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Title: Grid Resilience Design Methodologies, Tools, and Case Studies

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Grid Resilience Design Methodologies, Tools, and Case Studies

Russell Bent

Dec. 17, 2013

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Grid Resilience Program—Candidate Targets Preliminary Assessment → Feasible Targets

- Resilience to hazards that damage distribution grid infrastructure
 - Wind
 - Ice/Snow
 - Ground acceleration
 - Fire
 - Flood
 - During and after the hazard....
 - Serve 98% of critical load
 - Serve 50% of non-critical load
 - Reduce restoration time by 50%
 - Minimize budget requirements
- Addressed today
- Addressed today
- Partially addressed at first meeting

Grid Resilience Design Methodologies, Tools, and Case Studies

- Methodology
 - Integrated toolset
 - Process
- Tools
- Case Studies
- Conclusion

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Methodology—RestoreSims—DHS

Decision support tool for critical infrastructure disaster planning and response—Composed of interconnected modules:

- Inventory—Optimal pre-event stockpiles
- Restoration Set—Minimum set of repairs
- Restoration Order—Sequence of repairs
- Repair Crew Scheduling—Routing of repair crews
- Resilient Design—Survive large scale damage
- Emergency Operations—Optimal control during adverse conditions

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Methodology—Infrastructure Expansion Planning—LDRD/DOE

Decision support tool for upgrading and expanding critical infrastructure—Composed of interconnected modules:

- Transmission Expansion—Power line build out
- Generation Expansion—Generator build out
- Optimal Operations—Efficient control for normal operations
- Stochastic Modeling—Renewable fluctuations
- Resilient Design—Survive contingencies
- Coupled Systems—Operation of combined systems

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Methodology—Integration of Existing Tools

Resilient System Design
at the intersection of
these capabilities

DHS/NISAC

DOE/LDRD

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Methodology—Integration of Existing Tools

Components used
in studies for today

Components used
in studies for
previous meeting

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Methodology—Process

Hazard → Damage → System Impact → Optimal Design

- Hazard model to damage infrastructure
 - Wind, snow/ice, fire, flood
- System modeling and optimization
 - Assess damage
 - Design optimal upgrades—what and where
 - Microgrids
 - Switchable lines
- Optimization goals
 - Serve 98% of critical load
 - Serve 50% of non-critical load
 - Minimize capital budget

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Grid Resilience Design Methodologies, Tools, and Case Studies

- Methodology
- Tools
 - Fragility Model
 - System Model
 - Optimization Formulation
 - Algorithms
- Case Studies
- Conclusion

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Tools—Infrastructure Fragility Models

- Crucial design input—what should system be resilient to—Needs:
 - Model of the physical threat—wind speed, ice thickness, flood height, ground acceleration, fire boundaries/temperatures, etc.
 - Model the physical impact on infrastructure components...
 - To create damage predictions in terms of threat parameters

Tools—Infrastructure Fragility Models

- Crucial design input—what should system be resilient to? Needs:
 - Model of the physical threat—wind speed, flood height, ground acceleration, etc.
 - Model the physical impact of threat on system components...
 - To create damage probability curves for threat parameters

Tools—System Model/Optimization Formulation

$$\text{minimize } \sum_{i,j \in E} c_{ij} x_{ij} + \sum_{i,j \in E} \kappa_{ij} \tau_{ij} + \sum_{i \in N, k \in p_i} \zeta_i^k z_i^k + \sum_{i \in N} \mu_i u_i$$

$$\text{s.t. } -x_{ij} Q_{ij}^k |p_{ij}| \leq \sum_{k \in p_{ij}} f_{ij}^k \leq x_{ij} Q_{ij}^k |p_{ij}|$$

$$-(1 - \tau_{ij}) Q_{ij}^k |p_{ij}| \leq \sum_{k \in p_{ij}} f_{ij}^k \leq (1 - \tau_{ij}) Q_{ij}^k |p_{ij}|$$

$$-\beta_{ij} \frac{\sum_{k \in p_{i,j}} f_{ij}^k}{|p_{ij}|} \leq f_{ij}^{k'} - \frac{\sum_{k \in p_{i,j}} f_{ij}^k}{|p_{ij}|} \leq \beta_{ij} \frac{\sum_{k \in p_{i,j}} f_{ij}^k}{|p_{ij}|}$$

