LINEAR STATE ESTIMATION AT TVA FOR RELIABILITY AND RESILIENCY

Presentation for NASPI Workgroup Meeting, Salt Lake City

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April 16, 2024

OUTLINE

- LSE Introduction
- TVA LSE Deployment
  - Overview
  - Data Flow
  - Example Results
  - Visualization
- Summary and Looking Forward

WHY GRID OPERATORS ARE USING LINEAR STATE ESTIMATION

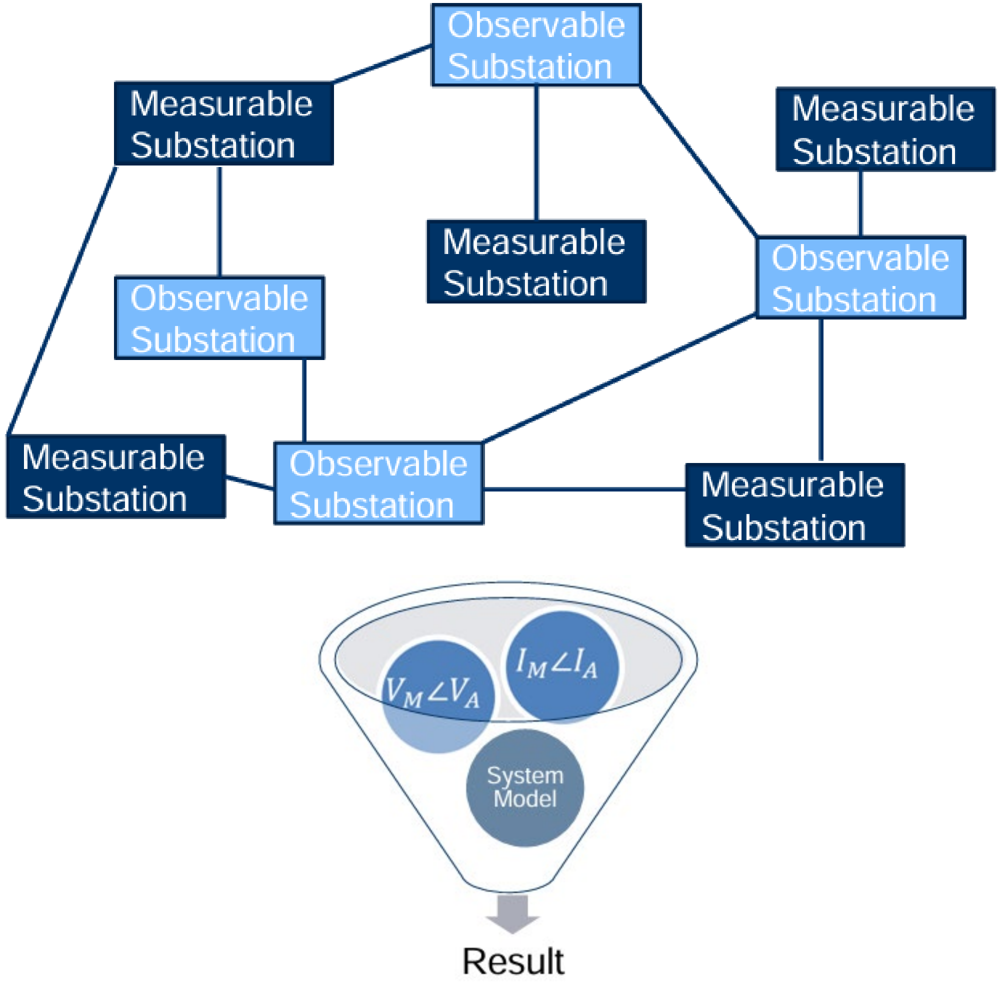
Why LSE Technology?

Limitations of Legacy SE	LSE Solution
State Estimator Not Solving	LSE Always Solves
Iterative and Slow (every few minutes)	Linear Solution, Solves at sampling rate (30 or 60 frames/sec)
Grid Dynamics Not Observable	Advanced Applications for Oscillations, Damping, Phase Angle Differences, Sensitivities
Data Quality	Real-time data conditioning
Costly PMU Deployment	Expands Real-Time Observability beyond current PMU coverage
EMS Degradation or Failures	Provides backup to EMS resulting from equipment failure, physical and cyber attacks

Platform for advanced applications

WHAT IS LINEAR STATE ESTIMATION (LSE)

