



Paper No. 22PESGM3804: Revisiting Resilience Indices

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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 NTRR project is that industry, e.g., TRC, wanted to see **dynamic resilience indicators** – shorter term measures of grid strength and grid ability to handle major events – for their potential use as indicators of tipping points in grid resilience in response to these major events.

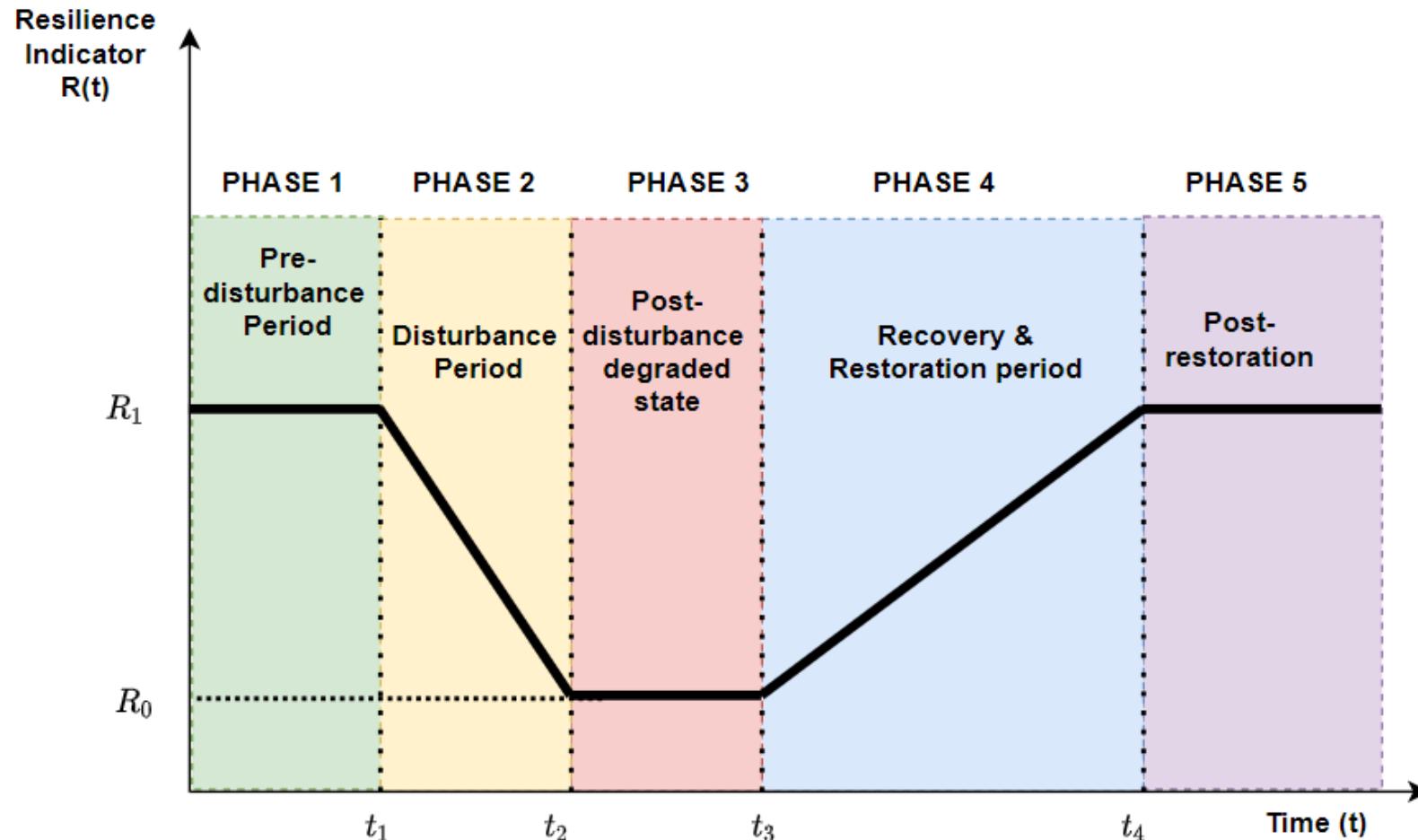
Resilience vs. Reliability

Major differentiator between them is **frequency and impact of an event**.

- Resilience:
 - High consequence, low probability events
 - Concerns operation of the grid during extreme and adverse events
 - Considers the cause to a metric
- Reliability:
 - Low consequence, high probability events
 - Concerns adequate grid operations in typical conditions
 - Does not attribute the cause to a metric

Resilience bridges the gap between the **system response and a root cause**.

