Business & Technology Report

November 2019

Distribution Optimal Resilience Design Tool "LPNORM"

NRECA Final Report

NRECA
America's Electric Cooperatives

Business & Technology Report
November 2019

Distribution Optimal Resilience Design Tool "LPNORM"

NRECA Final Report

Prepared By:

David Pinney
NRECA Analytics Research Program Manager

Contacts:

David Pinney
NRECA Analytics Research Program Manager
Business and Technology Strategies
david.pinney@nreca.coop

NRECA
America's Electric Cooperatives

Table of Contents

Executive Summary

As illustrated in recent years, extreme weather events (Superstorm Sandy, Hurricane Katrina, etc.) pose an enormous threat to the nation's electric power distribution systems and the associated socio-economic systems that depend on reliable delivery of electric power. While distribution utilities have software tools available for operations and planning under normal conditions, these tools do not include the ability to model damage from extreme events or suggest optimal design changes to improve resilience.

In this project, we delivered a software tool called "LPNORM" (an acronym for the Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), and National Rural Electric Cooperative Association (NRECA) Optimal Resiliency Model) for designing resilient distribution grids. The LPNORM tool allows users to import distribution circuit and pole models, model damage from extreme weather events, input resilience criteria, and generate optimal design solutions, including hardening, undergrounding, and microgrid deployment, to improve the resilience of the system. The tool has been delivered and is available as part of the Open Modeling Framework at https://omf.coop/newModel/resilientDist/finalReport This interface allows users at utilities to upload data in common utility formats, generate system damage and optimal design results, and investigate model outputs via a graphical user interface.

We developed this tool with the guidance of a utility advisory board consisting of seven utilities from three regions of the United States (south, midwest, and southwest). We worked with two of these utilities to perform detailed modeling of their system and identified novel resilience approaches. The feedback from the advisory utilities as well as from other NRECA members has been enthusiastic, and we look forward to helping them gain additional value from this tool.

Project Goals

A critical problem in modern distribution utilities is a lack of tools that support resiliency planning for extreme events. These events disrupt the ability to deliver power and cause significant social and economic impacts. They are becoming far more common and far more costly (see [EO13], Figure 1, and Figure 2). Distribution utilities rely on tools, such as Cymdist, Synergi, WindMil, and DEW, for their day-to-day operations, but these tools have limited ability to support reliability analysis, much less extreme event resiliency analysis and planning. Despite inadequate tools, utilities are redesigning, upgrading, and hardening their systems, often without being able to quantify the benefits. These upgrades are expensive and tend to be reactive (for example, United Illuminating Company spent $11 million hardening substations in their service territory after Superstorm Sandy [UIC13]). There is a critical need for a tool that allows utilities to proactively address resiliency in a systematic way and engineers to rigorously assess the cost versus resiliency value of new components.

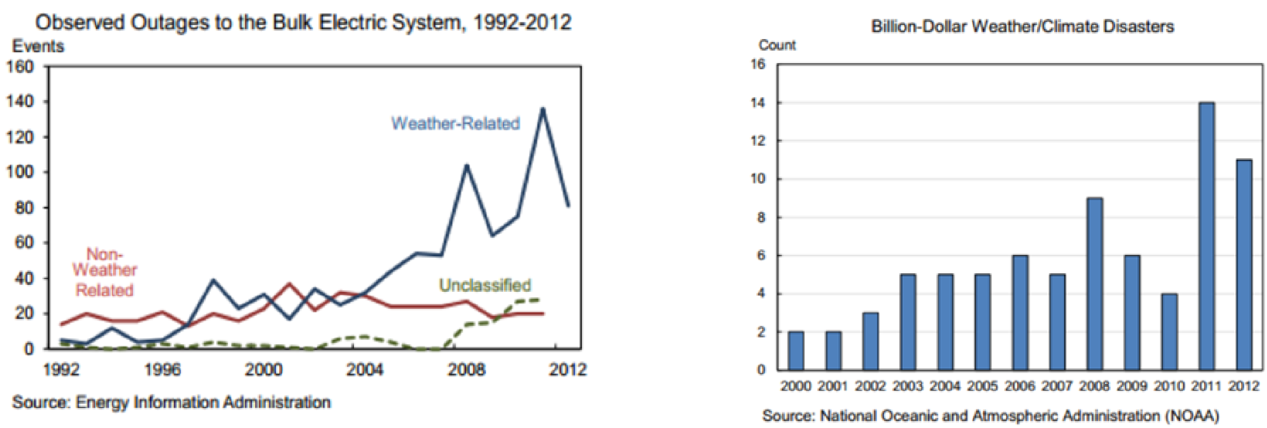
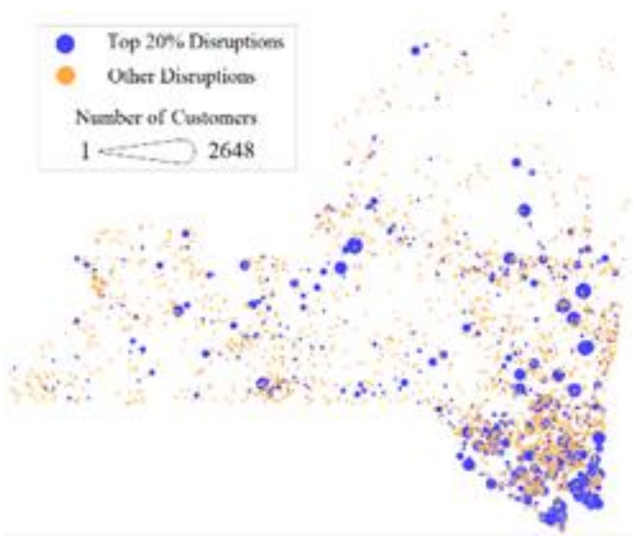


Figure 1. Graphics from [EO13] showing the increase in weather-related impacts in recent decades.



Recent Extreme Event Examples

- More than 20 major hurricanes, snow/ice storms in U.S., 2005-2017
- Each outage ~500,000 customers for days
- Hurricane Sandy - ~50,000 sq. miles out-of-service region (4 utilities)
- 2017 Hurricanes: Harvey, Irma, Maria, 2018 Hurricane Florence
- In NY, 20% of the failures accounted for 84% of the affected customers (image left, source: Toolkit for Resilient Cities Case Study: New York City Electrical Grid)

Figure 2. Specific examples of recent extreme event damage.

This project has provided the nation's distribution utilities with a tool that improves system resiliency, as defined by outage reduction and decreased restoration time. We have provided a new resiliency planning process integrated into an online assessment tool and gained adoption by an initial set of utility users. The tool is freely available at www.omf.coop and supports the U.S. Department of Energy – Office of Electricity (DOE OE) Resilient Distribution Grid research and development mission of deploying innovative resiliency technologies to utilities. The underlying process serves as a template and software environment for developing tools for designing resilient energy systems more generally.

This work was done in support the DOE OE Resilient Distribution Grid R&D mission of developing cutting edge resilience technologies that are deployed to utilities to reduce outage costs. More generally, within the context of the MYPP, resiliency is one of the significant problems facing power grids (see Activity 2 of Section 5, and Activity 2 of Section 6). These problems are connected to the MYPP and DOE national outcome that states a goal of a "10% reduction in the economic costs of power outages by 2025." Improving distribution system resiliency reduces outages, thereby achieving these goals. We also recognize linkages to other efforts in the MYPP that complement our efforts and present opportunities for mutually beneficial synergistic activities. In particular, Project 1.4.9 is developing new predictive models of how distribution systems respond to extreme events based on historical data and machine learning techniques. These models are possible inputs to the damage modeling portion (discussed below) of our tool. Project 1.4.17 includes a focus on discovering extreme events of interest, which provides another source of input to damage modeling. Project 1.4.15 is focused on delivering new models on combined distribution, transmission, and communication, and will serve as source of technology for the next generation of communication modeling in LPNORM. In short, this LPNORM effort addresses this underlying fundamental, crosscutting problem set out in the MYPP and creates linkages between other projects within the MYPP.

The primary deliverable of this project is an open-source software, called LPNORM, for resilient design, which is deployed to www.omf.coop for free use by the nation's distribution utilities.

LPNORM:

1) Integrates damage prediction modeling and user-defined damage events as part of a novel planning tool,

2) Models resiliency criteria, and

3) Makes recommendations on both the initial design and upgrades to existing distribution circuits and communication systems based on these resiliency criteria.

We have built the deliverable in three phases:

- Phase 1: We completed an alpha version of LPNORM that simultaneously models distribution networks, outage reduction criteria, and damage models for hazards induced by extreme weather events.
- Phase II: We developed the capability to include damage data provided by utilities and integrated LPNORM with the distribution engineering analysis tools of OMF and deployed it as a beta prototype on www.omf.coop.

- Phase III: We identified two NRECA member utilities and used their data and expertise to complete beta testing. We provided technical assistance to these utilities and solicited their input, as well as the input of a broader utility advisory board, on how to improve LPNORM (discussed below).

