July 2022 Microgrid R&D Program Meeting

Resilient Operations of Networked Microgrids (RONM)

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July 27, 2022

LA-UR-22-28129

Los Alamos NATIONAL LABORATORY EST.1943 NRECA America's Electric Cooperatives NREL NATIONAL RENEWABLE ENERGY LABORATORY Sandia National Laboratories

Resilient Operations of Networked Microgrids

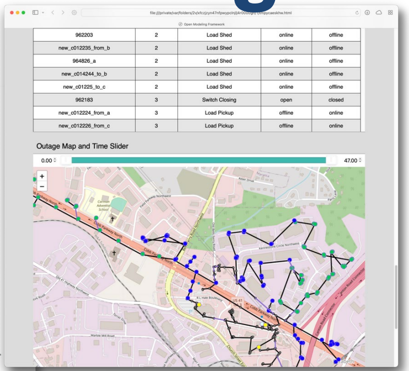
(RONM)

Objectives & Outcomes

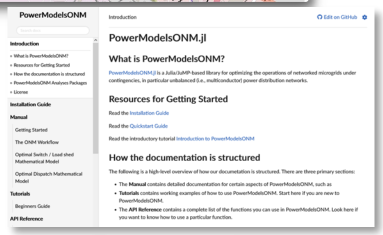
Objective: Improve the resiliency of power systems with optimization-based methods that leverage advanced microgrid technologies to reduce system recovery times after extreme-event-induced outages

Outcome: First-of-kind, high-fidelity physics-based optimization method for modeling networked microgrids, including key engineering constraints associated with system recovery after extreme events

GUI



Networked Microgrid Concept



Documentation

Technical Scope

- Combine state-of-the-art resilient network design and operations methodologies of GMLC 0057 LPNORM, DOE/OE Networked Microgrid program with black-start restoration methodologies of CleanStart DERMS.
- Develop a coordinated HIL evaluation framework for implementing networkable microgrid use-cases and testing resilient operations and recovery algorithms

Funding Summary ($K)

FY20 & prior, authorized	FY22, authorized	FY23, requested
3958K	1026K received / 1642K expected	0

Outline

- Introduction
  - Significance and Impact
- Research Approach
- Progress and Results
  - Algorithmic contributions
  - Use case and HIL evaluation
  - Software Demonstration
  - Economic Analysis
- Tech Transfer
- Conclusion

