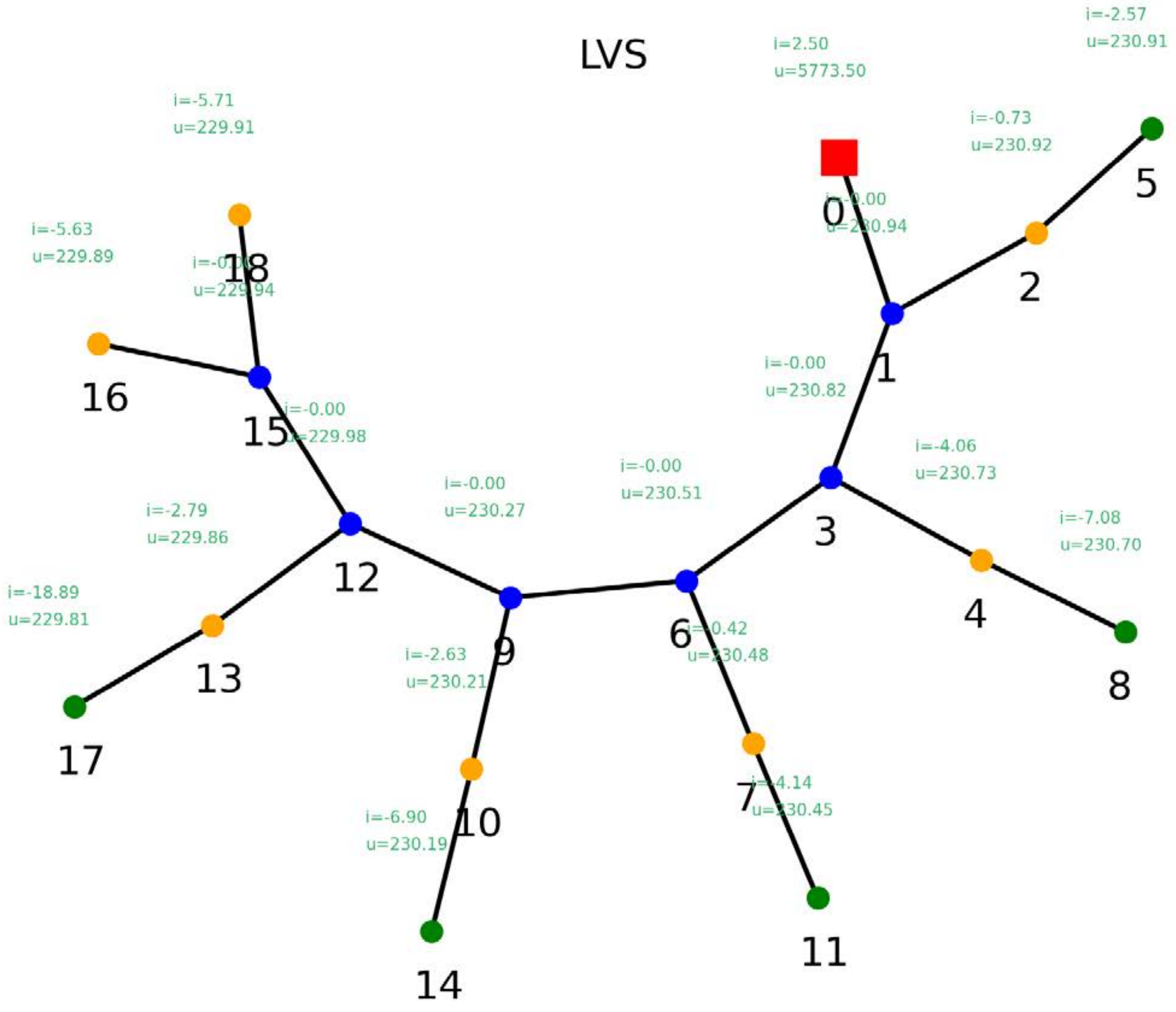
State Estimation

Example Grid, expected values

PandaPower Simulation



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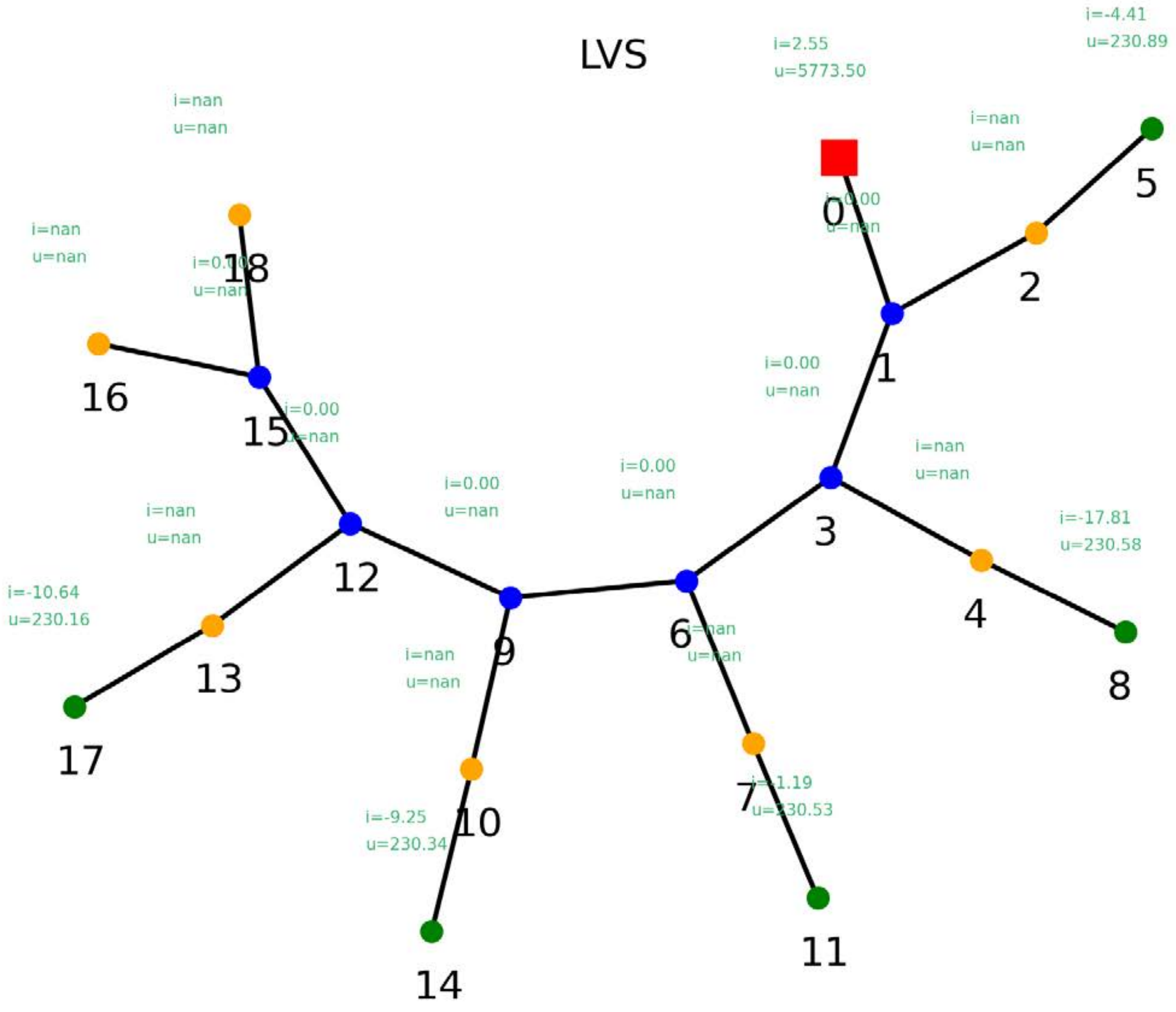
State Estimation