Solvers and software packages that can evaluate three-phase, unbalanced power flows on different topologies and provide system feasibility checks do exist, such as WindMil, CYMDIST, and Synergi Electric. However, these tools are closed source and offer little flexibility to implement new iterative algorithms or interfaces. In response to this challenge, we have implemented our resilient design solution using a combination of four flexible open source tools:

- GFM (the General Fragility Model),
- GridLAB-D,
- RDT (the Resilient Design Tool), and
- OMF (the Open Modeling Framework).

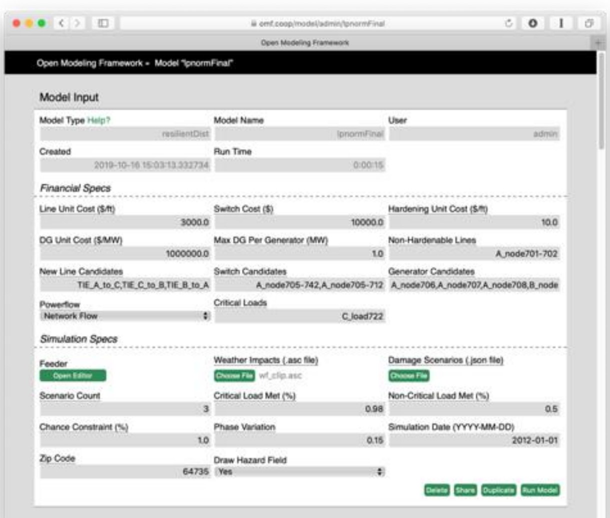
Algorithms and controls that modify infeasible topologies, such as recloser/sectionalizer switching and load shedding, were accessed through integration with existing GridLAB-D functionality [CSG08, SFC11, STE14]. Through GridLAB-D's interface with the OMF, we added a mechanism for visualizing the results of the system feasibility checks during the execution of LPNORM as well as ingesting, transforming, and editing distribution system models. RDT was integrated with GridLAB-D to aid in the exchange of data and solution feasibility checks. Communications and co-simulation ability have also been implemented in the Framework for Network Co-Simulation [CDFFMA14], providing a basis for further interaction between GridLAB-D and RDT's evaluation of communications on distribution systems.

Using the Tool

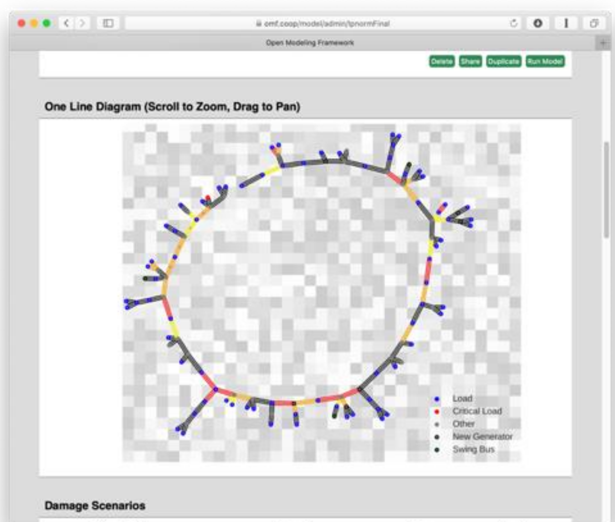
To run the tool:

1. Navigate to https://omf.coop/newModel/resilientDist/lpnormFinal
2. If you do not have an OMF account, please register using the link that will be displayed.
3. By default, there is a small 120 section circuit model provided, which you can view and edit with the "Open Editor" button. There is an option in that editing interface to upload a new circuit exported from Windmil, Cymdist, or GridLAB-D. We also provide a default hazard (wind damage map) file and financial and resilience criteria which can be edited.
4. Run the model and generate outputs with the "Run" button at the bottom.
5. You can also download, install, and run the model on a local machine by following the OMF installation instructions.

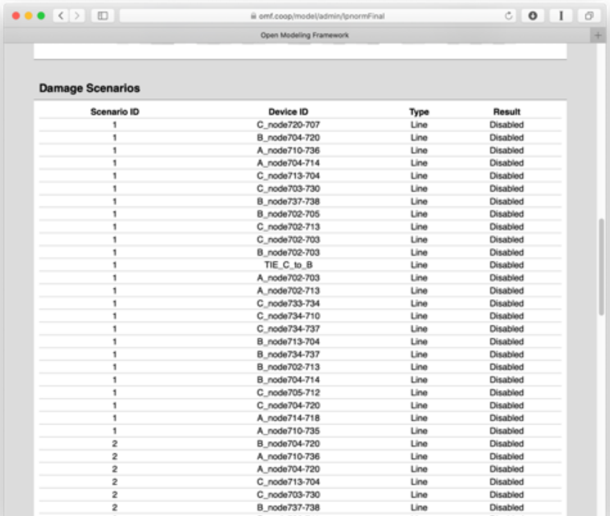
Overview of model interface:



Model Inputs



One-line Diagram with Resilience Improvements



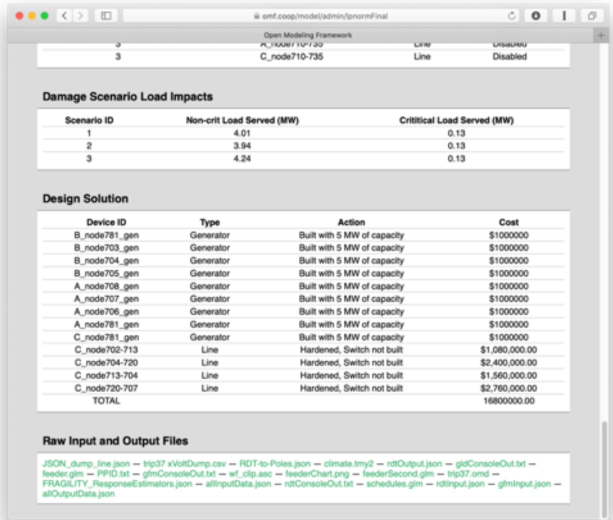
omf.coop/model/admin/lpnormFinal

Open Modeling Framework

Damage Scenarios

Scenario ID	Device ID	Type	Result
1	C_node720-707	Line	Disabled
1	B_node704-720	Line	Disabled
1	A_node710-736	Line	Disabled
1	A_node704-714	Line	Disabled
1	C_node713-704	Line	Disabled
1	C_node703-730	Line	Disabled
1	B_node737-738	Line	Disabled
1	B_node702-705	Line	Disabled
1	C_node702-713	Line	Disabled
1	C_node702-703	Line	Disabled
1	B_node702-703	Line	Disabled
1	TIE_C_to_B	Line	Disabled
1	A_node702-703	Line	Disabled
1	A_node702-713	Line	Disabled
1	C_node733-734	Line	Disabled
1	C_node734-710	Line	Disabled
1	C_node734-737	Line	Disabled
1	B_node713-704	Line	Disabled
1	B_node734-737	Line	Disabled
1	B_node702-713	Line	Disabled
1	B_node704-714	Line	Disabled
1	C_node705-712	Line	Disabled
1	C_node704-720	Line	Disabled
1	A_node714-718	Line	Disabled
1	A_node710-735	Line	Disabled
2	B_node704-720	Line	Disabled
2	A_node710-736	Line	Disabled
2	A_node704-720	Line	Disabled
2	C_node713-704	Line	Disabled
2	C_node703-730	Line	Disabled
2	B_node737-738	Line	Disabled

Detailed Damage Scenario Information



omf.coop/model/admin/lpnormFinal

Open Modeling Framework

3	C_node710-735	Line	Disabled

Damage Scenario Load Impacts

Scenario ID	Non-crit Load Served (MW)	Crititical Load Served (MW)
1	4.01	0.13
2	3.94	0.13
3	4.24	0.13

Design Solution

Device ID	Type	Action	Cost
B_node781_gen	Generator	Built with 5 MW of capacity	$1000000
B_node703_gen	Generator	Built with 5 MW of capacity	$1000000
B_node704_gen	Generator	Built with 5 MW of capacity	$1000000
B_node705_gen	Generator	Built with 5 MW of capacity	$1000000
A_node708_gen	Generator	Built with 5 MW of capacity	$1000000
A_node707_gen	Generator	Built with 5 MW of capacity	$1000000
A_node706_gen	Generator	Built with 5 MW of capacity	$1000000
A_node781_gen	Generator	Built with 5 MW of capacity	$1000000
C_node781_gen	Generator	Built with 5 MW of capacity	$1000000
C_node702-713	Line	Hardened, Switch not built	$1,080,000.00
C_node704-720	Line	Hardened, Switch not built	$2,400,000.00
C_node713-704	Line	Hardened, Switch not built	$1,560,000.00
C_node720-707	Line	Hardened, Switch not built	$2,760,000.00
TOTAL			16800000.00

Raw Input and Output Files

JSON_dump_line.json — trip37 xVoltDump.csv — RDT-to-Poles.json — climate.tmy2 — rdtOutput.json — gldConsoleOut.txt — feeder.glm — PPID.txt — gfmConsoleOut.txt — wf_clip.asc — feederChart.png — feederSecond.glm — trip37.omd — FRAGILITY_ResponseEstimators.json — allInputData.json — rdtConsoleOut.txt — schedules.glm — rdtInput.json — gfmInput.json — allOutputData.json

Recommended Resilience Improvements Detail

Methodology

To describe our solution, we must first define resiliency. This is difficult, because many standard definitions, such as the one appearing in the presidential policy directive PPD-21 ("The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resiliency includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents"), are not directly quantifiable. For the purposes of this project, we have defined resiliency as *a reduction in critical demand outage size as a means of demonstrating capability*. Subsequent work will demonstrate other definitions of resiliency, such as restoration time reduction.