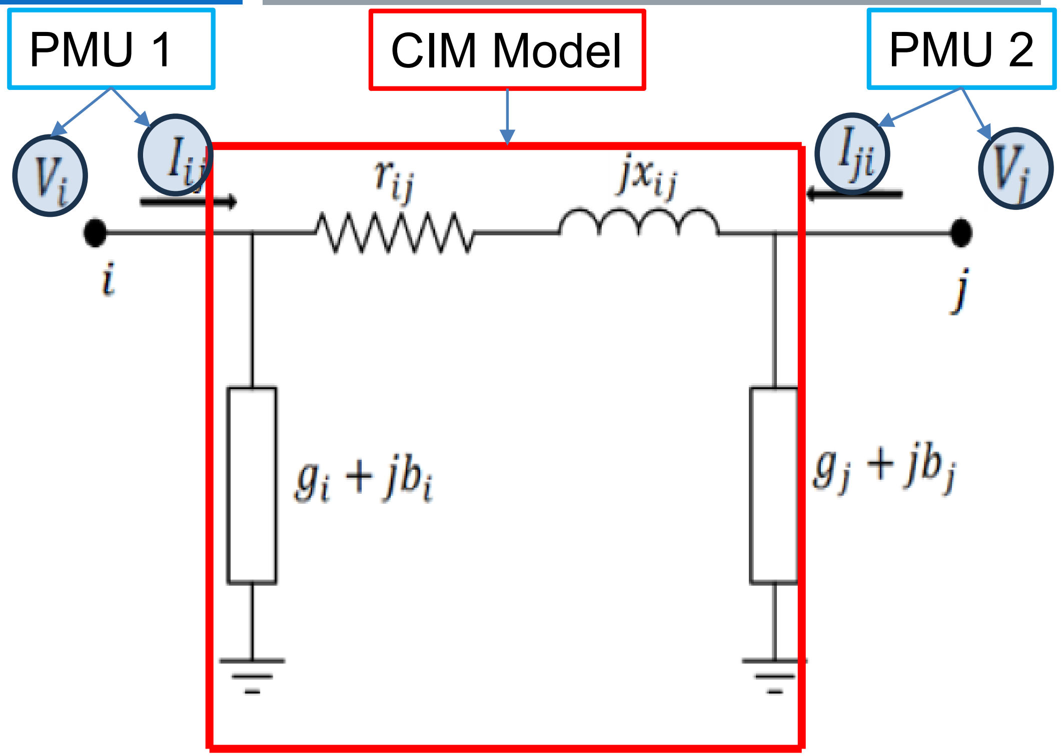
- Traditional SE use iterative methods which take time and don't always solve
- LSE is based on linear equations utilize models to provide estimated values
- Always solve at PMU reporting rate
- Data quality issues addressed by using model based estimated values
- Linear computations calculate estimated values for adjacent buses even without PMUs at those buses
- Essential platform for Smart Grid Applications



Source: Shaun Murphy, Linear State Estimation, PJM, May 2020

How LSE Works

- Uses measured voltage & current phasors at one end of equipment/TL to estimate voltage phasors at the other end, based on the physical relationship of equipment's π-equivalent model
- single pass without iteration, requiring only voltage and current phasors from PMUs
- leverages measurement redundancy to provide a weighted average calculation



$$Min\ \sigma^T W \sigma$$

$$s.t.\ [Z] = \begin{bmatrix} I \\ Y \end{bmatrix} [X] + [\sigma]$$

$$[H] = \begin{bmatrix} I \\ Y \end{bmatrix}$$

$$[Z] = \begin{bmatrix} V_{measure} \\ I_{measure} \end{bmatrix}$$

$$\therefore [X] = [(H^T W H)^{-1} H^T W][Z]$$

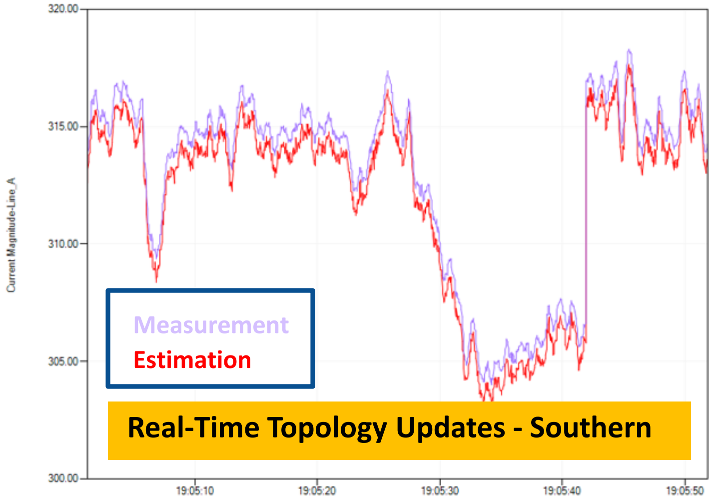
Z: measurement vector
X: estimation state vector
I: voltage incidence matrix
Y: admittance matrix
σ: vector of the errors in measurements
W: covariance matrix of measurements errors

