On Testing a Linear State Estimator Using Hardware in the Loop Testing Facilities

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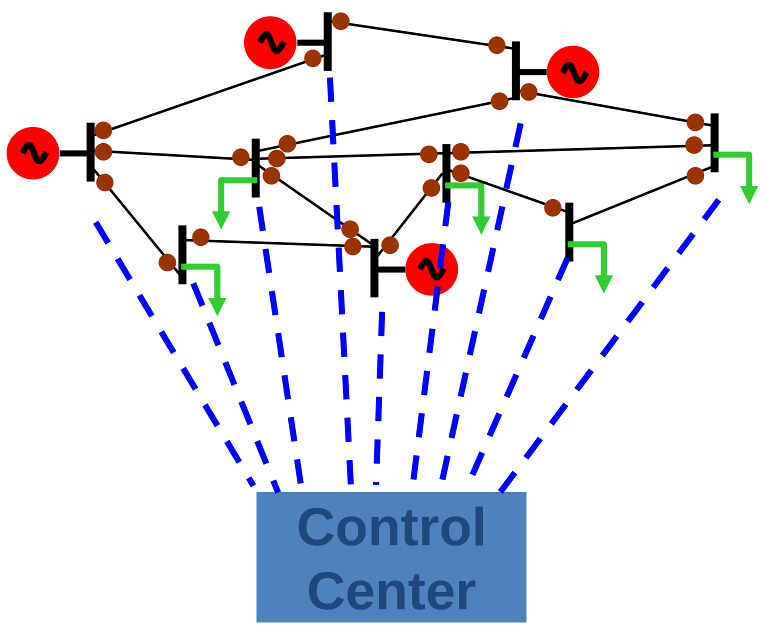
Power system state estimation

Present practice



Measurements
are scanned
and are NOT
time synchronized

Measurements
are primarily
P_i, Q_i, P_t, Q_t, V ([z])

State is the vector
of positive sequence
voltages at all
network buses ([E])

Phasor measurement based state estimation offers many advantages as will be seen later.

State Estimation Solution

Non-linear problem!

- The state vector **x** contains voltage magnitudes and phases at all busses (considered as unknown model parameters)

$$\mathbf{x}^T = \left[\theta_2 \theta_3 \cdots \theta_N V_1 V_2 \cdots V_N\right]$$

- m-dimensional measurement vector **z** is defined as follows:

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

- **h**(**x**) is a non-linear relationship between the measured data and unknown parameters (e.g. see equation bellow)
  - Real power injection at Bus *i*

$$P_i = V_i^2 \sum_{j=1}^{N} V_j \left(G_{ij} \cos\left(\theta_i - \theta_j\right) + B_{ij} \sin\left(\theta_i - \theta_j\right)\right)$$

  - Real power flow from Bus *i* to Bus *j*

$$P_{ij} = V_i^2 \left(g_{si} + g_{ij}\right) - V_i V_j \left(g_{ij} \cos\left(\theta_i - \theta_j\right) + b_{ij} \sin\left(\theta_i - \theta_j\right)\right)$$

State Estimation Solution

Non-linear problem!

- The WLS estimator will find the solution which minimizes the following objective function:

$$J(\mathbf{x}) = \sum_{i=1}^{m} \frac{\left(z_i - h_i(\mathbf{x})\right)^2}{R_{ii}} = \left[\mathbf{z} - \mathbf{h}(\mathbf{x})\right]^T \mathbf{R}^{-1} \left[\mathbf{z} - \mathbf{h}(\mathbf{x})\right]$$

- At the minimum, the first-order optimality condition will have to be satisfied:

$$\mathrm{g}(\mathbf{x}) = -\frac{1}{2}\frac{\partial J(\mathbf{x})}{\partial \mathbf{x}} = \mathbf{H}^T(\mathbf{x})\mathbf{R}^{-1}\left[\mathbf{z} - \mathbf{h}(\mathbf{x})\right] = \mathbf{0}$$

$$\mathbf{H}(\mathbf{x}) = \frac{\partial h(\mathbf{x})}{\partial \mathbf{x}}$$ Jacobian matrix

State Estimation Solution

Non-linear problem!

- Expanding the g(x) into Taylor series around the estimated state vector at the kth iteration, x^k

$$\mathrm{g}(\mathbf{x}) = \mathrm{g}(\mathbf{x}^k) + \mathbf{G}(\mathbf{x}^k)(\mathbf{x} - \mathbf{x}^k) + \mathrm{L}$$