$$l_i^k = y_i d_i^k$$

$$0 \leq g_i^k \leq z_i^k + g_i^{k+}$$

$$g_i^k - l_i^k - \sum_{j \in N} f_{ij}^k = 0$$

$$0 \leq z_i^k \leq u_i Z_i^k$$

$$\sum_{i,j \in s} (x_{ij} + (1 - \tau_{ij})) \leq |s| - 1$$

$$\sum_{i \in CL, k \in p_i} l_i^k \geq .98 \sum_{i \in CL, k \in p_i} d_i^k$$

$$\sum_{i \in N \setminus L, k \in p_i} l_i^k \geq .5 \sum_{i \in N \setminus L, k \in p_i} d_i^k$$

$$x, y, \tau, u \in \{0,1\}$$

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Tools—System Model/Optimization Formulation

$$\text{minimize } \sum_{i,j \in E} c_{ij} x_{ij} + \sum_{i,j \in E} \kappa_{ij} \tau_{ij} + \sum_{i \in N, k \in p_i} \zeta_i^k z_i^k + \sum_{i \in N} \mu_i u_i$$

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Minimize the capital cost for building microgrids, switches, and power lines

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Tools—System Model/Optimization Formulation

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Resilience Program Targets

Serve 98% of critical load on all phases

Serve 50% of non-critical load on all phases

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Tools—System Model/Optimization Formulation

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$$x, y, \tau, u \in \{0,1\}$$

Respect 3-phase
power flow limits

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$$x, y, \tau, u \in \{0,1\}$$

Use 3-phase power flow limits to include switching operations

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Tools—System Model/Optimization Formulation

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Limit phase-current imbalance

$$l_i^k = y_i d_i^k$$

$$0 \leq g_i^k \leq z_i^k + g_i^{k+}$$

$$g_i^k - l_i^k - \sum_{j \in N} f_{ij}^k = 0$$

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$$x, y, \tau, u \in \{0,1\}$$

No partial load shedding at a node

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$$l_i^k = y_i d_i^k$$

$$0 \leq g_i^k \leq z_i^k + g_i^{k+}$$

Respect microgrid
generation limits

$$g_i^k - l_i^k - \sum_{j \in N} f_{ij}^k = 0$$

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Tools—System Model/Optimization Formulation

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$$0 \leq g_i^k \leq z_i^k + g_i^{k+}$$

$$g_i^k - l_i^k - \sum_{j \in N} f_{ij}^k = 0$$

Satisfy radial power flow equations

$$0 \leq z_i^k \leq u_i Z_i^k$$

$$\sum_{ij \in s} (x_{ij} + (1 - \tau_{ij})) \leq |s| - 1$$

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Restrict topology
to radial—no loops

$$\sum_{i \in CL, k \in p_i} l_i^k \geq .98 \sum_{i \in CL, k \in p_i} d_i^k$$

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Combine Operations and Planning

Discrete variables for:

1. Build new lines
2. Load shedding
3. Switching operations
4. Build new generation

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Tools—Coupling to Other Tools

$$\begin{aligned}
 &\text{minimize } \sum_{ij \in E} c_{ij} x_{ij} + \sum_{i,j \in E} \kappa_{ij} \tau_{ij} + \sum_{i \in N, k \in p_i} \zeta_i^k z_i^k + \sum_{i \in N} \mu_i u_i \\
 &\text{s.t. } -x_{ij} Q_{ij}^k |p_{ij}| \leq \sum_{k \in p_{ij}} f_{ij}^k \leq x_{ij} Q_{ij}^k |p_{ij}| \\
 &\quad -(1 - \tau_{ij}) Q_{ij}^k |p_{ij}| \leq \sum_{k \in p_{ij}} f_{ij}^k \leq (1 - \tau_{ij}) Q_{ij}^k |p_{ij}| \\
 &\quad -\beta_{ij} \frac{\sum_{k \in p_{ij}} f_{ij}^k}{|p_{ij}|} \leq f_{ij}^{k'} - \frac{\sum_{k \in p_{ij}} f_{ij}^k}{|p_{ij}|} \leq \beta_{ij} \frac{\sum_{k \in p_{ij}} f_{ij}^k}{|p_{ij}|} \\
 &\quad l_i^k = y_i d_i^k \\
 &\quad 0 \leq g_i^k \leq z_i^k + g_i^{k+} \\
 &\quad g_i^k - l_i^k - \sum_{j \in N} f_{ij}^k = 0 \\
 &\quad 0 \leq z_i^k \leq u_i Z_i^k \\
 &\quad \sum_{ij \in s} (x_{ij} + (1 - \tau_{ij})) \leq |s| - 1 \\
 &\quad \sum_{i \in CL, k \in p_i} l_i^k \geq .98 \sum_{i \in CL, k \in p_i} d_i^k \\
 &\quad \sum_{i \in N \setminus L, k \in p_i} l_i^k \geq .5 \sum_{i \in N \setminus L, k \in p_i} d_i^k \\
 &\quad x, y, \tau, u \in \{0,1\}
 \end{aligned}$$