Example Grid, known values



State Estimation

Ohm's Law with incomplete Vectors

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{pmatrix} \cdot \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} = \begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \end{pmatrix}$$

$$\vec{U} * A = \vec{I}$$

State Estimation

Example Grid, Admittance matrix

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	(206.271...	(-5156.7...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
1	(-5156.7...	(129649....	(-207.36...	(-522.29...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
2	0j	(-207.36...	(429.906...	0j	0j	(-222.54...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
3	0j	(-522.29...	0j	(798.098...	(-119.14...	0j	(-156.65...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
4	0j	0j	0j	(-119.14...	(465.162...	0j	0j	0j	(-346.01...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
5	0j	0j	(-222.54...	0j	0j	(222.542...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
6	0j	0j	0j	(-156.65...	0j	0j	(487.126...	(-146.83...	0j	(-183.63...	0j	0j	0j	0j	0j	0j	0j	0j	0j
7	0j	0j	0j	0j	0j	0j	(-146.83...	(295.168...	0j	0j	0j	(-148.33...	0j	0j	0j	0j	0j	0j	0j
8	0j	0j	0j	0j	(-346.01...	0j	0j	0j	(346.016...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
9	0j	0j	0j	0j	0j	0j	(-183.63...	0j	0j	(476.167...	(-174.11...	0j	(-118.42...	0j	0j	0j	0j	0j	0j
10	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-174.11...	(589.015...	0j	0j	0j	(-414.90...	0j	0j	0j	0j
11	0j	0j	0j	0j	0j	0j	0j	(-148.33...	0j	0j	0j	(148.332...	0j	0j	0j	0j	0j	0j	0j
12	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-118.42...	0j	0j	(608.731...	(-189.17...	0j	(-301.13...	0j	0j	0j
13	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-189.17...	(598.722...	0j	0j	0j	(-409.54...	0j
14	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-414.90...	0j	0j	0j	(414.901...	0j	0j	0j	0j
15	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-301.13...	0j	0j	(619.252...	(-117.42...	0j	(-200.68...
16	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-117.42...	(117.429...	0j	0j
17	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-409.54...	0j	0j	0j	(409.547...	0j
18	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-200.68...	0j	0j	(200.689...

State Estimation

Transformation of Ohm's Law

$$\vec{U} \cdot A = \vec{I}$$

$$A[\beta,\gamma] \cdot \vec{U}[\gamma] - \vec{I}[\beta] = -A[\beta,\bar{\gamma}] \cdot \vec{U}[\bar{\gamma}]$$

γ, β are those row indices of known values in $\vec{U}$, $\vec{I}$

	0
0	(-29772753.66133539...
1	0j
2	(51387.97653982044-...
3	0j
4	(79807.97355003707-...
5	0j
6	(34199.548303289295...
7	0j
8	(95586.75897113197-...
9	0j
10	(94285.31958645425-...

=

	0	1	2	3	4	5	6	7	8	9	10	11	12
0	(-129649...	(207.363...	(522.292...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
1	(522.292...	(-0-0j)	(-798.09...	(119.146...	(156.659...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
2	(-0-0j)	(222.542...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
3	(-0-0j)	(-0-0j)	(156.659...	(-0-0j)	(-487.12...	(146.836...	(183.630...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
4	(-0-0j)	(-0-0j)	(-0-0j)	(346.016...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
5	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(183.630...	(-0-0j)	(-476.16...	(174.114...	(118.422...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
6	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(148.332...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
7	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(118.422...	(-0-0j)	(-608.73...	(189.174...	(301.134...	(-0-0j)	(-0-0j)
8	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(414.901...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
9	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(301.134...	(-0-0j)	(-619.25...	(117.429...	(200.689...
10	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(409.547...	(-0-0j)	(-0-0j)	(-0-0j)

$\cdot \vec{U}[\bar{\gamma}]$

State Estimation

Transformation of Ohm's Law

	0
0	(-29772753.66133539...
1	0j
2	(51387.97653982044-...
3	0j
4	(79807.97355003707-...
5	0j
6	(34199.548303289295...
7	0j
8	(95586.75897113197-...
9	0j
10	(94285.31958645425-...

