The Use of High-Speed Synchronized Measurements to Create Dynamic Indicators of Grid Resilience

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What is Missing in Resilience Metrics?

- There are many resilience metrics in use out there.
- However, no consistent studies on the benefits to each metric and when/how to use these metrics.
- Many of these metrics are economic and some are not precisely defined (e.g., subjective) ➔ Takes time and a lot of data (not always available) to calculate these metrics.
- One key lesson learned in recent DOE/GMLC resilience project is that industry wanted to see dynamic resilience indicators – shorter term measures of the grid’s capability to handle major events – potential indicators of tipping points in response to these events.
Resilience Trapezoid

# Resilience Phases

<table>
<thead>
<tr>
<th>Pre-Disturbance</th>
<th>Disturbance</th>
<th>Degraded</th>
<th>Recovery</th>
<th>Post recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource Adequacy <em>(Probabilistic Measures)</em></td>
<td>Generation lost per hour</td>
<td>Cumulative energy not served</td>
<td>Time to Infrastructure recovery</td>
<td>Post event analysis</td>
</tr>
<tr>
<td>Loss of Load Expectation (LOLE)</td>
<td>Transmission lines tripped per hour</td>
<td>Severity Risk Index</td>
<td>Time to operational recovery</td>
<td></td>
</tr>
<tr>
<td>Loss of Load Probability (LOLP)</td>
<td>Load lost per hour</td>
<td></td>
<td>Generation restored per hour</td>
<td></td>
</tr>
<tr>
<td>Effective Load-Carrying Capacity (ELCC)</td>
<td>Dynamic Resilience Indicator</td>
<td></td>
<td>Transmission lines restored per hour</td>
<td></td>
</tr>
<tr>
<td>Expected Unserved Energy (EUE)</td>
<td>Planning Reserve</td>
<td></td>
<td>Load restored per hour</td>
<td></td>
</tr>
</tbody>
</table>
# FLEP Metrics – Definitions

<table>
<thead>
<tr>
<th>FLEP Metrics</th>
<th>Description of Metrics</th>
<th>Generation Lost</th>
<th>Transmission Lines Tripped</th>
<th>Load Disconnected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ – Fast</td>
<td>How Fast does resilience drop?</td>
<td>% of MW lost/hour</td>
<td>% of lines tripped/hour</td>
<td>% of MW lost/hour</td>
</tr>
<tr>
<td>Λ – Low</td>
<td>How Low does resilience drop?</td>
<td>% of MW lost</td>
<td>% of lines tripped</td>
<td>% of MW lost</td>
</tr>
<tr>
<td>Ε – Extent</td>
<td>How Extensive is the degraded state?</td>
<td>hours</td>
<td>hours</td>
<td>hours</td>
</tr>
<tr>
<td>Π – Prompt</td>
<td>How Promptly does the system recover?</td>
<td>MW restored/hour</td>
<td>% of lines restored/hour</td>
<td>MW restored/hour</td>
</tr>
</tbody>
</table>

## FLEP Metrics – Calculations

<table>
<thead>
<tr>
<th>Metric</th>
<th>Mathematical Expression</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Φ</td>
<td>( \frac{R_0 - R_1}{t_2 - t_1} )</td>
<td>MW/hours, No. of lines tripped/hours, No. outages/hours, No. of unserved customers/hours</td>
</tr>
<tr>
<td>Λ</td>
<td>( R_1 - R_0 )</td>
<td>MW, No. of Lines tripped, No. of outages, No. of unserved customers</td>
</tr>
<tr>
<td>Ε</td>
<td>( t_3 - t_2 )</td>
<td>hours</td>
</tr>
<tr>
<td>Π</td>
<td>( \frac{R_1 - R_0}{t_4 - t_3} )</td>
<td>MW/hours, No. of lines restored/hours, No. of restored customers/hours</td>
</tr>
<tr>
<td>Area</td>
<td>( \int_{t_1}^{t_4} R(t) , dt )</td>
<td>MW X hours, No. of lines in service X hours, No. of outages X hours, No. of customers X hours</td>
</tr>
</tbody>
</table>
Severity Risk Index (SRI)