Introduction

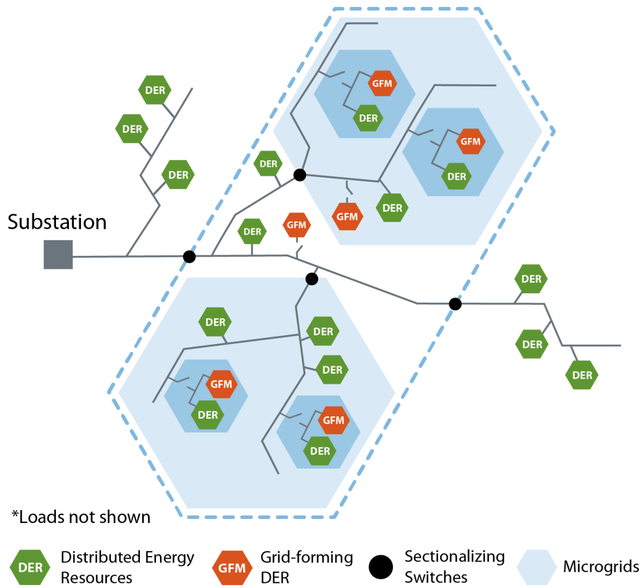
Significance and Impact

Project Objectives

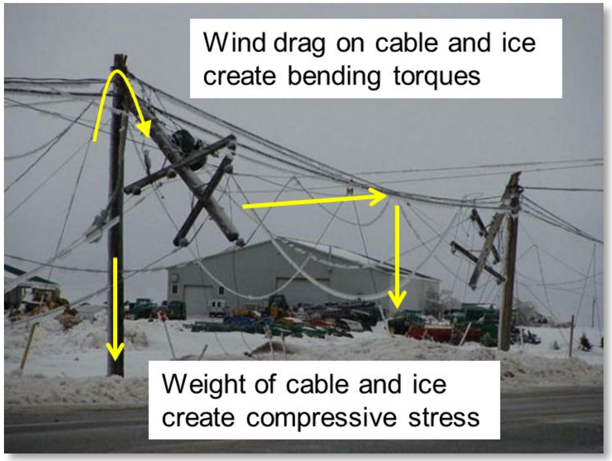
- The RONM project seeks to improve the resiliency of power systems with optimization-based operations and planning methods.
- Utilize microgrid networking to reduce system recovery times after extreme event induced outages.

Project Outcomes

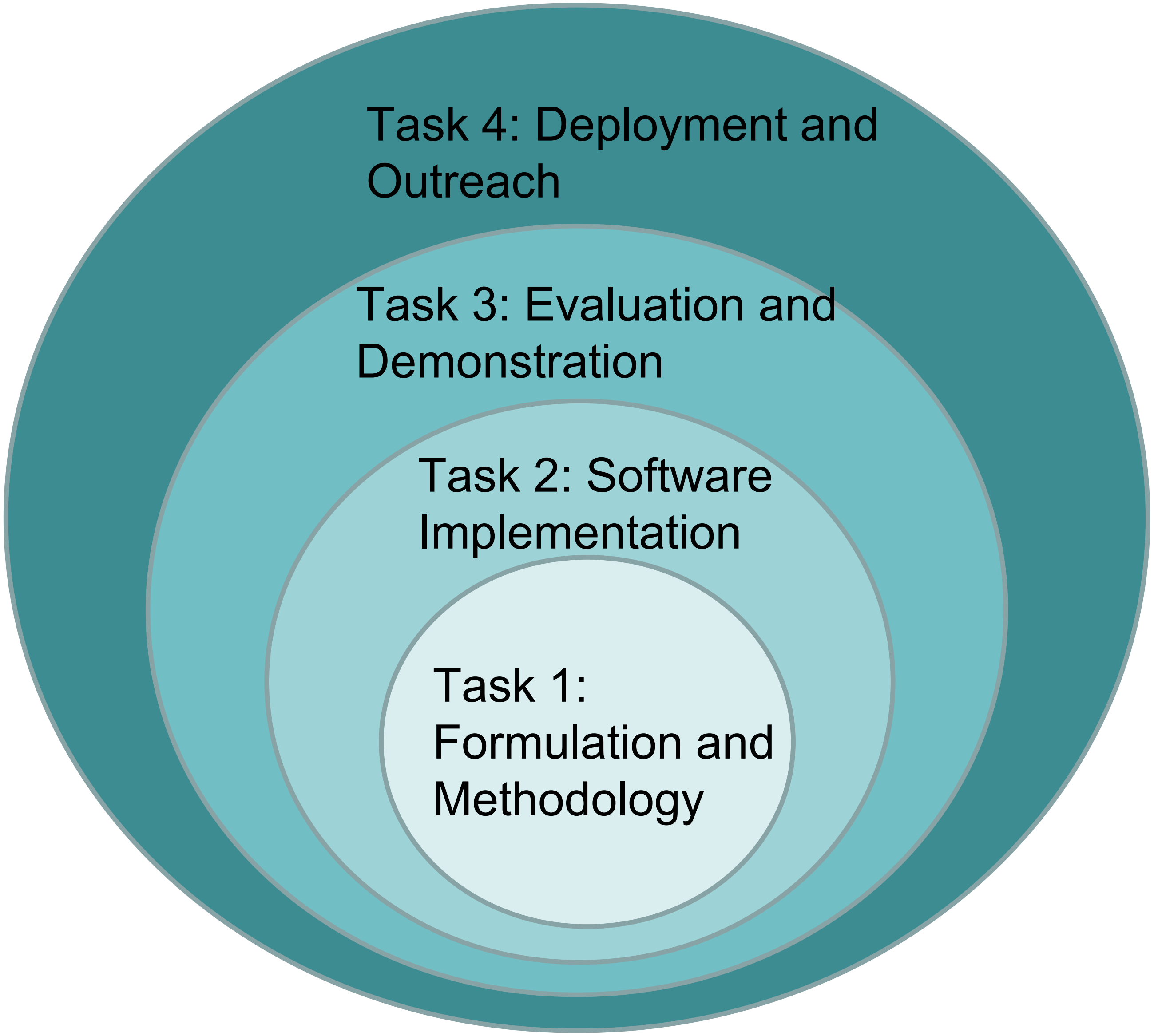
- Quantify resiliency value of networked microgrids during extreme conditions.
- Open source algorithms which enable self-healing grids through advanced black start restoration, network reconfiguration, and distributed energy resource (DER) management.
- Demonstrations that networked microgrids can isolate faulted sections during disturbances and restoration to protect the bulk electric systems from distribution system induced instabilities (i.e., concurrent load pickup).
- Evaluation and validation of RONM solutions on industry distribution networks modeled within advanced evaluation platforms.
- **Primary focus:** Reliability, resiliency, and security. Leveraging modular structure to consider evaluations of sustainability, affordability, and flexibility



