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Quantitative Power System Resilience Metrics and Evaluation Approach

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- Background
  - Power system resilience captures the performance of power systems under the influences of high-impact low-probability (HILP) events.
  - Power system resilience metrics are critical for resilience evaluation, analysis, and optimization.
  - Existing metrics have drawbacks (e.g., compared to SAIDI/SAIFI) such as:
    - Lack of clear physical interpretation from power system perspective
    - Heavy reliance on historical data and probabilistic analysis
    - Poor comparability
- Proposed Approach
  - Divide resilience quantification into two stages: pre- and post-event.
  - Quantitative metrics are proposed for both pre- and post-event resilience evaluation
- Objective
  - Comprehensively evaluate resilience of power systems against HILP events

Pre-event Resilience Quantification

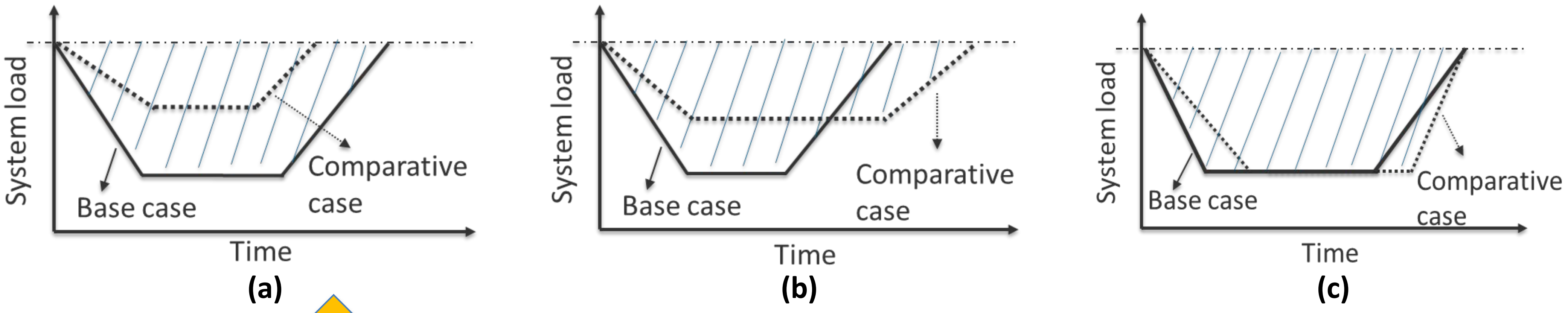
A New Pre-Event Resilience Metric : Performance-Damage-Duration (PDD):

- The PDD metric quantifies the capability of power system to maintain a certain level (*X*) of performance (e.g., load supply) when suffering from a certain level (*X*) of damage, for a predefined period of time (*Y*).

$$X := \max_{X\in[0,1]} \left\{ \inf_{s\in S, t\in[0,Y]} P_{s,t}^{1-X} \geq X \cdot P_{s,t} \right\}$$

- ❑ Let X=1%, it means the system can provide sustainable power supply to at least 1% of the load when losing 1% of its infrastructure/capacity, within the specified duration of Y. Most systems can achieve this (e.g., refer to N-1 or N-k contingency analysis used in reliability studies)
- ❑ Let X=20%, the system can provide sustainable power supply to at least 20% of the load when losing 20% of grid infrastructure/capacity.
- ❑ The ideal case is when X=100%. An example is a system where every customer has a sufficiently large battery and backup generator. It is reasonable to say this example is the most resilient case

Post-event Resilience Quantification



- Compared with the base case, the comparative case shows better resilience because its trapezoid is superior to the base case at all time
- **But is it always that straightforward?**
- Take a look at figures (b) and (c), if base case and comparative case has the same energy curtailment, which case has a better resilience?

Primary factors

- ❑ Total energy curtailment $E^{\text{shed}} = \int_{t=0}^{\infty} P^{\text{shed}}(t)dt$
- ❑ Peak load curtailment $P^{\text{peak}} = \max_{t} P^{\text{shed}}(t)$