- Daily metric where the generation loss, transmission loss and load loss due to a major event aggregates to a single value that indicates grid resilience.
- SRI can show the best and poorest performance of the grid over a long period of time.
- SRI can also illustrate the trend towards recovery due to a major event.
- Feedback from TRC in NTRR project on SRI:
  - No consistent agreement on weighting of these components.
  - No consistent agreement on how or even if SRI should be used.
Calculating SRI

For long time periods, e.g., days to weeks, SRI is calculated:
(Note: FLEP metrics are inputs to SRI)

Severity Risk Index = SRI = $\beta_1 \times GL + \beta_2 \times TLT + \beta_3 \times LD$

where $GL = \%$ of Generation Lost per hour/day

TLT = $\%$ of Transmission Lines Tripped per hour/day

LD = $\%$ of LoadDisconnected per hour/day

$\beta_1$, $\beta_2$, and $\beta_3$ are weighting indices such that $\beta_1 + \beta_2 + \beta_3 = 1$

Per NERC, $\beta_1 = 0.1$, $\beta_2 = 0.3$, $\beta_3 = 0.6$
Dynamic Resilience Indicator (DRI)

Measure of Reactive Reserves

Measure of Voltage Stability

- For shorter time periods (seconds to minutes to a couple hours)
- Calculated during the disturbance phase
- Can be used to identify precursors to major loss of resilience in grid
- Can be used as a post-event forensic metric
- Can be used as a means to identify where additional investments would be most needed
Calculating DRI

For short time periods (secs to mins to couple hours), data for SRI is unavailable => need dynamic metrics:

Dynamic Resilience Indicator = DRI = \( \alpha_1 \cdot RR + \alpha_2 \cdot LL + \alpha_3 \cdot FA \)

where

- \( RR \) = Measure of Reactive Reserves (e.g., phase angle sep. in p.u. between buses)
- \( LL \) = Loadability Limit in p.u. (e.g., tip of the nose curve => point of maximum load)
- \( FA \) = Measure of Frequency Agility = (e.g., % of Frequency Nadir)

\( \alpha_1, \alpha_2, \) and \( \alpha_3 \) are weighting indices such that \( \alpha_1 + \alpha_2 + \alpha_3 = 1 \)
Measures of Grid Strength

- Grid strength is another potential measure of resilience.
- Grid strength describes stiffness of terminal voltage in response to current injection variations.
- Strong grids $\Rightarrow$ Voltage and angle are relatively insensitive to current injection variations.
- Grid strength is closely related to short circuit current level $\Rightarrow$ The higher the short circuit level, the stronger the grid.
- IBRs provide minimal contribution to short circuit current due to inverter limitations.
- As more IBRs replace synchronous generators $\Rightarrow$ Decrease in short circuit level is expected.
- Therefore:
  - Need to monitor grid strength
  - Identify weak grid conditions
  - Develop mitigation strategies as IBRs proliferate
Weighted Short Circuit Ratio (WSCR)

A metric for grid strength that can be used to measure resilience is the Weighted Short Circuit Ratio (WSCR) defined as:

\[ WSCR = \frac{\sum_i^N SCMVA_i \times P_i}{\sum_i^N P_i} \]

where \( SCMVA_i \) is the short-circuit capacity at bus \( i \) without current contribution

\( P_i \) is the MW output of non-synchronous generation to be connected at bus \( i \)

\( N \) is the number total number of non-synchronous generation resources

ERCOT is using this metric to define operational limits for total transmission of power from IBRs across key power system interfaces*.

*NERC, Integrating Inverter-Based Resources into Low Short Circuit Strength Systems, 2017.
Next Steps

- Independent study of current resilience metrics in use: benefits, weaknesses, examples.
- Need to study how SRI, DRI, WSCR can be used to identify areas in the grid that need further investment to improve resilience and what these investments might be.
- Specific grid events should be studied ➔ Wildfire scenarios, extreme drought, polar vortex, etc., with high fidelity models.
- Tie in key infrastructures to the analysis, e.g., natural gas, to determine sensitivity of resilience to disruptions in these interdependencies.
- Engage industry as much as possible!
Acknowledgements

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Questions?

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