Enhanced State Estimation

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Results of the 2007 Survey of Reliability Issues

Participants were asked: “What do you believe is the likelihood of occurrence?”

<table>
<thead>
<tr>
<th>#</th>
<th>Question</th>
<th>% Highly Likely</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Limited Fuel Availability, Transportation, or Reduced Onsite Supplies</td>
<td>13%</td>
</tr>
<tr>
<td>2</td>
<td>System Protection and Controls - Imbalances and Malfunctions</td>
<td>17%</td>
</tr>
<tr>
<td>3</td>
<td>Aging Infrastructure and Limited New Construction</td>
<td>65%</td>
</tr>
<tr>
<td>4</td>
<td>Lack of Mandatory Standards for Reliable Operation</td>
<td>12%</td>
</tr>
<tr>
<td>5</td>
<td>Voltage/Reactive Reserve Availability</td>
<td>15%</td>
</tr>
<tr>
<td>6</td>
<td>Lack of Preventative Maintenance</td>
<td>22%</td>
</tr>
<tr>
<td>7</td>
<td>Operating closer to load limits</td>
<td>58%</td>
</tr>
<tr>
<td>8</td>
<td>Transmission System Congestion</td>
<td>62%</td>
</tr>
<tr>
<td>9</td>
<td>Vegetation-Related Transmission Outages</td>
<td>15%</td>
</tr>
<tr>
<td>10</td>
<td>Availability of Reliability Analysis Tools for Situational Awareness</td>
<td>13%</td>
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</tbody>
</table>
Load Limits

\[ P_{12} = \frac{V_1 V_2}{X} \sin \theta_{12} \]

- Steady State Limit
- Heavy Load Limit (Stability/Thermal)
- Medium Load
- Light Load
PTDFs are sensitive to topology changes.

Congestion

Gen 1

Power Transfer Distribution Factors PTDF

Gen 2

Buyer

PTDFs are sensitive to topology changes.
Role of State Estimator

- Monitor systems so that:
  - they can operate closer to their loading limits
  - transmission congestion can be managed
  - security margins are maintained

- Provide error free data base for other EMS functions such as:
  - Contingency Analysis and Security Constrained Optimal Power Flow
State Estimation

Measurements
\( P_i, Q_i, P_f, Q_f, V, I, \theta_{km} \)

Topology Processor

State Estimator

Network Observability Check

Bad Data Processor

Circuit Breaker Status
Barriers and Innovations

- Problem Formulation
  - Linear vs. nonlinear
  - Centralized vs. distributed
  - Errors [topology, parameter, calibration]
  - Static vs. dynamic
- Solution Algorithms
  - WLS vs. more robust estimators
  - Distributed approach
  - Dynamic estimators
- Measurement system design
  - Robustness
  - Multiple solutions
Problem Formulation

- Nonlinear
  - Conventional measurements
  - WLS formulation
  - Iterative solution
- Linear
  - Voltage and current phasors only
  - Direct solution
- Hybrid
  - Linear correction to nonlinear solution
Barriers and Innovations

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  – Robustness
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Problem Formulation

- Centralized
  - Raw measurements processed at the RTO
  - Very large scale system model and solution
  - Relies heavily on the system wide communication

- Distributed
  - Each Security Coordinator executes its own SE
  - Exchange and coordination of processed data
  - Topology / Analog errors are processed locally
Distributed SE Issues:

- Hierarchical design
  - RTO: high level coordinator
  - SC: local estimators

<table>
<thead>
<tr>
<th>Benefits</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; No Exchange of Raw Data</td>
<td>&gt; Inter-area or RTO-area Communication</td>
</tr>
<tr>
<td>&gt; Small Data Base</td>
<td>&gt; Sensitivity to Boundary Errors</td>
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<tr>
<td></td>
<td>&gt; Possible Inconsistency Between Estimators</td>
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New Technologies

- GPS
- RTO
- Control Area 1
- Control Area 2
- Control Area 3
- Substation Processors

Boundary Measurements
Estimated States
Barriers and Innovations

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• Measurement system design
  – Robustness
  – Multiple solutions
Errors

• Network parameters and topology are considered as “known”
• If undetected, substation configuration and breaker status errors will lead to rejection of multiple “good” measurements as bad
• Difficult to detect due to lack of explicit model of CB in the central SE formulation
• Parameters are numerous and not easily identified when they carry errors
Types of Topology Errors

Bus Reconfiguration

1

2

3

4

1

2

3

4

1

2

3

4
Types of Topology Errors

Bus Split / Merger

Load

1

2

3

4

Load

1

2

3

4

Load

1

2

3

4
State Estimator

CB/Switch Status Info

Analog Measurements

1. Stage State Estimator

Suspect Topology Error ?

