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Linear State Estimation: Foundation for Measurement-Based Advanced Applications

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SYNCHROPHASOR DATA AND STATE ESTMATION
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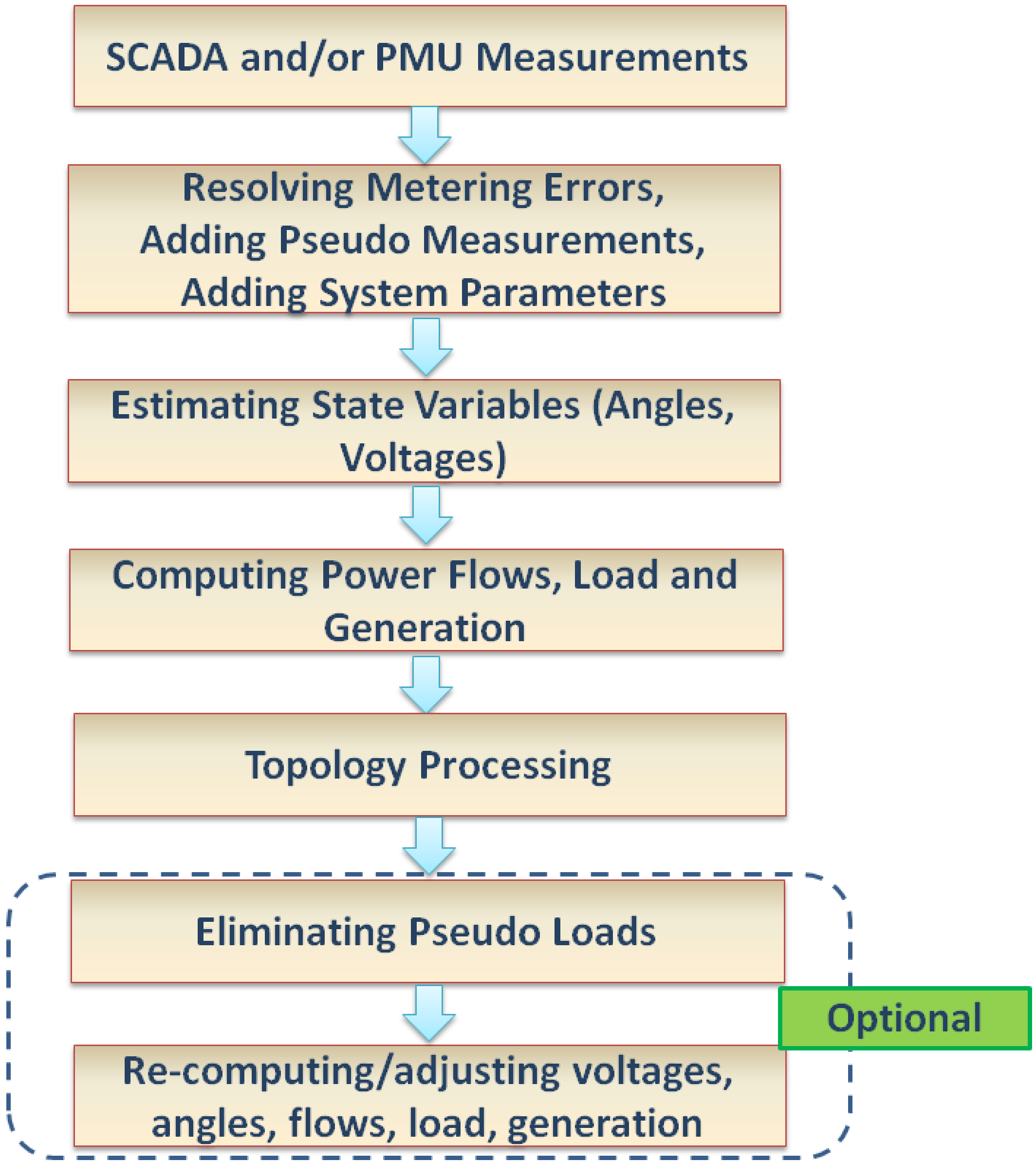
Purpose of State Estimator

- State Estimator (SE) is designed to produce a system state based on the "best estimate" of the system voltages and phase angles:
  - Provided that there are errors in the measured quantities; and
  - That there is a redundancy in measurements
- State Estimation is based on minimizing the sum of squares of the differences between the estimated and the measured values of a function:
  - The computation of least square estimation in use since early 19^{th} century
- Linear State Estimator (LSE) is based on PMU measurements of voltage and current:
  - Orthogonal component of voltage and current vectors is considered as the state variable

State Estimation Process



Advantages of Linear State Estimator

- Speed of state estimation due to using a direct non-iterative solution;
- Improving quality of PMU data;
- A check for conventional SE;
- May replace conventional SE when it looses its output.