=

	0	1	2	3	4	5	6	7	8	9	10	11	12
0	(-129649...	(207.363...	(522.292...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
1	(522.292...	(-0-0j)	(-798.09...	(119.146...	(156.659...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
2	(-0-0j)	(222.542...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
3	(-0-0j)	(-0-0j)	(156.659...	(-0-0j)	(-487.12...	(146.836...	(183.630...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
4	(-0-0j)	(-0-0j)	(-0-0j)	(346.016...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
5	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(183.630...	(-0-0j)	(-476.16...	(174.114...	(118.422...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
6	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(148.332...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
7	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(118.422...	(-0-0j)	(-608.73...	(189.174...	(301.134...	(-0-0j)	(-0-0j)
8	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(414.901...	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)
9	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(301.134...	(-0-0j)	(-619.25...	(117.429...	(200.689...
10	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(-0-0j)	(409.547...	(-0-0j)	(-0-0j)	(-0-0j)

$\cdot \vec{U}[\bar{\gamma}]$

Weighted Least Squares
- weights = measurement accuracies
- systematically fill in values in U
- minimize residuals between left side and right side

$\vec{U}[\bar{\gamma}]$ =

	0
0	(230.9299...
1	(230.9119...
2	(228.4224...
3	(230.6347...
4	(218.3800...
5	(230.5433...
6	(200.0866...
7	(230.3591...
8	(127.2110...
9	(230.1855...
10	(33.86325...
11	(-37.6570...
12	(-64.3566...

State Estimation

Fill partial vector into full vector

$\vec{U}[\bar{\gamma}]$ =

	0
0	(230.9299...
1	(230.9119...
2	(228.4224...
3	(230.6347...
4	(218.3800...
5	(230.5433...
6	(200.0866...
7	(230.3591...
8	(127.2110...
9	(230.1855...
10	(33.86325...
11	(-37.6570...
12	(-64.3566...

$\vec{U}$ =

	0
0	(5773.50...
1	(230.929...
2	(230.911...
3	(228.422...
4	(230.634...
5	(230.891...
6	(218.380...
7	(230.543...
8	(230.580...
9	(200.086...
10	(230.359...
11	(230.534...
12	(127.211...
13	(230.185...
14	(230.335...
15	(33.8632...
16	(-37.657...
17	(230.158...
18	(-64.356...

State Estimation

Preparation for Constrained Least Squares

$\vec{U}$ =

	0
0	(5773.50...
1	(230.929...
2	(230.911...
3	(228.422...
4	(230.634...
5	(230.891...
6	(218.380...
7	(230.543...
8	(230.580...
9	(200.086...
10	(230.359...
11	(230.534...
12	(127.211...
13	(230.185...
14	(230.335...
15	(33.8632...
16	(-37.657...
17	(230.158...
18	(-64.356...

Incomplete vector $\vec{I}_1$

$$\vec{I}_2 = A * \vec{U}$$

Minimize: $||\vec{I}_{2_c} - \vec{I}_{1_c}||_2$

State Estimation

Constrained Least Squares

Minimize: $$||\vec{I}_{2_c} - \vec{I}_{1_c}||_2$$

Constraints: sum(I) = 0
Boundaries:
- Consuming nodes: I < 0
- Producing nodes: I > 0
- Voltages in defined range e.g. 210 < U < 250

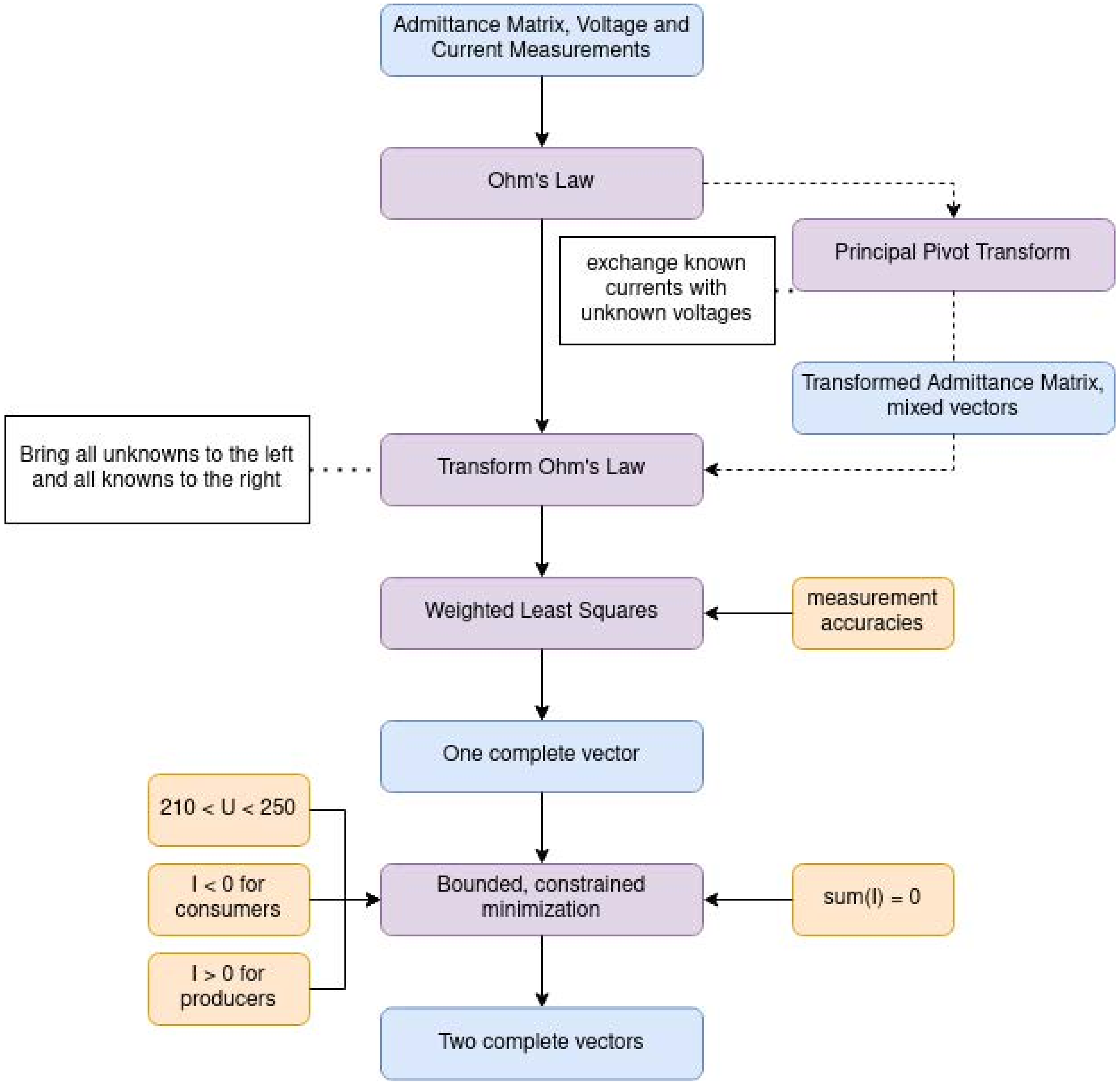
Weights:
- measurement accuracies

$\vec{I}$ =

	0
0	(5.79346...
1	(0.00099...
2	(-2.0878...
3	(0.00099...
4	(-9.4508...
5	(-4.4077...
6	(0.00099...
7	(-6.1344...
8	(-17.804...
9	(0.00099...
10	(-1.8111...
11	(-1.1925...
12	(0.00099...
13	(-6.6980...
14	(-9.2519...
15	(0.00099...
16	(-49.999...
17	(-10.637...
18	(-49.999...

