SAND2017-5398PE

Department 8831 Complex Systems & Resilience Capabilities Overview

May 4, 2017

Operations Research & Computational Analysis

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

- Complex Systems and Resiliency Overview
  - Modeling Focus and Approach
- Discuss three relevant capabilities
  - Improving the Resilience of Complex Systems
  - Multi-Hazard Investment Planning
  - Worst Case Scenario Determination

Resilience Modeling Focus/Approach

Sandia has unique capabilities to ***understand, quantify*** and ***control*** system resiliency in support of our national sponsors

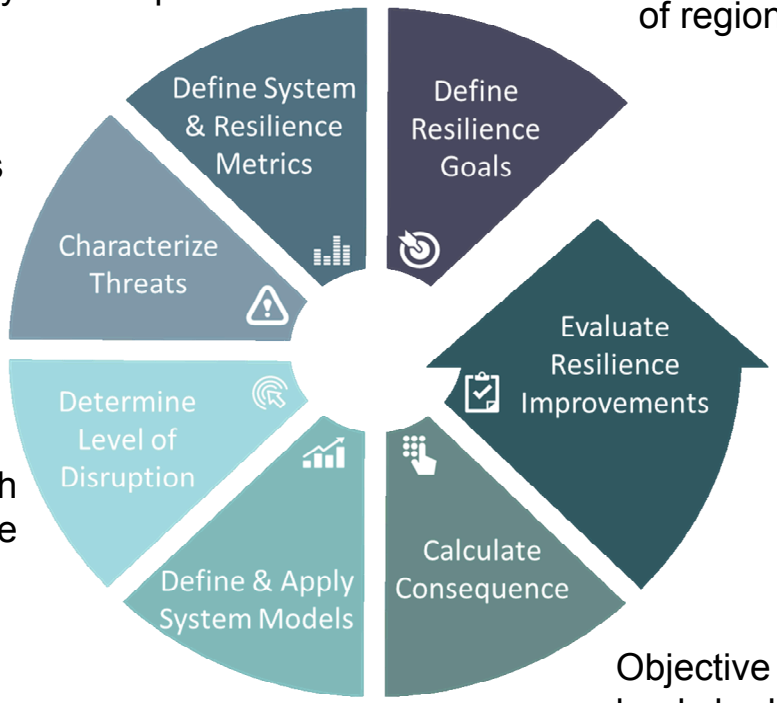
- Need ***quantitative metrics*** for resiliency
  - If we can't measure it, we can't change or control it
- Need to ***understand the uncertainty*** and impact of missing data
  - What uncertainty can we tolerate in our models and still achieve useful results?
- Need to understand how to ***validate and verify*** models
  - Lack of established foundational theory and sparse/uncertain data
  - Must have confidence in our results to provide confidence to decision makers
- Need to use a **multi-disciplinary** approach combined with **domain expertise**
  - Disciplines: Mathematics, operations research, optimization (traditional and heuristic), modeling and simulation
  - Expertise: Healthcare, disease, transportation, social dynamics, infrastructure

Resiliency Framework Example

Load shed weighted by criticality to transportation

Minimize power-related impacts to transportation system after loss of regional grid due to flood

Flood, wind (specified levels for both, as well as other network and generator contingencies)



Design alternatives (e.g. flood hardening) or preparation options in advance of a storm (spares for repair)