Resilience Trapezoid



Panteli, M., Mancarella, P., Trakas, D. N., Kyriakides, E., & Hatziaargyriou, N. (2017). Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems. *IEEE Transactions on Power Systems*. <https://doi.org/10.1109/TPWRS.2017.2664141>

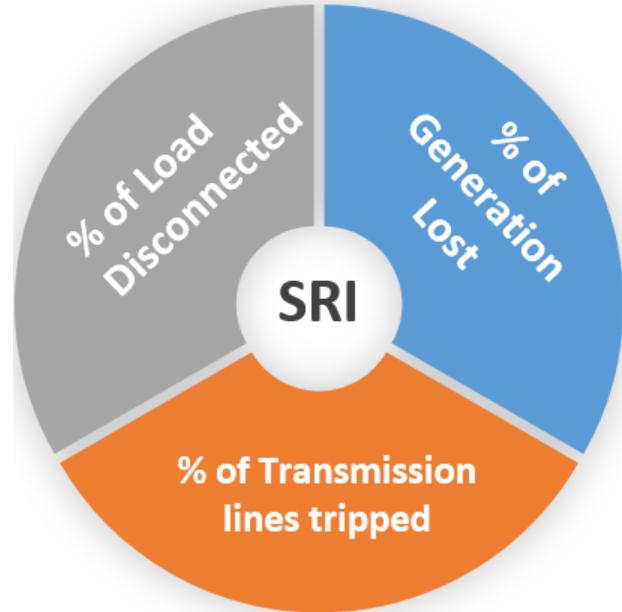
Resilience Phases

| Pre-Disturbance | Disturbance | Degraded | Recovery | Post recovery |
|--|---|---|---|---|
| <p>Resource Adequacy (<i>Probabilistic Measures</i>)</p> <ul style="list-style-type: none"> ❖ Loss of Load Expectation (LOLE) ❖ Loss of Load Probability (LOLP) ❖ Effective Load-Carrying Capacity (ELCC) ❖ Expected Unserved Energy (EUE) ❖ Planning Reserve | <ul style="list-style-type: none"> ❖ Generation lost per hour ❖ Transmission lines tripped per hour ❖ Load lost per hour ❖ Dynamic Resilience Indicator | <ul style="list-style-type: none"> ❖ Cumulative energy not served ❖ Severity Risk Index | <ul style="list-style-type: none"> ❖ Time to Infrastructure recovery ❖ Time to operational recovery ❖ Generation restored per hour ❖ Transmission lines restored per hour ❖ Load restored per hour | <ul style="list-style-type: none"> ❖ Post event analysis |

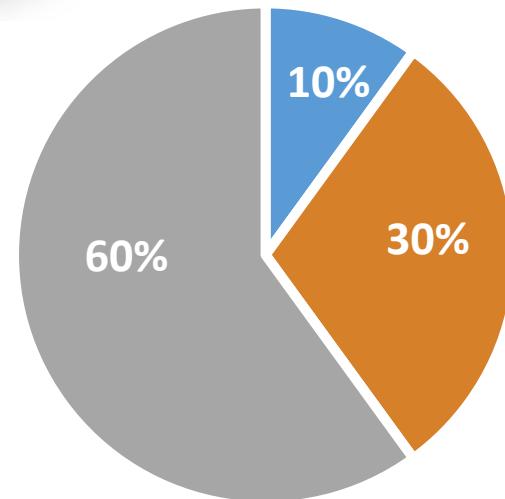
FLEP Metrics

| FLEP Metrics | Description of Metrics | Generation Lost | Transmission Lines Tripped | Load Disconnected |
|--------------|--|-------------------|----------------------------|-------------------|
| Fast | How Fast does resilience drop? | % of MW lost/hour | % of lines tripped/hour | % of MW lost/hour |
| Low | How Low does resilience drop? | % of MW lost | % of lines tripped | % of MW lost |
| Extensive | How Extensive is the degraded state? | hours | hours | hours |
| Promptly | How Promptly does the system recover? | MW restored/hour | % of lines restored/hour | MW restored/hour |

Severity Risk Index (SRI)



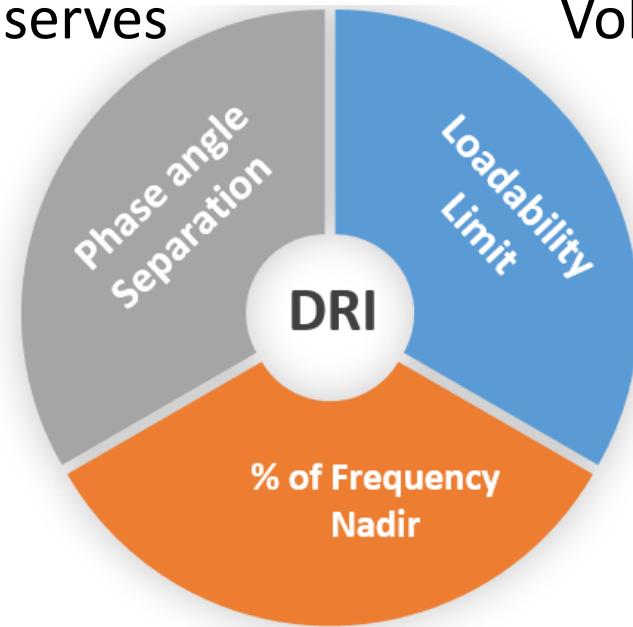
NERC →



- ❖ 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.

