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

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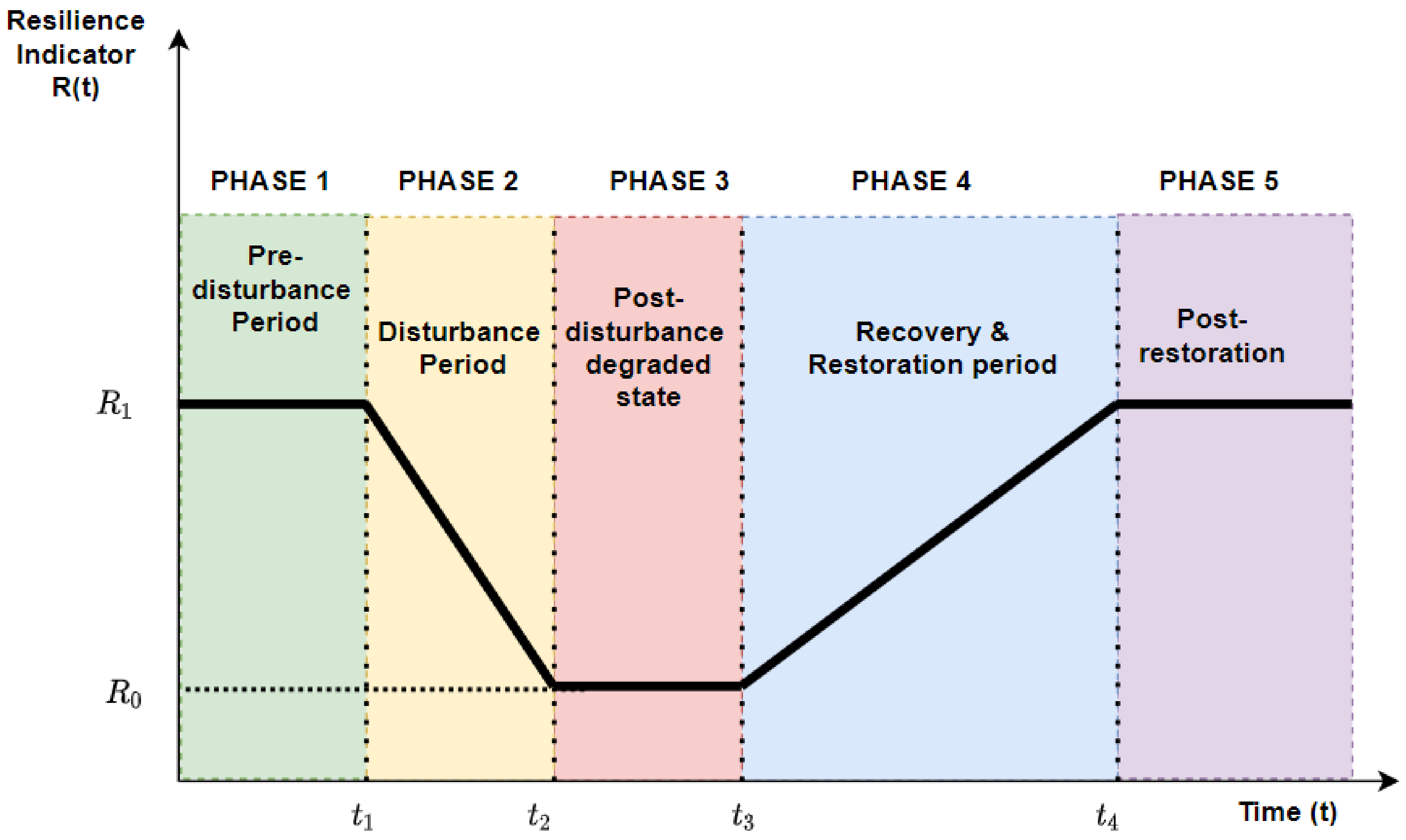
What is Missing in Resilience Metrics?

- 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



Panteli, M., Mancarella, P., Trakas, D. N., Kyriakides, E., & Hatziargyriou, 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

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Resilience Phases

Pre-Disturbance	Disturbance	Degraded	Recovery	Post recovery
Resource Adequacy (*Probabilistic Measures)* ❖ Loss of Load Expectation (LOLE) ❖ Loss of Load Probability (LOLP) ❖ Effective Load-Carrying Capacity (ELCC) ❖ Expected Unserved Energy (EUE) ❖ Planning Reserve	❖ Generation lost per hour ❖ Transmission lines tripped per hour ❖ Load lost per hour ❖ Dynamic Resilience Indicator	❖ Cumulative energy not served ❖ Severity Risk Index	❖ Time to Infrastructure recovery ❖ Time to operational recovery ❖ Generation restored per hour ❖ Transmission lines restored per hour ❖ Load restored per hour	❖ Post event analysis