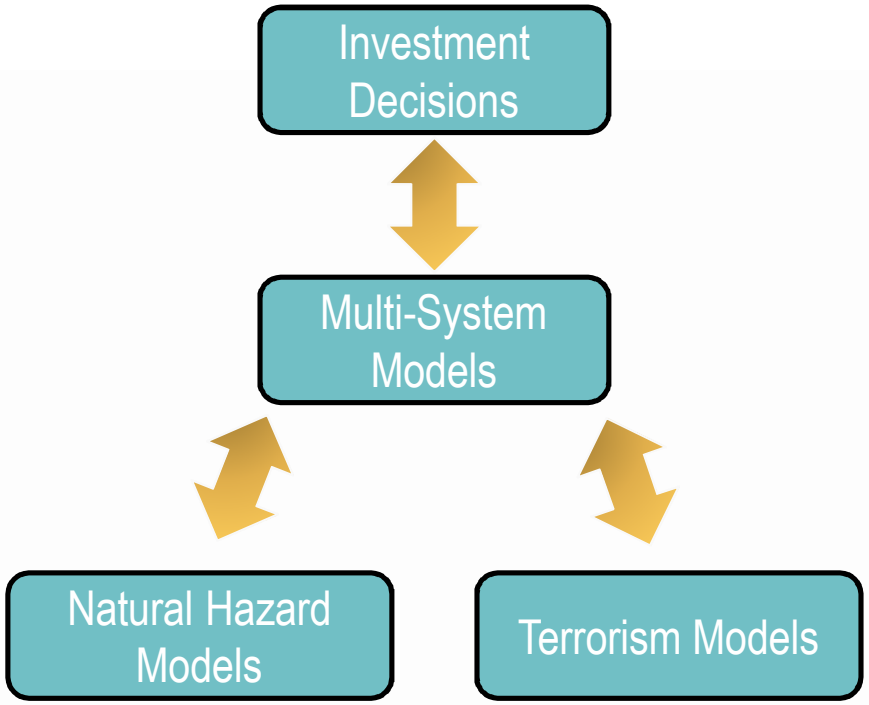
SME interviews and existing studies to determine flood/wind level at which each microgrid asset type would be damaged

Objective value of optimization gives load shed weighted by criticality to transportation

Linearized power flow model, modified economic dispatch

Multi-Hazard Investment Planning

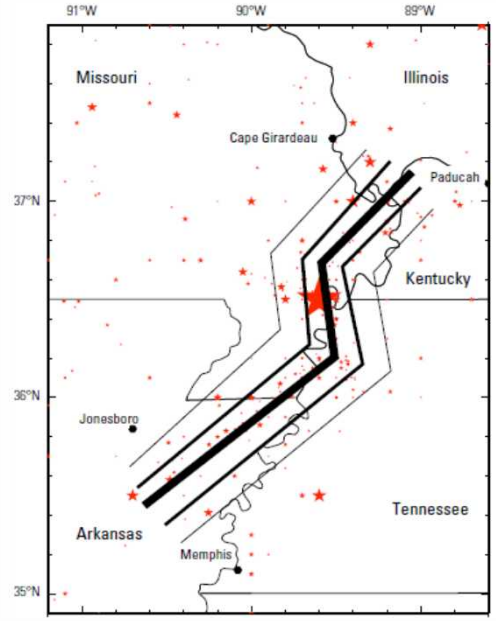
- Developed a mathematical approach for determining investment strategies to improve system resiliency subject to multiple hazards
  - Pre-event investment impacts post-event resiliency
  - Highly uncertain hazards: intentional acts, natural hazards
  - Many critical systems are complex
- Case study:
  - Infrastructure: Eastern interconnection
  - Hazard: New Madrid Seismic Zone
  - Mitigation: Seismic reinforcements and line capacity improvements