Dynamic Resilience Indicator (DRI)

Measure of
Reactive Reserves



Measure of
Frequency Agility

Measure of
Voltage Stability

- ❖ For shorter time periods. (Minutes to 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 SRI and DRI

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

$$\text{Severity Risk Index} = \text{SRI} = \beta_1 * \text{GL} + \beta_2 * \text{TLT} + \beta_3 * \text{LD}$$

where GL = % of Generation Lost per hour/day

TLT = % of Transmission Lines Tripped per hour/day

LD = % of Load Disconnected per hour/day

β_1 , β_2 , and β_3 are weighting indices such that $\beta_1 + \beta_2 + \beta_3 = 1$

Per NERC, $\beta_1 = 0.1$, $\beta_2 = 0.3$, $\beta_3 = 0.6$

- For short time periods (mins to hours), data for SRI is unavailable → need dynamic metrics

$$\text{Dynamic Resilience Indicator} = \text{DRI} = \alpha_1 * \text{RR} + \alpha_2 * \text{LL} + \alpha_3 * \text{FA}$$

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)

α_1 , α_2 , and α_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 → Voltage and angle are relatively insensitive to current injection variations.
- Grid strength is closely related to short circuit current level → 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 → 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

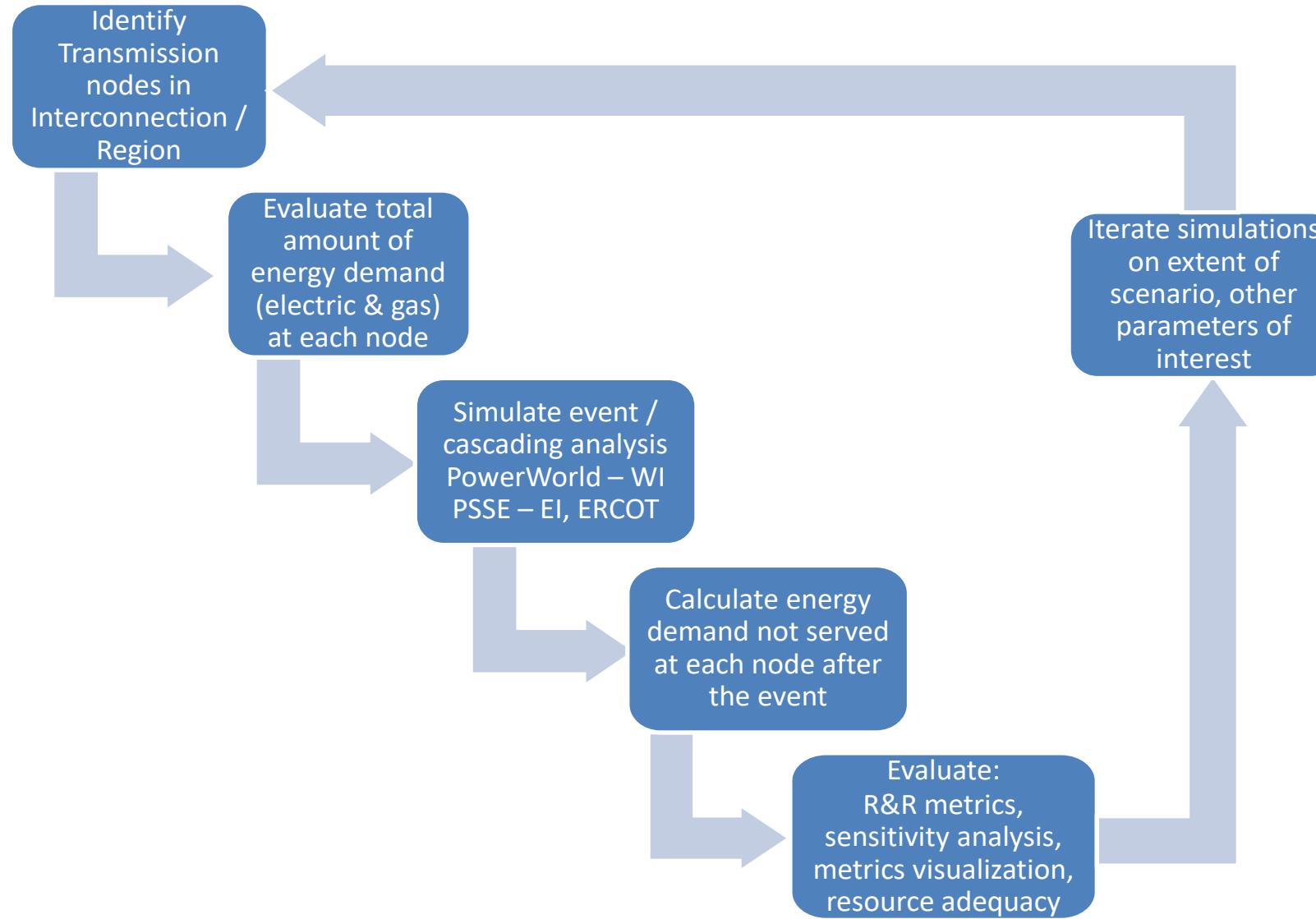
P_i is the MW output of non-synchronous generation to be connected at bus i

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.

Resilience Analysis Process



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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