Generalized State Estimation for Distribution Networks with a CIM Interface

Kemal Celik
Nexant, Inc.
Power Network State Estimation

- State Estimation is a statistical process
  - Solution depends on the majority of the data
  - As redundancy decreases, the noise filtering capability diminishes
  - Gateway to several advanced analytical applications
- Analog measurements for voltage magnitudes, power flows and power injections

$$z_i = f(x_i) + e_i$$

- Small errors (noise) in analog measurements
  - $L_2$ norm minimization of measurement residuals results in well-known WLS based algorithms
- Functions, $f(x)$, are known
- Large (gross) errors in analog measurements are detected and identified by (normalized) measurement residuals
State Estimation for Distribution Networks (Feeders)

- Distribution networks are (mostly) managed in a reactionary mode
- There are very few measurements
  - Redundancy is (much) less than 1
  - Some current magnitude and voltage measurements at the substation (at xmers, regulators)
  - Recently, more measurements at remotely controllable xmer and capacitor banks, switches
  - Pseudo measurements are used (may lead to numerical solution problems)
- Most (residential) networks are radial (ad-hoc algorithms to utilize the few measurements available)
- Some DMSs without state estimation function
  - DMSs are typically being used for monitoring
State Estimation for Distribution Networks

• Order of magnitude difference in the length of distribution lines
  – Several hundred/thousand smaller/disjoint networks with major network impedance data problems

• SCADA/RTU is expensive

• Finally, the stars are shining on distribution operations and planning
  – Smart Grid efforts focusing mainly on distribution
  – (Small? size) renewables, community storage, electric vehicles
  – Micro-grids are being implemented
  – Meshed/looped networks are becoming common
  – (Small/residential) demand response is becoming feasible
  – Several deployments/pilot projects of proactive voltage control
  – Traditional protection schemas are being threatened
State Estimation for Distribution Networks

• New types of sensors/measurements
  – Smart meters
  – Line monitors/fault detectors
  – PMUs
  – Access to information system that were typically silos until now

• Robust algorithms for DSE are needed
  – Innovatively deal with low redundancy
  – Handle all types of measurements
  – Handle all types of network topologies/equipment
State Estimation – Typical (Conventional) Approach

- Bus/branch network model through network topology processor
- Assume that
  - the digital (switch) measurements are 100% correct (topology is exactly known)
  - branch parameters are correct
  - there is enough redundancy in analog measurements for some amount of gross errors

\[ z_i = f(x_i) + e_i \]
Modeling Challenges (Errors)

Assume a linear model

Calculate best \( m \) & \( b \) given \((x,y)\) set

\[ y_i = mx_i + b \]

This residual is too big

Mark/eliminate this as bad data
Modeling Challenges (Errors)

$y_i = mx_i + b$

If assumption of linear model is wrong

$y_i = mx_i^2 + b$

And, the model is quadratic

Measurements identified as bad data change

- Topology & branch parameter errors lead to similar problems
State Estimation – Generalized Approach

- Node/breaker network model is preserved (whenever necessary)
- Redundant measurements ($z$), and flows through switches ($s$) and network impedances ($p$) in addition to conventional state variables ($x$)
- A single interacting set of data of switch statuses, analog measurements & device parameters
- Small errors (noise) in sensor data following normal distribution

$$z_i = f(x_i, s_i, y_i) + e_i$$
# Modeling of Switches & Uncertain Branch Parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>Diagram</th>
<th>Model</th>
<th>Pseudo-Measurement</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed Switch</td>
<td><img src="image" alt="Closed Switch Diagram" /></td>
<td>$P_{mn} = -P_{nm}$</td>
<td>Zero Voltage Difference</td>
<td>$p_{mn}$ $q_{mn}$</td>
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<td>$0 = V_m - V_n$</td>
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<td>Series Branch</td>
<td><img src="image" alt="Series Branch Diagram" /></td>
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<td>Zero Current Difference</td>
<td>$p'<em>{mn}$ $q'</em>{mn}$</td>
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<td>$Q_{mn} = Q_{mm} + Q'_{mn}$</td>
<td>$0 = p'<em>{mn} V_n + (p'</em>{mm} \cos \theta_{mn} - q'<em>{mm} \sin \theta</em>{mn}), V_m$</td>
<td>$p'<em>{mn}$ $p'</em>{mm}$</td>
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<td>$P_{nm} = P_{nn} + P'_{nm}$</td>
<td>$0 = q'<em>{mn} V_n + (p'</em>{mm} \sin \theta_{mn} + q'<em>{mm} \cos \theta</em>{mn}), V_m$</td>
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<tr>
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<td>Zero Admittance Difference</td>
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<td>$Q_{mn} = Q_{mm} + Q'_{mn}$</td>
<td>$0 = p_{mm} V_n^2 - p_{mn} V_n^2$</td>
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*From O. Alsac, N. Vempati, B. Stott & A. Monticelli IEEE Paper*

**3-phase formulation is a bit more complicated**
Conventional vs. Generalized State Estimation

Conventional
• Read in node/breaker data
• Run measurement plausibility
• Run network topology processing
• Run SE on bus/branch model
• Run bad data (BD) analysis
  – If none, stop
  – Delete measurements with the largest normalized residuals & run SE again

Generalized
• Read in node/breaker data
• Run measurement plausibility
• ** Run network topology processing
• Run SE on bus/branch model
• Run bad data (BD) analysis
  – If none, stop
  – If BD are detected, go to next SE run
• Read in node/breaker data
• Build bad data pockets
• Use a hybrid model & model bad data pockets in detail
• Zoom around BD in pockets & perform combinatorial analysis
  – Correct topology errors & eliminate BD
  – Go to **
Applying Generalized State Estimation to Distribution Networks

Pockets & windows do not grow in size with total number of buses, thus their solutions are system size independent.
Common Information Model

- Equipment (EQ)
- Connectivity (CN)
- Geographical (GEO)
- Measurement (MS)
- Topology (TP)
- State (SV)
- Graphics (GR)
- Boundary (BO)

CDPSM
- Equipment
- Connectivity
- Measurement
- Geographical

ENTSO-E
- Equipment
- Topology
- State
Modular CIM Profile for Generalized SE

- Equipment
- Connectivity
- Geographical
- Topology
- Boundary
- Graphics
- State
- Measurement

- Visualization
- Calculations
- Simulation Scenarios
- Storage
Complications & Challenges

- Network topology processing
  - Needs to be consistent at different layers/functions
- Boundary profile group
  - As multiple network models used in the simulations/calculation increase, so do the complications for retaining data in both node/breaker & bus/branch models
  - Multiple sequential SE runs require mapping between node/breaker (N/B) & bus/branch (B/B) models to persist accurately
    - First run is a conventional SE
    - Second run is a more detailed analysis
    - During the whole sequence, N/B $\leftrightarrow$ B/B mapping needs to persist and remain consistent
- Visualization
  - Needs both node/breaker & bus/branch to be consistently available
Conclusions

• Generalized SE is much more powerful and robust than the conventional state estimation
• DSE will get more attention and become a regular DMS component as network modeling accuracy requirements become more stringent
• CIM is a powerful data interface for generalized DSE
  – Meets the requirements for tailoring to both node/breaker & bus/branch models
  – Similar to the problems/challenges that have been traditionally a big problem for transmission network operators vs. planners
  – Further complications due to its ever-evolving nature and not necessarily a user friendly format
  – Still the best choice for hybrid data requirements