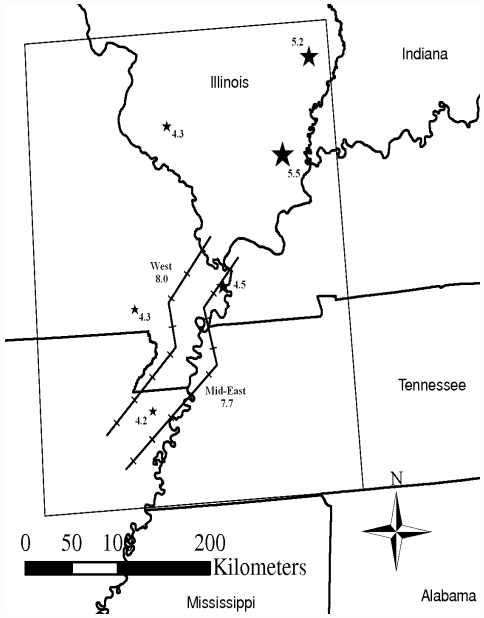
Multi-Hazard Investment Planning

- Created efficient techniques for modeling earthquake uncertainty and the associated damage to the grid
- Used stochastic programming and heuristic solution methods to identify optimal anchoring and capacity investment strategies to minimize load shed, given the seismic hazard

Complete Set of 453 Events



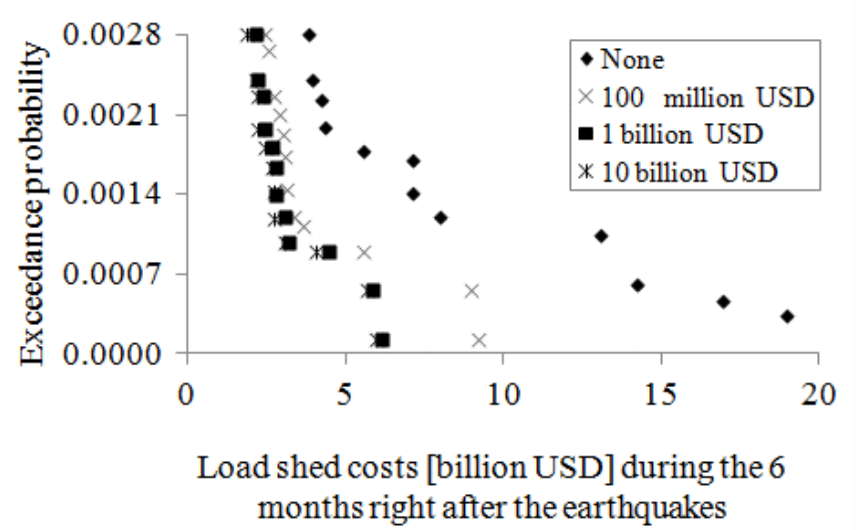
8 Events Selected through Optimization



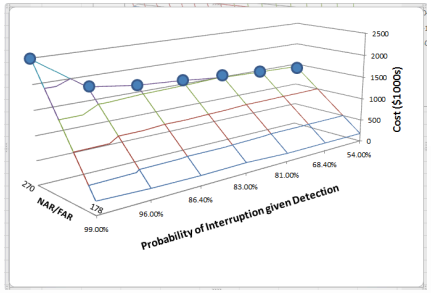
Multi-Hazard Investment Planning

- Identify the optimal investment strategy subject to a given budget
- The uncertainty associated with the seismic hazard is captured in the exceedance probability outputs
- Performance under various budgets can be compared to support decision making

Load Shed Exceedance Curves under Various Investment Budgets



A Complex Systems Approach to More Resilient Multi-Layered Security Systems



Summary

- 3-year/$1.5M LDRD motivated by incidents at Y-12
- Create a mathematical framework using complex systems techniques to characterize:
  - emergent behavior
  - vulnerabilities
  - resiliency
- Account for budget constraints and competing security priorities

Highlights

Developed a software implementation that:

- Automatically generates optimized/robust investment options for new/existing PPS designs
- Optimizes across multiple environmental and adversary scenarios
- Models the impacts of system NAR/FAR on alarm station operators

