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Optimal Investments to Improve Grid Resilience Considering Initial Transient Response and Long-term Restoration

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Agenda and Acknowledgments

- Agenda
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  - Grid resilience
  - Modeling the initial impact
  - Modeling the restoration
  - Full optimization formulation
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  - Conclusions

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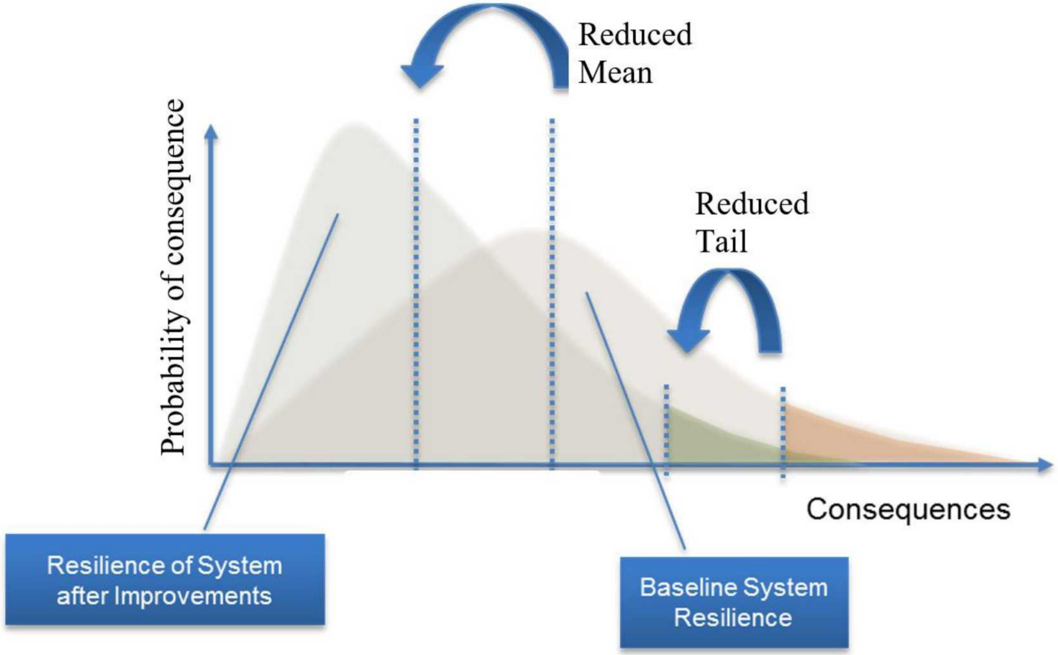
Project Objective

Develop a multi-time period two-stage stochastic mixed-integer linear optimization model which determines the optimal hardening investments to improve power system resilience to disaster threat scenarios while considering long-term restoration *and* initial transients/cascading failures.

- Improve grid resilience to major disruptions such as earthquakes, hurricanes, or physical attack.
- Determine optimal components to harden: buses, lines, transformers, generators, and loads (distribution systems).
- Minimize resilience metric represented by a weighted loss of load over the restoration timeframe and the weighted loss of load from the initial impact .



Grid Resilience

- High Consequence Low Probability events.
  - Hurricanes
  - Wildfires
  - Tsunami
  - Winter storm
- When making decisions, modeling initial impact transients and cascades is important, especially for events that may remove many large-scale grid components simultaneously.
  - Earthquake
  - Coordinated physical attack
  - Cyber-attack
  - EMP
- When the grid does not have time to resettle to a new steady-state before another component is removed, it is more vulnerable to cascading failure.

Model the Initial Impact

- Electromechanical transient simulations (such as using General Electric's PSLF) are used to model the initial impact and cascading failures.
- The dynamic model includes protection elements which can trip components and create secondary transients which can lead to cascade.