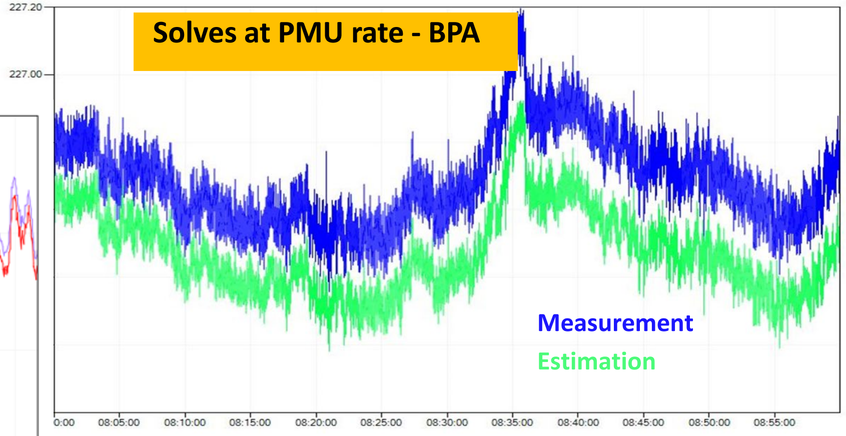
$$\begin{bmatrix} V_i \\ V_j \\ I_{ij} \\ I_{ji} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ y_{ij} + y_{i0} & -y_{ij} \\ -y_{ji} & y_{ji} + y_{j0} \end{bmatrix} \begin{bmatrix} V_{i,est} \\ V_{j,est} \end{bmatrix}$$

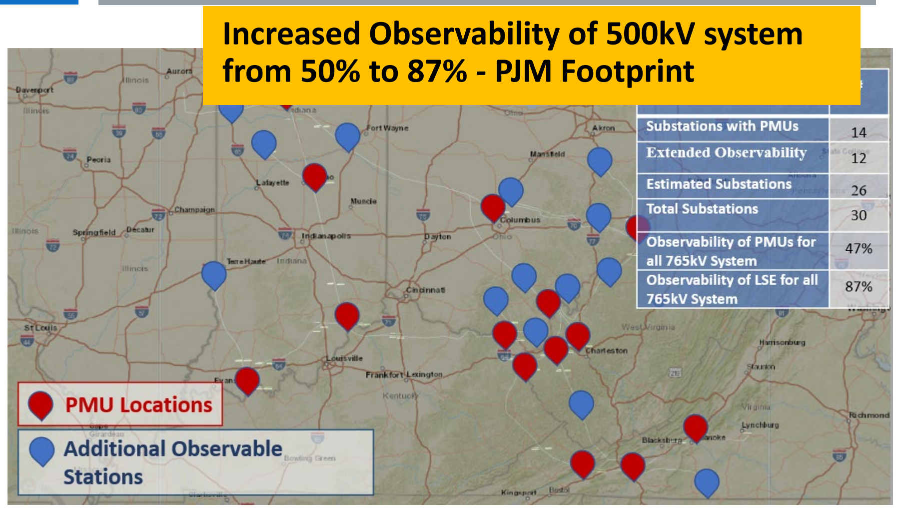
[Z] [H] [X]

