Detecting Circuit Breaker Status Errors in Substations

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Outline

- Introduction
- Motivation and Objectives
- Method 1: Two Stage State Estimation
- Method 2: Single Stage SE with Reduced Size Model
- Remarks and Conclusions
Introduction

- Substations are rapidly acquiring advanced computational and communication capabilities.
- EMS functions do not model substations in detail due to the complexity of the model.
- Certain measurements that are available at the substation can not be used by the central EMS functions.
- Such measurements can be readily processed at the substation to aid topology error detection.
Motivation

- There are no well established and commonly implemented methods to detect, identify and eliminate topology errors.
- Computational and communication capabilities at the substation can be exploited for this purpose.
- Measurements which would otherwise be discarded, could be used if processing were done at the substation.
Project Objectives

- Make use of all available measurements at the substation.
- Take advantage of CPU at the substation to improve EMS functions at the control center.
- Specifically, develop ways of detecting and identifying substation breaker status errors, so that State Estimation results will be more reliable and accurate.
Effect of Breaker Status Errors on State Estimation

Analog Measurements
$P_i, Q_i, P_f, Q_f, V, I, \theta_{km}$

Topology Processor

State Estimator

V, \theta

Bad Data Processor

Network Observability Check

Circuit Breaker Status

Assumed or Monitored

Link to be developed
Types of Topology Errors

Bus Reconfiguration
Types of Topology Errors

Bus Split / Merger

Load
Types of Topology Errors

Branch In/(Out of) Service

1

Out of Service

Out of Service

Line charging C

Out of Service

Line charging C
Proposed Two-Stage Approach

- **Stage 1:** Identify the suspected buses by normalized residuals of measurements.

- **Stage 2:** Introduce detailed models of suspected substations. Repeat the SE process using the expanded system model.
Two-stage State Estimator

CB/Switch Status Info

Analog Measurements

Measurement Processor

Substation Simulator

1. Stage State Estimator

2. Stage State Estimator

Suspect Topology Error?

Estimated Status of CB/Switches

Next Scan
Estimation of Breaker Status

- Estimation procedure:
  1. Identification of error location (substation).
     Use of measurement residuals
  2. Insert detailed substation model into SE.
     Model the substation using breaker / tie switch models and all internal measurements
  3. Estimate the status for all breakers.
     Concur the most likely substation configuration based on the estimated status of breakers and report it to the control center.
Measurement Equations

\[ z = h(x, f) + e \]

Where:
- \( z \) is the measurement vector;
- \( h(.) \) is the measurement function;
- \( x \) is the state vector;
- \( f \) is the vector of breaker flows;
- \( e \) is the measurement noise vector.
Model Used in Stage II:

Model Used in Stage I:

Load

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

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

\rightarrow: breaker flow

Load
Integrating Breakers into the Measurement Equations

\[ \Delta z = H \cdot \Delta x + M \cdot f + e \]

if the measurement \( i \) is an injection:

\[ M_{ij} = \begin{cases} 
1 & \text{if the injection is at the to-end of the breaker } j \\
-1 & \text{if the injection is at the from-end of the breaker } j \\
0 & \text{otherwise} 
\end{cases} \]

if the measurement \( i \) is a power flow:

\[ M_{ij} = \begin{cases} 
-1 & \text{if the flow is at the to-end of the breaker } j \\
1 & \text{if the flow is at the from-end of the breaker } j \\
0 & \text{otherwise} 
\end{cases} \]
State Estimator

CB/Switch Status Info

Analog Measurements

LAV Estimator (Automatic rejection of BD)

1. Stage State Estimator

Error Processing
- Normalized residuals of rejected measurements
- Selection of suspect substations

Suspect Topology Error?

N

Next Scan
CB Status Estimator

CB Status Estimator

Modified LAV Estimator
- Substation Model with CBs
- Flows through CBs
- Zero injections at inter. nodes

2. Stage State Estimator

Measurement Processor

Substation Simulator

Analog Measurements

Estimated Status of CB/Switches

Augmented State

\[ X = \begin{bmatrix} v_1 \\ v_2 \\ v_n \\ f_1 \\ f_k \end{bmatrix} \]
Example: IEEE 30 Bus System
Substation Configuration of Bus 15
## Estimated State of Circuit Breaker

<table>
<thead>
<tr>
<th>Circuit Breaker</th>
<th>Normalized P Flow</th>
<th>Normalized Q Flow</th>
<th>Estimated Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>15-32</td>
<td>-85.51</td>
<td>-23.39</td>
<td>Closed</td>
</tr>
<tr>
<td>15-33</td>
<td>7.63</td>
<td>-0.36</td>
<td>Closed</td>
</tr>
<tr>
<td>15-34</td>
<td>0.00</td>
<td>0.00</td>
<td>Open</td>
</tr>
<tr>
<td>15-35</td>
<td>0.00</td>
<td>0.00</td>
<td>Open</td>
</tr>
<tr>
<td>31-32</td>
<td>0.00</td>
<td>0.00</td>
<td>Open</td>
</tr>
<tr>
<td>31-33</td>
<td>0.00</td>
<td>0.02</td>
<td>Open</td>
</tr>
<tr>
<td>31-34</td>
<td>4.36</td>
<td>-7.38</td>
<td>Closed</td>
</tr>
<tr>
<td>31-35</td>
<td>-4.36</td>
<td>7.39</td>
<td>Closed</td>
</tr>
</tbody>
</table>
Weakness of the method:
How to identify the suspect substations?