State Estimation

Overview



State Estimation

Principal Pivot Transform

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ u_5 \end{pmatrix} \cdot \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} = \begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \end{pmatrix}$$

$$\vec{U} * A = \vec{I}$$

Exchange elements from
Current to voltage vector
- requires Matrix transformation

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ i_5 \end{pmatrix} \cdot \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \\ b_{41} & b_{42} & b_{43} & b_{44} & b_{45} \\ b_{51} & b_{52} & b_{53} & b_{54} & b_{55} \end{bmatrix} = \begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ u_5 \end{pmatrix}$$

State Estimation

Principal Pivot Transform

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \\ \boxed{i_5} \end{pmatrix} \cdot \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \\ b_{41} & b_{42} & b_{43} & b_{44} & b_{45} \\ b_{51} & b_{52} & b_{53} & b_{54} & b_{55} \end{bmatrix} = \begin{pmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ \boxed{u_5} \end{pmatrix}$$

$$ppt(A, \alpha) = \begin{bmatrix} A[\alpha]^{-1} & -A[\alpha]^{-1} * A[\alpha, \bar{\alpha}] \\ A[\bar{\alpha}, \alpha] * A[\alpha]^{-1} & A[\bar{\alpha}] - A[\bar{\alpha}, \alpha] * A[\alpha]^{-1} * A[\alpha, \bar{\alpha}] \end{bmatrix}$$

State Estimation

Principal Pivot Transform

$A =$

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	(206.271...	(-5156.7...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
1	(-5156.7...	(129649....	(-207.36...	(-522.29...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
2	0j	(-207.36...	(429.906...	0j	0j	(-222.54...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
3	0j	(-522.29...	0j	(798.098...	(-119.14...	0j	(-156.65...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
4	0j	0j	0j	(-119.14...	(465.162...	0j	0j	0j	(-346.01...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
5	0j	0j	(-222.54...	0j	0j	(222.542...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
6	0j	0j	0j	(-156.65...	0j	0j	(487.126...	(-146.83...	0j	(-183.63...	0j	0j	0j	0j	0j	0j	0j	0j	0j
7	0j	0j	0j	0j	0j	0j	(-146.83...	(295.168...	0j	0j	0j	(-148.33...	0j	0j	0j	0j	0j	0j	0j
8	0j	0j	0j	0j	(-346.01...	0j	0j	0j	(346.016...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
9	0j	0j	0j	0j	0j	0j	(-183.63...	0j	0j	(476.167...	(-174.11...	0j	(-118.42...	0j	0j	0j	0j	0j	0j
10	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-174.11...	(589.015...	0j	0j	0j	(-414.90...	0j	0j	0j	0j
11	0j	0j	0j	0j	0j	0j	0j	(-148.33...	0j	0j	0j	(148.332...	0j	0j	0j	0j	0j	0j	0j
12	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-118.42...	0j	0j	(608.731...	(-189.17...	0j	(-301.13...	0j	0j	0j
13	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-189.17...	(598.722...	0j	0j	0j	(-409.54...	0j
14	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-414.90...	0j	0j	0j	(414.901...	0j	0j	0j	0j
15	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-301.13...	0j	0j	(619.252...	(-117.42...	0j	(-200.68...
16	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-117.42...	(117.429...	0j	0j
17	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-409.54...	0j	0j	0j	(409.547...	0j
18	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-200.68...	0j	0j	(200.689...

$\alpha =$ [1, 3, 6, 9, 12, 15]