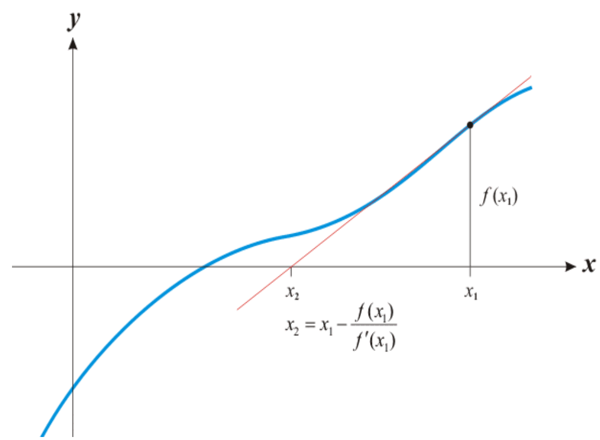
where

$$\mathbf{G}(\mathbf{x}^k) = \frac{\partial \mathrm{g}(\mathbf{x}^k)}{\partial \mathbf{x}} = -\mathbf{H}^T(\mathbf{x}^k)\mathbf{R}^{-1}\mathbf{H}(\mathbf{x}^k)$$

- Using the Newton-Raphson method, the solution is given through an <u>iterative procedure</u>, as follows

$$\mathbf{x}^{k+1} = \mathbf{x}^k - \left[\mathbf{G}(\mathbf{x}^k)\right]^{-1} \mathrm{g}(\mathbf{x}^k) = \mathbf{x}^k + \Delta\mathbf{x}^k$$

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



State Estimation Solution

Non-linear problem!

- Convergence is checked after each iteration

$$\max\left(\Delta\mathbf{x}^k\right) < \xi$$

- If this condition is not satisfied

$$\mathbf{x}^{k+1} = \mathbf{x}^k + \Delta\mathbf{x}^k$$

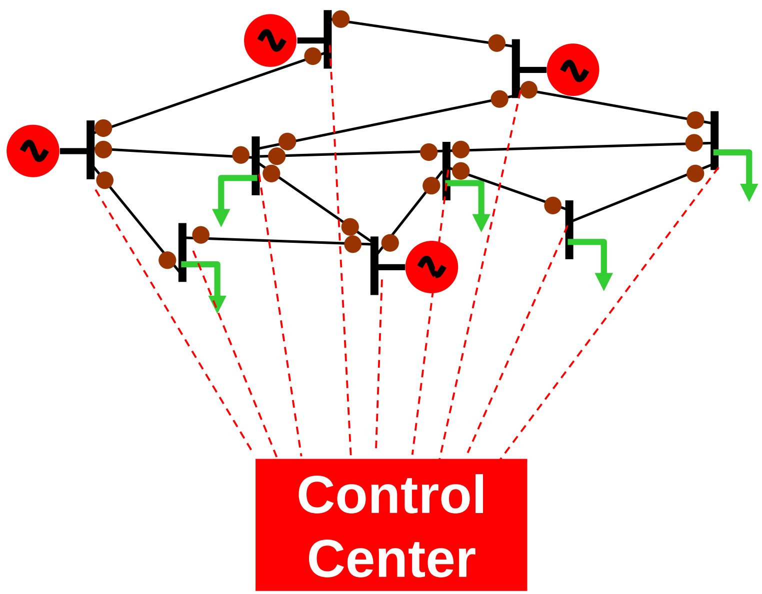
$$k = k + 1$$

Go to the previous step

- The final estimate is found when the convergence criterion is satisfied within the pre-defined maximum iteration number. Or, the state equation is divergent, and the measurement set should be checked.

State Estimation Using SMT

Estimation with phasors



Since the currents and voltages are linearly related to the state vector, the estimator equations are linear, and no iterations are required.

[Z] = [A] [E] , and once again the weighted least square solution is obtained with a constant gain matrix.

State Estimation Using SMT

Formulation of the A matrix:

$$\mathbf{A} = \begin{bmatrix} \mathbf{II} \\ \mathbf{yB} + \mathbf{y}_s \end{bmatrix}$$

where II is a unit matrix whose rows corresponding to missing bus voltages are removed, y is a diagonal matrix of diagonal matrix of admittances, B is the branch-bus incident matrix, and y_s is the matrix of shunt admittances.

For the phasor based state estimator, the matrix M is given by

$$M = (A^T R^{-1} A)^{-1} A^T R^{-1}$$

and the state estimate is given by

$$\hat{E} = Mz$$

State Estimation Using SMT

$\hat{E}_B = Mz$

Unlike the earlier state estimator, this equation is LINEAR, and hence no iterations are needed. As soon as the measurements are obtained, the estimate is obtained by matrix multiplication.

The matrix **M** which converts the measurements to the state estimate is constant as long as the bus structure does not change. It can be computed off-line, and stored for real time use.