Secondary factors

- ❑ Outage duration T^{r}
- ❑ Degradation duration T^{d}

$$R^{s} = \frac{T^{\text{d}}}{T^{\text{r}}}$$

Simulation Results

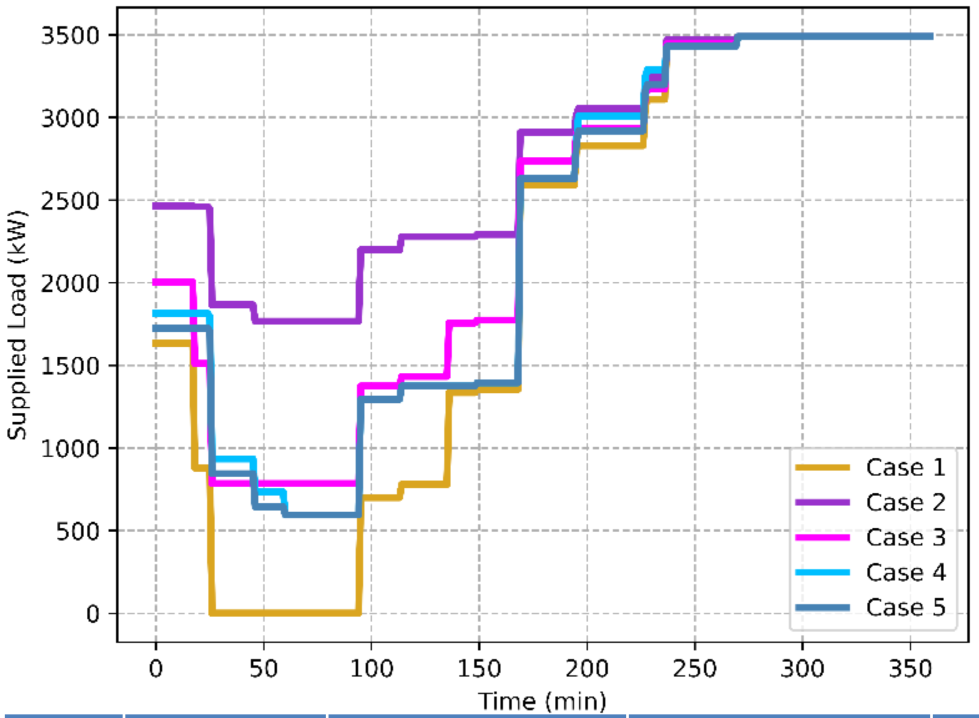
- **Test system**: IEEE 123-bus system, peak load capacity is 3500 kW
- **Scenarios**: 10 sets of event scenarios are created, each of which contains 20 distribution line outages that are randomly generated.
- **Timeframe**: The simulation timeframe is 6-hour with 1-minute time-resolution.

  - Case 1: 0% photovoltaic (PV) penetration.
  - Case 2: 50% PV penetration, 83 small-size PVs are deployed in a scattered manner.
  - Case 3: 25% PV penetration, 83 small-size PVs are deployed in a scattered manner.
  - Case 4: 50% PV penetration, 6 large-size PVs are deployed.
  - Case 5: 25% PV penetration, 6 large-size PVs are deployed.

Topology-based metrics in existing literature

Case	Branch count effect	Repetition of sources	**Proposed PDD metric (%)**
1	131	0.01	8.59
2	131	0.92	50.99
3	131	0.92	22.50
4	131	0.08	29.41
5	131	0.08	22.21

Simulation Results



Selected three metrics

Case	Degradation rate (kW/hr)	Degradation intensity (hr)	Recovery rate (kW/hr)	E^{shed} (kWh)	P^{peak} (kW)	R^s
1	7756	1.15	1203	8814	3490	0.10
2	2200	0.82	594	4443	1723	0.17
3	6011	0.57	777	6894	2705	0.10
4	2848	0.58	998	7236	2895	0.23
5	2848	0.58	998	7387	2895	0.23

Commonly used metrics in existing literature

Case	Pre-event ranking	Average post-event ranking	Highest post-event ranking	Lowest post-event ranking
1	5	5	5	5
2	1	1.1	1	2
3	3	3.1	2	4
4	2	2.3	1	3
5	4	3.5	3	4

pre-event evaluation and average post-event evaluation results in 10 scenarios

The developed pre- and post-event metrics perform quite consistently, although pre-event evaluation does not consider event information at all.

Conclusions/Recommendations

- A new resilience metric named PDD is proposed to evaluate resilience in the pre-event context, and a set of metrics are developed to evaluation resilience in the post-event context.
- Calculating PDD metric is computationally intensive, a heuristic process is used in this study, more work is needed to provide a better estimation
- How to integrate the quantitative resilience metrics into optimization models to help system operators to improve resilience performance is our next step task.

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