Boosting Grid Resilience Using Microgrid Concepts

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What is Resilience?

• We define resilience to be:
  – Risk-based: Vulnerability, Threat, Consequence
  – Low probability, high consequence threats
  – Characterized by a probability density function

• It complements reliability
  – Reliability is not risk based
  – Reliability focuses on high probability, low consequence events
  – Operationally, reliability is binary. E.g there is no difference between N-5 and N-10
Least Cost Topology for a Single Large Microgrid

Solution Subset: Steiner Tree Problem
How Do We Design for Resilience?

• Engage stakeholders
• Establish a design basis (design basis threat doc)
• Define performance metrics
• Define system boundaries
• Collect system and operations info and data
• Generate feasible designs
  – measure performance against the design basis
  – improve the design
  – repeat
Flood Maps for Hoboken

FEMA 100 Year Flood + 2.5 Feet
Pareto Optimality Using Genetic Algorithms

Event Driven Simulation
Topology
Monte Carlo Analysis

Genetic algorithm continues until population approximates the Pareto frontier.

- Initial population selected at random
- 2nd population selected by genetic algorithm (GA)
- 3rd population selected by GA

Performance
Cost
A Hoboken Microgrid Solution
Standardizing Resilience Metrics

• Desirable Properties of Resilience Metrics
  – Useful for making decisions
  – Provide a means of comparison
  – Can be used for operations, planning and policy
  – Are scalable in geography, time, and analytic methodology
  – Are quantitative
  – Quantify uncertainty
  – Support a risk-based approach
  – Consider recovery time
Energy System Resilience Metric Framework

Consequence X

Mean

Probability of Consequence X given Threat Y

Extreme Values:

Consequence X

Mean
Moving Forward with Resilience Analysis

1. Define System & Resilience Metrics
2. Define Resilience Goals
3. Characterize Threats
4. Determine Level of Disruption
5. Define & Apply System Models
6. Calculate Consequence
7. Evaluate Resilience Improvements
Identify Threat Types

A infrastructure is designed to be resilient to a specific set of possible disruptions

Definition of possible disruptions can proceed via construction of a scenario tree
Alternatives exist, but they are more nuanced in terms of definition

We begin with high-level threat definitions

Probabilities are uniform (all-hazard), or skewed to reflect different emphases

High-level scenario identification is expected to be an output from an iterative and interactive stakeholder-driven process
Characterize Individual Threat

*Given high-level threat characterization, the next step is to further refine the description of the specific threats*

Historical information and forecast models is used to guide specification of possible events and their relative likelihoods:

- $p_1$
- ... (omitted)
- $p_n$

- Category 2, landfall at high tide
- Category 4, north-of-peninsula storm track
- Category 5, eye tracks over metropolitan area
Operations Model

Operations model is used to quantify system impact

91 loads
54 generators
186 lines

Basic Model:
- Reliability unit commitment
- Multi-period scheduling
- 24 hour horizon
- Dispatch and commitment

Modified IEEE 118 Bus Test Case System
http://motor.ece.iit.edu/data/ltscuc
Expressing Model as a Mixed-Integer Program

Core electricity grid operations problems are expressed as algebraic optimization problems, typically mixed-integer or linear programs.

Standard unit commitment formulation

\[
\begin{align*}
\min_x & \quad c^u(x) + c^d(x) + Q(x) \\
\text{s.t.} & \quad x \in \mathcal{X}, \\
& \quad x \in \{0, 1\}^{|G| \times |T|}
\end{align*}
\]

The feasible set \( \mathcal{X} \) implicitly captures minimum up and downtime constraints on thermal units.

Multi-period economic dispatch

\[
\overline{Q}(x) = E_\xi Q(x, \xi(\omega))
\]

\[
Q(x, \xi(\omega)) =
\begin{align*}
\min_{p,q} & \quad \sum_{i \in T} \sum_{g \in G} c^b_g(p^i_g) + \sum_{i \in T} Mq^i \\
\text{s.t.} & \quad \sum_{g \in G} p^i_g - q^i = D^i(\xi(\omega)), \quad \forall t \in T \\
& \quad P_g x^i_g \leq p^i_g \leq \overline{P}_g x^i_g, \quad \forall g \in G, t \in T \\
& \quad p^i_g - p^{i-1}_g \leq RU(x^{i-1}_g, x^i_g), \quad \forall g \in G, t \in T \\
& \quad p^{i-1}_g - p^i_g \leq RD(x^{i-1}_g, x^i_g), \quad \forall g \in G, t \in T.
\end{align*}
\]

where

\[
RU(x^{i-1}_g, x^i_g) = R^u_g x^{i-1}_g + S^u_g (x^i_g - x^{i-1}_g) + \overline{P}_g (1 - x^i_g)
\]

\[
RD(x^{i-1}_g, x^i_g) = R^d_g x^i_g + S^d_g (x^{i-1}_g - x^i_g) + \overline{P}_g (1 - x^{i-1}_g)
\]

Transmission elements modeled via DC power flow, with possible integration of AC feasibility checks.
Consequences

• Consequence data, on a per-bus basis, is defined for the economic impact on the economy
• We assume the following for purposes of resilience analysis
  – Economic impact is different at different load buses according to factors such as type of load
  – A piecewise linear transformations is employed to translate MWh not served to consequence (economic loss) at those load buses
Assess Baseline Resiliency

Assessing the economic losses incurred by a hypothetical hurricane event on the IEEE 118 bus test system

Methodology
1. Sample 100 scenarios specifying potential damage from a hurricane
2. For each scenario, compute a minimal-cost dispatch and associated loss of load
3. For each scenario, compute the cumulative economic losses incurred

Assumptions
1. No recovery possible for first 48 hours
2. Independent scenario analysis

Mean = $990M
Change the Dispatch Objective

Operating in a resilience-focused, as opposed to standard economic- and reliability-focused, manner leads to dramatic reductions in consequence.

In our IEEE 118 bus resiliency example, it is possible to mitigate nearly all economic consequences of the posited hurricane.
Investment Options

• Investment Option A
  – Build flood walls around generators with greater than 180 MW capacity (~20% of the thermal fleet)
  – Proxy for protection against flooding
  – 11 Generators at $9.1M for a total of $100M

• Investment Option B
  – Bury high-capacity lines – those with greater than 250 MW thermal limits (~5% of the network)
  – Proxy for protection against high winds and tree faults
  – 25 lines at $4M for a total of $100M
Baseline Resiliency

Histogram of Economic Losses Due to Hurricane

Mean = $990.3M
Analysis of Investment Alternatives

Both alternatives improve baseline mean of $990M

With generator flood walls

Mean = $546M

With line burying

Mean = $673M

Result: Line burying admits some higher-consequence events, with approximately the same mean impacts
Optimal Investment Portfolio

Evaluate Resilience Improvements

- Baseline mean was $990M
- Invest the same $100M in both flood walls and burying cables

- $100M of generator flood walls only: Mean = $546M
- $100M of burying lines only: Mean = $673M
- $100M of burying lines and generator flood walls: Mean = $405M
Advanced Metrics and Control Strategies for Grid Resiliency

- Network Description
- Resiliency Metrics
- Circuit Simulation (Spice, EGSim)
- Uncertainty Quantification

Control Actions:
- Dispatch Levels
- Transmission Switching
- Unit Cycling

Human in the Loop

Stochastic Optimization

Optimal Control Action

Preferences:
- Financial
- Security
- Safety

Political and SME-derived

Uncertainty:
- Loss of load costs
- Economic impacts

Projections of Future State

SCADA

IEEE PES

Power & Energy Society