Under certain conditions of measurement configuration, the matrix M becomes real, simplifying the computations

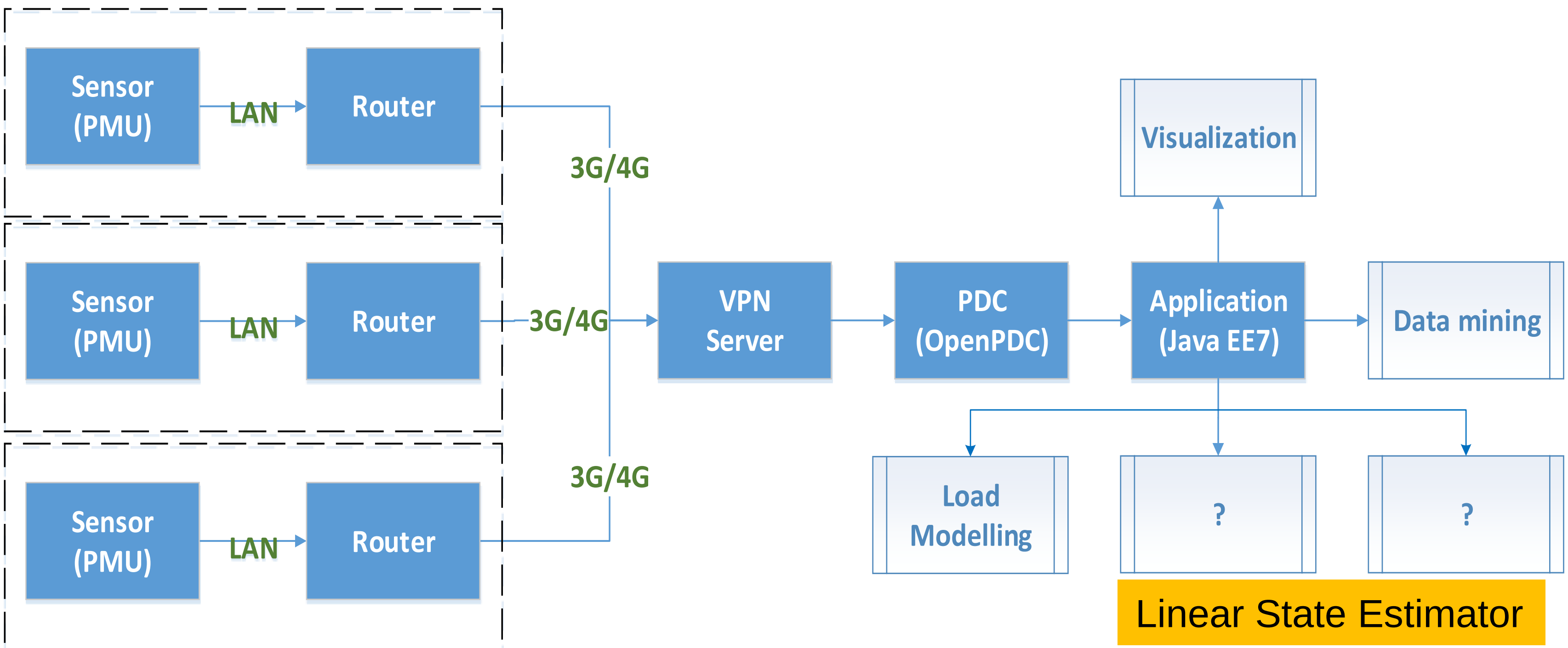
It is also possible to mix phasor measurements with traditional measurements to obtain a Hybrid estimator.

Data Acquisition Platform - Synchrohub

- Flexible data acquisition platform
- Data storage, visualisation, applications
- PMU-based applications: Synchrohub
- Synchrohub encompasses multiple PMUs from different vendors, manages detailed information about the measurement chain and its uncertainties and exploits a unique communication infrastructure with OpenPDC as the underlying layer for data fusion

Synchrohub Architecture

The modular design of the flexible platform makes it extendable with additional applications

