Linear State Estimation

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“Classification of mathematical problems as linear and nonlinear is like classification of the Universe as bananas and non-bananas.”

Math joke, unknown source
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 19th century
Input Data for Conventional State Estimator: Measurements

- Input data consists of imperfect power system measurements and system parameters.
- Power system measurements may include:
  - Voltage magnitudes at some buses;
  - Real and reactive components of power flows on some lines and transformers;
  - Real and reactive outputs of some of the generators;
  - Real and reactive components of some loads;
  - Targets of some of the control devices.
System parameters may include:

- Parameters of lines, transformers, generators, fixed shunts needed to produce a system state (such as thermal/voltage limits of lines, transformers, generators);
- Voltage setpoints of generators, control transformers, switched shunts, FACTS devices;
- Bandwidth of discrete devices;
- Estimated/planned values of generation and load.
Linear State Estimation

- Based on PMU measurements of voltage and current:
  - Orthogonal component of voltage and current vectors is considered as the state variable
- Advantage is speed of state estimation due to using a direct non-iterative solution
Output of State Estimation

Output of SE is the “best estimates” of the input quantities that satisfy the laws of physics (for example, Kirhgoff’s law), including:

- System voltages and phase angles at all buses;
- Real and reactive power flows on all branches (lines, transformers, breakers);
- Generator MW/MVAR output and real/reactive power components of load;
- ULTC tap positions and admittances of switched shunts.
V&R’s State Estimators

- V&R has 3 state estimator applications:
  - Conventional state estimator:
    - Advantage – no pseudo loads.
    - Based on SCADA data.
  - Linear state estimator:
    - Based on PMU data only.
  - Hybrid state estimator:
    - Uses both SCADA and PMU data.
    - Allows for different options to incorporate PMU data.

- State Estimator is a part of the ROSE software.
POM – State Estimator

- Can use V&R’s SE or export from any EMS vendor
- Model-based, measurement-based & hybrid State Estimator
- Integrated voltage and transient stability analyses
- Boundary-based solution
- Automatic analysis of cascading outages
- Automatic remedial actions to mitigate steady-state & transient stability violations
ROSE – Hybrid Approach

High Level Data Flow Diagram
WECC WISP-EMS System Modules
Updated by Sergio Rodriguez, March-12-2013

openPDC
- Input (From PMU/PDCs): Volt, Amp, Freq
- Output (To PhasorPoint):-Streams of Phasor Data
- Output (To openPDC):-Streams of Phasor Data

PhasorPoint
- PhasorPoint PDC’s Local Historian
- EMAS M-Tech SW KR (WASA Services)

VSA POM-ROSE SW KR
- Input (From openPDC):-Streams of Phasor Data
- Output To EMS GSA Power App

EMS Consoles
- ETV and WebFG UI
- VSA POM-ROSE Results

PhasorPoint Workbench UI
- Advanced Power Apps.

EMAS Consoles
- ETV Viewer
- WebFG Viewer
- WECC.PIW RCWorkBook SharePoint

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WECC-ROSE Real-Time Mode

- WECC-ROSE has three inputs:
  - State Estimator data
    - Node-breaker model
  - PMU data in C37.118
  - RAS status points (if available)

- Use of measurement-based real-time case:
  - Run the analysis when SE case is not available or the system approaches stability limits between the two SE cases.
  - Run the analysis continuously without interruption all the time:
    - Case is created and computations are performed with approx. the sampling PMU rate

- WECC-ROSE output includes:
  - Tabular results which are archived
  - Visualization
  - Alarming
State Estimation Process: One of the Implementations of the Hybrid SE

1. SCADA and PMU Measurements
2. Resolving Metering Errors, Adding Pseudo Measurements, Adding System Parameters
3. Estimating State Variables (Angles, Voltages)
5. Eliminating Pseudo Loads
6. Re-computing/adjusting voltages, angles, flows, load, generation (Optional)
Uses of State Estimation at V&R

- “Bad data” detection, including:
  - Bad PMU data;
  - Bad SCADA data;
  - Bad system parameters;
  - Errors in the process of conventional state estimation.

- Separating bad data with an onset of an event.

- Topology estimation, if breaker status is not available.