- Use of Normalized residuals:
  - Suspect substation measurements may not have the largest normalized residuals.
  - Including too many substations in the suspect list may degrade the second stage state estimator performance due to increased complexity of the system model.
Alternative Method: Use of Reduced Model

\[ z = h(x_I, x_{CB}) + e \]
\[ c(x_I, x_{CB}) = 0 \]
\[ x_{CB} = 0 \]

\[ x_I = [\theta_1, p_2]^t \]
\[ x_{CB} = [\theta_{13}, \theta_{23}, \theta_{14}, p_{12}, p_{24}]^t \]
Steps of Topology Error Identification Procedure

- **Step 1. Topology Processing**
  First a proper tree is selected for each substation. Based on the tree, the state variables are categorized into two groups:
  \[ X_I \text{ and } X_{CB} \]

- **Step 2. State Estimation**
  Essentially identical to traditional state estimation carried out by existing methods.
  Obtain both:
  - the measurement residual vector \( r \)
  - and the Lagrange multiplier vector of zero injections
Steps of Topology Error Identification Procedure

- **Step 3.** Compute the normalized residuals for the measurements and the normalized Lagrange multipliers for the circuit breaker variables.

- **Step 4.** Bad Data and Topology Error Identification

  Check the largest normalized residual or Lagrange multiplier.

  If it is larger than the threshold, suspect the corresponding measurement or the breaker to be the source of error in estimation.
Reduced Model Formulation

Form the Lagrangian:

\[ L = \frac{1}{2} r^t W r - \mu^t c(x_1, x_{CB}) - \lambda^t x_{CB} \]

Optimality conditions:

\[
\begin{bmatrix}
I & 0 & H_1 \\
0 & 0 & C_1 \\
H_1^t W & C_1^t & 0
\end{bmatrix}
\begin{bmatrix}
r \\ \mu \\ x_1
\end{bmatrix}
= \begin{bmatrix}
z \\ c_1 \\ 0
\end{bmatrix}
\]

Note that \( x_{CB} \) is zero!

Then, \( \lambda \) can be solved as:

\[ \lambda = T \begin{bmatrix} r \\ \mu \end{bmatrix} \]

where:

\[ T = -\begin{bmatrix} WH_{CB} \\ C_{CB} \end{bmatrix} \]

State Variables Used

<table>
<thead>
<tr>
<th>Model</th>
<th>State Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>( \theta_1, \theta_2, \theta_3, \theta_4, p_{13}, p_{14}, p_{23}, p_{24}, p_{12} )</td>
</tr>
<tr>
<td>Implicit</td>
<td>( \theta_1, p_2 )</td>
</tr>
</tbody>
</table>
## Simulated Topology and Measurement Errors

<table>
<thead>
<tr>
<th>Test System</th>
<th>Wrong status CB &amp; Outaged Line/Meas.</th>
<th>Test A</th>
<th>Test B</th>
</tr>
</thead>
<tbody>
<tr>
<td>14-bus</td>
<td>$CB_{34-32}$</td>
<td>Line 5-6</td>
<td>$P_{34-32}$</td>
</tr>
<tr>
<td>30-bus</td>
<td>$CB_{74-68}$</td>
<td>Line 10-22</td>
<td>$P_{74-68}$</td>
</tr>
<tr>
<td>57-bus</td>
<td>$CB_{80-78}$</td>
<td>Line 4-6</td>
<td>$P_{80-78}$</td>
</tr>
</tbody>
</table>
Example: IEEE 30 Bus System
# Results of Error Identification

## 30-Bus System

<table>
<thead>
<tr>
<th>Test A</th>
<th>Test B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Measurement/Topology</strong></td>
<td><strong>Normalized residual / $\lambda^N$</strong></td>
</tr>
<tr>
<td>$CB_{74-68}$</td>
<td>212.30</td>
</tr>
<tr>
<td>$CB_{70-68}$</td>
<td>199.09</td>
</tr>
<tr>
<td>$CB_{10-71}$</td>
<td>160.95</td>
</tr>
<tr>
<td>$CB_{105-104}$</td>
<td>157.04</td>
</tr>
<tr>
<td>$CB_{106-104}$</td>
<td>157.04</td>
</tr>
</tbody>
</table>
## Results of Error Identification

### 57-Bus System

<table>
<thead>
<tr>
<th>Measurement/Topology</th>
<th>Normalized residual / $\lambda^N$</th>
<th>Test B</th>
<th>Measurement/Topology</th>
<th>Normalized residual / $\lambda^N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CB_{80-78}$</td>
<td>371.63</td>
<td>$P_{80-78}$</td>
<td>96.40</td>
<td></td>
</tr>
<tr>
<td>$CB_{82-78}$</td>
<td>371.63</td>
<td>$P_{1228-124}$</td>
<td>39.08</td>
<td></td>
</tr>
<tr>
<td>$CB_{81-82}$</td>
<td>282.65</td>
<td>$CB_{80-78}$</td>
<td>37.87</td>
<td></td>
</tr>
<tr>
<td>$CB_{76-75}$</td>
<td>212.03</td>
<td>$CB_{82-78}$</td>
<td>37.87</td>
<td></td>
</tr>
<tr>
<td>$CB_{77-75}$</td>
<td>212.03</td>
<td>$CB_{79-80}$</td>
<td>36.93</td>
<td></td>
</tr>
</tbody>
</table>
Critical Breaker Pairs

Either one of breakers 2-3 and 2-4 can disconnect the line incident to bus 4.

Hence, status errors in these Breakers can be DETECTED but can NOT be IDENTIFIED.
CONCLUSIONS

- Measurements can be processed at the substation in order to assist breaker error detection and identification.
- State estimation results can be improved by proper identification of topology errors.
- Two-stage approach works well as long as the suspect substation is properly identified.
- Reduced order SE allows topology error identification without the need to identify suspect substations. Implementation may be more involved.