Resilient Energy Systems
Mission Campaign

DYNAMICS-INFORMED OPTIMIZATION FOR RESILIENT ENERGY

Resilience planning optimization for wide-area power system emergencies—in which multiple components fail rapidly across a wide area—requires treatment of hazard uncertainty, system dynamics, and protective device behavior.

THE CHALLENGE

This project challenges existing paradigms of resilience optimization by considering vastly more challenging hazard scenarios. Current approaches are incapable of addressing "wide-area emergency" hazards that involve rapid failure of multiple components across a wide area, such as electromagnetic pulse (EMP), geomagnetic disturbance (GMD), or the first wave of a well-coordinated cyber and/or kinetic attack.

During wide-area emergency hazards, major system dynamics and widespread component-protecting behavior (e.g., switching/tripping) are likely to ensue, with the potential to cause system instability and/or cascading failure. Modeling these phenomena is crucial to understanding system survivability and ensuring restorability. Preventing or minimizing cascading failure is a key objective, since restoring any failed areas is considerably more difficult under the widespread damage and limited system visibility posed by such hazards.

Prior resilience optimization work is insufficient in this case due to the assumption of minor or localized hazards. Most work relies on non-dynamic impact models, which cannot detect loss of stability. The small body of existing dynamic work does not incorporate protective devices and therefore cannot address cascading behavior; instead, tight constraints on system behavior are typically imposed, which are not feasible in wide-area emergencies.

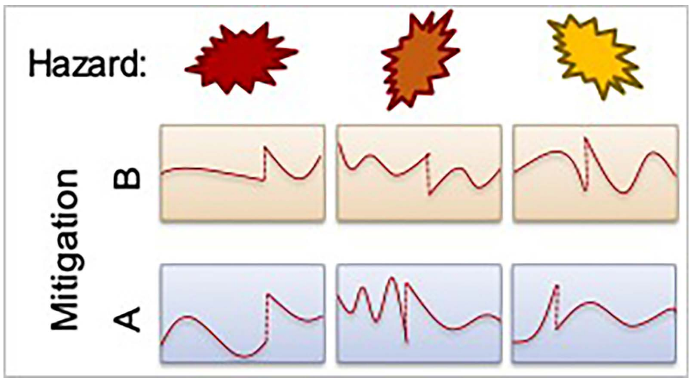
APPROACH

Our research will develop formulation, proof of concept, and solution insights for resilience optimization for wide-area emergencies.
A stochastic optimization will choose from proposed hardening and mitigation measures and locations, to optimize dynamically assessed resilience across a set of potential hazard scenarios (such as different EMP burst locations or cyber-physical attack scenarios).

Objectives are to minimize cascading failure and permanent damage to key devices, and to improve restorability. Mitigation options may include hardening; preventive and emergency control; and strategic spare purchases and pre-positioning.

Our phased approach involves:

1. building foundational stochastic and (continuous) dynamic optimization models,
2. adding appropriate (discrete) decision variables representing the available mitigation options, and
3. adding variables and constraints to represent discrete dynamics from protective devices, and addressing the associated time-discretization challenges with discrete dynamics.



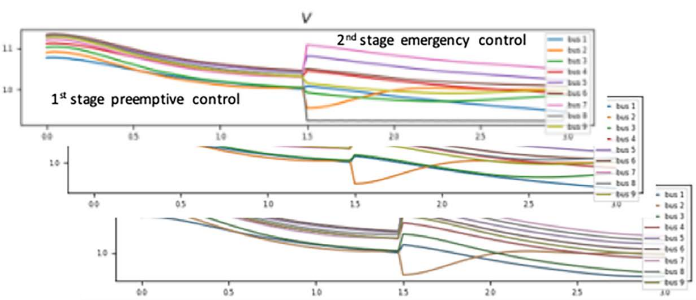
Power system behavior is hybrid nonlinear-discrete, and different for each mitigation and hazard considered, implying a stochastic optimization approach with hybrid dynamical impact modeling.

EXPECTED RESULTS

This project will deliver several novel outcomes:

- Dynamic Pyomo.DAE optimization model for continuous emergency corrective control
- Stochastic PySP optimization model for preventive control against uncertain hazards
- Stochastic mitigation planning optimization with (continuous) dynamic post-hazard impact model
- Stochastic mitigation planning optimization with (hybrid continuous-discrete) dynamic and protective behavior in the hazard impact model

The research will be demonstrated on a modestly sized notional power system and provide a foundation for future research into solving such problems at greater scale and for additional domains and hazards.



Early results show the ability of preventive control (before 1.5 s) to optimally prepare the system against multiple hazards, and for corrective control to maintain acceptable post-hazard behavior.

EXPECTED IMPACT OF THIS RESEARCH

This research provides foundational work in resilience planning to mitigate impacts of severe threats to complex critical energy infrastructures. Directly coupling optimization with hybrid dynamical simulation addresses a significant capability gap in energy resilience and dynamic optimization methods.

Formulation and solution methods are relevant to a variety of other infrastructures and hybrid dynamical systems. Insights regarding scalability, solution methods, and discretization will be relevant to the Pyomo and broader optimization communities. The work will pave the way for larger-scale, domain-specific applications, allowing capabilities to be leveraged for Department of Energy, Department of Homeland Security, and Department of Defense missions.

While initially demonstrated on power systems, the work is relevant to a variety of infrastructures, and to any system whose dynamics are governed by switching differential equations.

RESILIENT ENERGY SYSTEMS

Sandia's investment in this project is part of the 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.

This project primarily supports the Network Algorithms & Optimization, Energy System Transient & Dynamics Algorithms, and Modeling for N-Many Events (Combined Attacks) objectives of the Mission Campaign's *System-Level Threat-Informed Computational Science* research thrust.

Insights from the *Science of Vulnerabilities* and *Materials, Device, and Cyber Innovation* thrusts can be incorporated into this project, e.g., to improve modeling of hazard scenarios and mitigation options.

PYOMO PYOMO DAE PySP

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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