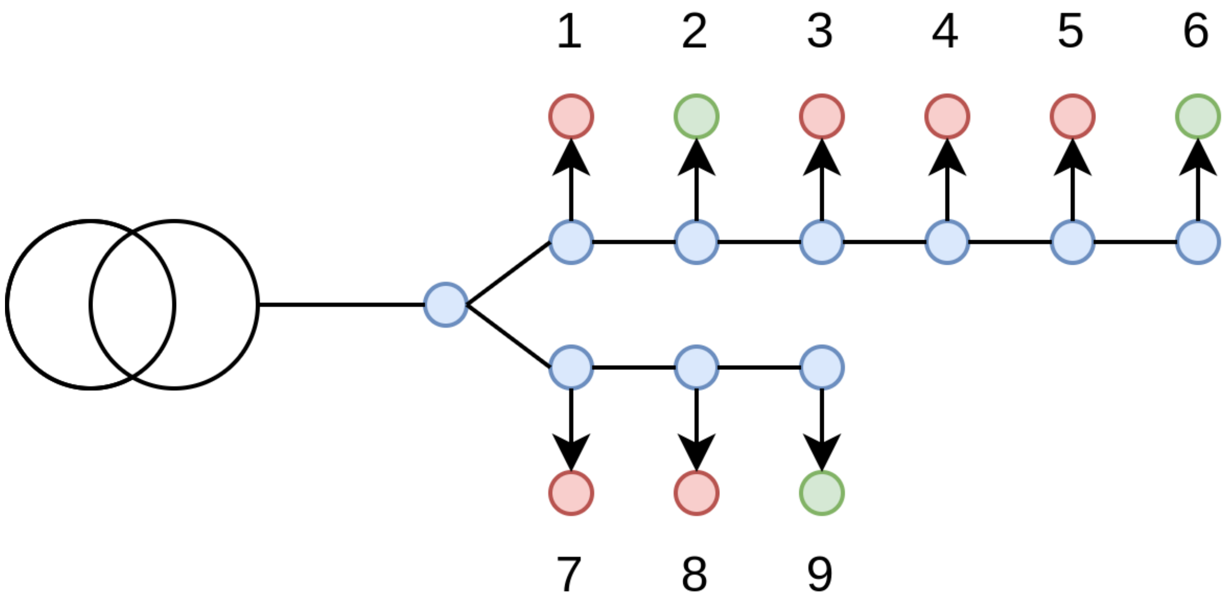
$ppt(A, \alpha) =$

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
0	(0.57480...	(-0.0398...	(-8.2714...	(-0.0282...	(-3.3613...	0j	(-0.0107...	(-1.5771...	0j	(-0.0044...	(-0.7702...	0j	(-0.0011...	(-0.2143...	0j	(-0.0005...	(-0.0647...	0j	(-0.1105...
1	(0.03988...	(6.86590...	(0.00160...	(4.85608...	(0.00065...	(-0-0j)	(1.84876...	(0.00030...	(-0-0j)	(7.61476...	(0.00014...	(-0-0j)	(1.95062...	(4.15691...	(-0-0j)	(9.48561...	(1.25480...	(-0-0j)	(2.14449...
2	(-8.2714...	(-0.0016...	(429.573...	(-0.0011...	(-0.1351...	(-222.54...	(-0.0004...	(-0.0634...	0j	(-0.0001...	(-0.0309...	0j	(-4.5566...	(-0.0086...	0j	(-2.2158...	(-0.0026...	0j	(-0.0044...
3	(0.02821...	(4.85608...	(0.00113...	(0.00120...	(0.16180...	(-0-0j)	(0.00045...	(0.07591...	(-0-0j)	(0.00018...	(0.03707...	(-0-0j)	(4.84284...	(0.01031...	(-0-0j)	(2.35500...	(0.00311...	(-0-0j)	(0.00532...
4	(-3.3613...	(-0.0006...	(-0.1351...	(-0.1618...	(445.884...	0j	(-0.0616...	(-9.0453...	(-346.01...	(-0.0253...	(-4.4177...	0j	(-0.0064...	(-1.2295...	0j	(-0.0031...	(-0.3711...	0j	(-0.6343...
5	0j	0j	(-222.54...	0j	0j	(222.542...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
6	(0.01074...	(1.84876...	(0.00043...	(0.00045...	(0.06160...	(-0-0j)	(0.00233...	(0.38574...	(-0-0j)	(0.00096...	(0.18839...	(-0-0j)	(0.00024...	(0.05243...	(-0-0j)	(0.00011...	(0.01582...	(-0-0j)	(0.02705...
7	(-1.5771...	(-0.0003...	(-0.0634...	(-0.0759...	(-9.0453...	0j	(-0.3857...	(238.527...	0j	(-0.1588...	(-27.663...	(-148.33...	(-0.0406...	(-7.6992...	0j	(-0.0197...	(-2.3241...	0j	(-3.9719...
8	0j	0j	0j	0j	(-346.01...	0j	0j	0j	(346.016...	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j
9	(0.00442...	(7.61476...	(0.00017...	(0.00018...	(0.02537...	(-0-0j)	(0.00096...	(0.15888...	(-0-0j)	(0.00238...	(0.46813...	(-0-0j)	(0.00061...	(0.13029...	(-0-0j)	(0.00029...	(0.03932...	(-0-0j)	(0.06721...
10	(-0.7702...	(-0.0001...	(-0.0309...	(-0.0370...	(-4.4177...	0j	(-0.1883...	(-27.663...	0j	(-0.4681...	(507.506...	0j	(-0.1199...	(-22.685...	(-414.90...	(-0.0583...	(-6.8478...	0j	(-11.703...
11	0j	0j	0j	0j	0j	0j	0j	(-148.33...	0j	0j	0j	(148.332...	0j	0j	0j	0j	0j	0j	0j
12	(0.00113...	(1.95062...	(4.55660...	(4.84284...	(0.00649...	(-0-0j)	(0.00024...	(0.04069...	(-0-0j)	(0.00061...	(0.11991...	(-0-0j)	(0.00207...	(0.44258...	(-0-0j)	(0.00101...	(0.13359...	(-0-0j)	(0.22832...
13	(-0.2143...	(-4.1569...	(-0.0086...	(-0.0103...	(-1.2295...	0j	(-0.0524...	(-7.6992...	0j	(-0.1302...	(-22.685...	0j	(-0.4425...	(514.996...	0j	(-0.2152...	(-25.273...	(-409.54...	(-43.192...
14	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-414.90...	0j	0j	0j	(414.901...	0j	0j	0j	0j
15	(0.00055...	(9.48561...	(2.21581...	(2.35500...	(0.00316...	(-0-0j)	(0.00011...	(0.01979...	(-0-0j)	(0.00029...	(0.05831...	(-0-0j)	(0.00101...	(0.21522...	(-0-0j)	(0.00192...	(0.25459...	(-0-0j)	(0.43511...
16	(-0.0647...	(-1.2548...	(-0.0026...	(-0.0031...	(-0.3711...	0j	(-0.0158...	(-2.3241...	0j	(-0.0393...	(-6.8478...	0j	(-0.1335...	(-25.273...	0j	(-0.2545...	(87.5320...	0j	(-51.095...
17	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	0j	(-409.54...	0j	0j	0j	(409.547...	0j
18	(-0.1105...	(-2.1444...	(-0.0044...	(-0.0053...	(-0.6343...	0j	(-0.0270...	(-3.9719...	0j	(-0.0672...	(-11.703...	0j	(-0.2283...	(-43.192...	0j	(-0.4351...	(-51.095...	0j	(113.366...

