Enhancing the System Resiliency using PMU based RAS Scheme

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Introduction

- In order to minimize the wind power curtailment and protect the transmission lines from overload or stability problems, RAS can be deployed for faster control actions.

- Existing RAS are hard coded based on pre-determined control actions. These are non-optimal and controls are designed for local level but may not be good at system level.

- A new dynamic and adaptive RAS is needed using measurements and system status to make control actions.

- New fault-tolerant computational approach needs to be developed to provide fast and correct data to dynamic and adaptive RAS
Classification of RAS - Based on architecture

**Centralized**
- Not resilient to node failures
- Not scalable

**De-centralized**
- Resilient to single node failure
  - Requires communication among nodes
- Data exchange is crucial

**Distributed**
- Similar to de-centralized
- More complex
Classification of RAS – Based on data

Hardcoded
- Model based
- Not suitable for changing operating conditions
- May not be fast
- Non scalable
- Threshold based

Adaptive
- Measurement based
- Adapts to changes in system parameters and configuration
  - Fast
- Depends on high resolution measurement data
  - Scalable

More Classification
- Event based
- Response based
- Measurement based
- Precalculated
Formulation of Wind Curtailment RAS

- RAS is developed as a linear programming based optimization of DC power flow

\[ P_{Gen} - P_{Load} = B \times \theta \]

\[ \theta = B^{-1}(P_{Gen} - P_{Load}) \]

\[ P_{ij} = B_{ij}(\theta_i - \theta_j) \leq LR_{ij} \]

- Objective function

\[ \text{Max } f(x) = \sum_{i=1}^{N_G} x_i \times P_{G_i} \]

Subject to line constraints

Maximize wind connected to the grid but with no overload and no voltage violation
Specifications and Functions for Wind Curtailment RAS

Key modules in Wind curtailment RAS are:

- **Data Acquisition**: Protocol conversion, periodic data input, event data input, time stamping, buffer input data, time aligning
- **DLSE**: Noise filtering, bad data, topology processing
- **RAS**: Initialization, get state variables, optimization, solution update, generate control actions
- **System testing actor**: Testing of system under static and dynamic conditions before deployment
Why resiliency?

- Traditionally, the performance of power system is quantified using reliability indices like SAIDI, SAIFI, etc.

- Extreme events and real-time operating conditions are not considered in the statistics of reliability indices.

- In this study, resiliency of power systems is defined as the system’s ability to maintain continuous power supply to priority/critical loads (as defined by the user) under disruptive events.

- Resiliency metric is quantified based on:

  1. Network based indices (using graph theory approach)
  2. Electrical factors based indices (using real-time measurements to assess the current operating state of the system)
Source-Path-Destination (SPD) index

- This index takes into account the network configuration and redundancy in connectivity along with the physical-based electric flow properties (resistance offered to electric flow).

\[
\text{SPD index} = \sum_{i=1}^{N_G} \frac{k_i^2}{BVI_i \times HI_i \times (1 + \text{Average cost}_i)}
\]

Branch Vulnerability Index

- It is the measure of number times a branch appears in ‘k’ source-destination paths.

\[
BVI_i = \sum_{N_L}^{n_k} \frac{n_k}{k_i}
\]

Hops Index

- It is the measure of number of hops (transmission lines, transformers, etc.) linking ‘k’ source-destination paths.

\[
HI_i = \sum_{k} \frac{n_{lk}}{k}\]
Electrical based indices

The existence of a connection between source (generator) and destination (substation) doesn’t always imply that power can be transferred. Thus, electrical factors need to included while computing the resiliency metric for power systems.