Generator under/over frequency protection
Generator under/over voltage protection
Under frequency load shedding
Line/transformer protection relays

- Each threat scenario with every possible investment package under consideration are run through the custom dynamic cascading framework.
- Each investment package includes lines, generators, buses, transformers, and loads (a percentage of distribution feeders) to harden. If hardened they are assumed to not fail during the threat scenarios.
- This requires thousands of dynamic electromechanical simulations.
- The result of the transient simulation initializes the restoration process (generation dispatch, load shed).

Model the Restoration

- The optimization formulation uses a DC optimal power flow for the multi-time period restoration process.
- This determines the optimal generator dispatch levels, generator commitment values, and optimal transmission switching for every time period throughout the restoration process.
- Time-period decisions are tied together through generator ramp rate constraints.
- The optimal investment package is determined to minimize the resilience metric, represented by the weighted load shed over the restoration process.

Optimization Model

*Note: without animation this slide is difficult to understand. Please see the IEEE publication for explanation of the model

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- Minimize load shed over all time periods
- Minimize initial impact load shed
- Weighted scenarios
- Weighted loads
- Budget constraints
- Power balance
- Generator ramp and limit constraints
- Load shed constraints
- Line flow limit constraints

minimize

$$\sum_{\omega\in\Omega} q^{\omega}\left(\sum_{t\in T} t \sum_{b\in B} A_b p^{\omega}_{b,t} + \sum_{b\in B}\sum_{i\in I} A_b x_i P^{\omega}_{b,i}\right) \quad (1)$$

subject to

$$\sum_{i\in I} C_i x_i \le K \quad (2)$$

$$\sum_{i\in I} x_i = 1 \quad (3)$$

$$\sum_{g\in G_b} p^{\omega}_{g,t} + \sum_{l\in L_b^{to}} p^{\omega}_{l,t} - \sum_{l\in L_b^{from}} p^{\omega}_{l,t} = \sum_{g\in G_b}\left(P^d_{d,t} - p^{\omega}_{b,t}\right) \quad \forall b\in B, \forall t\in T, \forall \omega\in\Omega \quad (4)$$

$$p^{\omega}_{g,t} - p^{\omega}_{g,t-1} \le RU_g \quad \forall g\in G, \forall t\in T, \forall \omega\in\Omega \quad (5)$$

$$p^{\omega}_{g,t-1} - p^{\omega}_{g,t} \le RD_g u^{\omega}_{g,t} + \overline{P}_g\left(1 - u^{\omega}_{g,t}\right) \quad \forall g\in G, \forall t\in T, \forall \omega\in\Omega \quad (6)$$

$$\underline{P}_g u^{\omega}_{g,t} \le p^{\omega}_{g,t} \le \overline{P}_g u^{\omega}_{g,t} \quad \forall g\in G, \forall t\in T, \forall \omega\in\Omega \quad (7)$$

$$\left(1 - z^{\omega}_{d,t}\right)\underline{P}^{\omega}_{d,t} \le p^{\omega}_{d,t} \le P^d_{d,t} \quad \forall d\in D, \forall t\in T, \forall \omega\in\Omega \quad (8)$$

$$\left(1 - s^{\omega}_{b,t}\right)P^d_{d,t} \le p^{\omega}_{d,t} \le P^d_{d,t} \quad \forall b\in B, \forall d\in D, \forall t\in T, \forall \omega\in\Omega \quad (9)$$

$$p^{\omega}_{l,t} = y^{\omega}_{l,t} S_l\left(\theta^{\omega}_{B_l^{to},t} - \theta^{\omega}_{B_l^{from},t}\right) \quad \forall l\in L, \forall t\in T, \forall \omega\in\Omega \quad (10)$$

$$-\frac{\pi}{3} - \frac{5\pi}{3}\left(1 - y^{\omega}_{l,t}\right) \le \theta^{\omega}_{B_l^{to},t} - \theta^{\omega}_{B_l^{from},t} \le \frac{\pi}{3} + \frac{5\pi}{3}\left(1 - y^{\omega}_{l,t}\right) \quad \forall l\in L, t\in T, \forall \omega\in\Omega \quad (11)$$