State Estimation

Principal Pivot Transform

- Transformation results in equation system with fewer equations and fewer unknowns
- Mostly similar results
- Results in different matrix shape m x n with m >= n
  - Allows minimization for overdetermined systems using QR Decomposition
- Python Library for PPT published on Github

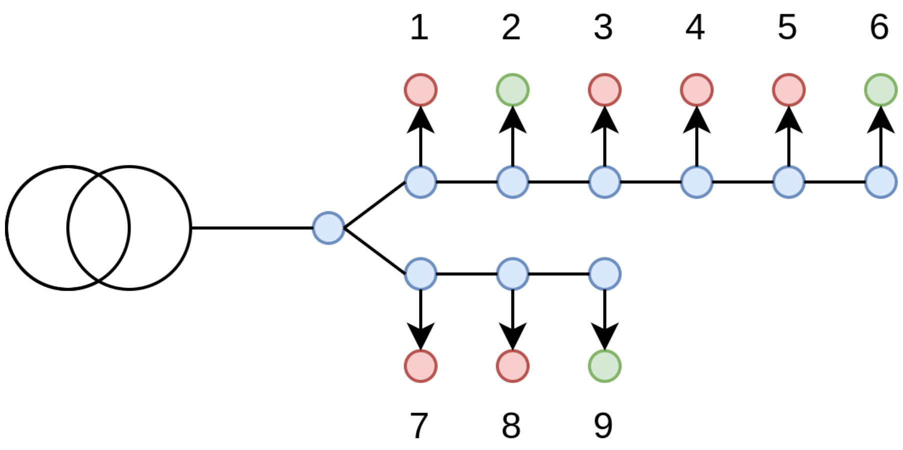


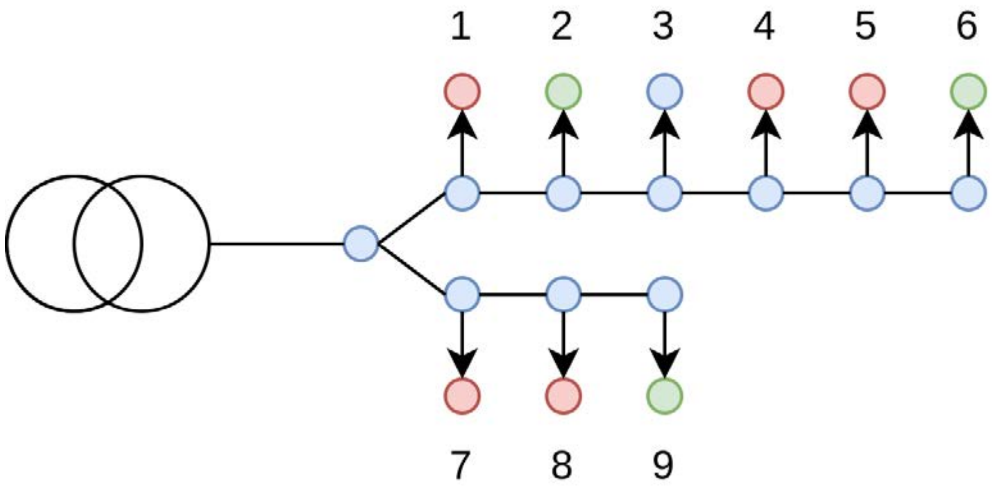
Worst Case Analysis

Worst Case Analysis

Improvement Strategies

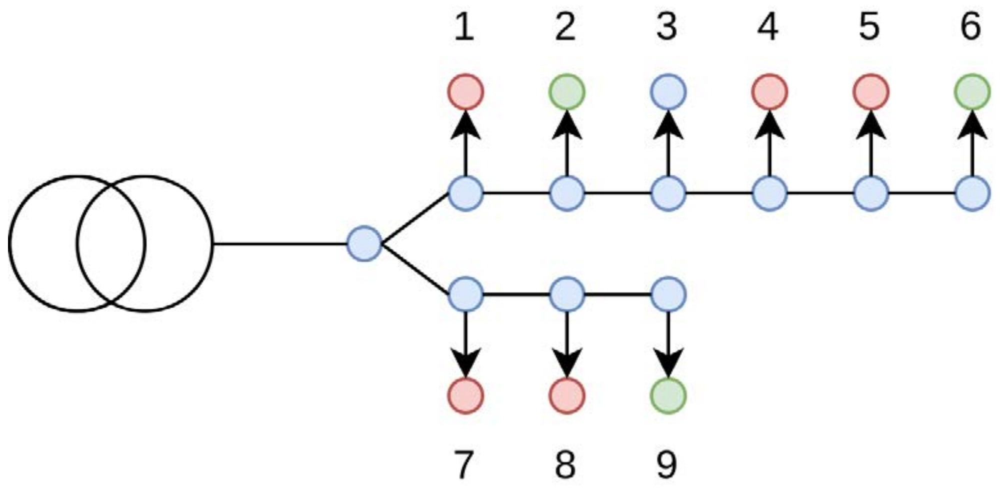
- Transform estimation bus to Zero Injection Bus (ZIB)
- Worst case:
  - Power consumption at the end of line
  - Results in highest line currents
  - And highest voltage drops
- Remove estimation bus at the beginning of line (closest to nearest measurement bus)