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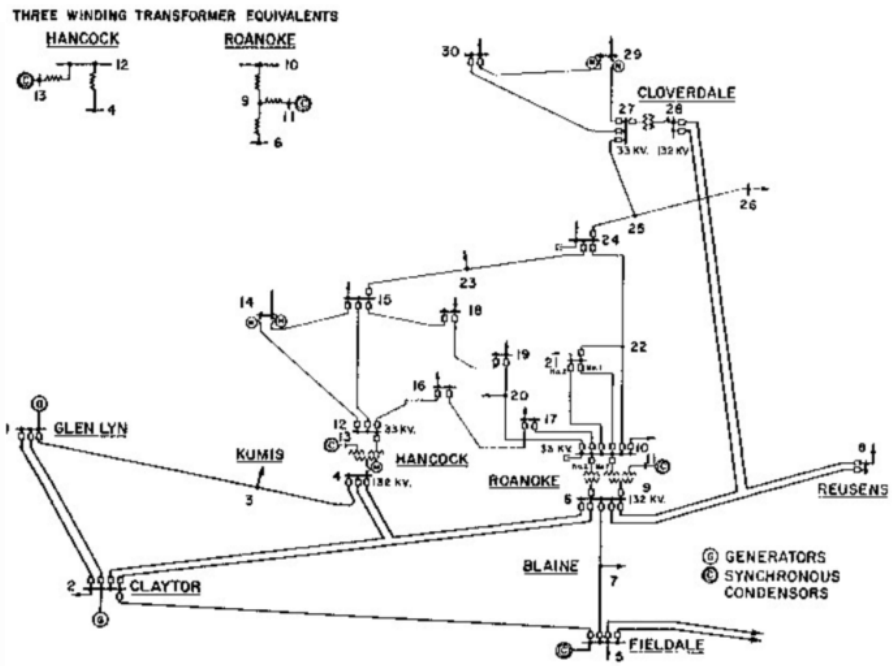
Power Grid Optimization

- Mathematical programming has been used to operate power grids since the 1960's. The difficulty—convex vs nonconvex, linear vs nonlinear, integer vs continuous—of a grid model depends on the task.