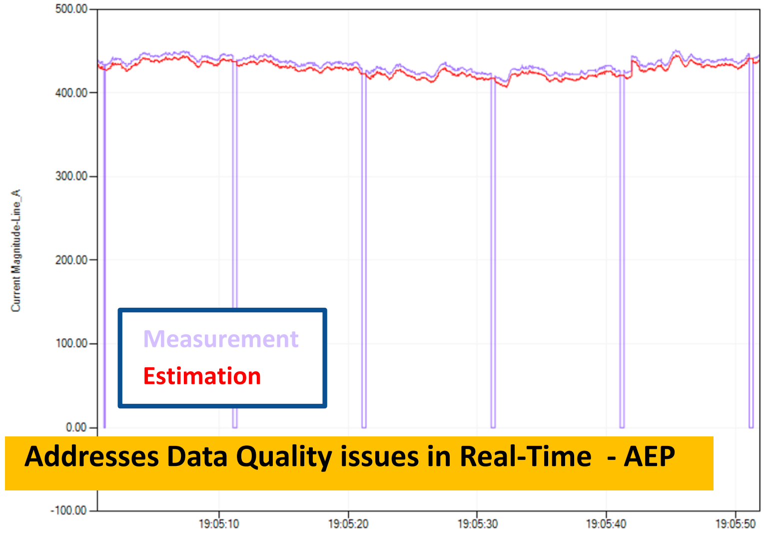
$$\begin{cases} y_{ij} = y_{ji} = r_{ij} + jx_{ij} \\ y_{i0} = g_i + jb_i \\ y_{j0} = g_j + jb_j \end{cases}$$

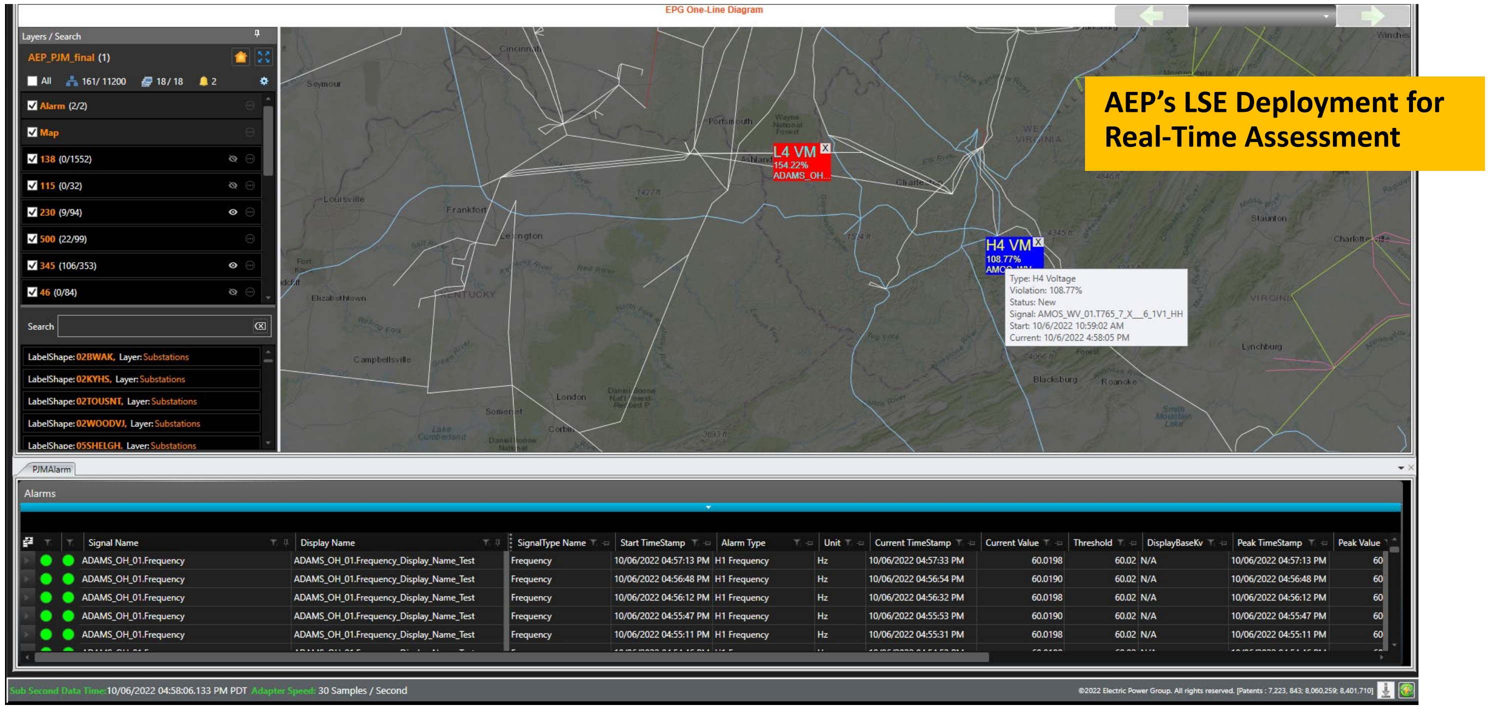
Use Case Examples











TVA eLSE DEPLOYMENT

TVA PMUs - OVERVIEW

TVA PMU Locations in PDC 11-31-2023

916 PMUs located across 116 sites including:

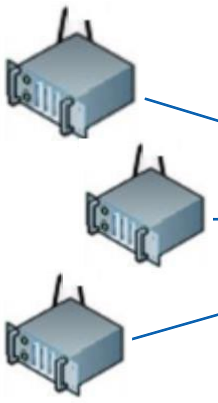
- DFR
- GE N60
- GE D90
- SEL311C
- SEL411L
- SEL787
- SEL735

