SAND2022-8053C

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A Framework to Model and Analyze Electric Grid Cascading Failures to Identify Critical Nodes

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June, 13th, 2022

U.S. DEPARTMENT OF ENERGY NNSA

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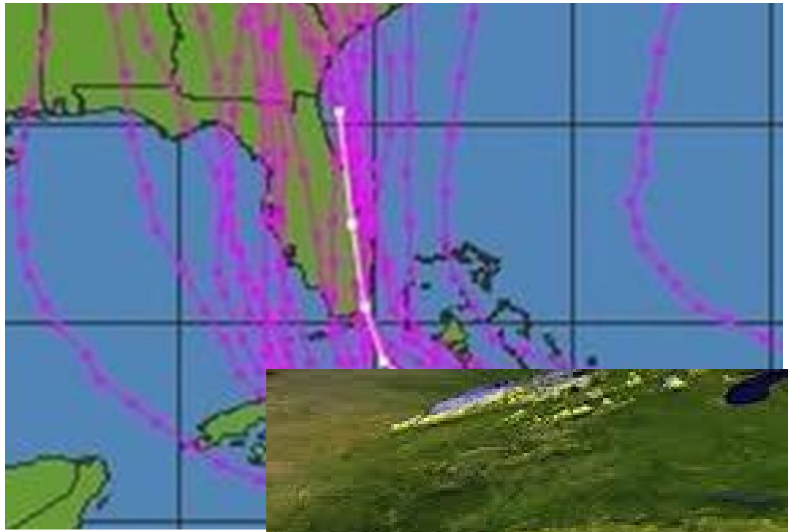
Electric Grid Critical Nodes Background

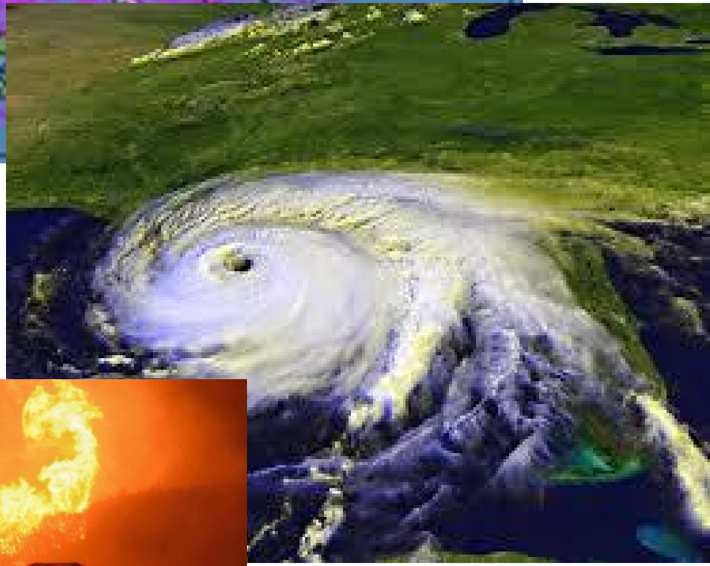
Problem: A lack of understanding of which components and nodes in the electric grid are most critical to our grid resilience and which nodes are most vulnerable. Specifically interested in preventing cascading failure.

Goal: Build the framework to identify electric grid critical nodes and their levels of vulnerability to a specified threat (e.g. hurricanes).

Critical and Vulnerable Node Definitions

- A node will be deemed **critical** if its removal from service causes a severe consequence
  - Nodes with critical loads (e.g. military installations, water services, hospitals).
  - Nodes that repeatably cause cascading failures





- Node **vulnerability** level is high if a high percentage of threat scenarios cause the node to be removed:
  - Directly by the threat
  - Or indirectly from cascading outages.

Framework to Identify Electric Grid Critical Nodes

Create Threat Scenarios

Develop scenarios based on a regional threat to analyze. Scenarios must capture the uncertainty of the threat and the probability a threat will take out major power system components.