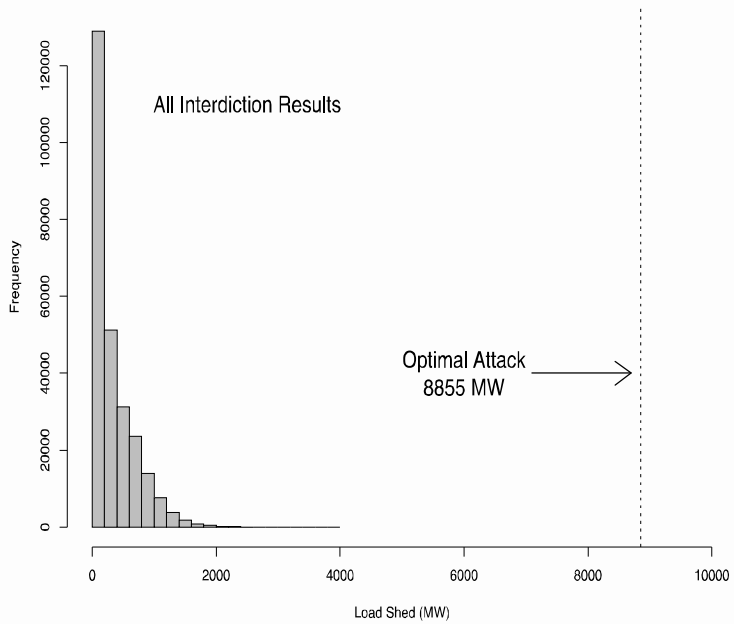
IEEE 30 bus test case

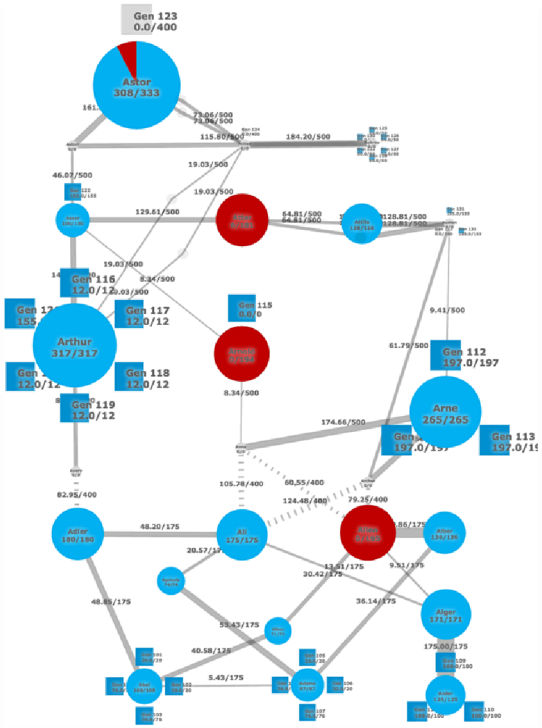


Interdiction against attacks on the electric power grid

Interdiction model: modified version of model described in Motto et al, IEEE Transactions on Power Systems (2005)

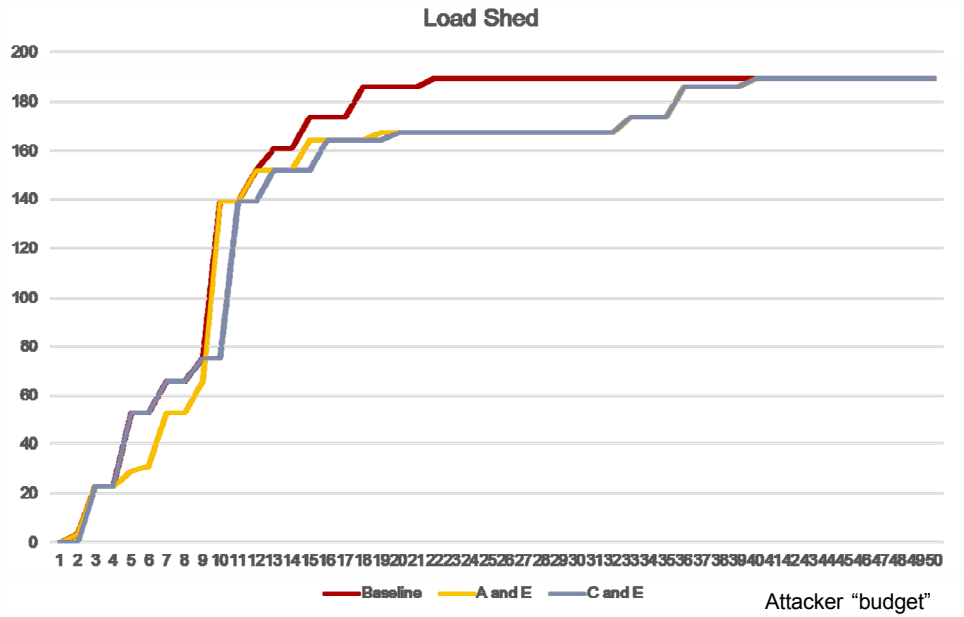
- Units of attacker strength ("attacker budget") represent how hard it is for them to attack a bus or a line/branch
- Represents real-world limitations like size of group, equipment available, or skill level of attacker





Investment Planning to Defend Against Attacks on the Electric Power Grid

- Develop a single investment strategy to improve resilience of the grid against multiple hazards (natural and man-made)
- **PARADE model:** investment planning for hardening measures against multiple threats, incorporating:
  - Subjective and qualitative metric evaluation via the Analytic Hierarchy Process (AHP) if needed
  - Potential downstream impacts on other infrastructures
  - Initial and recurring costs
  - Uncertainty around benefit of investments



Potential load shed reduction from investments depends on attacker capability

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Conclusion

- These capabilities are representative of the research being done in 8831 to address the resiliency of Complex Systems to support Sandia's broader national security mission
- This research is in direct support of the Resilience in Complex Systems Research Challenge, which is addressing three critical needs:
  - The development of quantitative metrics for measuring the resilience of Complex Systems
  - Researching and developing techniques for addressing system uncertainty
  - Creating methods for validation and verification of non-physics-based systems