TVA LSE DEPLOYMENT - OVERVIEW

- LSE implemented for 500 KV TVA Transmission System
- **Inputs**
  - PMU Data in C37.118 format at 30 frames/second
  - CIM Model
  - One Line diagrams
  - Breaker Status Information through PMU digital Signals
- **LSE solution rate – 30 frames/second**
- **Statistics**
  - Total number of directly Observed Substations at 500 KV = 28
  - Total number of extended observable substations at 500 KV = 18
  - Total Observable footprint at 500 kV = 46 substations
  - Observability increased by 64%
  - Residuals on Voltage Estimates < 2%

Data Flow

Data Collection & concentration	LSE & Data Quality Management	Real Time Monitoring	Visualization



PMU Data from Field

TVA PDC

- Data Concentration
- Receive Data from PMUs, synchronize data etc.

- PMU Data
- Breaker/Switch Status

enhanced Linear State Estimator (*e*LSE)

Network Model (CIM)

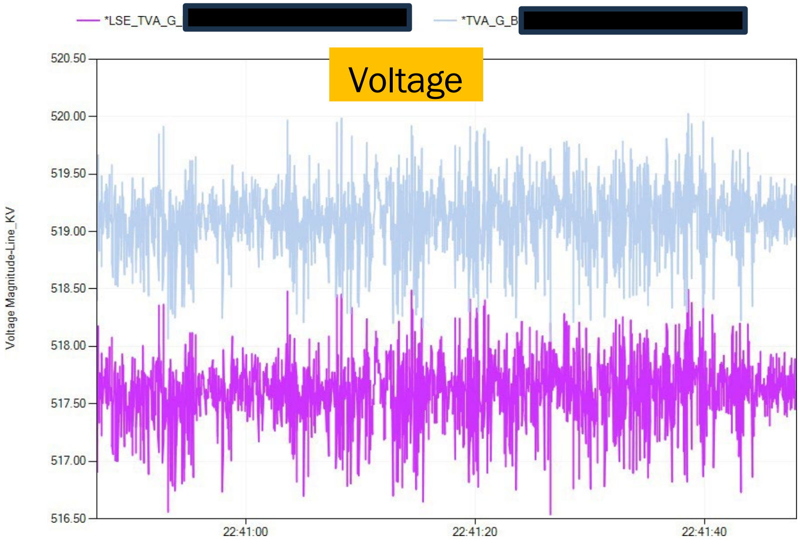
- Topology Processing
- Real Time Observability
- State Estimation