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FLEP Metrics – Definitions

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

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FLEP Metrics – Calculations

Metric	Mathematical Expression	Unit
Φ	$\frac{R_0 - R_1}{t_2 - t_1}$	MW/hours, No. of lines tripped/hours, No. outages/hours, No. of unserved customers/hours
Λ	$R_1 - R_0$	MW, No. of Lines tripped, No. of outages, No. of unserved customers
E	$t_3 - t_2$	hours
Π	$\frac{R_1 - R_0}{t_4 - t_3}$	MW/hours, No. of lines restored/hours, No. of restored customers/hours
Area	$\int_{t_1}^{t_4} R(t)dt$	MW X hours, No. of lines in service X hours, No. of outages X hours, No. of customers X hours

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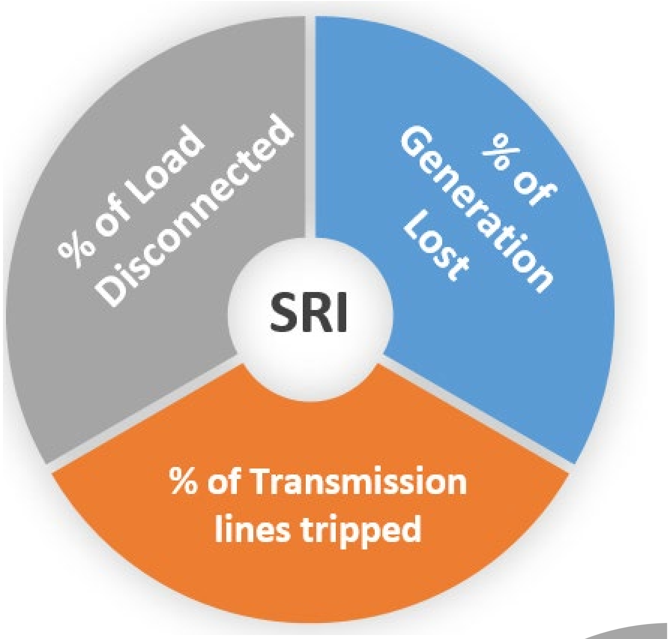
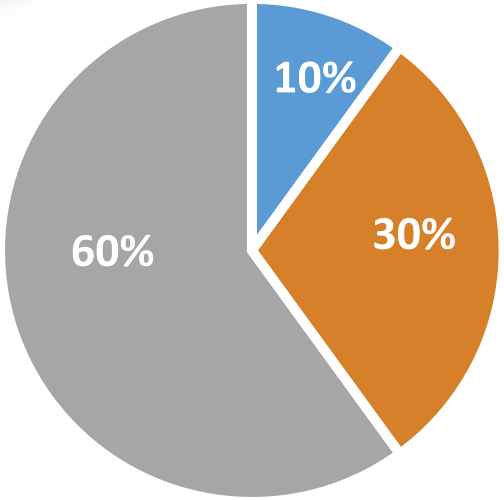
Severity Risk Index (SRI)



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.

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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 = β_1*GL + β_2*TLT + β_3*LD

where GL = % of Generation Lost per hour/day

TLT = % of Transmission Lines Tripped per hour/day

LD = % of Load Disconnected per hour/day

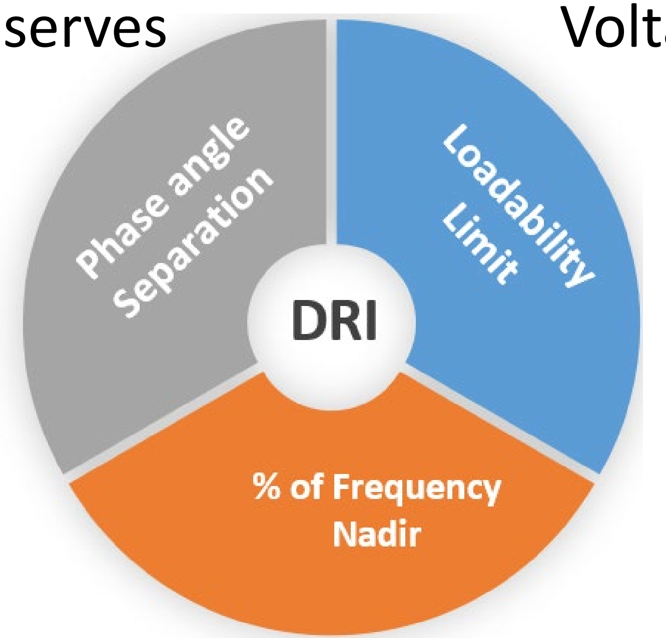
β_1, β_2, and β_3 are weighting indices such that $\beta_1 + \beta_2 + \beta_3 = 1$

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

Dynamic Resilience Indicator (DRI)

Measure of
Reactive Reserves

Measure of
Voltage Stability



Measure of
Frequency Agility

- 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

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Calculating DRI

For short time periods (secs to mins to couple hours), data for SRI is unavailable

➔ need dynamic metrics:

Dynamic Resilience Indicator = DRI = α_1*RR + α_2*LL + α_3*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.

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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!

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Questions?

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