A high-level overview of the resilient design methodology is given in Figure 3. In step one, we take a distribution system that the user is interested in performing resiliency analysis on as an input through either a manual circuit editor or import from Milsoft Windmil, CYMEDIST, or GridLAB-D. This model is converted to GridLAB-D, GFM, and RDT formats to feed further steps in the design process. In step two, we model extreme events using the damage models in GFM. LPNORM requires multiple scenarios of extreme event damage and uses those to choose a design that is resilient to all scenarios. Damage or models are specified by the user through either a hazard map (e.g. a wind field in ESRI ASC Format) or a list of past examples of damage (i.e. a list of damaged components). In step 3, RDT is used to calculate a design solution, which consists of a set of line hardening, additional switching, and backup generation recommendations. This is based on the solution to an optimization routine with the objective of minimizing outages to critical and non-critical load across all damage scenarios. To narrow the design recommendations and account for infeasible component upgrades, users can provide candidate locations and costs for hardening, new lines, and distributed generation. Finally, LPNORM calculates power flow and the load served for the recommended design choices to validate the recommendations. The updated system is an output that can then serve as input to future runs of the model to provide further or iterative design improvements.

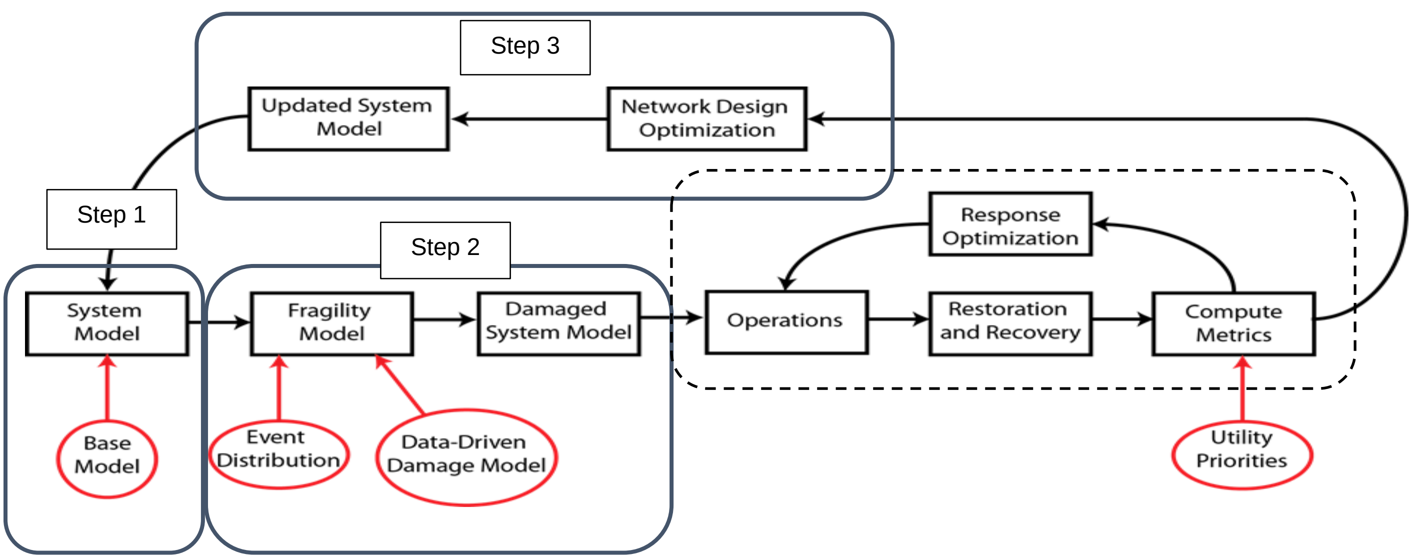


Figure 3: overview of LPNORM resilient design methodology.

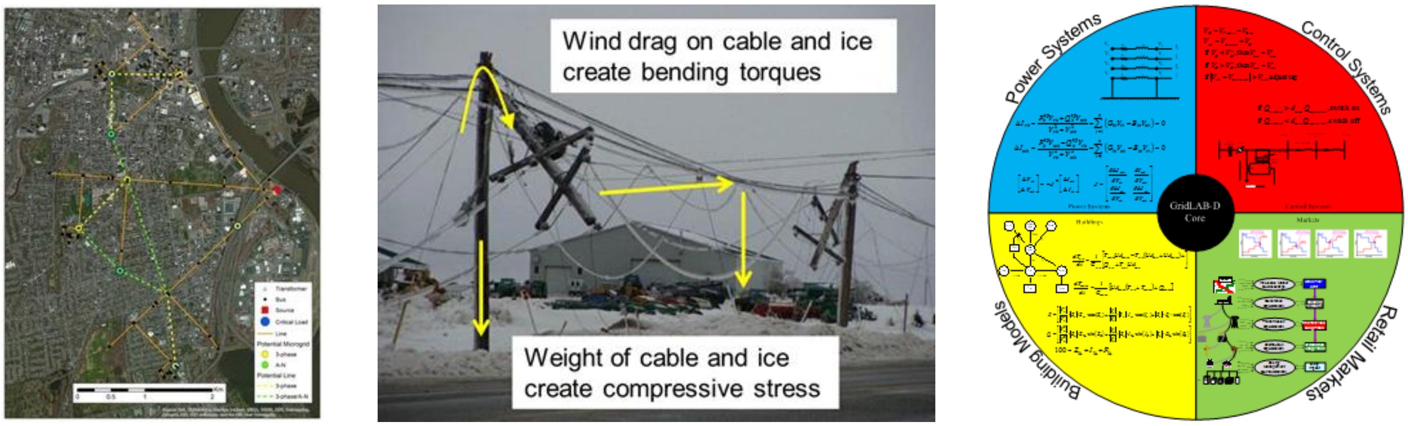


Figure 4: example network input (left), GFM ice damage model (center) and GridLAB-D distribution simulation capabilities (right).

The primary novelty of this implementation is the ability to define which of these changes to the topology is feasible (via user-defined constraints) and providing the information and "improved" topology back to RDDT, the Resilient Distribution Design Tool optimization solver, for further enhancement. In the work plan, elements of Tasks 2 (new capability for communication system design) and 3 (integrating these models with the other software modules) are associated with developing this capability. We will build LPNORM using a two-part strategy. First, we will leverage existing capabilities (discussed below) and develop software that links these capabilities together, as shown in Figure 2. Second, we will develop new solutions where gaps exist in current capabilities. Our tool will ingest utility power models and prototypical communication data (block 1), ingest user-defined damage or damage prediction models (block 2), recommend design and upgrades to distribution circuits and communication (block 3), and verify solution feasibility (block 4). We will deploy the capability on the OMF (block 5).

LPNORM's system architecture is modular. This structure maximizes the use of existing software — GFM, GridLAB-D, OMF, and RDT — and enables easy integration for future projects. We have enhanced these four modules and released all code as open source. In Figure 5 below, we provide a diagram of the existing libraries, the extensions, their integration points, and the data flow through the system. The team utilized a continuous integration process to release the LPNORM software after every stable change. Unit and acceptance tests are integrated with this system and are run after every change, stable or otherwise. This approach offered large benefits in speed and correctness of the development process.