LSE for Measurement-Based Analysis

Linear State Estimation

- Observability Analysis
- Bad Data Detection/Conditioning

Advanced Applications

- Contingency Analysis
- Voltage Stability Analysis
- Automatic Corrective Actions
- Phase Angle Limit Computation
- Analysis of Cascading Outages

Visualization/Alarming

Visualization of:
- Limits
- Critical Contingencies/Cascades
- Trending

Alarming on:
- Voltage/Transient Stability Limits
- Phase Angle Limit
- Critical Contingencies/Cascades

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Observability Analysis

- Observability in terms of voltage stability (or other advanced applications)
- Additional installations of PMUs needed to utilize measurement-based advanced applications

LSE for Bad Data Detection

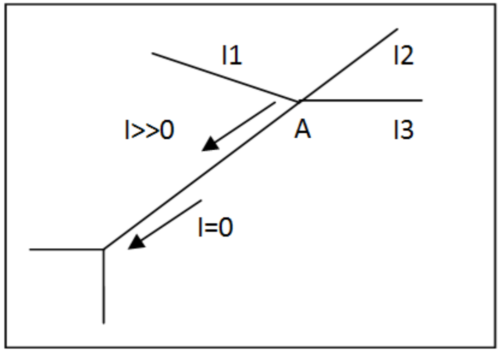
- "Bad data" detection, including:
  - Bad PMU data;
  - Bad SCADA data;
  - Bad system parameters;
  - Errors in the process of conventional state estimation.
- Topology estimation, if breaker status is not available.
- Separating bad data with an onset of an event.

Bad Data Detection and Conditioning

- Bad PMU data detection is done using a combination of two approaches:
  - Heuristic (logical) rules
  - Statistical methods

Heuristic-Based Analysis

- Heuristic (logical) rules for bad data detection are used, including:
  - Detecting inconsistency between different measurement data:
    - e.g. real power computed using measured voltage and current at the From side should be greater than at the To side; OR active and reactive power of a line does not agree with phase angle measurement data
  - Considering previous measurements;
  - Detecting (and correcting) data based on availability of measured data:
    - For example, currents are measured on all lines at one bus (bus A); They are significantly non-zero and satisfy Kirchhoff law $I1 + I2 + I3 + I = 0$,
    - But I = 0 at another end of the line.
    - Then, we can detect this bad measurement and estimate the value of current at this end of the line.



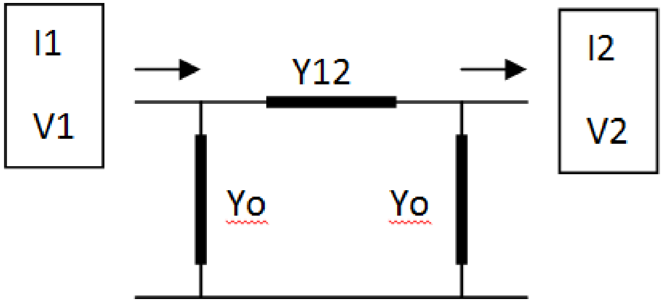
Statistical Analysis

- The chi-square criterion after performing least square minimization.
  - Measurements with high values of residual differences are not used;
  - If high number/ majority of measurement points show high values of residual differences, topology mismatch of the system model is suspected.