$$-\overline{P}_l y^{\omega}_{l,t} \le p^{\omega}_{l,t} \le \overline{P}_l y^{\omega}_{l,t} \quad \forall l\in L, t\in T, \forall \omega\in\Omega \quad (12)$$

$$y^{\omega}_{l,t} \le \sum_{i\in I_l} x_i \quad \forall l\in L, \forall t\in X^{\omega}_l, \forall \omega\in\Omega \quad (13)$$

$$u^{\omega}_{g,t} \le \sum_{i\in I_g} x_i \quad \forall g\in G, \forall t\in X^{\omega}_g, \forall \omega\in\Omega \quad (14)$$

$$z^{\omega}_{d,t} \le \sum_{i\in I_d} x_i \quad \forall d\in D, \forall t\in X^{\omega}_d, \forall \omega\in\Omega \quad (15)$$

$$s^{\omega}_{b,t} \le \sum_{i\in I_b} x_i \quad \forall b\in D, \forall t\in X^{\omega}_b, \forall \omega\in\Omega \quad (16)$$

$$y^{\omega}_{l,t} \le s^{\omega}_{b,t} \quad \forall l\in L_b, \forall b\in B, \forall \omega\in\Omega \quad (17)$$

$$u^{\omega}_{g,t} \le s^{\omega}_{b,t} \quad \forall g\in G_b, \forall b\in B, \forall \omega\in\Omega \quad (18)$$

We linearize the model with a McCormick relaxation by re-placing (10) with

$$S_l\left(\theta^{\omega}_{B_l^{to},t} - \theta^{\omega}_{B_l^{from},t}\right) - \frac{\pi}{3}S_l\left(1 - y^{\omega}_{l,t}\right) \le p^{\omega}_{l,t} \quad \forall l\in L, \forall t\in T, \forall \omega\in\Omega \quad (19)$$

$$p^{\omega}_{l,t} \le S_l\left(\theta^{\omega}_{B_l^{to},t} - \theta^{\omega}_{B_l^{from},t}\right) + \frac{\pi}{3}S_l\left(1 - y^{\omega}_{l,t}\right) \quad \forall l\in L, t\in T, \forall \omega\in\Omega \quad (20)$$

- Investment/outage constraints
- Linear reformulation of the line limit constraint

Earthquake Scenarios

Example – hardening components to become resilient to three earthquake scenarios.