Project Duration:
Dec. 1, 2019 – Nov. 30, 2022



RONM Technical Approach



Layered Organization

- Develop the modeling approach
- Implement the approach
- Evaluate and demonstrate the approach
- Deploy the approach

Inputs

- Load flow model
- Protection system
- Damage scenarios
- Critical loads

Outputs

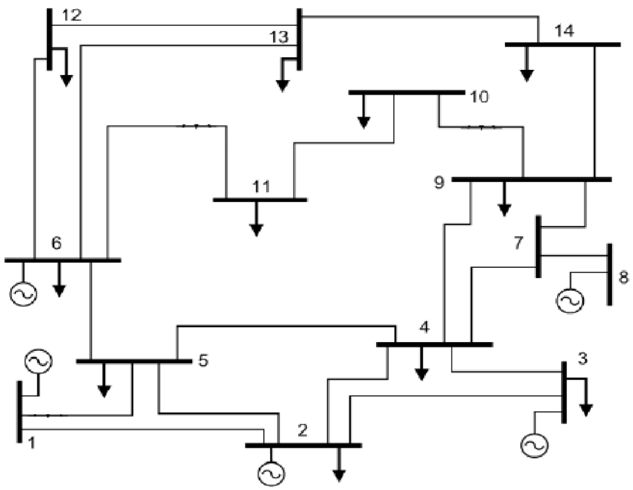
- Power Flows
- Sequence of operation/restoration actions

RONM Technical Approach

Task 1—Formulation and Methodology

Overview

- Develop the core formulation for combining resilient reconfiguration algorithms and restoration algorithms to handle extreme events
- Develop first-of-kind advanced engineering objectives and constraints on system stability, device protection, regulatory restrictions, and economic considerations

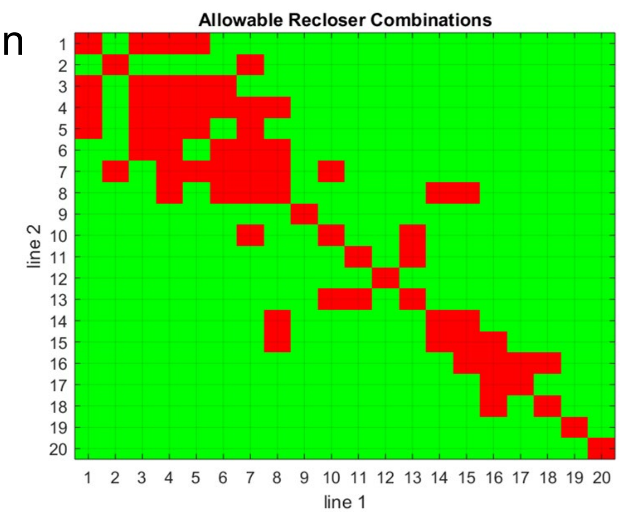


Innovation

- "Gold-standard" formulation for end-to-end resilience decision support
  - Network design and resource deployment
  - Control and operations of networked microgrids
  - Restoration and recovery after extreme events