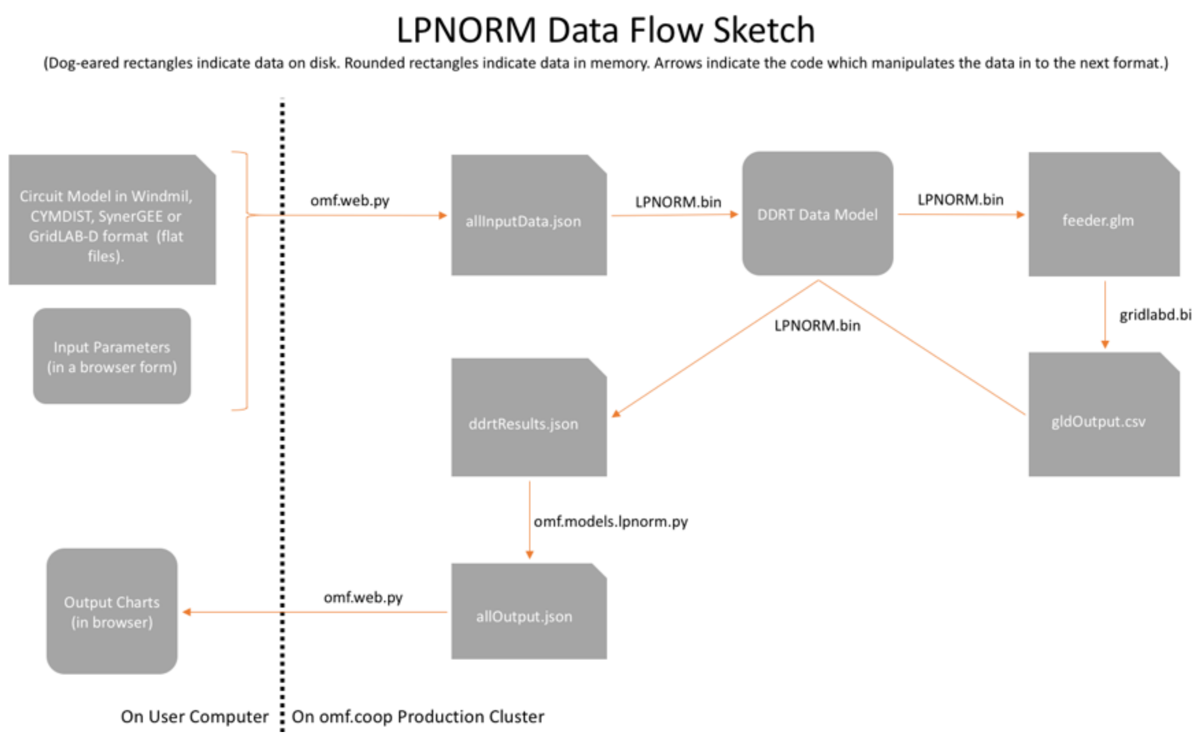


Figure 5. Overview of the flow of data in LPNORM

We built a graphical user interface (GUI) to make the software developed in this project easy for distribution utility system planners to use. All existing engineering analysis tools that utilities have adopted present their users with a single line diagram and menu-driven interfaces to allow manipulation of system data without writing code. GUI development was accomplished primarily by using existing capabilities in the OMF, including code that allows users to visualize and edit circuits, set up simulation parameters, manage the execution of simulations, and monetize and visualize the results via charts and tables. The OMF user interface was implemented as a web application to allow system users to get started in seconds, access the software from anywhere, and share data and results with other users of the system instantly. Existing distribution engineering analysis software packages are, by comparison, Windows desktop applications.

A core component of our solution is a distribution damage modeling capability built using capabilities in GFM. We have incorporated existing capability that model how water, wind, and ice damage components into LPNORM. These capabilities are based on the FEMA-developed tool, HAZUS [FEMA15], and other sources available in the engineering literature [S02, EK13]. This capability was developed under DHS funding. Figure 6 provides an example of these models. Although modeling damage based on specified extreme events is an important capability, it neglects utility-specific domain expertise about events of concern. Thus, we have also allowed users to import their own models of damage. The primary novelty here that was lacking in distribution modeling software was the coupling of damage modeling (both user-specified and hazard-specified) with distribution systems.

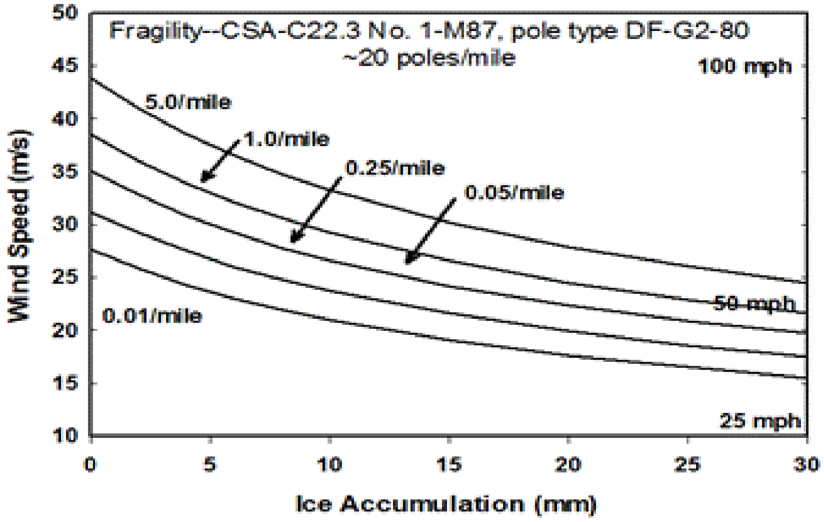


Figure 6. Reference [S02] provided extensive testing of distribution utility poles and their response to ice and wind. From their data, we developed a probabilistic model of how likely a pole is to break based on its exposure to wind speed and ice accumulation.

The core element of the LPNORM tool is an optimal distribution design and upgrade method. Here we have heavily leveraged the RDT capability developed for the DOE-OE Smart Grid R&D Program to design and upgrade distribution grids for resilience. The core (existing) contributions within RDT are the mathematical optimization model shown in overview in Figure 7 and the algorithms we have developed to solve this problem [YBB15] show in Figure 8. The optimization model poses the problem as a two-stage, mixed-integer stochastic program with full details in https://arxiv.org/abs/1801.03520. The first stage minimizes the cost of the design of the network. The second stage evaluates the feasibility of the design under the extreme event damage scenarios provided by the damage-modeling portion of LPNORM. We based our algorithm on a decomposition strategy that exploits the scenario (two-stage) structure of the problem. The algorithm proposes design solutions, checks their performance in each scenario, and iterates until a solution that meets the resiliency criteria in all scenarios is proposed. We have designed this approach to find globally or high-quality, locally optimal designs, depending on the size of the problem and the time-to-solution requirements of the user.

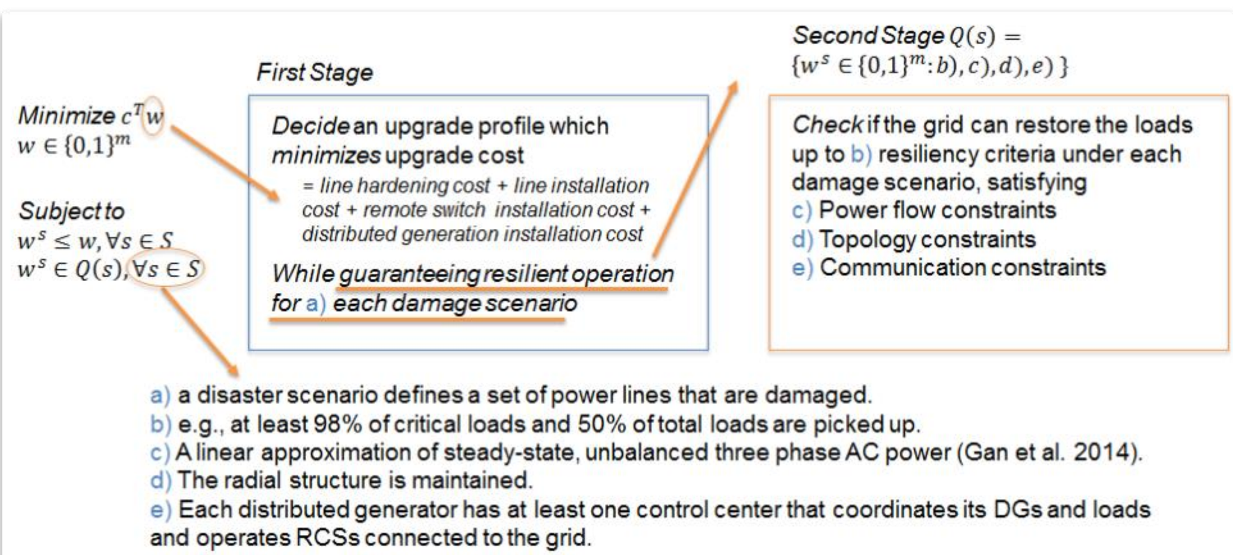


Figure 7. Overview of the RDT optimization formulation.