Diagram of the RTS-GMLC system

An upgraded version IEEE RTS-96 system, a Reliability Test System from 1996

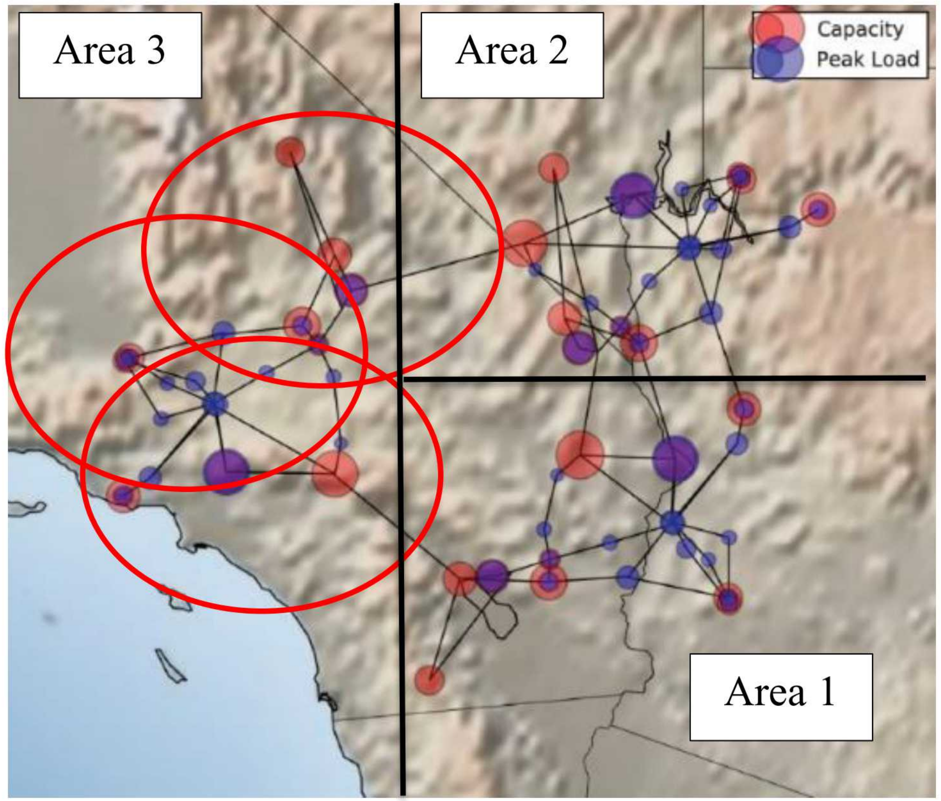


Table of Initiating Events Caused by the Earthquakes

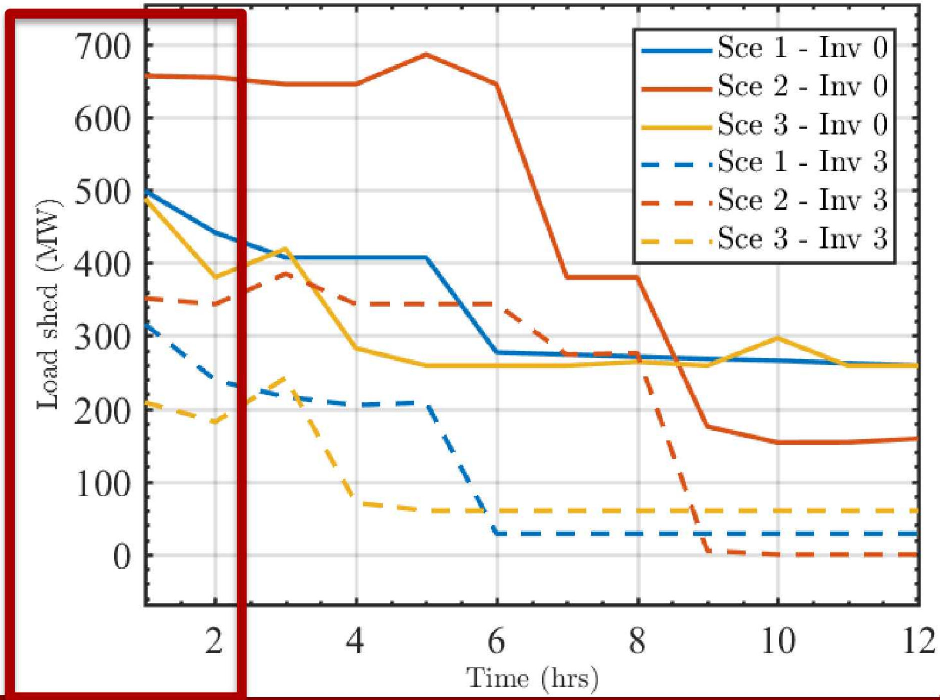
Components	Scenario 1	Scenario 2	Scenario 3
Generator at bus 315*	12 hours	12	12
Generator at bus 316	12	12	12
Generator at bus 318	12	-	-
Generator at bus 323*	-	-	12
Brach 311-313	-	8	3
Brach 314-316	6	6	-
Brach 315-324	5	8	-
Brach 325-121	-	-	12
40% Load at bus 319	-	-	8
80% Load at bus 319	-	6	-

*Multiple generators exist at these buses only the largest is removed. 12 hours indicates the component did not recover during the time horizon.