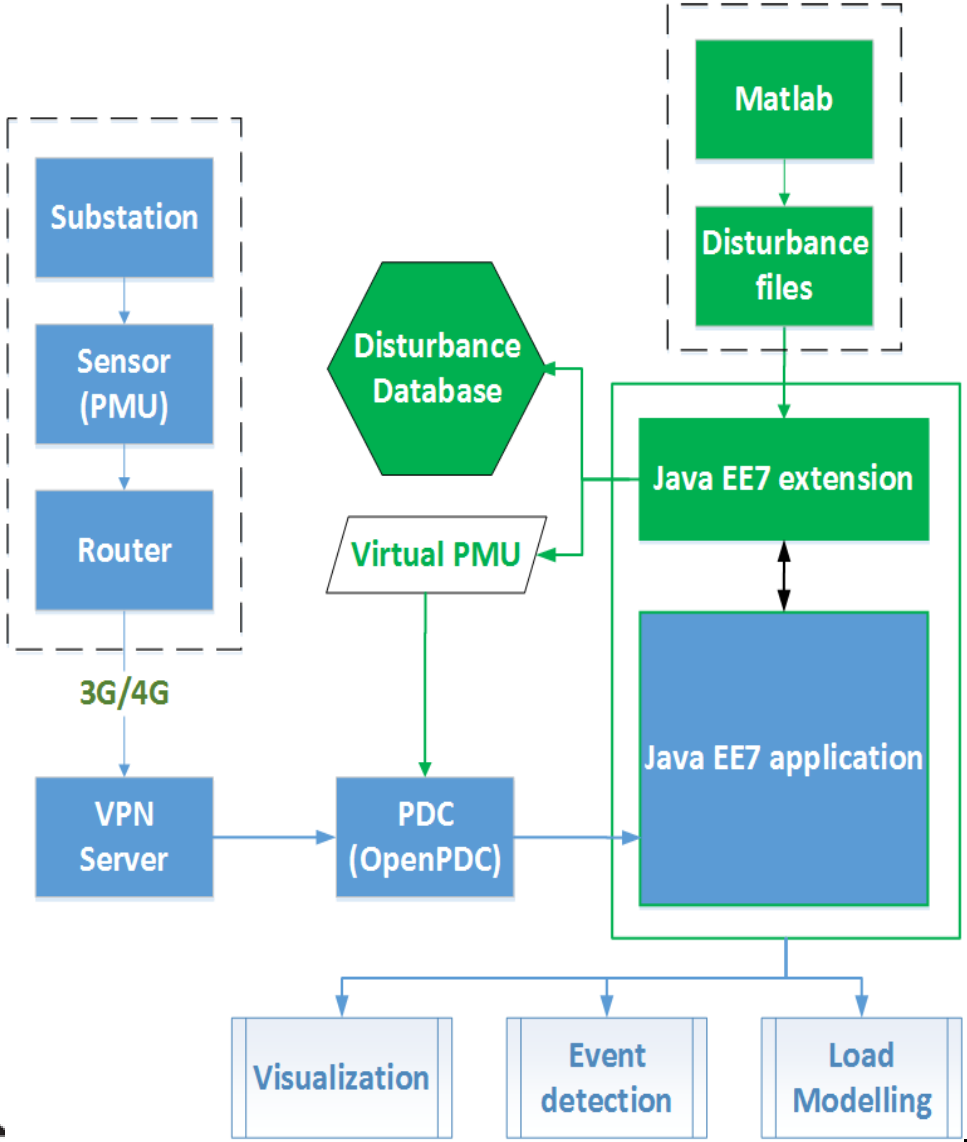


Synchrohub Capabilities

Several of the current capabilities are enumerated below, but are not limited to

- Data aggregation
- Data extraction with time alignment and bad data detection
- Automatic detection of network disturbances
- Real time visualization
- Network disturbance repository
- Estimation of dynamic load model parameters
- Linear State Estimation – LiSE

Synchrohub Extensions



Matlab generated data

External disturbances (e.g. Comtrade files)

PMU data according to IEEE C37.118:

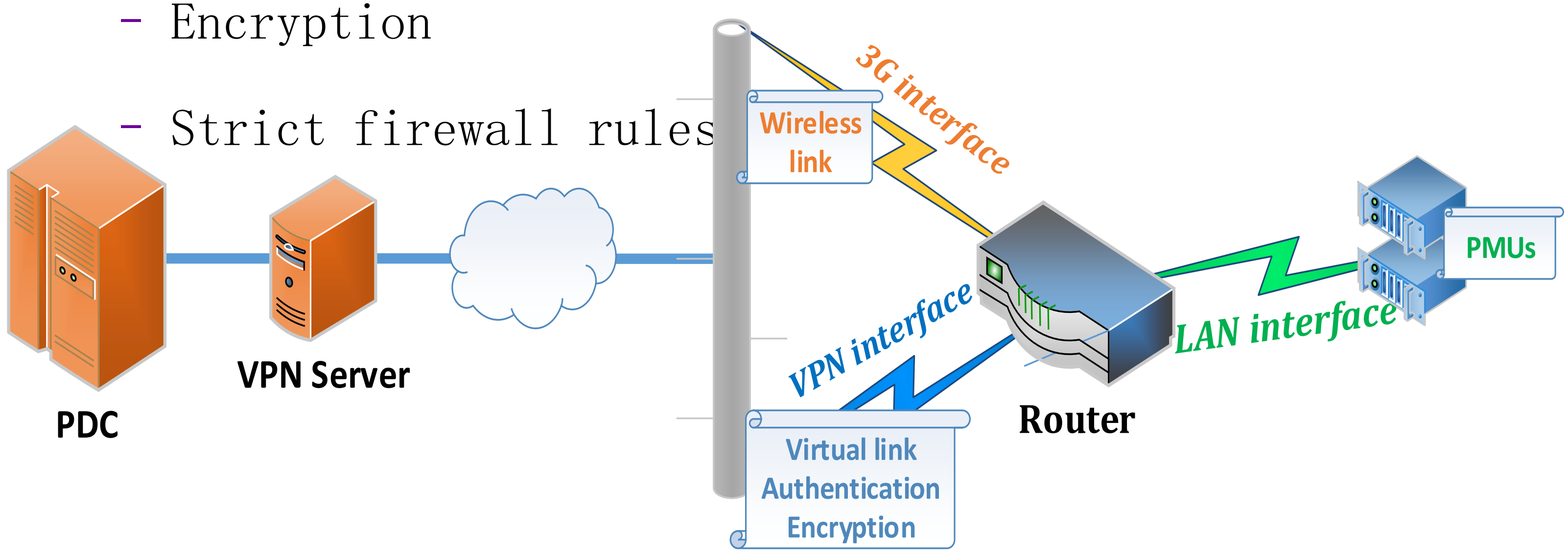
- Real PMUs
- RTDS virtual PMUs

RTDS – Real Time Digital Simulator

Synchrohub Security

The whole infrastructure has been designed for enhanced security – at least three layers of security:

- Authentication
- Encryption
- Strict firewall rules



Manchester RTDS Lab

- **Manchester Real Time Digital Simulator (RTDS)** is employed to demonstrate a Linear State Estimator - LiSE
- **RTDS** consists of 6 racks with 30 PB5 processor card:
  - GTSync card for synchronisation of the RTDS
  - GTNet cards for high level communication (e.g. IEC 61850, C37.118 and IEC 60870 protocols)
  - GTWIF cards to connect to Admin PC

Hardware in the Loop Building Blocks

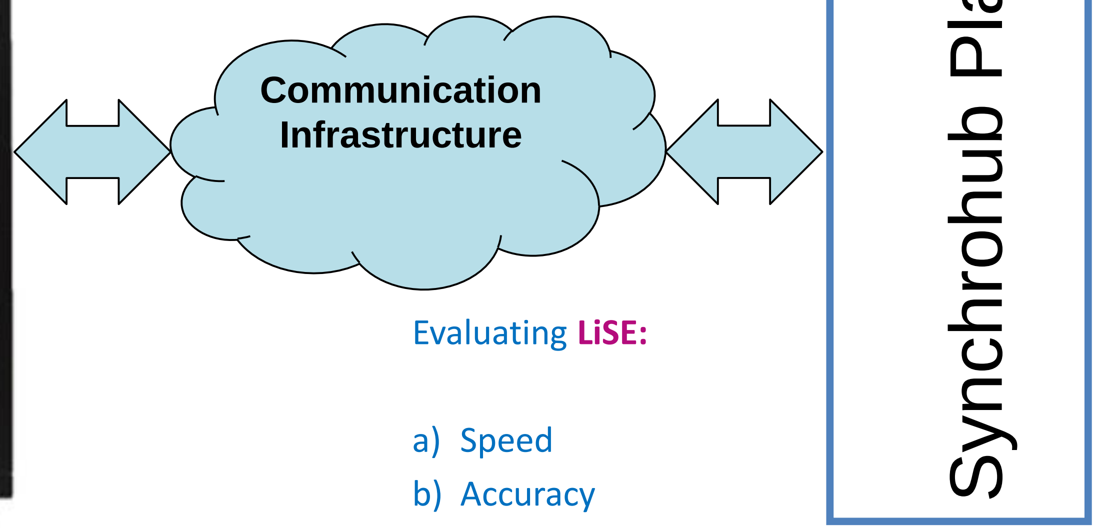
RTDS

Admin PC

to control simulation runs and visualise results

RTDS to perform flexible HiL tests

IEEE C37.117

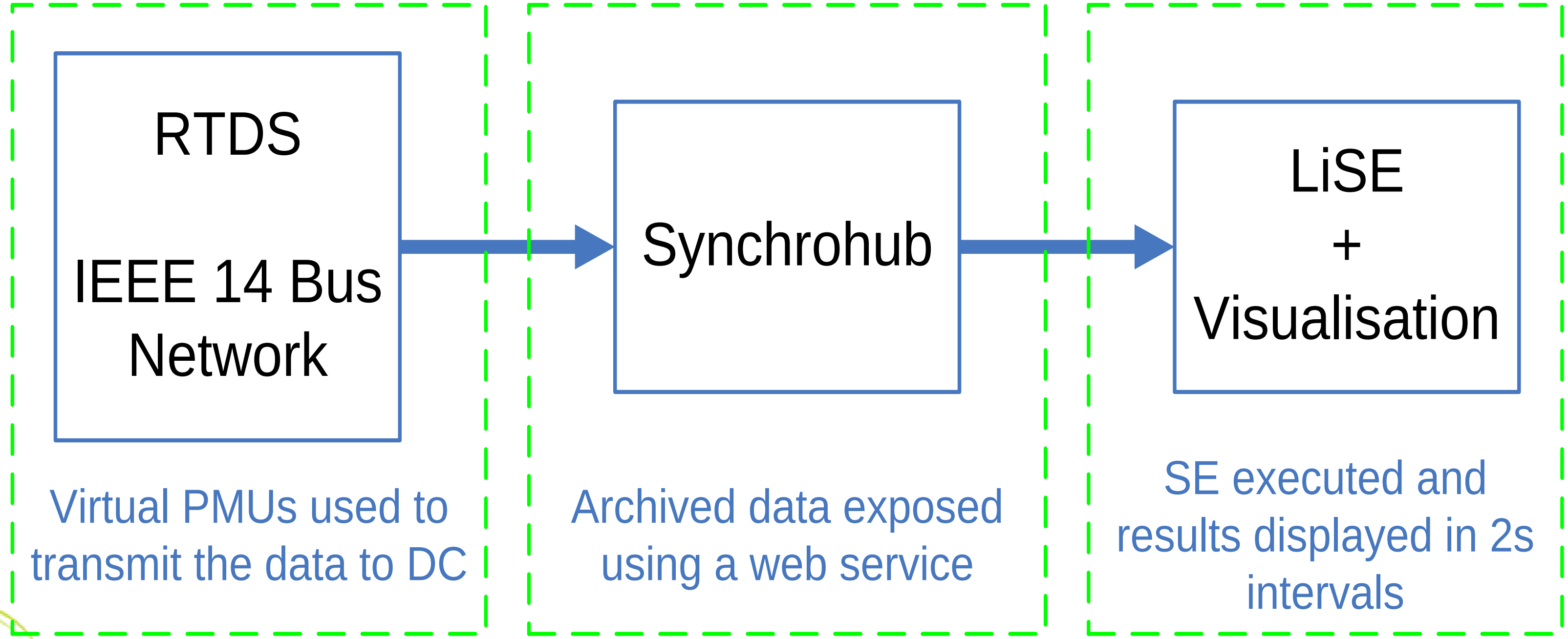


Evaluating **LiSE:**

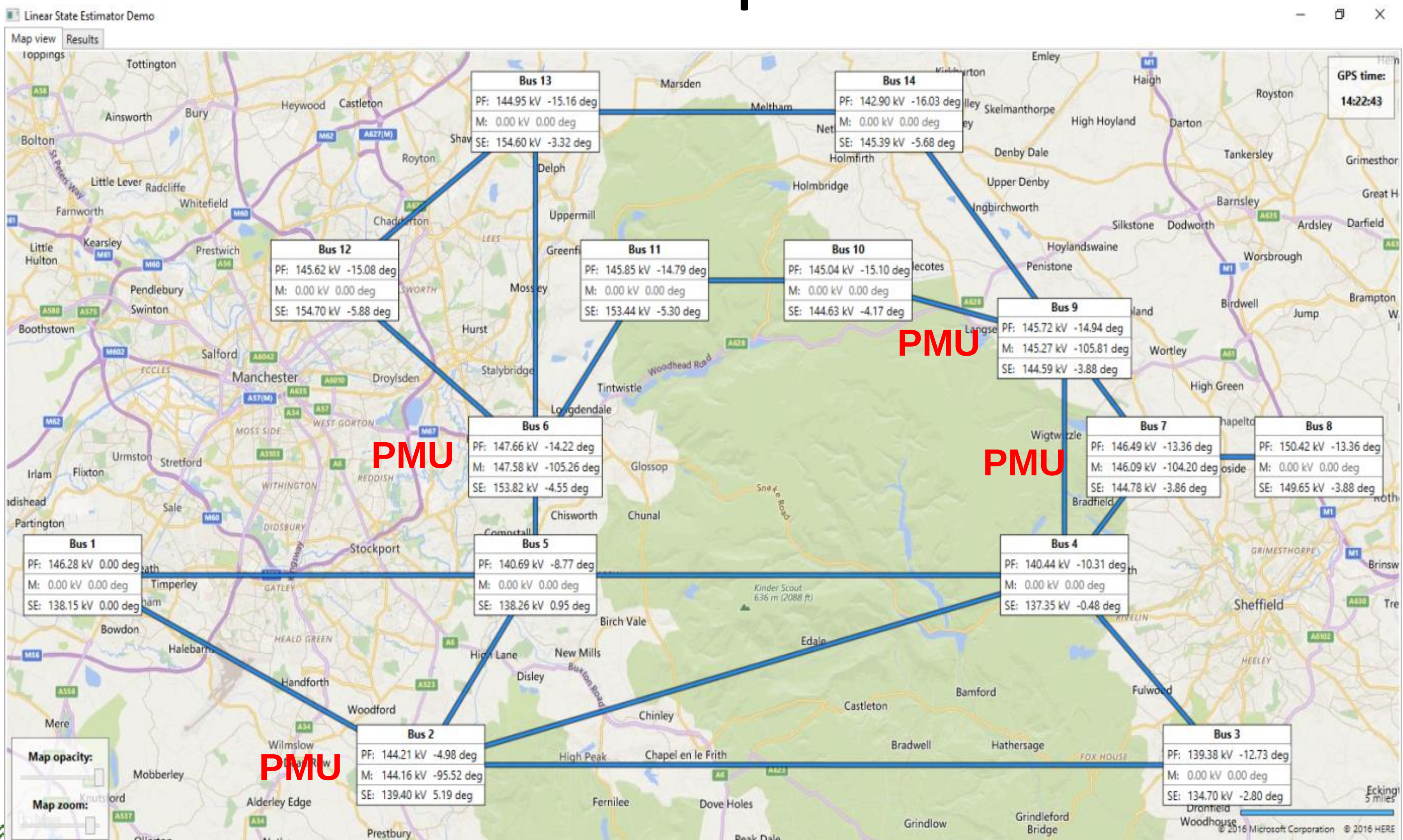
a) Speed
b) Accuracy
c) Robustness

Linear State Estimator - LiSE

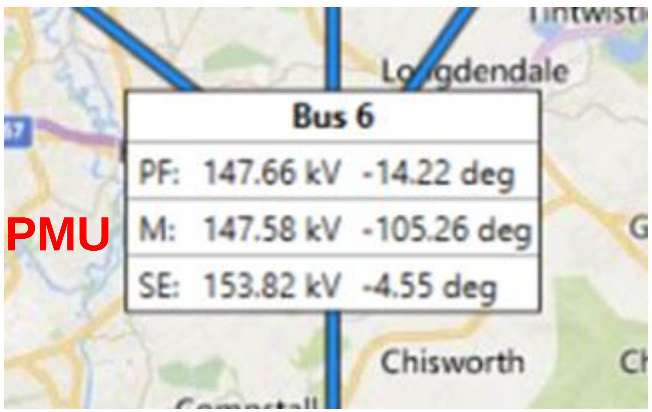
LiSE is a demonstration of an online linear state estimator. The example runs on an IEEE 14 bus network modelled using RTDS (minimum PMU number scenario – 4 devices). State is updated every 2 seconds.



LiSE – Map View



LiSE – Map View



- Power flow (PF) – voltage obtained by solving the power flow equations for base conditions