Bad Parameter Detection

- If, as a result of statistical computation, too many measurements should be excluded or sum of the squares of the differences between the measured values and state variables can't be minimized:
  - Parameters of the network model used in SE significantly differ from the actual system parameters.
- Parameters should be adjusted based on measurements:
  - In some cases, they can be recomputed directly using measurements
  - Provided that there are 2 PMUs, parameters of the network Y12 and Yo:

$$Y_{12} = \frac{V_1 I_2 + V_2 I_1}{V_1^2 - V_2^2}, \quad Y_0 = \frac{I_1 - I_2}{V_1 + V_2}$$



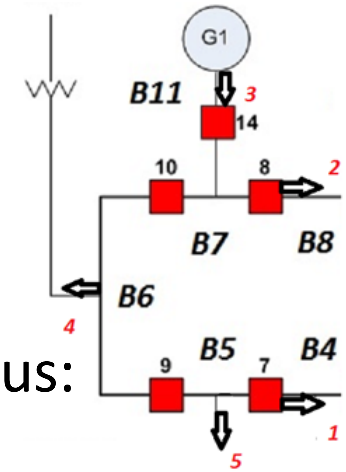
  - Identification of the parameters becomes:

$$\min_{Y} \left(f(V,Y) - I\right)^T \left(f(V,Y) - I\right)$$

  - V – is complex vector of voltages, I – complex vector of current, Y – is vector of admittances

Estimating Topology Using Measurements

- Part of the substation:
  - PMUs 1,2,3 at breakers 7, 8 and 14
  - PMUs 4 and 5 on line sections

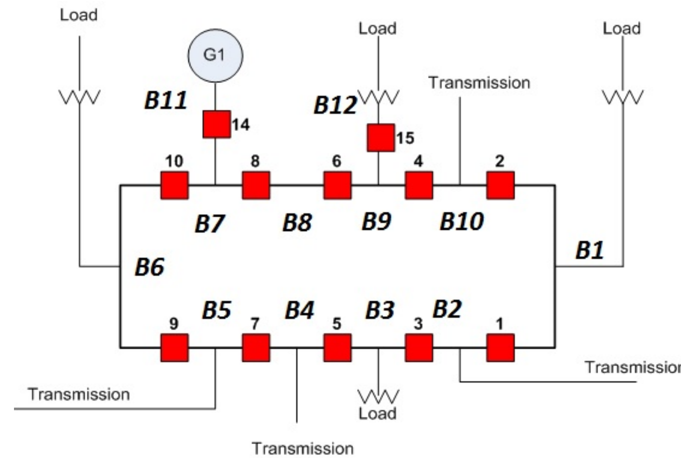


- Estimating breaker status:
  - Using 1st Kirchhoff Law, relationship between measured currents and breaker currents is

$$\begin{pmatrix} I_{M1} \\ I_{M2} \\ I_{M3} \\ I_{M4} \\ I_{M5} \\ 0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 1 \\ -1 & 0 & 0 & 1 & 0 \\ 0 & -1 & 1 & 0 & -1 \end{pmatrix} \begin{pmatrix} I_7 \\ I_8 \\ I_{14} \\ I_9 \\ I_{10} \end{pmatrix}$$

  - or $I_M = A\,I$

- Substation



  - Breaker current *I* is calculated as:

$$\min_I \left(I_M - A I\right)^T \left(I_M - A I\right)$$

  - Then, $I = \left(A^T A\right)^{-1} A^T I_M$
  - If $I_M^T = \begin{pmatrix} 1 & 1 & 4 & 3 & -1 & 0 \end{pmatrix}$ $I^T = \begin{pmatrix} 1 & 1 & 4 & 0 & 3 \end{pmatrix}$
  - Then breakers 7, 8, 10 and 14 are closed, and breaker 9 is open