Modeling the Initial Impact: Transient Simulation vs. DC Power Flow

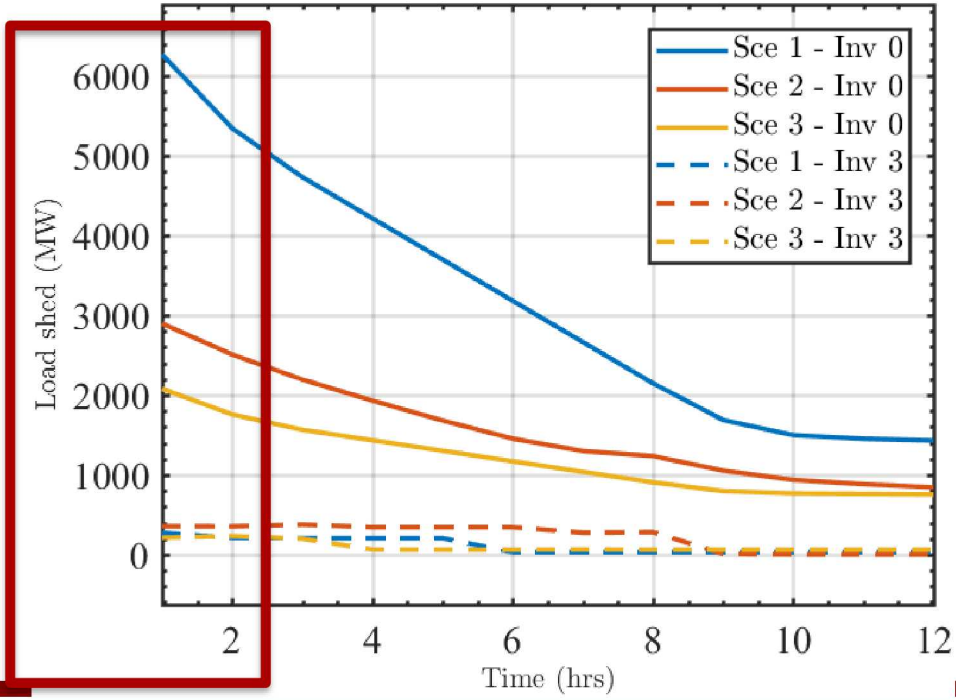
- Modeling the initial impact with DC power flow significantly underestimates the initial load shed because cascading failures are not accounted for.

Initial impact measured with DC power flow



Load shed over time for the three scenarios with no investments vs. 3 components hardened

Initial impact measured with transient simulation

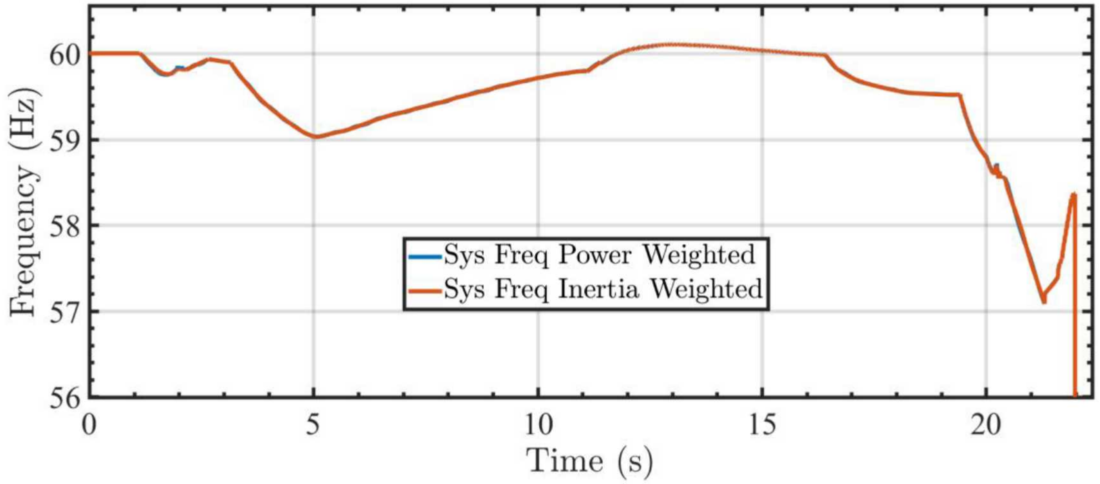


Investment Decisions Address Cascades

- Including the transient simulations in the optimization formulation allows the optimal decisions to protect against cascading failures.
- Protecting against cascading failures significantly hardens the grid to the worst case contingencies.