$$\text{minimize} \ \sum_{ij\in E} c_{ij}x_{ij} + \sum_{i,j\in E} \kappa_{ij}\tau_{ij} + \sum_{i\in N,k\in p_i} \zeta_i^k z_i^k + \sum_{i\in N} \mu_i u_i + \sum_{ij\in E} \alpha_{ij}t_{ij} \quad \mathbf{(1)}$$

$$\text{s.t.} \quad -\mathrm{x}_{ij}^s Q_{ij}^k \le \sum_{k\in p_{ij}} f_{ij}^{sk} \le x_{ij}^s Q_{ij}^k \quad \mathbf{(2)}$$

$$-\left(1 - \tau_{ij}^s\right) Q_{ij}^k \le \sum_{k\in p_{ij}} f_{ij}^{ks} \le \left(1 - \tau_{ij}^s\right) Q_{ij}^k \quad \mathbf{(3)}$$

$$-\beta_{ij}\frac{\sum_{k\in p_{i,j}} f_{ij}^{ks}}{|p_{ij}|} \le f_{ij}^{k's} - \frac{\sum_{k\in p_{i,j}} f_{ij}^{ks}}{|p_{ij}|} \le \beta_{ij}\frac{\sum_{k\in p_{i,j}} f_{ij}^{ks}}{|p_{ij}|} \quad \mathbf{(4)}$$

$$x_{ij}^s \le x_{ij}, \tau_{ij}^s \le \tau_{ij}, t_{ij}^s \le t_{ij}, z_{ij}^{sk} \le z_i^k, u_i^s \le u_i \quad \mathbf{(5)}$$

$$z_i^k \le M_i^k u_i, x_{ij}^s = t_{ij}^s, x_{ij}^s \le \overline{x}_{ij}^s, \tau_{ij}^s \le x_{ij}^s \quad \mathbf{(6)}$$

$$3 - x_{ij}^s - \overline{\tau}_{ij}^s \ge \tau_{ij}^s \ge x_{ij}^s + \overline{\tau}_{ij}^s - 1 \quad \mathbf{(7)}$$

$$\mathrm{l}_\mathrm{i}^\mathrm{ks} = y_i^s d_i^k \quad \mathbf{(8)}$$

$$0 \le g_i^{sk} \le z_i^{ks} + g_i^{k^+} \quad \mathbf{(9)}$$

$$\mathrm{g}_\mathrm{i}^\mathrm{ks} - l_i^{ks} - \sum_{j\in N} f_{ij}^{ks} = 0 \quad \mathbf{(10)}$$

$$0 \le z_i^{ks} \le u_i^s Z_i^k \quad \mathbf{(11)}$$

$$\sum_{ij\in s}\left(\overline{x}_{ij}^s + \left(1 - \overline{\tau}_{ij}\right)\right) \le |s| - 1 \quad \mathbf{(12)}$$

$$\sum_{i\in CL,k\in p_i} l_i^{ks} \ge \lambda \sum_{i\in CL,k\in p_i} d_i^k \quad \mathbf{(13)}$$

$$\sum_{i\in N\setminus L,k\in p_i} l_i^{ks} \ge \gamma \sum_{i\in N\setminus L,k\in p_i} d_i^k \quad \mathbf{(14)}$$

$$x, y, \tau, u, t \in \{0,1\} \quad \mathbf{(15)}$$

$$v_j^a = v_i^a - 2(r_{ij}^{aa}P_{ij}^a + x_{ij}^{aa}Q_{ij}^a + \overline{r}_{ij}^{ab}P_{ij}^b + \overline{x}_{ij}^{ab}Q_{ij}^b + \underline{r}_{ij}^{ac}P_{ij}^c + \underline{x}_{ij}^{ac}Q_{ij}^c) \quad \mathbf{(16)}$$

$$v_j^b = v_i^b - 2(\underline{r}_{ij}^{ba}P_{ij}^a + \underline{x}_{ij}^{ba}Q_{ij}^a + r_{ij}^{bb}P_{ij}^b + x_{ij}^{bb}Q_{ij}^b + \overline{r}_{ij}^{bc}P_{ij}^c + \overline{x}_{ij}^{bc}Q_{ij}^c) \quad \mathbf{(17)}$$

$$v_j^c = v_i^c - 2\left(\overline{r}_{ij}^{ca}P_{ij}^a + \overline{x}_{ij}^{ca}Q_{ij}^a + \underline{r}_{ij}^{cb}P_{ij}^b + \underline{x}_{ij}^{cb}Q_{ij}^b + r_{ij}^{cc}P_{ij}^c + x_{ij}^{cc}Q_{ij}^c\right) \quad \mathbf{(18)}$$

$$\mathrm{g(q)}_\mathrm{i}^\mathrm{ks} - l(q)_i^{ks} - \sum_{j\in N} f(q)_{ij}^{ks} = 0 \quad \mathbf{(19)}$$

$$v_-^k \le v^k \le v_+^k \quad \mathbf{(20)}$$

Figure 8. This set of equations forms the underlying mixed integer mathematical program that defines the resilient design problem that RDT was designed to solve.

Due to space constraints, this figure does not provide the full notation. Instead, this picture is intended to convey the complexity of the problem and is used as a device for discussing the modeling used by RDT.

Eq. 1 minimizes the cost of design a distribution network, which includes new lines (x), hardening existing lines (t), building switches (τ), building distributed microgrid generation (u), and generation capacity (z).

Eq. 2 enforces limits (Q) each phase flow (f) on each line.

Eq. 3 allows flow only when a switch is closed.

Eq. 4 ensures unbalanced phase flow is with limits (β).

Eq. 5-7 link design variables with operation variables under each scenario.

Eq. 8 allows all or no load to be shed at each node (y).

Eq. 9 limits the capacity for distributed generation on the system.

Eq. 10 and 19 ensure balanced flow at each node.

Eq. 11 ensures that generation capacity exists only if the generator has been built.

Eq. 12 enforces radial operation of the network.

Eq. 13 and 14 ensures a minimum amount of critical and regular load is served, respectively (λ and γ).

Eq. 15 states the binary variables in the problem.

Eq. 16-18 state the lindist power flow equations.

Eq. 20 states voltage limits.

This optimization approach provides solutions to a specific network design problem. Network design problems and their variations are generally NP-complete [TPZ13], which is a theoretical result indicating that the problem is computationally very difficult to solve. The team's past capability developments [BBT, YBB15] demonstrated that optimization-based methods for solving this problem can lead to substantial advances. Interestingly, our approach shares some similarities with successes in other application areas. For example, the flow of electric power in tree-like distribution networks is related to multi-commodity network flows, making our problem similar to the design of multi-commodity flow networks with stochastic link and edge failures [SAGS03, GS08]. However, the second stage of our formulation (the extreme event scenarios) requires binary variables, making our problem considerably more difficult than typical second-stage flow problems. Related power system interdiction capabilities include max-min or min-max problems, where the goal is to operate or design a system to make it as resilient as possible to an adversary, who can damage up to k elements. Such models are similar to ours, if the chosen k bounds the worst-case extreme event [CP13, CCFP14, DAA10, SWB09]. Binary variables at all stages make the models of [CP13, CCFP14, DAA10, SWB09] computationally challenging, solvable only for small k, and impractical for use on this problem. In the methods developed in this project, we exploit the probabilistic nature of our adversary to increase the size of tractable problems, eliminating a stage of binary variables.

In power engineering tools, resilience advances, including state-of-the-art advances by this team that we will leverage, have focused primarily on resilient system operation [KSS07, LNLS14, GFW14], using controls such as line switching. There are also tools that focus on power grid expansion planning applications for stochastic events [J13]. Like stochastic multi-commodity flow, the second-stage variables in these models are not binary and are not directly applicable here. Finally, most of the existing work and tools on combined communication and power system networks has focused on developing high quality simulation [CDFFMA14, FCDFH13, KTSWM15, NP09, NKMMS07, CDAFMF14,HPSMS15] and addressing questions related to network latency and congestion. In LPNORM, the key challenge is system design, which is not the focus of these existing approaches. Overall, our tool is fundamentally state-of-the-art in resilient distribution systems design and was a chapter in a PhD thesis [Y15].

Our primary new capability expanded RDT to handle the design of the communication system that controls the distribution system. We focus on the coupling between communication system availability and automatic switches. We choose this coupling for capability demonstration because 1) switches play a critical role in emergency operations and reduce the need for design [LMLS14, COZKABS15], and 2) the current implementation of RDDT assumes complete availability of switches when making design decisions. To account for the dependence on communication, we modify the problem statement in Figure 4 as shown in Figure 9. This is a considerably more difficult problem due to the presence of two networks. However, we have had success in developing methods for combined design of networks (gas and electric power) [BBBBHV15], which gave us confidence that we could have success here. We address this problem by decomposing it across the boundaries between networks, similar to how the existing approach in RDT separates between the base network configuration and the extreme event scenarios, using a Bender's-like approach. The primary novelty is the coupling of communication and distribution networks into a single design problem, which had not previously been.

$$\text{minimize } \sum_{ij\in E} c_{ij}^c x_{ij}^c + \sum_{ij\in E} \alpha_{ij}^c t_{ij}^c \quad (\mathbf{1})$$

$$\text{s.t.} \quad -x_{ij}^{sc} Q_{ij}^c \leq \sum f_{ij}^{sc} \leq x_{ij}^{sc} Q_{ij}^c \quad (\mathbf{2})$$

$$x_{ij}^{sc} \leq x_{ij}^c,\ t_{ij}^{sc} \leq t_{ij}^c, \ (\mathbf{3})$$

$$x_{ij}^{sc} = t_{ij}^{sc}, \ (\mathbf{4})$$

$$0 \leq d_i^c \leq 1 \ (\mathbf{5})$$

$$0 \leq s_i^c \leq M \ (\mathbf{6})$$

$$\mathrm{s}_\mathrm{i}^{\mathrm{cs}} - l_i^{ks} - \sum_{j\in N} f_{ij}^{ks} = 0 \quad (\mathbf{7})$$

$$\tau_{ij}^s \leq d^c(ij), 1 - \tau_{ij}^s \leq d^c(ij) \quad (\mathbf{8})$$

Figure 9. This set of equations describes the resilient communication model and its connection to the distribution system.

