Resilient Energy Systems
Mission Campaign

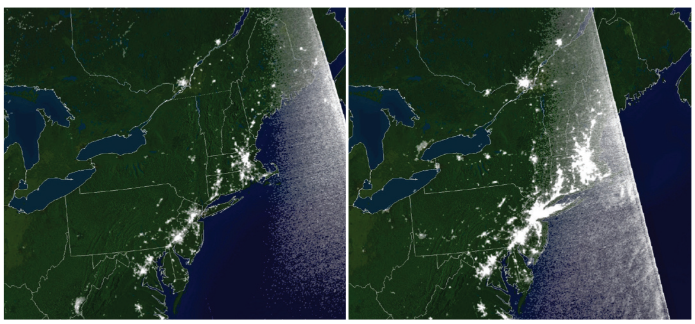
CRITICAL NODE IDENTIFICATION, VULNERABILITY MODELING, AND TOPOLOGY OPTIMIZATION FOR THE ELECTRIC GRID

This project will develop large-scale models and algorithms to identify electric grid critical nodes and their vulnerability levels to severe man-made and natural threats using advanced modeling techniques and an innovative dynamic cascading failure model. A multi-stage stochastic topology optimization model, informed by node criticality, will optimize resilience planning and recovery through grid hardening and grid topology investment decisions, preemptive topology actions, and topology management during the restoration process.

THE CHALLENGE

The electric grid is vital to our everyday lives, the economy, and critical services. There is a need for a better understanding of the critical nodes in the electric grid and their vulnerabilities to both man-made and natural disasters.

This project seeks to identify electric grid critical nodes and their vulnerability levels to evolving threats and then improve grid resilience to those threats through optimal decisions.



An example of potential impact: on the left, the electric grid after a major disaster, and on the right, the grid after a major disaster with better critical node awareness and optimal topology management and investments.

The first step to address grid vulnerabilities and improve grid resilience is a better understanding of the critical nodes in the system, how those nodes may lead to electric grid collapse, and the vulnerability of those nodes to specific threats.

The threats to our grid are continuously evolving. Additionally, our grid is endlessly changing and constantly in different system states. A scalable framework that can dynamically identify the critical nodes and their vulnerability levels is vital for grid operators and planners to protect the grid from intentional and natural threats. Informed by critical nodes and their vulnerability levels, optimal decisions can be made to decrease system consequence to specified threats. One of these optimal decisions is grid topology planning, preemptive topology actions, and topology management during a multi-time period restoration process.

Combining vulnerability awareness with optimal decisions will decrease the consequences of those vulnerabilities, significantly improving U.S. electric grid resilience to man-made and natural threats.

APPROACH

A grid **critical node** is a node that, if removed from service, causes a severe consequence that exceeds a threshold (every node will receive a criticality weighting factor). Nodes that repeatedly cause cascades when removed and/or nodes with critical loads (e.g., military bases, hospitals) are more likely to be deemed critical.

A grid node with a **high vulnerability level** is defined as a node that is removed from service significantly more often than most nodes throughout all threat scenarios due to the threat directly or the cascading failures.

To identify electric grid critical nodes and vulnerability levels, a novel interdiction model will be developed with AC approximation/relaxation techniques. The interdiction model will identify the threat scenarios that cause the greatest grid impact from a grid steady-state perspective. However, scenarios that remove multiple components will likely cause electric transients and dynamics that can cause cascading failures. Therefore, the interdiction model is used to down-select the number of possible scenarios to be run in a dynamic electric grid cascading failure model. Scenario restriction needed. For example, running every contingency that removes four grid components on a typical bulk electric system would require trillions of simulations, which is not computationally feasible. The interdiction results will indicate the critical nodes from a steady-state perspective, and the cascading failure framework will indicate the critical nodes from a dynamics perspective. Together the two models can determine power system critical nodes and their vulnerability levels.

Informed by node criticality, a multi-stage stochastic topology optimization model will improve grid resilience to intentional threats. The model will minimize system consequence of intentional threats through:

Stage 1: topology and hardening investment decisions,

Stage 2: preemptive topology and generator dispatch actions, and

Stage 3: topology management and generator dispatch during a multi-time period restoration process.

These stages can be progressively combined to achieve a better-informed optimal solution. To achieve scalability, we will utilize the latest optimization techniques, second-order conic programming, nested and logic-based Benders decomposition, and concurrent optimization.

EXPECTED RESULTS

From this project, we expect a critical node identification framework to identify:

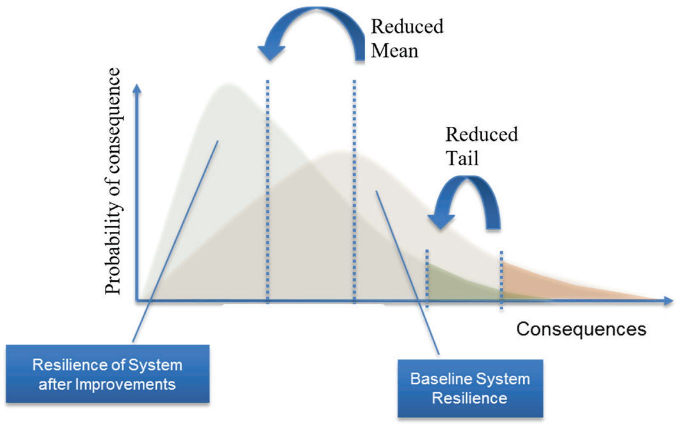
1. The most critical nodes to a resilient grid.
2. The most vulnerable nodes to a specified threat.

We also expect to develop a topology optimization framework to identify:

1. The optimal hardening decisions and topology investments to increase resilience of critical nodes.
2. The optimal topology reconfiguration to brace for a threat.
3. The optimal topology reconfiguration during a multi-time period restoration.

EXPECTED IMPACT OF THIS RESEARCH

The primary outcomes of the project will be the two novel frameworks. If the project is successful, the algorithms and frameworks can be leveraged by the Department of Energy (DOE), the Department of Homeland Security, policy makers, and—most of all—the electric power industry to improve



critical node awareness and guide investments that will save lives and billions of dollars in the event of severe man-made attacks or catastrophic natural disasters. Multiple high-impact journal and conference papers are planned. We will work closely with DOE, external collaborators, and grid utilities to identify opportunities to apply the results of this research to real-world problems faced by the electric industry.

RESILIENT ENERGY SYSTEMS

Sandia's investment in this project is part of its Resilient Energy Systems portfolio of projects, coordinated R&D that addresses the resiliency of the nation's energy systems and other critical infrastructures to threats.

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