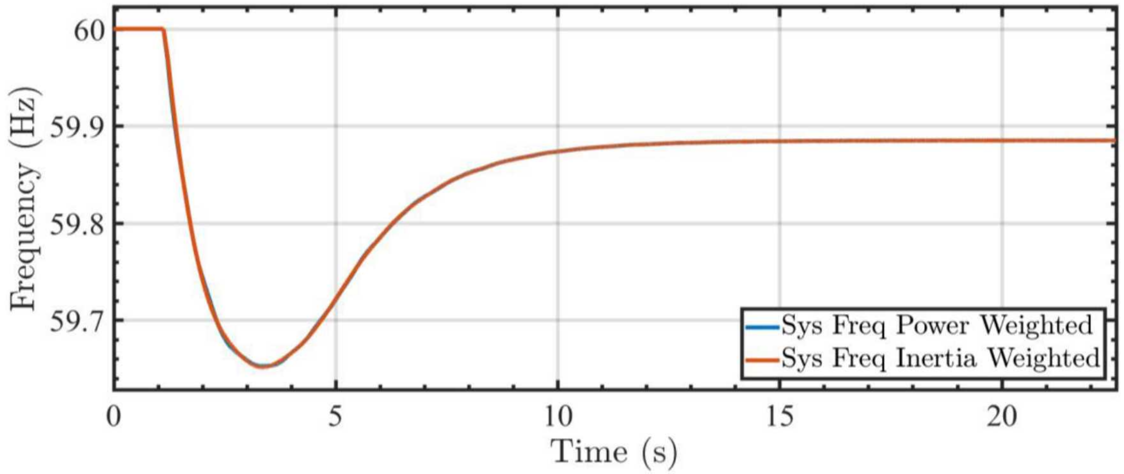
<u>Earthquake scenario with no investments</u>