- Measurements (M) – PMU measured voltage phasors in selected buses
- State estimator (SE) – voltage estimated by LiSE

LiSE – Results View

Linear State Estimator Demo

Map view | Results

Results

Buses:

Number	Name	Vn [kV]	Measurements?	V(PF) [pu]	Ang(PF) [deg]	V(M) [pu]	Ang(M) [deg]	V(SE) [pu]	Ang(SE) [deg]
1	Bus 1	138	☐	1.0600	0.0000	0.0000	0.0000	1.0011	0.0000
2	Bus 2	138	☑	1.0450	-4.9826	1.0446	-95.5186	1.0102	5.1864
3	Bus 3	138	☐	1.0100	-12.7251	0.0000	0.0000	0.9761	-2.7989
4	Bus 4	138	☐	1.0177	-10.3129	0.0000	0.0000	0.9953	-0.4774
5	Bus 5	138	☐	1.0195	-8.7739	0.0000	0.0000	1.0019	0.9472
6	Bus 6	138	☑	1.0700	-14.2209	1.0694	-105.2583	1.1146	-4.5508
7	Bus 7	138	☑	1.0615	-13.3596	1.0587	-104.2014	1.0491	-3.8587
8	Bus 8	138	☐	1.0900	-13.3596	0.0000	0.0000	1.0844	-3.8800
9	Bus 9	138	☑	1.0559	-14.9385	1.0527	-105.8132	1.0478	-3.8789
10	Bus 10	138	☐	1.0510	-15.0973	0.0000	0.0000	1.0481	-4.1693
11	Bus 11	138	☐	1.0569	-14.7906	0.0000	0.0000	1.1119	-5.2975
12	Bus 12	138	☐	1.0552	-15.0756	0.0000	0.0000	1.1210	-5.8843
13	Bus 13	138	☐	1.0504	-15.1563	0.0000	0.0000	1.1203	-3.3240
14	Bus 14	138	☐	1.0355	-16.0336	0.0000	0.0000	1.0536	-5.6751

Branches:

Bus i	Bus j	Name	Measurements i?	Measurements j?	Ii Mag(PF) [pu]	Ii Ang(PF) [deg]	Ii Mag(M) [pu]	Ii Ang(M) [deg]	Ij Mag(PF) [pu]	Ii Ang(PF) [deg]	Ij Mag(M) [pu]	Ij Ang(M) [deg]
1	2	Line 1-2	☐	☑	1.4925	7.4103	0.0000	0.0000	1.4840	-174.7019	1.4735	-84.7752
1	5	Line 1-5	☐	☐	0.7133	-2.9226	0.0000	0.0000	0.7139	172.9814	0.0000	0.0000
2	3	Line 2-3	☑	☐	0.7017	-7.7656	0.6986	-98.3026	0.7023	168.5692	0.0000	0.0000
2	4	Line 2-4	☑	☐	0.5373	-3.4005	0.5453	-86.8871	0.5359	172.8621	0.0000	0.0000
2	5	Line 2-5	☑	☐	0.3974	-6.5982	0.4065	-84.4880	0.3989	168.2675	0.0000	0.0000

LiSE – Data View

Buses:

Number	Name	Type	Vn [kV]	V [pu]	Pg [MW]	Qg [Mvar]	Pl [MW]	Ql [Mvar]	V Mag	V Ang	Measurements?	Latitude	Longitude
1	Bus 1	SlackVA	138.00	1.0600	0.00	0.00	0.00	0.00			☐	53.3972	-2.3918
2	Bus 2	GenerationPV	138.00	1.0450	40.00	0.00	21.70	12.70			☑		
3	Bus 3	GenerationPV	138.00	1.0100	0.00	0.00	94.20	19.00			☐		
4	Bus 4	LoadPQ	138.00	1.0000	0.00	0.00	47.80	-3.90			☐	53.3972	-1.6200
5	Bus 5	LoadPQ	138.00	1.0000	0.00	0.00	7.60	1.60			☐	53.3972	-2.0359
6	Bus												
7	Bus												
8	Bus												
9	Bus												
10	Bus												
11	Bus												
12	Bus												
13	Bus												
14	Bus												