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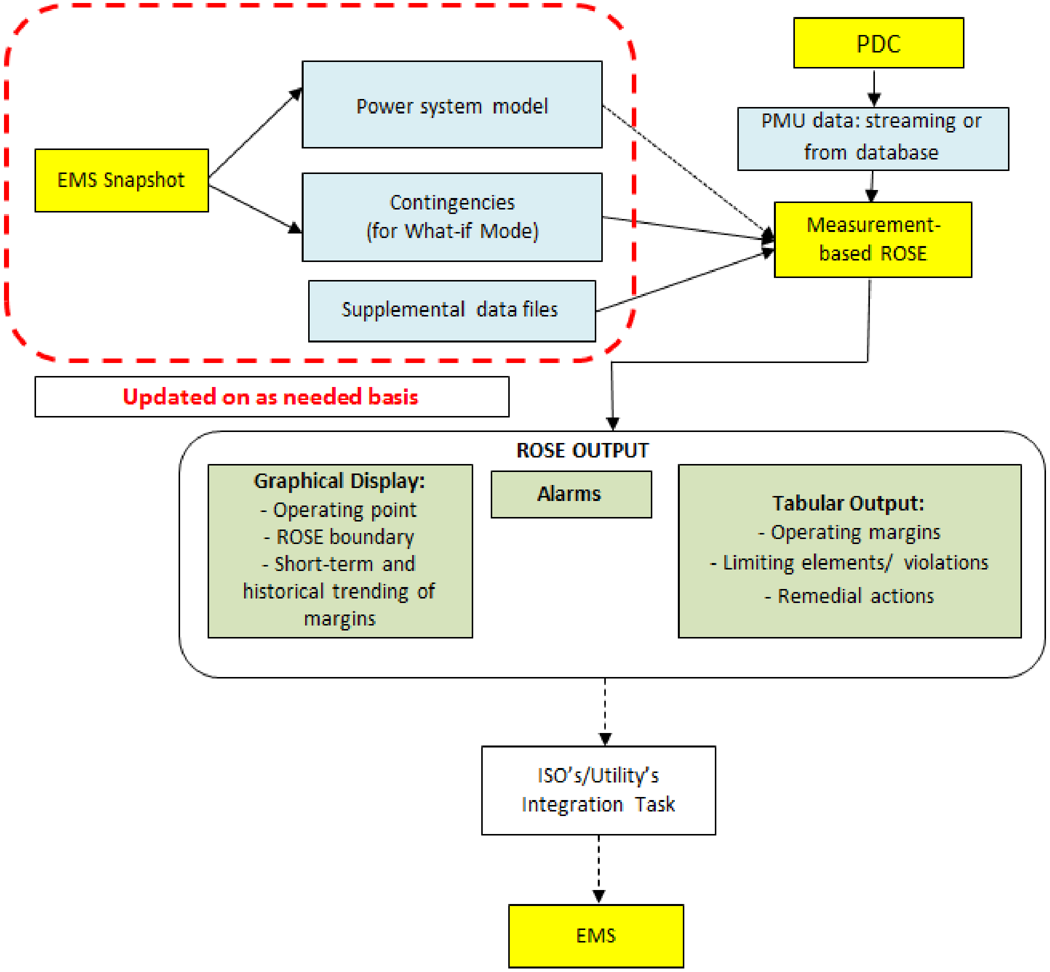
Estimating Breaker Status

- If measurement exists (non-zero), determining an error is based on a number of methods:
  - Weight factors;
  - Correlation analysis.

Architecture for Measurement-Based Analysis

- Main input is synchrophasor data
- Additionally, a power flow case is needed to obtain model parameters, locations of PMUs
- Supplemental files as needed to perform contingency analysis, voltage stability analysis, etc.



Measurement – Based Analysis

- Cases created by LSE may be used to perform:
  - AC contingency analysis;
  - Voltage stability analysis.

DOE PRSP Grant

- Grid Operator Monitoring and Control Assistant (GOMCA) under Peak Reliability Synchrophasor Program (PRSP)
- GOMCA Project Objectives include:
  - Demonstration of V&R Energy's LSE, including:
    - Observability analysis;
    - Bad synchrophasor data detection and conditioning;
    - Validation of cases created by LSE and their applicability to voltage stability analysis.
  - Measurement-based analysis:
    - Measurement-based voltage stability analysis;
    - Automatic determination of corrective remedial actions;
    - Situational awareness wall to visualize in an easy effective way synchrophasor data, and results of voltage stability analysis.

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Conclusions

- Linear State Estimation (LSE) is a solid foundation for measurement-based advanced applications.
- Use of the power system model created using LSE allows to perform contingency analysis and determine power system operating limits.
- LSE will allow to utilize synchrophasors to the full extent.
- LSE will transition from the concept to an operational tool as:
  - The number of PMU installation increases;
  - The methodology/process of LSE is tested and validated by the industry.

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