Results in a cascading outage



<u>Earthquake scenario with one optimal investment</u>

Does not result in a cascading outage

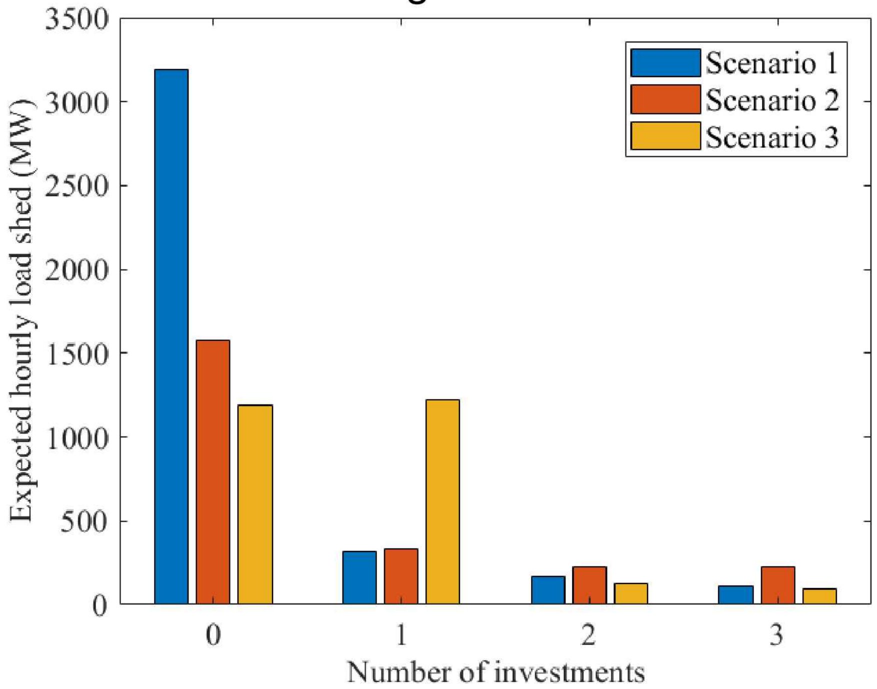


Results – Optimal Investments to Improve Resilience

- With the optimal investments there is significant improvement in initial load shed (right figure), and load shed over time (left figure)

Expected hourly load shed over all time periods

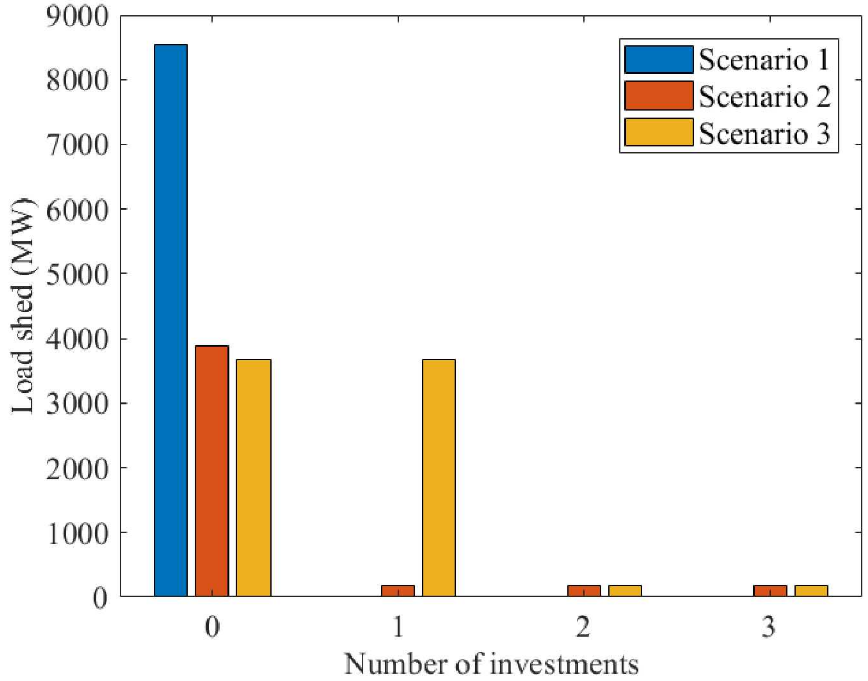
Diminishing returns on investment



Optimal investments significantly decrease the load shed during earthquake scenarios.

Initial load shed

The first investment protects against two scenarios



Primary Takeaway of this Paper/Presentation

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- When making decisions to improve resilience to large-scale events, initial transients and cascading failures need to be accounted for.

- When N-*k* components are removed from service, a cascading failure can be triggered.

- If decisions are based solely on steady-state power flows, the decisions may not address the cascading failures, which are often the worst case contingencies.

Conclusions

- A multi-time period two-stage stochastic optimization model was presented to improve grid resilience to catastrophic events.
- The optimization model determines the components to harden for the specified threat.
- The objective of the optimization model is to minimize the expected weighted load shed from the initial impact and the restoration process over all threat scenarios.
- The optimization model considers the initial impact of the event with electromechanical transient dynamic simulations, which allow for secondary transients from protection devices and cascading failures.
- The restoration, after the initial shock, is modeled in the optimization with a multi-time period DC optimal power flow which is initialized with the solution from the dynamic simulation.
- The first stage of the optimization model determines the optimal investments.
- The second stage, given the investments, determines the optimal generator dispatch, generator commitment values, and transmission line switching during the multi-time period restoration.
- Results indicate modeling the initial impact with a dynamic transient simulation is extremely important, and optimal investments can significantly improve resilience.

Questions?

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