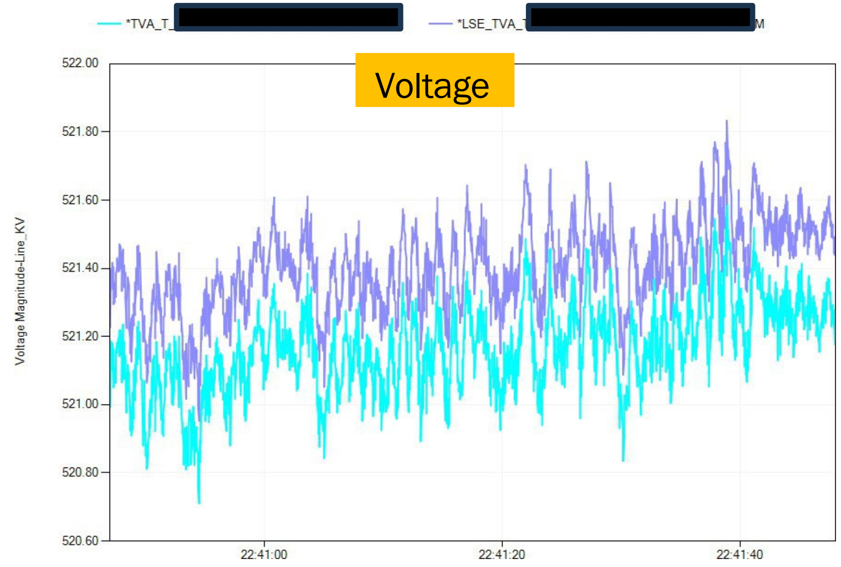
RTDMS WAMS

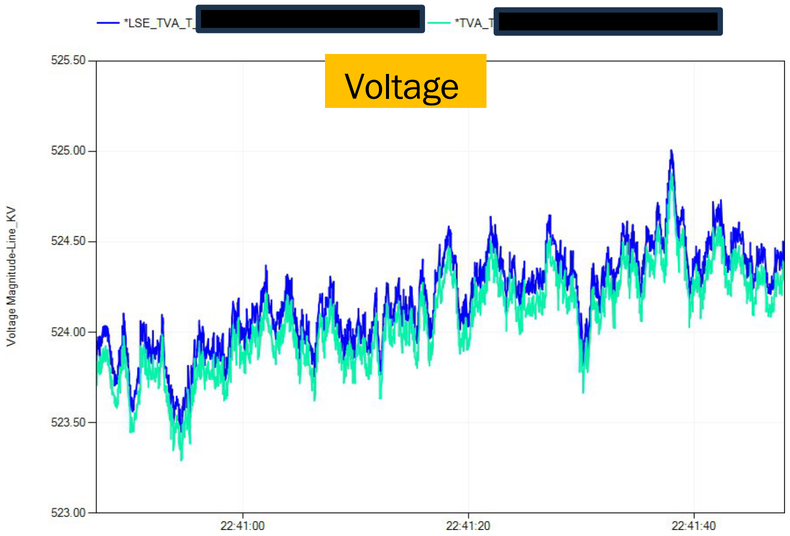
- Perform Advanced Calculations
- Set Alarm limits
- Stream data to downstream applications

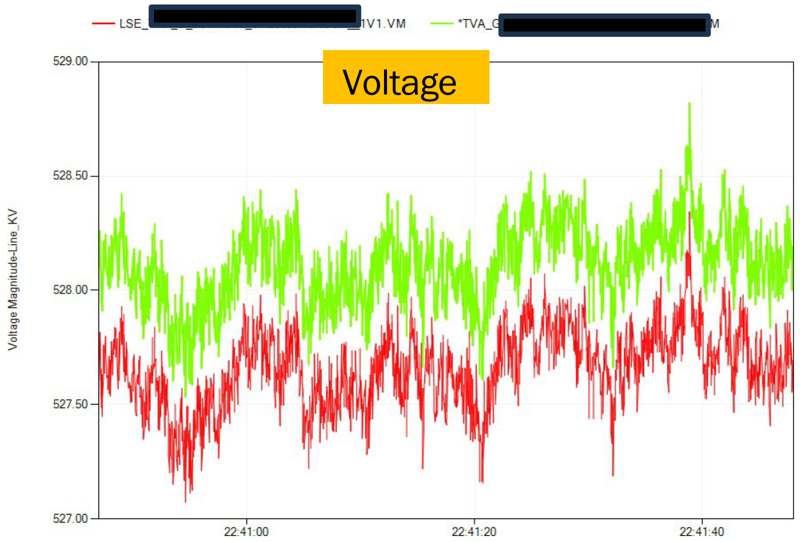
- Visualization of Real-Time LSE Results
- Replay data and events
- OneLines,Trends, Maps, Alarms etc.

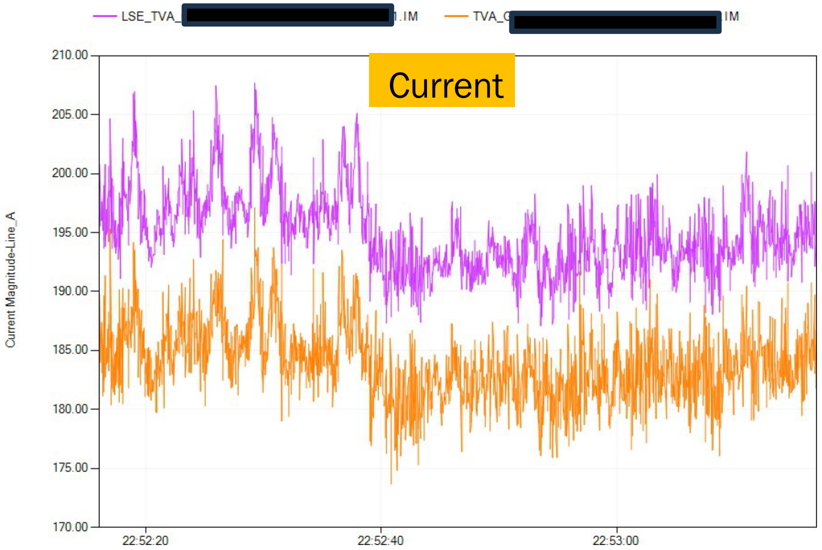
Linear State Estimation captures System Dynamics and Trends