Error Processing

LAV Estimator (Automatic rejection of BD)

Normalized residuals of rejected measurements

Selection of suspect substations

Next Scan

N
Model Used in Stage II:

Model Used in Stage I:

\[ f = [f_1, \ldots, f_3, \ldots, f_8] \]

\[ f_1 = 0 \]
\[ f_3 = 0 \]
\[ f_6 = 0 \]

breaker flow
CB Status Estimator

- CB/Switch Status Info
- Analog Measurements
- Measurement Processor
- Substation Simulator

2. Stage State Estimator

Estimated Status of CB/Switches

Augmented State

\[ X = \begin{bmatrix} v_1 \\ v_2 \\ v_n \\ f_1 \\ f_k \end{bmatrix} \]

Modified LAV Estimator

- Substation Model with CBs
- Flows through CBs
- Zero injections at inter. nodes
Identifying Parameter Errors

• Augment the state vector with the suspected parameters
• Simultaneously estimate the states and parameters

\[ v = [x_1, x_2, \ldots, x_n \mid p] \]

AUGMENTED STATE VECTOR
Challenges

• No reliable way to determine the suspect set of parameters
• May require inclusion of too many parameters
• How to differentiate between bad data and parameter errors?
Every network parameter is assumed to have an error:

\[ p = p_t + p_e \]

\[
\min J(x, p_e) = \frac{1}{2} [z - h(x, p_e)]^T W [z - h(x, p_e)]
\]

\[ s.t. \quad p_e = 0 \]

\[ c(x, p_e) = 0 \]

Lagrangian will be:

\[
L = \frac{1}{2} r^T W r - \mu^T c(x, p_e) - \lambda^T p_e
\]
Calibration Problem

- All measurements have errors
- Some errors are random, some others are not random, but systematic.
- Bad data are not systematic but random, however they appear as outliers.
- Some measuring instruments have systematic errors: bias, proportional drift, nonlinear effects.
- Can such measurements be calibrated remotely?
Measurement Errors

$z_i + e_i$

$z_1 + e_1$
$z_2 + e_2$
$z_3 + e_3$

State Estimator

$z_i :$ true measurement
$e_i :$ measurement error
$e_i = e_s + e_r$

systematic random
Assume a calibration function:

$$\bar{z} = f(z, p)$$

Non-calibrated Measurements

Calibrated Measurements

Calibration Parameters

$$\Delta \bar{z} = F_z \cdot \Delta z + F_p \cdot \Delta p$$

$$\Delta z = H \cdot \Delta x + e$$

$$\Delta \bar{z} = F_z \cdot H \cdot \Delta x + F_p \cdot \Delta p + e'$$
Barriers and Innovations

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• Measurement system design
  – Robustness
  – Multiple solutions
Static:

– Measurements are scanned every few seconds, SE runs every few minutes
– Time-skew exists between conventional measurements
– SE solution provides a snapshot and does not consider time-dependent variations
– Easy to implement and can be run in tracking mode
Dynamic:

- Scan rate estimation
- Requires a model for the state dynamics
- Computationally more involved
- Can be used to detect changes due to topology and parameters
- Potential to be used as a short-term predictor for the system state
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Weighted Least Squares

- Easy to implement
- Computationally fast
- Vulnerable to bad data in leverage points
- Normal equations can be ill-conditioned
- Divergent cases do not allow bad data processing
Solution Algorithms

Alternative methods
Re-weighted LS, LAV Simplex, LAV IP, Equality Constrained, Orthogonal Transformation, Trust Region
– Convergent under diverse conditions
– Computationally competitive
– Insensitive to bad data in leverage points
– Easily decentralized
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Dynamic estimators

- Potential for short term state prediction to facilitate preventive action control
- Improvements in identification of bad data and detection of topology errors
- Depending on the scan rate, possibility of incorporating dynamic models for power system components
Three stage procedure:
- Identification of the parameter matrix which defines the state dynamics
- Forecasting the next step system state
- State filtering
Improvements

- Dynamic state model must be determined
  - Parameter matrix in state model is not diagonal. Can it be identified as a sparse matrix?