Resilient System Design
tool coupled to 3-phase
OpenDSS models of
distribution grid

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Tools—Coupling to Other Tools

$$\text{minimize } \sum_{i,j \in E} c_{ij} x_{ij} + \sum_{i,j \in E} \kappa_{ij} \tau_{ij} + \sum_{i \in N, k \in p_i} z_i^k z_i^k + \sum_{i \in N} \mu_i u_i$$

$$\text{s.t. } -x_{ij} Q_{ij}^k |p_{ij}| \leq \sum_{k \in p_{ij}} f_{ij}^k \leq x_{ij} Q_{ij}^k |p_{ij}|$$

$$-(1 - \tau_{ij}) Q_{ij}^k |p_{ij}| \leq \sum_{k \in p_{ij}} f_{ij}^k \leq (1 - \tau_{ij}) Q_{ij}^k |p_{ij}|$$

$$-\beta_{ij} \frac{\sum_{k \in p_{i,j}} f_{ij}^k}{|p_{ij}|} \leq f_{ij}^{k'} - \frac{\sum_{k \in p_{i,j}} f_{ij}^k}{|p_{ij}|} \leq \beta_{ij} \frac{\sum_{k \in p_{i,j}} f_{ij}^k}{|p_{ij}|}$$

$$l_i^k = y_i d_i^k$$

$$0 \leq g_i^k \leq z_i^k + g_i^{k+}$$

$$g_i^k - l_i^k - \sum_{j \in N} f_{ij}^k = 0$$

$$0 \leq z_i^k \leq u_i Z_i^k$$

$$\sum_{i,j \in s} (x_{ij} + (1 - \tau_{ij})) \leq |s| - 1$$

$$\sum_{i \in CL, k \in p_i} l_i^k \geq .98 \sum_{i \in CL, k \in p_i} d_i^k$$

$$\sum_{i \in N \setminus L, k \in p_i} l_i^k \geq .5 \sum_{i \in N \setminus L, k \in p_i} d_i^k$$

$$x, y, \tau, u \in \{0,1\}$$

Coupling to other system models/simulations straightforward

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Tools—Algorithms

- Structured as a Mixed-Integer Program (MIP)
 - MIP's are generally computational difficult
 - Best practice – First, try commercial MIP solvers (Cplex, Gurobi, etc.)
 - < 2 CPU seconds per scenario for our case studies
 - Complexity will grow quickly with system size
- Proposed Scalable Alternative: Heuristics
 - Simulated Annealing, Genetic, Tabu, Ant Colony, Squeaky Wheel, etc.
- We use state-of-the-art Large Neighborhood Search
 - Combines the strengths of MIPs with heuristics
 - Significantly outperforms alternative approaches on large MIP problems

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Grid Resilience Design Methodologies, Tools, and Case Studies

- Methodology
- Tools
- Case Studies
 - Technologies Utilized
 - Operations Practices
 - Assumptions
 - Hartford Ice and Wind
 - Los Alamos Wildfire
- Conclusion

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Case Studies—Technologies Utilized

- Adding microgrids that include firm generation:
 - Natural gas generators and/or CHP
 - Diesel generators
- Adding (3-phase or 1-phase) inter-ties between:
 - Distribution circuits
 - Loads
 - Microgrids
- Adding switches (manual or automatic) to:
 - Reconfigure circuits
 - Shed circuits and/or loads
- Not included for today
 - Physical hardening

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Case Studies—Practices Utilized

- Optimal circuit switching for:
 - Distribution circuit reconfiguration
 - Load shedding
 - Networking of microgrids beyond their “dedicated” loads
 - Respecting circuit power flow limits
 - Respecting generator limits
 - Maintaining balance of phase-currents

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Case Studies—Assumptions

- Microgrids provide firm generation, e.g. natural gas CHP
- Added distribution lines and switches are underground and not vulnerable to damage (will be relaxed in a future robust formulation)
- Circuits or sections of circuits configured as trees
- Loads and/or generators stay on the phases where they were installed
- Costs.....