Buses

Branches:

Bus i	Bus j	Name	R [pu]	X [pu]	G [pu]	B [pu]	ri Mag	ri Ang [deg]	rj Mag	rj Ang [deg]	Ii Mag	Ii Ang	Measurements i?	Ij Mag	Ij Ang	Measurements j?
1	2	Line 1-2	0.01938	0.05917	0	0.0264	1	0	1	0			☐			☑
1	5	Line 1-5	0.05403	0.22304	0	0.0246	1	0	1	0			☐			☐
2	3	Line 2-3	0.04699	0.19797	0	0.0219	1	0	1	0			☑			
2	4	Line 2-4	0.05811	0.17632	0	0.017	1	0	1	0			☑			
2	5	Line 2-5	0.05695	0.17388	0	0.0173	1	0	1	0			☑			☐
3	4	Line 3-4	0.06701	0.17103	0	0.0064	1	0	1	0			☐			☐
4	5	Line 4-5	0.01335	0.04211	0	0	1	0	1	0			☐			☐
4	7	Trafo 4-7	0	0.20912	0	0	0.978	0	1	0			☐			☑
4	9	Trafo 4-9	0	0.55618	0	0	0.969	0	1	0			☐			☑
5	6	Trafo 5-6	0	0.25202	0	0	0.932	0	1	0			☐			☑
6	11	Line 6-11	0.09498	0.1989	0	0	1	0	1	0			☑			☐
6	12	Line 6-12	0.12291	0.25581	0	0	1	0	1	0			☑			☐
6	13	Line 6-13	0.06615	0.13027	0	0	1	0	1	0			☑			☐
7	8	Line 7-8	0	0.17615	0	0	1	0	1	0						
7	9	Line 7-9	0	0.11001	0	0	1	0	1	0						

Branches

Shunt Elements:

At bus	Name	G [pu]	B [pu]	I Mag	I Ang	Measurements?
9	Shunt 1	0	0.19			☐
						☐

Shunt elements

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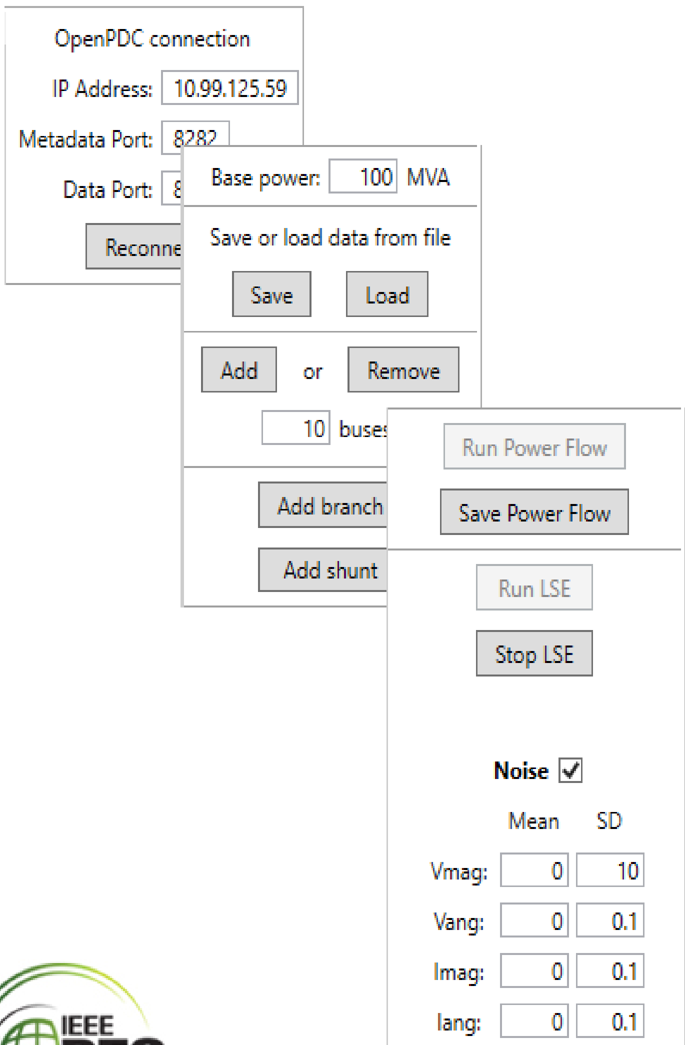
LiSE – Data View



- Changing PDC connection parameters
- Building new network models and modifying the existing ones (not only limited to the 14 bus network anymore)
- Adding noise to the incoming measurements for testing purposes

LiSE – Demonstration

Video demonstration

Future Plans

- To test the speed of the platform/LiSE
- To improve performance of the OpenPDC
- To test the functionality using larger networks, i.e. larger number of PMUs
- To more rigorously test the robustness of the LiSE
- Other…

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