Eq. 1 adds costs associated with building and hardening communication components.

Eq. 2 constrains signals between communication components to occur only when the link is available.

Eq. 3 and 4 links the design variables to the operating conditions during events.

Eq. 5. defines a control device that needs communication.

Eq. 6 defines locations that can send control signals to devices.

Eq. 7 models signals as flows and Eq. 8 locks automatic reclosers of the power system to their default state when signals cannot reach the device.

After optimal design changes are found, we assess the behavior of proposed designs under damage. Here, we heavily leverage existing GridLAB-D capability to evaluate the electrical feasibility of the proposed design, incorporating full three-phase, unbalanced power flow evaluations [CSG08, SFC11, STE14]. The outputs of the evaluations also provide indications of potential electrical stress. In our optimization routine, we have used GridLAB-D to assess the performance of design solutions and, hence, generate “solution cuts” for a feedback loop to RDT when RDT proposes a solution that is not physically viable. This is an iterative algorithm tuned to ensure that the RDDT procedure provides an implementable solution. To improve this procedure, we enhanced GridLAB-D to provide support to adjust control (communication) parameters under stressed conditions to further evaluate RDT solutions. Our enhancement of GridLAB-D involved the development of a new software object to implement this iterative algorithm. Utilizing policies provided through user input, GridLAB-D adjusts the proposed solution via voltage adjustments, switching actions, and potential DER actions. Utilizing existing capabilities within GridLAB-D, it applies these actions to devices on the distribution system model to search for feasible system configurations. Performing these actions within GridLAB-D allows the optimizations within RDT to be more focused and prevent unnecessary evaluations of power systems that will never reach stability conditions.

Utility Test Results

We selected two NRECA utility members for in-depth testing of the LPNORM prototype, Shenandoah Valley Electric Cooperative (SVEC) in Virginia and United Cooperative Services (UCS) in Texas. A summary of those results is included in the following pages. This demonstration provided the first industry-tested impact of resilient design. In addition, we formed an industry advisory board (IAB) of seven utilities with broad geographical coverage (see Table 1 and Figure 10 below). Conducting all tool development within the OMF platform has provided a distinct advantage. Over 900 NRECA member utilities have access to OMF, providing a rich and varied set of data for testing and outreach purposes.

Table 1. Industry Advisory Board Members

Name	Title	Utility	State
David Bryan	Planning Engineer	Sulphur Springs Valley Electric Cooperative	Arizona
Jason Burch	Manager of System Engineering	Shenandoah Valley Electric Cooperative	Virginia
Kelly Fritz	GIS and Staking Supervisor	Wake EMC	North Carolina
Kevin Jordan	Supervisory Engineer	Horry Electric	South Carolina
Mark Scheibe	Director of Engineering	Maquoketa Valley REC	Iowa
Steve Estes	System Engineer	EnergyUnited	North Carolina
Michael Lattner	Electrical Engineer	United Cooperative Services	Texas

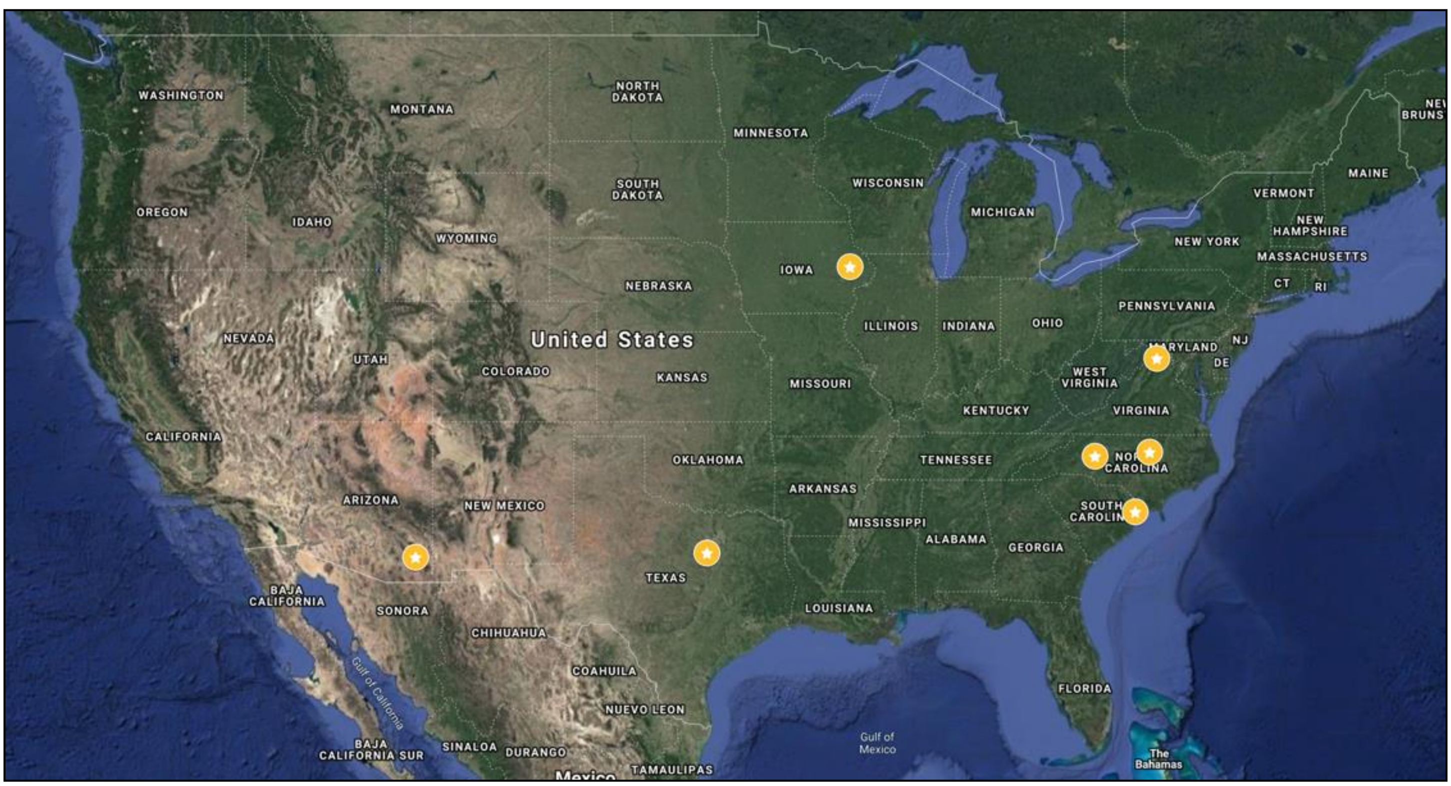
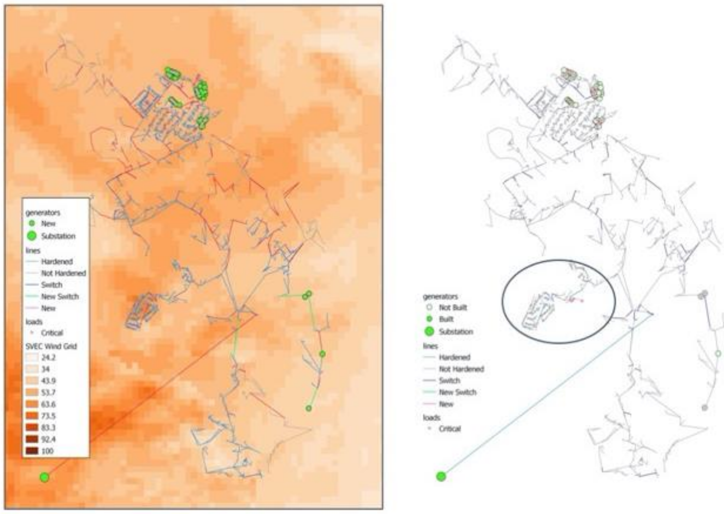


Figure 10. Map of Industry Advisory Board Members

Resuls of Testing of the LPNORM Prototype with Shenandoah Valley Electric Cooperative