Three factors that are included are:
- MW availability index
- MVAr availability index
- Loss of load index

MW availability index is the measure of availability of MW power from different generation sources.

\[
\text{MW availability index} = \frac{\sum_{i=1}^{N_G} \text{MW availability}_i \times \text{Generator Availability}_i}{\text{MW critical/priority load}}
\]

MVAr availability index is the measure of availability of MVAr power to sustain voltages at distribution level.

\[
\text{MVAr availability index} = \sum_{N_{RR}} \frac{\text{MVAr availability}}{\text{MVAr priority/critical load}}
\]
Electrical based indices

- Loss of Load Index is the measure of total amount of critical/priority load being supplied by the system.

\[
\text{Loss of load index} = \frac{\text{Actual priority load supplied}}{\text{Total priority load}}
\]

Resiliency metric

- All the above indices are combined together using Analytical Hierarchical Process into a single resiliency metric.
- The weights are the eigenvector of the combination matrix that is defined by the user indicating the co-relation between different indices.
Enabling resiliency in transmission systems

- Redundancy (standby, backup, spare)
- Maintenance (corrective, preventive, etc.)
- Different architectural implementation
- Prognostic health management
- Automation of substations
- Wide-area automated protection schemes

More resilient but less cost effective

Use of incoming data

Control actions based on present condition
Cyber-physical RAS simulations test bed
<table>
<thead>
<tr>
<th>Bus 10</th>
<th>SPD index</th>
<th>MW availability index</th>
<th>MVAr availability index</th>
<th>Loss of load index</th>
<th>Resiliency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>23.315</td>
<td>37.908</td>
<td>68.830</td>
<td>1</td>
<td>1.000</td>
</tr>
<tr>
<td>Excess wind generation (without RAS)</td>
<td>7.539</td>
<td>39.375</td>
<td>63.097</td>
<td>1</td>
<td>0.851</td>
</tr>
<tr>
<td>Excess wind generation (with RAS)</td>
<td>23.315</td>
<td>39.173</td>
<td>68.780</td>
<td>1</td>
<td>1.002</td>
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</tbody>
</table>
### Performance of RAS during a cyber attack

<table>
<thead>
<tr>
<th>Normal condition</th>
<th>Wind Gen-1</th>
<th>Wind Gen-2</th>
<th>Wind Gen-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW generation data input during excessive wind generation (MW)</td>
<td>37.52</td>
<td>97.78</td>
<td>71.72</td>
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<tr>
<td>MW generation with centralized and de-centralized RAS under normal operation</td>
<td>11.75</td>
<td>24.22</td>
<td>67.64</td>
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</table>

<table>
<thead>
<tr>
<th>Cyber attack (False data injection)</th>
<th>Wind Gen-1</th>
<th>Wind Gen-2</th>
<th>Wind Gen-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW generation data input to RAS during excessive wind generation (MW)</td>
<td>37.52</td>
<td><strong>60</strong></td>
<td>71.72</td>
</tr>
<tr>
<td>MW generation with centralized RAS under normal operation</td>
<td>FAILED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MW generation with distributed and RAS under normal operation</td>
<td>18.32</td>
<td>20.97</td>
<td>16.14</td>
</tr>
</tbody>
</table>
Modified IEEE 39 bus system

Excessive wind
# IEEE 39 bus system

<table>
<thead>
<tr>
<th>Bus 6</th>
<th>SPD index</th>
<th>MW availability index</th>
<th>MVAr availability index</th>
<th>Loss of load index</th>
<th>Resiliency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>43.179</td>
<td>59.49</td>
<td>94.065</td>
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<td>1.000</td>
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<tr>
<td>Excess wind generation (without RAS)</td>
<td>17.881</td>
<td>51.461</td>
<td>103.375</td>
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<td>0.863</td>
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<td>Excess wind generation (with RAS)</td>
<td>43.179</td>
<td>60.422</td>
<td>101.669</td>
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<td>1.004</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Bus 8</th>
<th>SPD index</th>
<th>MW availability index</th>
<th>MVAr availability index</th>
<th>Loss of load index</th>
<th>Resiliency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>47.728</td>
<td>9.518</td>
<td>12.542</td>
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<td>1.000</td>
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<tr>
<td>Excess wind generation (without RAS)</td>
<td>12.5113</td>
<td>8.234</td>
<td>13.783</td>
<td>0.806</td>
<td>0.703</td>
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<tr>
<td>Excess wind generation (with RAS)</td>
<td>47.728</td>
<td>9.668</td>
<td>13.556</td>
<td>1</td>
<td>1.004</td>
</tr>
</tbody>
</table>
We would like to thank CREDC, DOE ARPA-E, and PSERC for supporting this work
Thank You