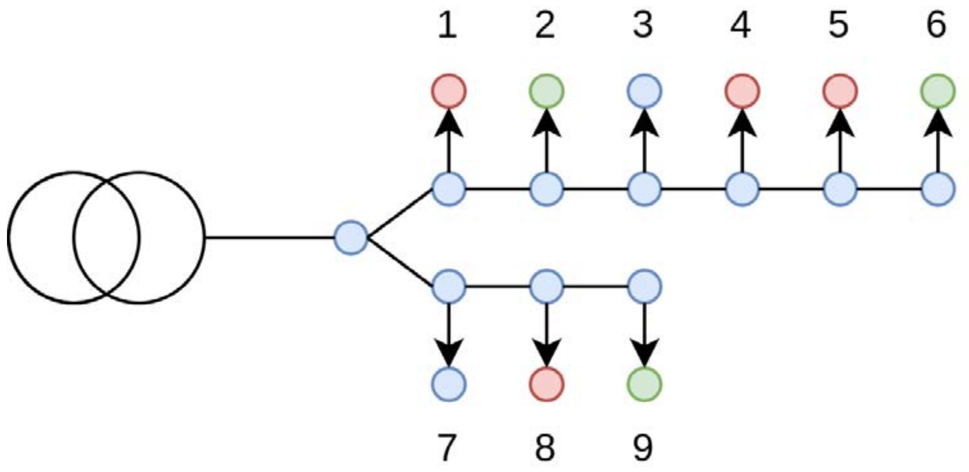




Worst Case Analysis

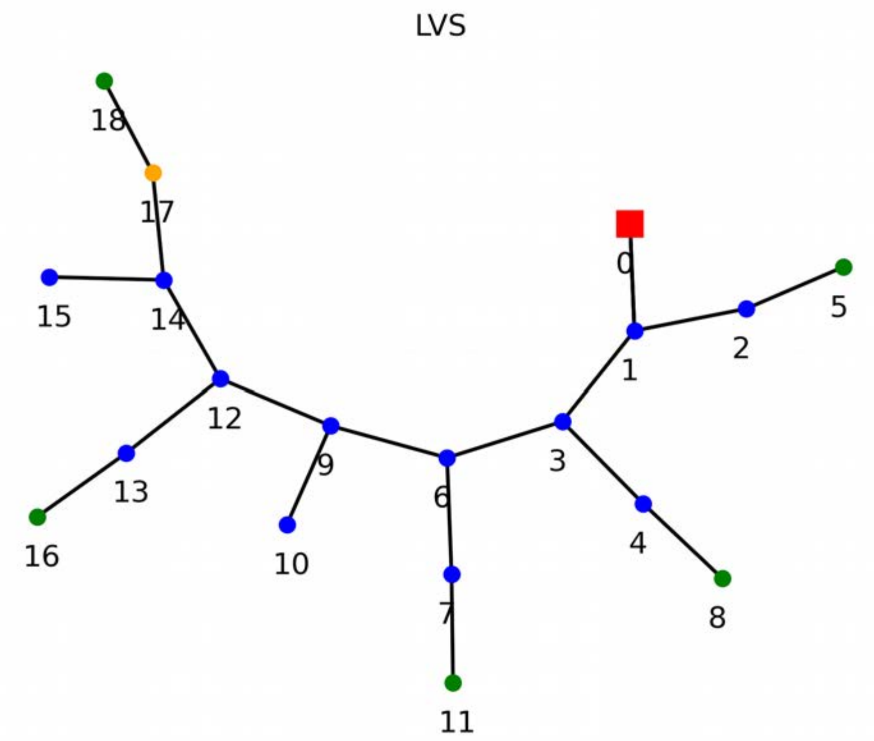
Improvement Strategies





Worst Case Analysis

Problematic Topologies



	0	1	2	3	4	5	6	7	8	9
u_exp	(5773.50...	(230.939...	(230.924...	(230.581...	(230.405...	(230.875...	(230.402...	(230.209...	(230.266...	(230.229...
u_xlm	(5773.50...	(230.939...	(230.924...	(230.556...	(230.405...	(230.875...	(230.346...	(230.209...	(230.266...	(230.058...
u_elm	(5773.50...	(230.944...	(230.867...	(230.536...	(230.410...	(230.875...	(230.373...	(230.203...	(230.266...	(229.992...

	10	11	12	13	14	15	16	17	18
u_exp	(230.225...	(230.090...	(230.180...	(230.125...	(230.067...	(230.031...	(230.123...	(230.028...	(229.973...
u_xlm	(253.912...	(230.090...	(215.817...	(230.125...	(150.164...	(-33.981...	(230.123...	(230.028...	(229.973...
u_elm	(248.761...	(230.090...	(218.932...	(230.125...	(210.000...	(22.6306...	(230.123...	(230.028...	(229.973...

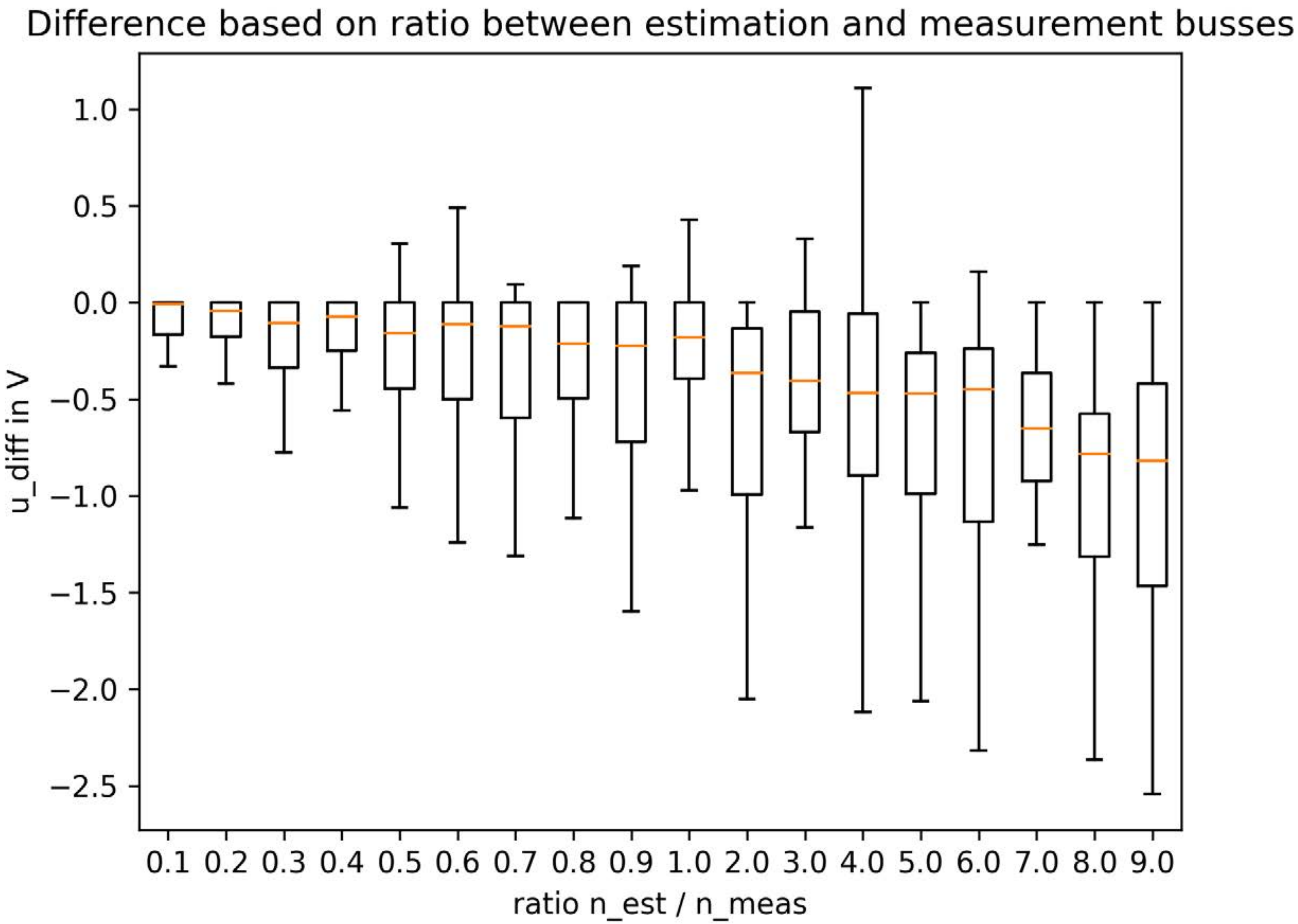
	0	1	2	3	4	5	6	7	8	9
i_exp	(3.20986...	(-0+0j)	(-3.2780...	(-0+0j)	(-3.5292...	(-6.1295...	(-0+0j)	(-6.8708...	(-19.778...	(-0+0j)
i_xlm	(4.03873...	(0.001+0...	(0.001+0...	(0.001+0...	(0.001+0...	(-6.1302...	(0.001+0...	(0.001+0...	(-19.779...	(0.001+0...
i_elm	(0.02724...	0j	0j	0j	0j	(-6.1305...	0j	0j	(-19.779...	0j