- Measurements are not totally independent
  - R_z is not diagonal

- Topology, parameter and measurement errors should be detected
  - Use of innovations vector to detect and identify errors in modeling and measurements.
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Define the state vector for each area $i$: $X^i = \begin{bmatrix} X^i_{\text{int}} \\ X^i_b \\ X^i_{\text{ext}} \end{bmatrix}$.
Measurement vector for each area $i$:

$$
\begin{bmatrix}
Z^i_c \\
Z^i_p
\end{bmatrix}
$$

Unusable Measurements

Conventional Measurements

Phasor (PMU) Measurements
Properties of $z^i$

- Should render an observable area.
- External boundary buses may or may not be observable.
- Redundancy must be sufficient to make the internal bad data detectable and identifiable. Else, employ optimal meter placement methods to address this problem.
Measurements used by the RTO

- Boundary measurements from each area $Z_{b_i}$.
- Any available PMU measurements from area $i$, $Z_{p_i}$.
- Network data at area boundaries.
• **No boundary** measurements are discarded.
• **All** detectable / identifiable bad data are detected and identified.
• **PMU** measurements are effectively used, but **not required** for this scheme to work.
• Areas **do not share** network data (internal system details) or intermediate iteration results. They **only provide** boundary network model and measurements and their estimated states.
Barriers and Innovations

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Robust Design

Given a measurement configuration \{Z\} and the network topology \{T\}:

• Can the state \([X]\) be estimated?
• Can \([X]\) be estimated from the same \{Z\} for different topologies \{T1\}, \{T2\}, ..etc?
• Can \([X]\) be estimated for the same \{T\} if a measurement is lost \{Z\} \rightarrow \{Z'\}?
Robustness Against Topology Changes
Optimal Meter Placement

- Network remains observable under considered contingencies, network switching or loss of measurements
- Minimize meter cost, maximize robustness
- Constraints:
  - Must use meters (tie line monitoring)
  - Radial branches
  - Zero injections (cost free meters)
Optimal RTU/PMU Placement

• Placing Flows and Injections
• Placing Phasor (V and I) Measurements
• Objectives:
  – Full network observability
  – Full bad data detectability
  – Robustness against topology changes and loss of measurements
Lower Limits

- Placing Flows and Injections
  - \((N-1)\) measurements
- Placing Phasor (V and I) Measurements
  - \([\left(\frac{N-1}{2}\right)]\) Single Branch PMUs
Example: 14-bus System

Only **12 Flows** make the entire system observable. Note that **bus 7 is a zero injection bus**.
Synchronized Measurements

- PMUs will have higher accuracy than conventional measurements, hence will improve accuracy of SE and subsequent market functions (e.g. LMP)
- Reduce effects of time-skew among measurements
- Useful for many other applications such as system protection, control and stability assessment
- Aid topology error identification, parameter error detection and correction
- Improve robustness via more effective bad data processing
Example: 14-bus System

Only 7 PMUs make the entire system observable. Note that bus 7 is a zero injection bus.
• Bad data appearing in critical measurements can not be detected.
• Critical measurements are a result of low measurement redundancy.
• Adding measurements (conventional or PMU type) will eliminate them.
• Location of the new measurements must be strategically chosen.
Example: All Critical Measurements
Form the Candidate Matrix

- Contingencies
- Measurement Losses
- Critical measurements
0/1 Integer Programming

minimize \( C^T \cdot X \)

Subject to \( A \cdot X \geq b \)

\[
A_{ij} = \begin{cases} 
1 & \text{If meas. } j \text{ is a candidate for contingency } i \\
0 & \text{otherwise}
\end{cases}
\]

\[
X (i) = \begin{cases} 
1 & \text{If meas. } i \text{ is selected} \\
0 & \text{otherwise}
\end{cases}
\]

\( b^T = [1 \ 1 \ 1 \ \ldots \ 1] \)

\[
C (i) = \begin{cases} 
c_i & \text{if meas. } i \text{ already exist} \\
0 & \text{otherwise}
\end{cases}
\]
Single PMU ➔ No Critical Measurements
Multiple Solutions

• Multiple solutions satisfying the same measurement set
• More than one estimated state appear as viable solutions, passing the plausibility tests such as negative load, generation, voltage.
• Most likely when current magnitude and phasor measurements are present.
Multiple Solutions

Observable Island 1

Observable Island 2

K

L

PHASOR CURRENT

$V_k$, $V_{k1}$, $V_{k2}$, $V_{L1}$, $V_{L2}$, $V_i$, $I_{kl}$, $z_{kl}$
Concluding Remarks

• State estimation plays a key role in today’s EMS centers.

• Next generation state estimators ought to address the issues in problem formulation, solution algorithms and measurement design.

• Under scenarios involving distributed generation and loads, systems may be forced to operate under conditions for which they are not designed. Monitoring of such systems will be more challenging and the contributions by GCEP will have an impact on the methods to be used.