Cascading Transient Model

Run power system dynamic transient simulations that capture the initial impact of the event and the cascading failures throughout the system, including protection tripping

Analyze Stochastic Simulations

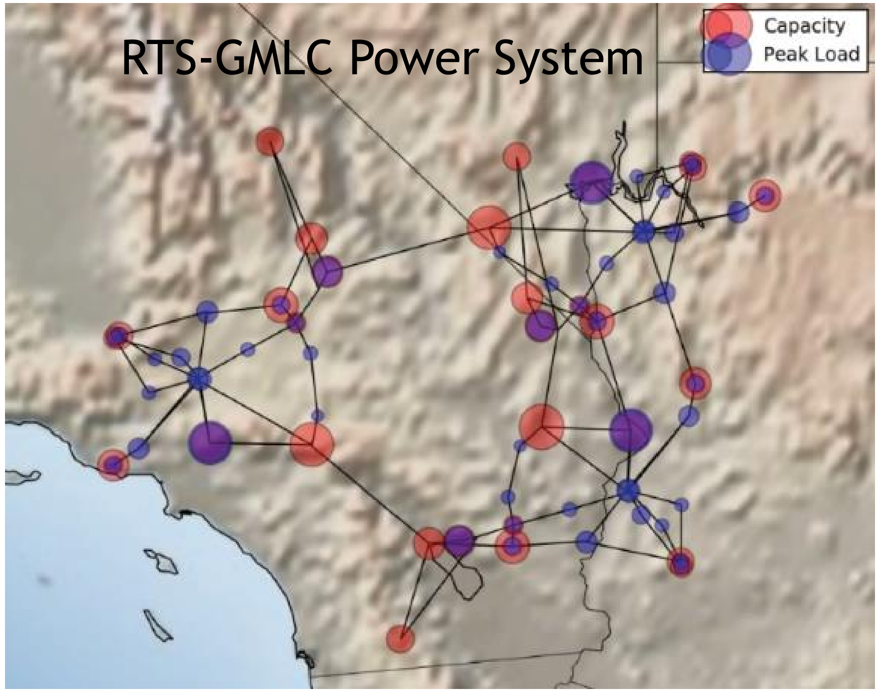
The analysis framework uses combinations of ordination, clustering flow analysis, and network theoretic approaches.

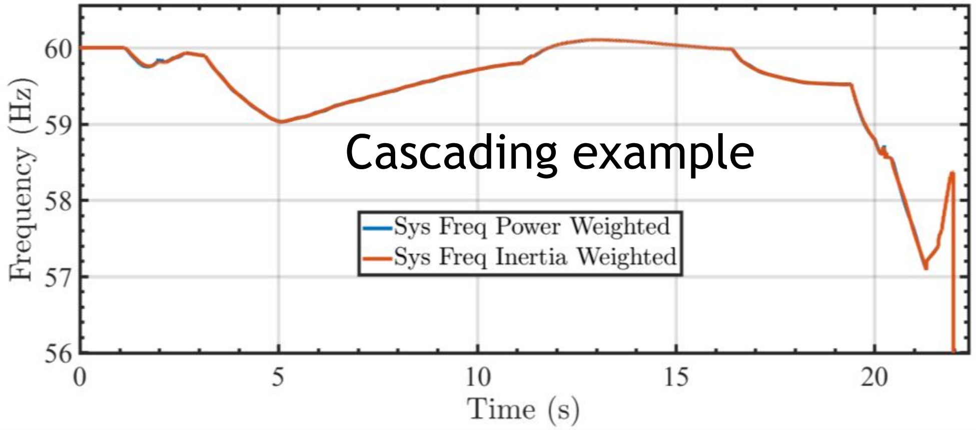
Interpret Critical Node Results

Identify trends, unique system behaviors, and critical components whose failure is more likely to cause serious systemic effects

Cascading Outage Model using Transient Simulations (N-k modeling)

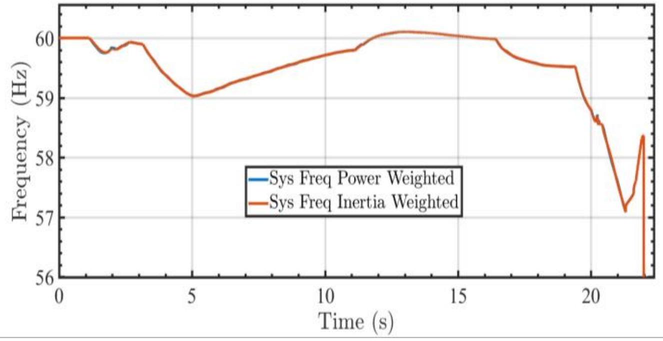
- Thousands of earthquake scenarios are created
- Each earthquake scenario identifies which grid components are damaged and removed from service, and at what time.
- An electromechanical transient simulation is run for each earthquake scenario (N-k event).
- The transient simulation includes grid protection models (i.e. under/over frequency/voltage protection, overload protection, and underfrequency load shedding).
- The protection elements allow for secondary transients and cascades to occur.