Device	Type	Cost Range	Suggested cost	Source
$c_{i,j}$	overhead 3-phase	\$60k-\$150k/mile	\$95k/mile	State of Virginia Study on Underground Circuits
$c_{i,j}$	overhead 1-phase	\$40k-\$75k/mile	\$55k/mile	
$c_{i,j}$	underground 3-phase	\$40k-\$1,500k/mile	\$500k/mile	
$c_{i,j}$	underground 1-phase	\$40k-\$1,500k/mile	\$100k/mile	
$\kappa_{i,j}$	automatic, 3-phase, overhead	—	\$15k	Tom Bialek (SDG&E)
$\kappa_{i,j}$	automatic, 3-phase, underground	—	\$30k	-
$\kappa_{i,j}$	manual, 3-phase, overhead	—	\$7.5k	-
$\kappa_{i,j}$	manual, 3-phase, underground	—	\$20k	-
$\kappa_{i,j}$	automatic, 1-phase, overhead	—	\$10k	-
$\kappa_{i,j}$	automatic, 1-phase, underground	—	\$25k	-
$\kappa_{i,j}$	manual, 1-phase, overhead	—	\$5	-
$\kappa_{i,j}$	manual, 1-phase, underground	—	\$15k	-
$\zeta_{i,j}$	Natural gas CHP variable	—	\$1,500k/MW	EIA 2025 Study
$\zeta_{i,j}$	Natural gas CHP fixed	—	\$500k

Case Studies—Hartford Snow/Ice/Wind Storm

Considered Two Configurations—“Urban” and “Residential”
to explore the trade offs between microgrids and new lines

Both cases:

- Three feeders
- 5.1 MW of total load
- 2.1 MW of critical load

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Case Studies—Hartford Snow/Ice/Wind Storm

Fragility—both models damaged by Ice + Wind

For each damage rate:

- 100 samples of damage
- Each sample drives an independent optimal resilience design
- Future—robust optimization over all damage samples

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Case Studies—Hartford Snow/Ice/Wind Storm

Capital budgets to meet resilience program targets

Case Studies—Hartford Snow/Ice/Wind Storm—Upgrades

Case Studies—Hartford Snow/Ice/Wind Storm

“Urban” topology—network from combination of new underground lines and probabilistic survival of existing overhead lines

Case Studies—Los Alamos/Cerro Grande Fire

- Significant damage to distribution system, but.....
- Many of the outaged homes no longer existed--235 homes
- Resilience design (and restoration) must be aware of what parts of the system are NOT worth protecting/restoring

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Case Studies—Los Alamos/Cerro Grande Fire

Fragility—damage to transformers by heat stress of insulation, if not burned

Case Studies—Los Alamos/Cerro Grande Fire—Actual

Loss of Power
and Demand

Loss of
Power

No additional system components required to meet resilience program goals:

- No undestroyed critical load loses access to power
- > 50% of undestroyed load has access to power

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Case Studies—Los Alamos/Cerro Grande Fire—Plus Slightly Larger Extent

- Extend Cerro Grande ½ mile deeper into the canyons
- System separates into several islands
- < 98% critical load served
- < 50% non-critical load served

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Case Studies—Los Alamos/Cerro Grande Fire—Plus Resilient Upgrades

Resilience easier to achieve in this case:

- Loss of service and loads → can't serve load that isn't there
- Fire damage is more "directed" compared to ice/wind case

\$250K expansion enables:

- 98% critical load served
- 50% non-critical load served

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Grid Resilience Design Methodologies, Tools, and Case Studies

- Methodology
- Tools
- Case Studies
- Conclusion

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Grid Resilience Program—Candidate Targets

Preliminary Assessment → Feasible Targets

Summary

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Conclusions—Important Future Enhancements/Extensions

- Integrate with more distribution solvers
- Robust formulation of the optimal resilience design
- Couple two current separate tools
 - Resilience design (presented today)
 - Optimal restoration (covered in October meeting)
- Expand to larger systems → computational complexity
- Tool Deployment

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Conclusions—Desired End State

Integration of DHS and DOE/LDRD tools to gain a comprehensive view of system resilience

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