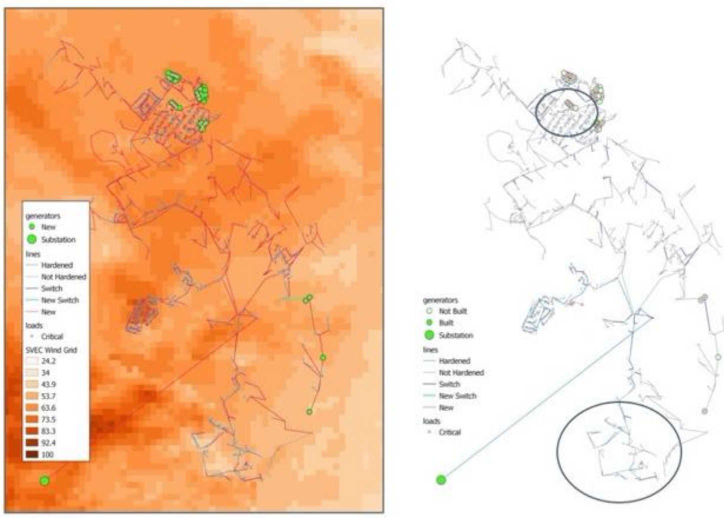
<u>10% Damage Intensity:</u>

Damage Profile

- The main connection to the transmission system is severed
- Damage in the north
- Some additional damage in the west

Solution Profile

- Harden the main connection to the transmission system
- Harden connections to the critical load in the north
- Additional hardening in the west (circle)



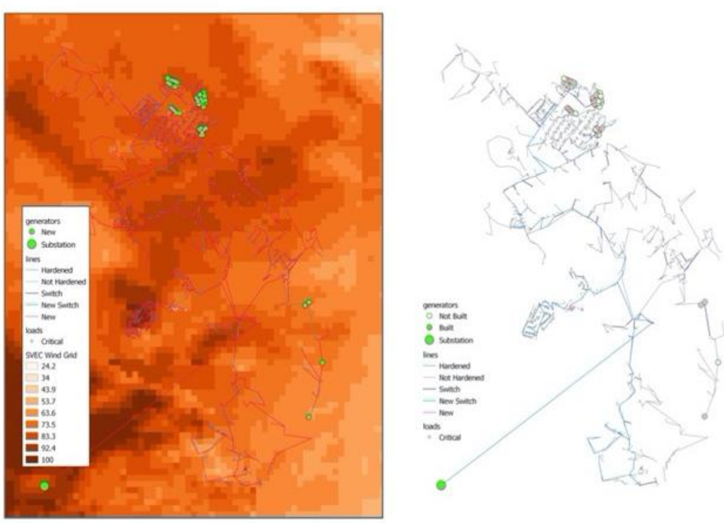
<u>30% Damage Intensity:</u>

Damage Profile

- Damage begins to show up in the south
- Damage continues to increase in the north

Solution Profile

- Hardening in the north is no longer completely sufficient.
- Distributed generation is now added to the north
- Additional hardening now occurs in the south



<u>70% Damage Intensity:</u>

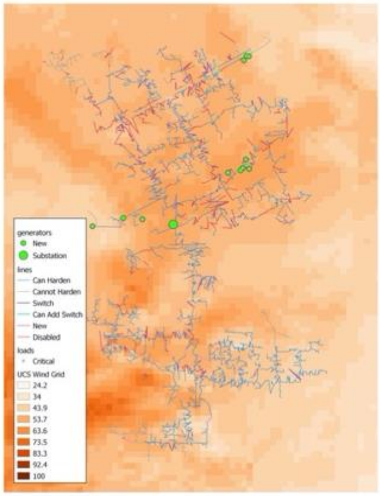
Damage Profile

- The main connection to the transmission system is severed
- Damage is severe

Solution Profile

- There is a now fully hardened path from the substation to the critical loads in the north

Resuls of Testing of the LPNORM Prototype with United Cooperative Services



Resilience Targets:

- Meet 90% of critical load
- Meet 50% of non critical load

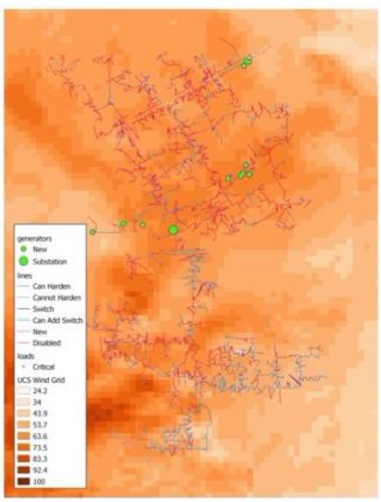
10% Damage Intensity:

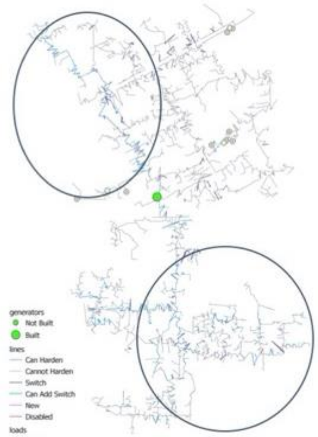
Damage Profile

- Lots of damage in the north
- Limited damage in the south

Solution Profile

- Hardens a few lines to achieve the resilience targets
- Hardening and new lines focused in the south to achieve the 50% non-critical load target





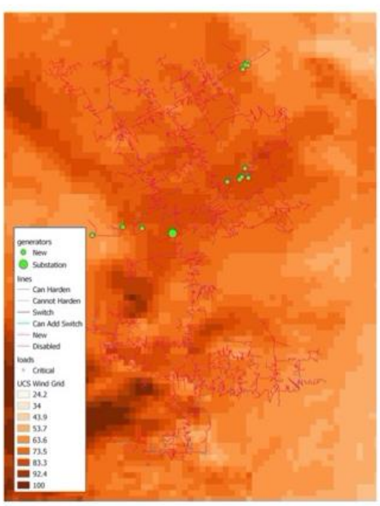
30% Damage Intensity:

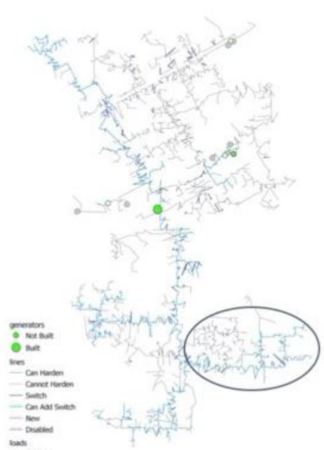
Damage Profile

- Increased damage in the south

Solution Profile

- New lines and hardening increases in the southern portion of the network
- A hardening path is now required in the north to pick up 50% non-critical load





70% Damage Intensity:

Damage Profile

- Extensive damage throughout the solution

Solution Profile

- Design solution creates hardened backbones to serve a sufficient amount of non-critical load.
- Eastern network is allowed to fail, with critical load served by a local distributed generated.
- Shifted the hardened backbone in the southeast

In the course of the development work, we demonstrated intermediate versions of the resilient design application to the IAB. The following summarizes the feedback received:

Interface

Feedback on the application interface was very positive. All of the IAB board members agreed that there were no additional graphical interface features that would be needed to use the application at their utilities, that the data requirements were reasonable, and the planning methodology was similar enough to existing planning practices that integrating the results of the model would be straightforward. We did receive feedback that choosing lines to prioritize for hardening would be difficult, and as a result, we changed the interface to consider all lines for hardening with the option to exclude a subset as necessary. There wer also requests for GIS outputs from the model, which we added as part of the second version. In general, there was strong interest in looking at the tool results alongside current distribution work plans.

Data

We discussed data used to make decisions on reliability upgrades at the utilities, and there was good agreement between current datasets and the model input requirements. The average distribution circuit model has over 10k variables, but the IAB was happy to see that we mitigated this challenge by automating import from existing engineering analysis tools. Pole data is not held in a common format, collected instead in inspections and recorded in spreadsheets including detail on year of installation, height, class, material, assemblies, framing, and location. In our application, we created a common data format and an API for ingesting this pole information.

Another key input to the model is historical outage data, which all of the IAB members collect. Outage data is typically kept private, but is used to calculate reliability metrics (SAIDI, SAIFI, CAIDI, etc.) and reported to management and boards on a regular (typically monthly) basis. Outage records typically included location, cause, and outage staticstics, and was supplemented by data on vegetation, and lightning strikes. To accommodate the sensitivity of this data, we support deployment of our application locally to avoid moving or storing data off-site.

Weather data for our modeling work was built using publicly available NOAA datasets which were also commonly used by the IAB members, although some subscribed to commercial weather services for additional forecasting, lightning, and radar features.

Data on communication systems, like pole data, were typically kept in ad hoc formats that include path information and equipment specifications; some of the utilities outsourced network management.

Engineering Upgrade Suggestions and Constraints

Engineering upgrade suggestions provided by the model were in good agreement with current practices, as were the constraints we chose (radial operation, voltage, phase balance) to determine safe operation. Additional limits, such as VAR limits and current limits on protective devices, were added in the GridLAB-D models and are candidates for optimization constraints in future versions. Some of the IAB members suggested that constraints can be loosened during operations in extreme weather events and that tools for determining operational controls (load shed, switching orders) would be helpful; these are out of scope for our software, but have been addressed in other GMLC projects. Distributed generation upgrades were seen as helpful and innovative, although the economics of backup power on rural systems are not currently seen as generally favorable, and islanding parts of circuits as microgrids was seen as a technique that is currently not done, but would become viable in the future.