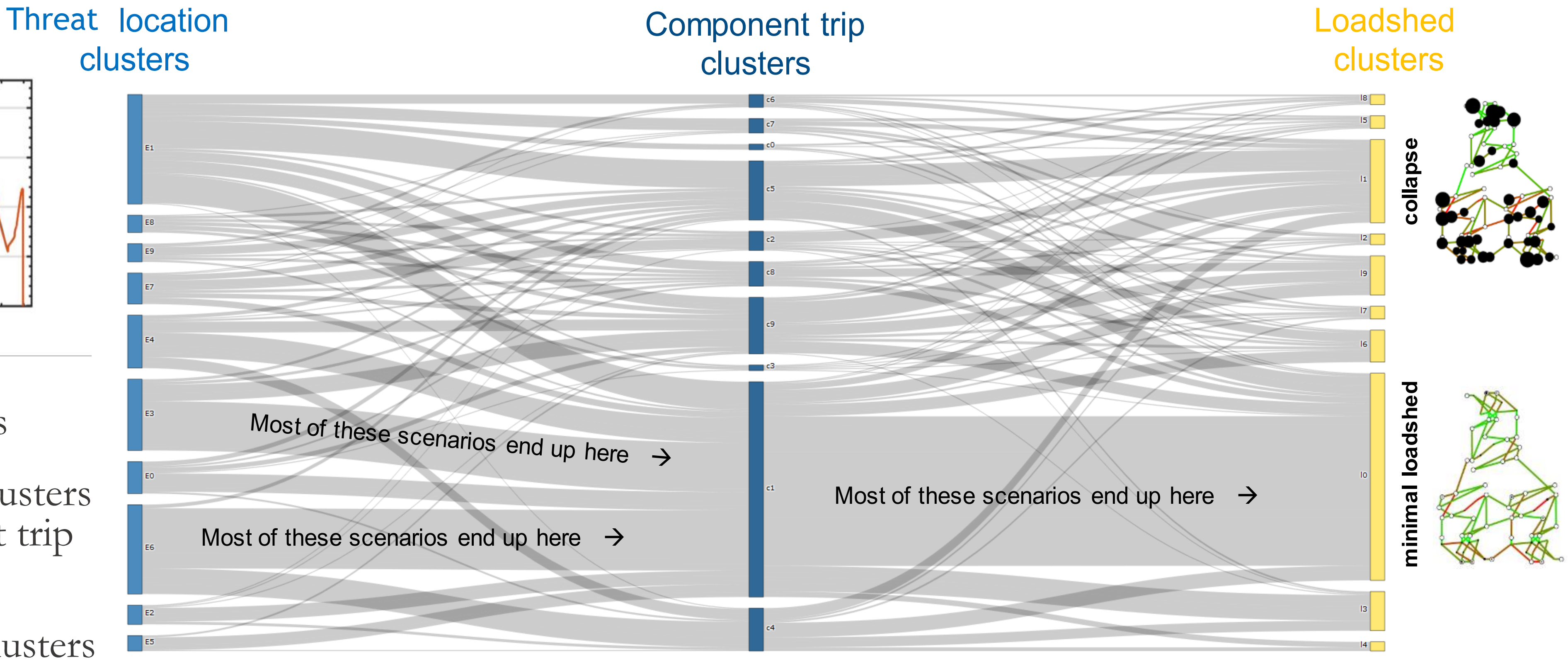




Identify Electric Grid Critical Nodes

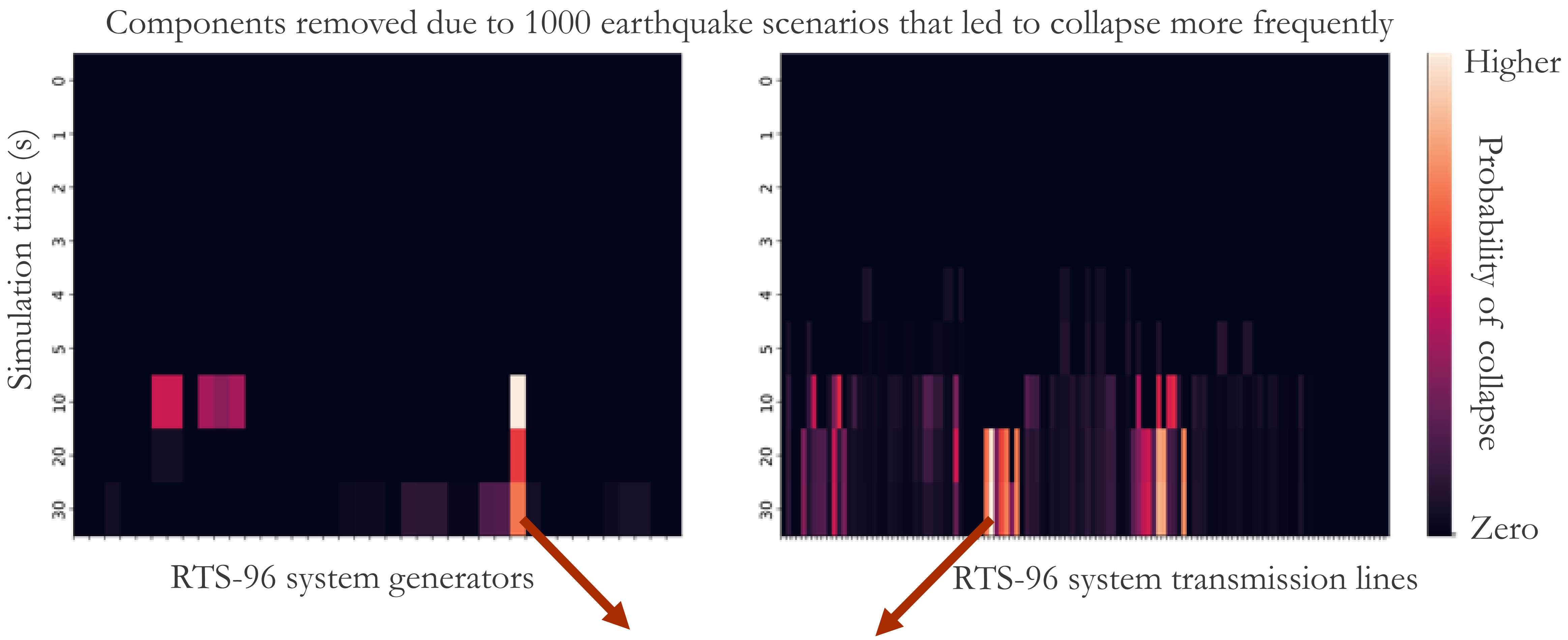
- Run thousands of dynamic simulations.





- Analyze cumulative results
- Certain threat locations clusters lead to certain component trip clusters
- Certain component trip clusters lead to specific grid outcomes.