	10	11	12	13	14	15	16	17	18
i_exp	(-1.2594...	(-17.014...	(-0+0j)	(-6.4813...	(-0+0j)	(-5.1670...	(-1.0108...	(-2.3495...	(-6.5113...
i_xlm	0j	(-17.015...	(0.001+0...	0j	(0.001+0...	(-50+0j)	(-1.0116...	0j	(-6.5121...
i_elm	(-1.4793...	(-17.013...	0j	(-4.7888...	0j	(-49.999...	(-1.0118...	(-4.4290...	(-6.5122...

Results

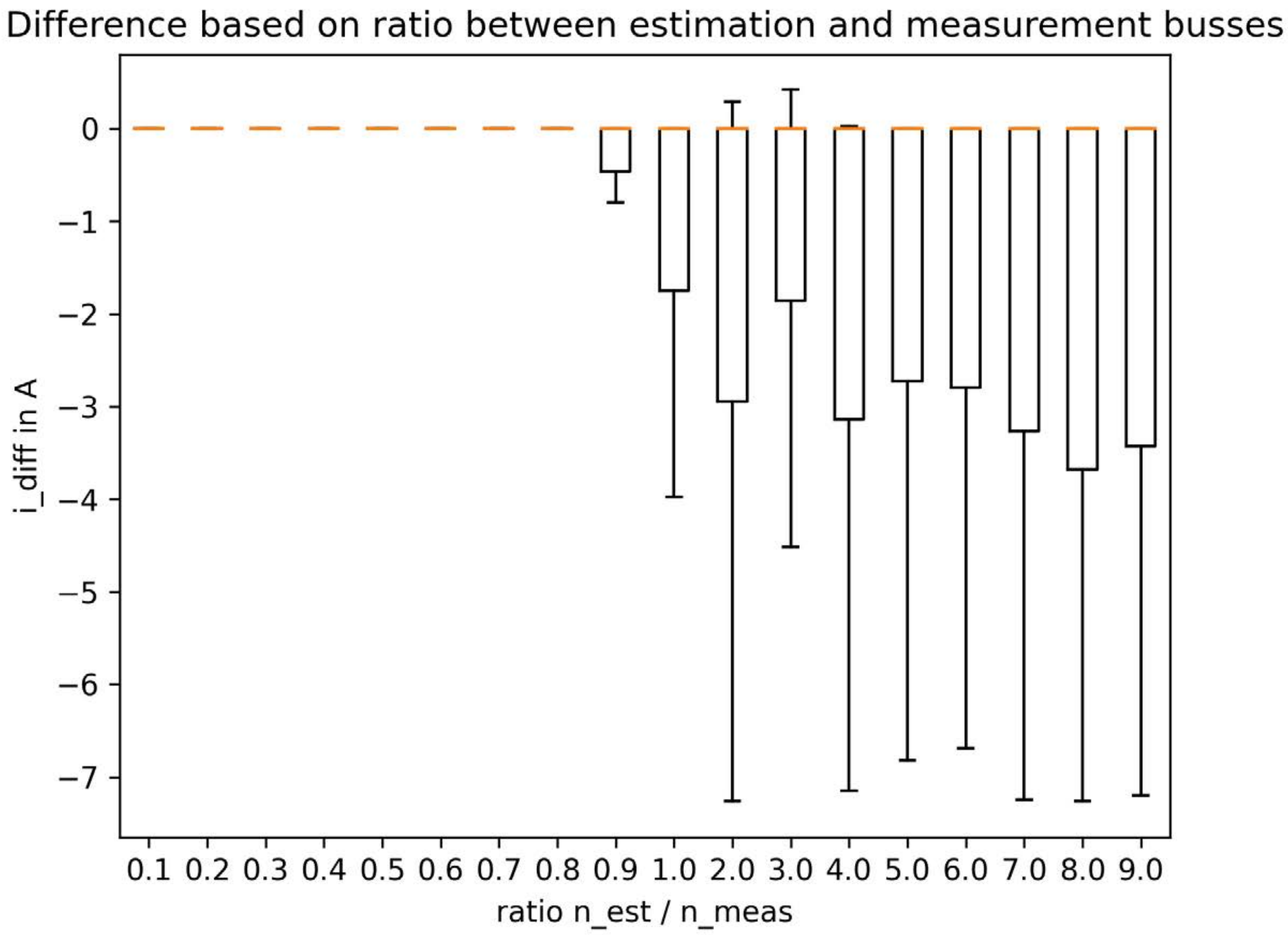
Results

- Lower ratios:
  - more known values
  - better results
- 21000 grids



Results

- Extremely accurate for low ratios
- Caveats:
  - Also shows ZIB
  - Outliers removed
  - Not all ratios represented equally



Outlook

Outlook

- Combination of Topology Estimation and State Estimation
- Improve worst case assumptions
- Asymmetrical network calculations
- Compare multiple algorithms