Future Work

A number of enhancements to the model were requested in the course of development:

Hardening Options

Currently, after hardening options are returned, utility engineers would have to determine the exact form of the hardening (undergrounding, reconductoring, additional protective devices, pole or attachment change-outs, etc.). A more advanced hardening model could automatically select the most relevant options for a given span.

Vegetation Encroachment

The IAB also identified vegetation encroachment as an important variable in damage modeling, as vegetation falling on lines was for many of the members the predominant cause of outages. We currently develop hazard models manually based on a combination of weather and vegetation presence in the right-of-way, but including detailed vegetation information as a model input could automate the calculation of the combined hazard risk.

Outage lengths

There were also requests for including outage lengths as a parameter in the model to allow (for example) de-prioritizing upgrades for line section that are implicated in shorter outages.

Communication modeling

Communication modeling is another area where future work is anticipated. In addition to the power system, the communication system that some distribution utilities (could) rely on during extreme events is at risk. The ability to operate devices remotely allows the utility to execute mitigation strategies, like dispatching backup generators and operating switches, during and after an extreme weather event [COZKABS15]. While communications features were integrated in to RDT as part of this project, communication inputs to the model interface were not added. One of the challenges is that distribution utilities do not typically maintain models of the underlying communication network they use to control their system. Furthermore, there are no widely deployed software tools for designing and simulating distribution utility communications networks. Finally, because communication technology is not yet ubiquitous in distribution utilities, there is an opportunity to ensure that future technology adoptions are installed with resiliency considerations.

Additional Development with Cooperatives

We anticipate working closely with additional utilities to further deploy our software tool. Horry Electric in South Carolina is interested in modeling hardening options that would have increased their resilience during recent hurricanes Matthew and Florence. They have detailed outage and weather records from those events, so this is an excellent opportunity to validate the damage modeling components of the LPNORM tool. We have also been approached by White River Valley Electric Cooperative in Missouri to work them on methods for hardening against flood damage.

References

[BDH09] R. Bent, T. Djidjeva, B. Hayes, J. Holland, H. Khalsa, S. Linger, M. Mathis, S. Mniszewski, B. Bush. Hydra: A Service-Oriented Architecture for Scientific Simulation Integration. Proceedings of the Forty-Second Annual Simulation Symposium (ANSS 2009), Spring Simulation Multi Conference, 1-8, March 2009, San Diego, California.

[BBT] R. Bent, G. L. Toole, and A. Berscheid. Transmission Network Expansion Planning with Complex Power Flow Models, IEEE Transactions on Power Systems, Volume 27 (2): 904-912, 2012.

[BBBBHV15] C. Borraz-Sanchez, R. Bent, S. Backhaus, S. Blumsack, H. Hijazi, and P. van Hentenryck. Convex Optimization for Joint Expansion Planning of Natural Gas and Power Systems. HICSS, 2016.

[COZKABS15] D. Cheng, A. Onen, D. Zhu, D. Kleppinger, R. Arghandeh, R. Broadwater, and C. Scirbona. Automation Effects on Reliability and Operation Costs in Storm Restoration. Electric Power Components and Systems. 43 (6) 656-664, 2015.

[CDAFMF14] S. Ciraci, J. Daily, K. Agarwal, J. Fuller, L. Marinovici, and A. Fisher. Synchronization Algorithms for Co-Simulation of Power Grid and Communication Networks. IEEE 22nd International Symposium on Modelling, Analysis & Simulation of Computer and Telecommunication Systems. 355-364, 2014.

[CDFFMA14] S. Ciraci, J. Daily, J. Fuller, A. Fisher, L. Marinovici, and K. Agarwal. FNCS: a framework for Power System and Communications Networks Co-Simulation, Proceedings of the Symposium on Theory of Modeling and Simulation (DEVS), 2014.

[CP13] Chen, R. L.-Y., and Phillips, C. A. K-edge failure resilient network design. Electronic Notes in Discrete Mathematics 41 (0):375–382, 2013.

[CCFP14] Chen, R. L.-Y.; Cohn, A.; Fan, N.; and Pinar, A. Contingency-Risk Informed Power System Design. IEEE Transactions on Power Systems 29 (5):2087–2096, 2014.

[CSG08] Chassin, D.; Schneider, K.; and Gerkensmeyer, C. GridLAB-D: An open-source power systems modeling and simulation environment. IEEE 2008 PES General Meeting. 2014.

[DAA10] Delgadillo, A.; Arroyo, J.; and Alguacil, N. Analysis of Electric Grid Interdiction with Line Switching. IEEE Transactions on Power Systems 25 (2):633–641, 2010.

[EO13] Executive Office of the President. Economic Benefits of Increasing Electric Grid Resilience to Weather Outages, 2013.

[EK13] Eidinger, J. M., and L. Kempner. Reliability of Transmission Towers under Extreme Wind and Ice Loading. G&E Engineering Systems Inc. and Bonneville Power Administration, 2013.

[FCDFH13] J. Fuller, S. Ciraci, J. Daily, A. Fisher, and M. Hauer. Communication Simulations for Power System Applications. 2013 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2013.

[FEMA15] https://www.fema.gov/hazus/, accessed Sept. 4, 2015.

[HPSMS15] T. Hansen, B. Palmintier, S. Suryanarayanan, A. Maciejewsk, and H. Siegel. Bus.py: A GridLAB-D Communication Interface for Smart Distribution Grid Simulations. IEEE PES General Meeting, 2015.

[J13] Jabr, R. A. Robust Transmission Network Expansion Planning With Uncertain Renewable Generation and Loads. IEEE Transactions on Power Systems 28 (4):4558–4567, 2013.

[GFW14] Golari, M., Fan, N., and Wang, J. Two-stage stochastic optimal islanding operations under severe multiple contingencies in power grids. Electric Power Systems Research 114 (0):68–77, 2014.

[GS08] Garg, M., and Smith, J. C. Models and algorithms for the design of survivable multicommodity flow networks with general failure scenarios. Omega 36(6):1057–1071, 2008.

[KSS07] Khushalani, S.; Solanki, J. M.; and Schulz, N. N. Optimized restoration of unbalanced distribution systems. IEEE Transactions on Power Systems 22(2):624–630, 2007;

[KTSWM15] B. Kelley, P. Top, S. Smith, C. Woodward, and L. Min. A Federated Simulation Toolkit for Electric Power Grid and Communication Network Co-Simulation. 2015 Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), 2015.

[LMLS14] Li, J.; Ma, X.-Y.; Liu, C.-C.; and Schneider, K. P. Distribution System Restoration With Microgrids Using Spanning Tree Search. IEEE Transactions on Power Systems PP (99):1–9, 2014.;

[NERC14] North American Electric Reliability Corporation, Hurricane Sandy Event Analysis Report, 2014.

[NKMMS07] J. Nutaro, P. Kuruganti, L. Miller, S. Mullen, M. Shankar. Integrated Hybrid-Simulation of Electric Power and Communications Systems. IEEE Power Engineering Society General Meeting, 2007.

[NP09] J. Nutaro and V. Protopopescu. The Impact of Market Clearing Time and Price Signal Delay on the Stability of Electric Power Markets. IEEE Transactions on Power Systems. 24(3):1337-1345, 2009.

[SAGS03] Santoso, T., Ahmed, S., Goetschalckx, M., and Shapiro, A. A stochastic programming approach for supply chain network design under uncertainty. Stochastic Programming EPrint Series. Institut fr Mathematik, 2003.

[SFC11] Schneider, K.; Fuller, J.; and Chassin, D. Multi-state Load Models for Distribution System Analysis. IEEE Transactions on Power Systems, vol. 25, no. 4, pp.2425-2433, 2011.;

[STE14] Schneider, K.; Tuffner, F.; and Elizondo, M. Microgrids as a Resiliency Resource. PNNL technical report, PNNL-23674, 2014.

[SWB09] Salmeron, J.; Wood, K.; and Baldick, R. Worst-case interdiction analysis of large-scale electric power grids. IEEE Transactions on Power Systems 24 (1):96–104, 2009.

[S02] Y. Sa, Reliability analysis of electric distribution lines. Ph.D. dissertation, McGill University, Montreal, Canada, 2002.

[TPZ13] Tomaszewski, A., Pioro, M., and Zotkiewicz, On the complexity of resilient network design. Networks 55(2):108–118, 2010.; Nace, D., Piro, M., Tomaszewski, A., and Zotkiewicz, M. Complexity of a classical flow restoration problem. Networks 62(2):149–160, 2013.

[UIC13] United Illuminating Company; One Year After Sandy, What Has Changed - UI Implements Measures To Improve Storm Response, Readiness; New Release, Oct. 28, 2013.

[Y15] Yamangil, E. Valid Inequalities for Mixed-Integer Linear Programming Problems, Rutgers University, 2015.

[YBB15] E. Yamangil, R. Bent, S. Backhaus. Designing Resilient Electrical Distribution Grids. Proceedings of the 29th Conference on Artificial Intelligence (AAAI 2015), January 2015, Austin, Texas.