Critical Component Damage can Lead to Grid Collapse

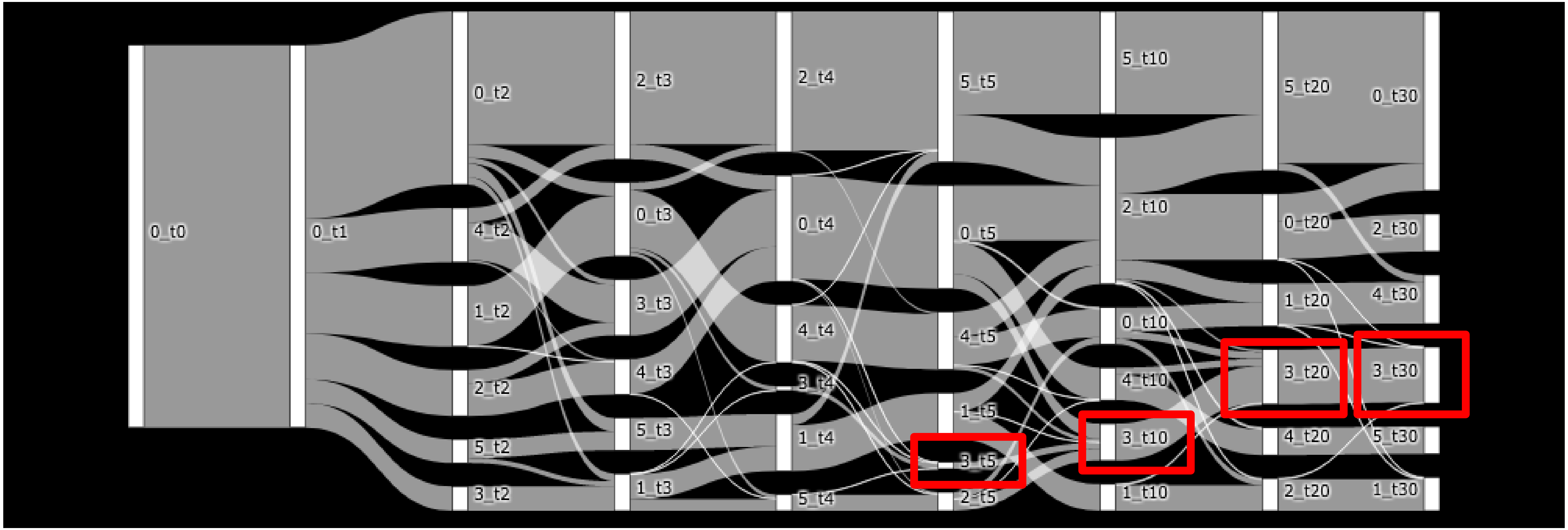


Most critical generator and line

Predicting Grid Cascade

Earthquake driven cascading state transitions

Initial results – predicting future grid system states based on the current state during disasters and cascading events.



Cluster analysis of 1000 earthquake scenarios at times slices 0,1,2,3,4,5,10,20,30 seconds.

High Level Takeaways

- We can use a combination of threat modeling, grid modeling, and data analytics to identify electric grid critical components to resilience, which is useful when planning for a resilient grid

- We can identify which grid components lead to cascade and collapse more frequently.

- It may be possible to predict grid cascade transitions. That is, predict future system states based on the current state during major disasters.

Peer Reviewed Journal and Conference papers

1. B. J. Pierre, D. Krofcheck, K. Munoz-Ramos, B. Arguello, "A Framework to Model and Analyze Electric Grid Cascading Failures to Identify Critical Nodes," Proceedings IEEE Probabilistic Methods Applied to Power Systems (PMAPS), June 2022.
2. B. Austgen, M. Garcia, B. J. Pierre, J. Hasenbein, E. Kutanoglu, "Winter Storm Scenario Generation for Power Grids Based on Historical Generator Outages," Proceedings IEEE PES Transmission and Distribution (T&D) Conference and Exposition, April 2022.
3. M. Garcia, B. Austgen, B. J. Pierre, J. Hasenbein, E. Kutanoglu, "Risk Averse Investment Optimization for Winter Storm Grid Resiliency," Proceedings IEEE PES Transmission and Distribution (T&D) Conference and Exposition, April 2022.
4. K. Garifi, E. Johnson, B. Arguello, B. J. Pierre, "Transmission Grid Resiliency Investment Optimization Model with SOCP Recovery Planning," *IEEE transactions on Power Systems*, vol. 37, no. 1, pp. 26-37, Jan. 2022.
5. S. Raja, B. Arguello, B. J. Pierre, "Dynamic Programming Method to Optimally Select Power Distribution System Reliability Upgrades," *IEEE Open Access Journal of Power and Energy*, vol. 8, pp. 118-127, Feb. 2021.
6. B. J. Pierre, B. Arguello, M. J. Garcia, "Optimal Investments to Improve Resilience Considering Initial Transient Response and Long-term Impacts," Proceedings IEEE Probabilistic Methods Applied to Power Systems (PMAPS), Aug. 2020.
7. B. J. Pierre, B. Arguello, "Investment Optimization to Improve Power Distribution System Reliability Metrics," Proceedings IEEE Power & Energy Society General Meeting, Aug. 2018.
8. B. J. Pierre, B. Arguello, A. Staid, R. T. Guttromson, "Investment Optimization to Improve Power System Resilience," Proceedings IEEE Probabilistic Methods Applied to Power Systems (PMAPS), June 2018.

Thank you to all my Sandia colleagues and partner colleagues

Thank you to our funding organizations

- Laboratory Directed Research and Development (LDRD) program at Sandia National Laboratories
- U.S. Department of Energy Office of Electricity Delivery & Energy Reliability
  - Advanced Grid Modeling Program managed by Ali Ghassemian
  - Electricity Delivery System Transformation (EDST) Program managed by Joseph Paladino

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