- Performing contingency analysis and voltage stability analysis:
  - Uses a case created by LSE when conventional SE case not available or in case of an alarming situation.

- Incorporating real-time data into planning data for off-line studies
Tested the effectiveness of linear state estimation based on AC power system model:

- Used a real-time case of a POM user with:
  - Buses 625
  - Loads 68
  - Generators 105
  - Branches 922

- Assumed that measurements are available on 777 branches with flows of 20 MW and above
Effectiveness of State Estimation: 2

- Added a random metering error with:
  - Average value 0.057
  - Standard deviation 1.145

- Ran state estimation

- After state estimation:
  - Average value 0.018
  - Standard deviation 0.428

Result of state estimation:
- Metering errors decreased in 2.7 times
Bad PMU data detection is done using a combination of two approaches:

- **Heuristic (logical) rules, such as:**
  - Real power computed using measured voltage and current at the From side should be greater than at the To side;
  - 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 Kirhgow law \( I_1 + I_2 + I_3 + I = 0 \),
    - 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 methods, such as:**
  - The chi-square criterion after performing least square minimization.
    - Measurements with high values of residual differences are not used.
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 $Y_{12}$ and $Y_0$:

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

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 Kirghoff Law, relationship between measured currents and breaker currents is

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

- or $I_M = AI$

Substation

- Breaker current $I$ is calculated as:

$$\min_I (I_M - AI)^T (I_M - AI)$$

- Then, $I = (A^T A)^{-1} A^T I_M$

- If $I_M^T = (1 \ 1 \ 4 \ 3 \ -1 \ 0) \quad I^T = (1 \ 1 \ 4 \ 0 \ 3)$

- Then breakers 7, 8, 10 and 14 are closed, and breaker 9 is open
If measurement exists (non-zero), determining an error is based on a number of methods:

– Weight factors;
– Correlation analysis.
Use of Results of Linear State Estimator in ROSE Real-Time

- When ROSE uses linear state estimator?
  - If conventional state estimator case doesn’t arrive or
  - System quickly approaches the limit

- ROSE creates a PMU-based “emergency” case very fast:
  - Using linear state estimation

- Then performs voltage stability analysis, phase angle limit computation, etc. using measurement-based case
Use of Results of Hybrid State Estimator in ROSE

Why ROSE uses hybrid state estimator?
- Uses PMU measurements, where available
- The rest of the network is represented using conventional state estimator:
  - Without pseudo loads

Then performs voltage stability analysis, phase angle limit computation, etc. using hybrid-based case
ROSE Off-Line

WECC-ROSE has three inputs:
- State Estimator data
  - Node-breaker model
- PMU data in the form of a saved file (capture file, flat file)
- RAS status points
  - If RAS actions are armed
Analysis Process and Data for Combining Real-Time and Planning Data

- PI
- POM-SE
  - Creates the model
- Real-time Loadflow Case
- Planning Data
  - POM
    - Combined Case
      - Near Real-Time Analysis
      - Planning Studies
      - Play-back/Operations Studies
Purpose of Combining Real-Time and Planning Data

The use of State Estimator:
- Resolve the imbalances in the system
- Resolves missing measurements that are either temporarily not reporting or ones that do not exist

Combined approach uses actual measurements/real-time data for advanced analysis; for example prediction and analysis of impact of cascades
Use of Combined Approach for Analysis of Cascading Outages

The process currently implemented (for Con Edison):

- Take available real-time measurements from historical database
- Based on these measurements and system parameters, perform state estimation
- Create a real-time case representing actual system conditions
- Embed this real-time case into a planning model to address NERC recommendations (see the following slide):
  - To account for global (interregional) phenomenon of cascading
  - Account for “potential internal or external contingencies”
NERC/FERC Recommendations from 2011 Southwest Outage

File “MRC_Item_9 - SW Blackout rev 05072013.pptx” from www.frcc.com

Key Findings

- Weaknesses in two broad areas:
  - Operations planning
  - Real-time situational awareness

Situational Awareness

- Recommended Improvements in WECC:
  - Improve use of real-time tools to ensure constant monitoring of potential internal or external contingencies
  - TOPs should review their real-time monitoring tools (State Estimator and RTCA) to ensure critical facilities are represented