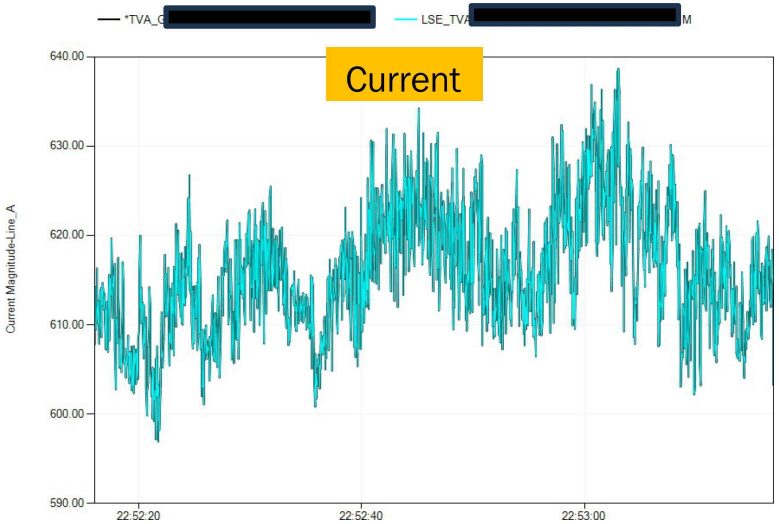




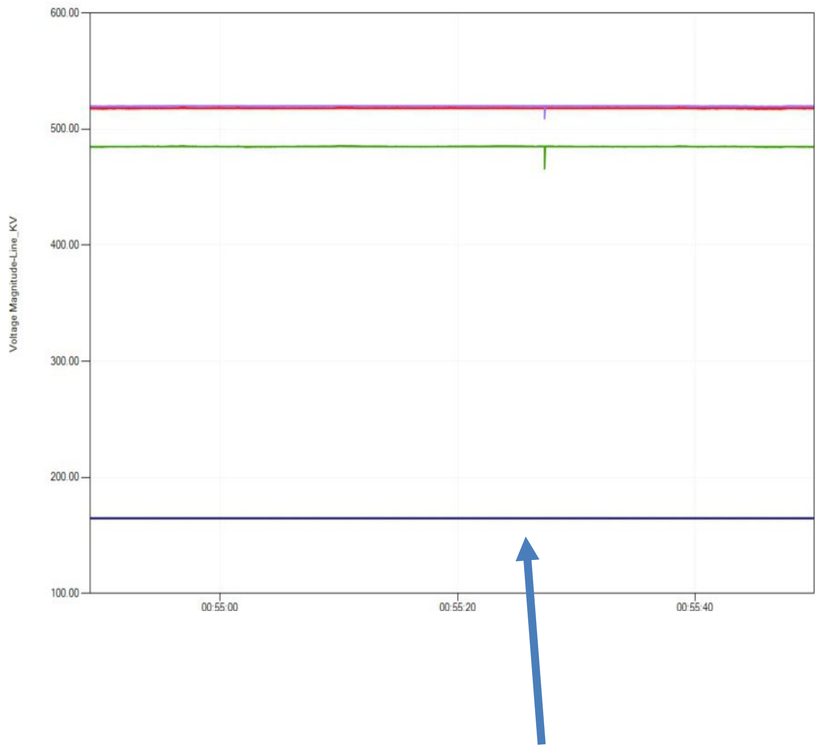




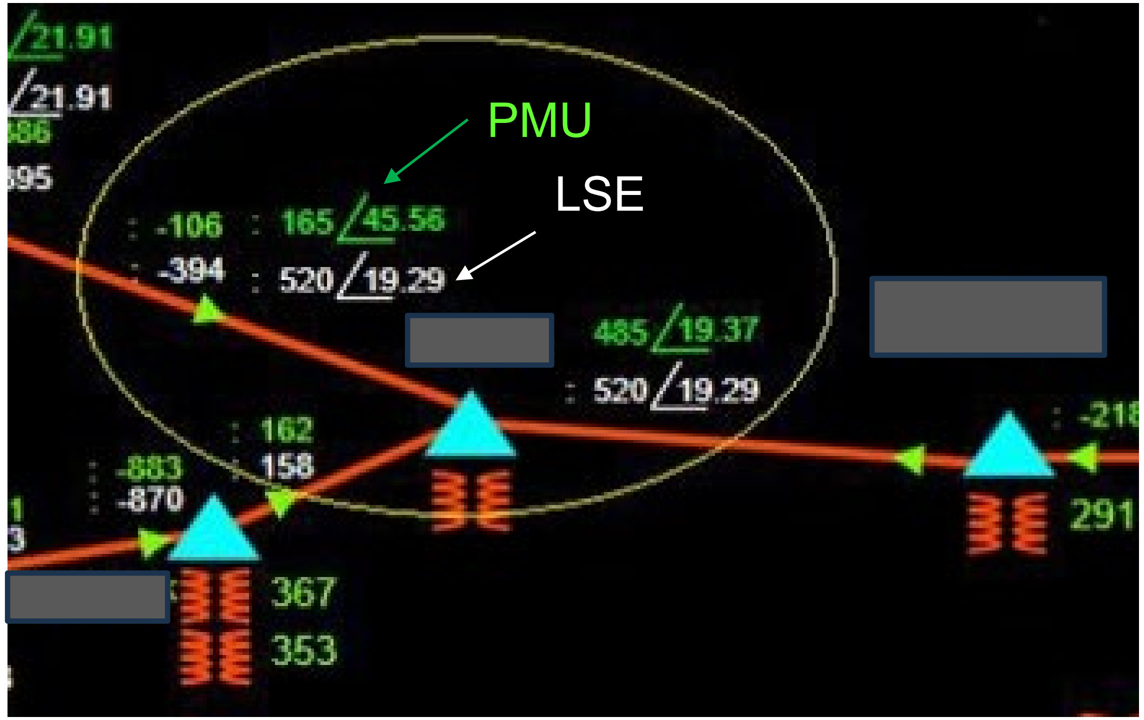




*e*LSE Results – Example 1



Wrong voltages were selected for the lines when the DFR was initially set up



eLSE results provide accurate estimates in spite of measurement errors

*e*LSE Results – Example 2

Estimated Values are correct

Incorrect Measurements Causes Large Residuals

Time Alignment Status | Validation Performance | LSE Monitor | LSE Reports

Fri Dec 8 08:35:11 2023

	..	Phasor Type	Raw Phasor	Estimated Phasor	Magnitude Residual (%)	Angle Residual
1	TVA_G_ IT_1I1	Current	304051.34 A / 134.31 °	207.41 A / -49.76 °	146493.63% (-303843.93 A)	175.92 °
2	TVA_G_ _1I1	Current	303798.81 A / 134.31 °	1052.61 A / -103.83 °	28761.42% (-302746.20 A)	121.86 °
3	TVA_G_ _1I1	Current	303817.59 A / 134.25 °	1256.50 A / -107.74 °	24079.62% (-302561.09 A)	118.02 °
4	TVA_T_ _1I1	Current	514.41 A / -126.14 °	46.59 A / -53.43 °	1004.10% (-467.82 A)	72.71 °
5	TVA_G_ _1I1	Current	1660.60 A / 48.28 °	553.84 A / 57.54 °	199.83% (-1106.76 A)	9.26 °

Voltage and Current inputs were swapped resulting in incorrect measurements (line to neutral voltage fed as the input instead of current)

***e*LSE can provides accurate estimates even when measurement has extremely large errors**

eLSE Results– Example 3

- PMU Measurements Indicate large difference in currents on both ends of a line
- LSE provides consistent current estimates

RESULTS VISUALIZATION ON ONE-LINE DIAGRAMS

500 kV System Overview

Substation One Line Diagram

SUMMARY AND LOOKING FORWARD

- LSE provides significant benefits for wide area monitoring and real-time operations
  - Improves PMU Data Quality
  - Identify Measurement or Model Errors
  - Extends PMU Observability
  - Improves Grid Reliability and Resiliency by providing independent solution for state estimation
  - Provides foundation/platform for advanced applications – e.g. RTCA, Power Flow Solutions for Real-Time Assessments
- Looking forward for TVA
  - Apply LSE to 161 kV system
  - Use LSE and PMU Measurements as backup to SCADA
  - Consider/Evaluate Synchrophasor-based RTCA

Q&A, DISCUSSION

Thank you!

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