Expected Outcome

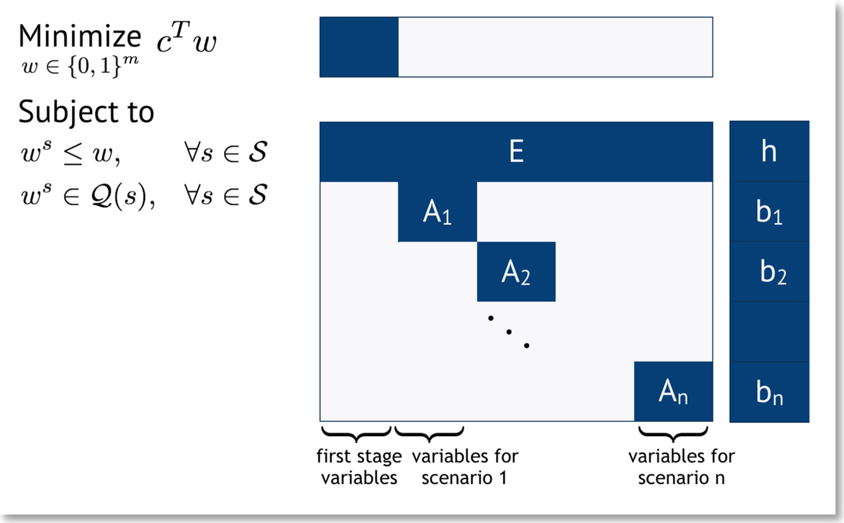
- Methodology for evaluating the design and operations of networked microgrids for different classes of extreme events



Example: Protection Constraints

RONM Technical Approach

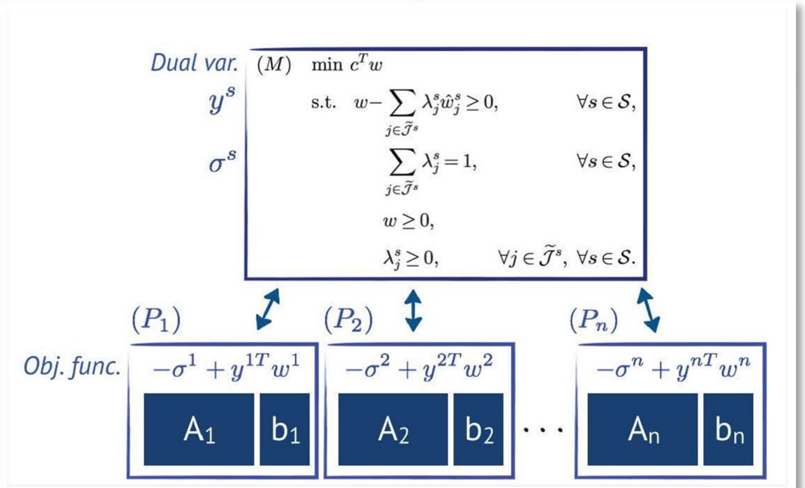
Task 2—Software Implementation



Overview

- Develop and implement a scalable algorithm for solving the problem formulated in Task 1
- This algorithm is constructed by leveraging software previously built to support projects like Networked Microgrids (ODO), LPNORM, and CleanStartDERMS programs.
- Delivery of a formal lifecycle development plan for maintaining and building the software over the course of the project and beyond.

Example: LPNorm Algorithm



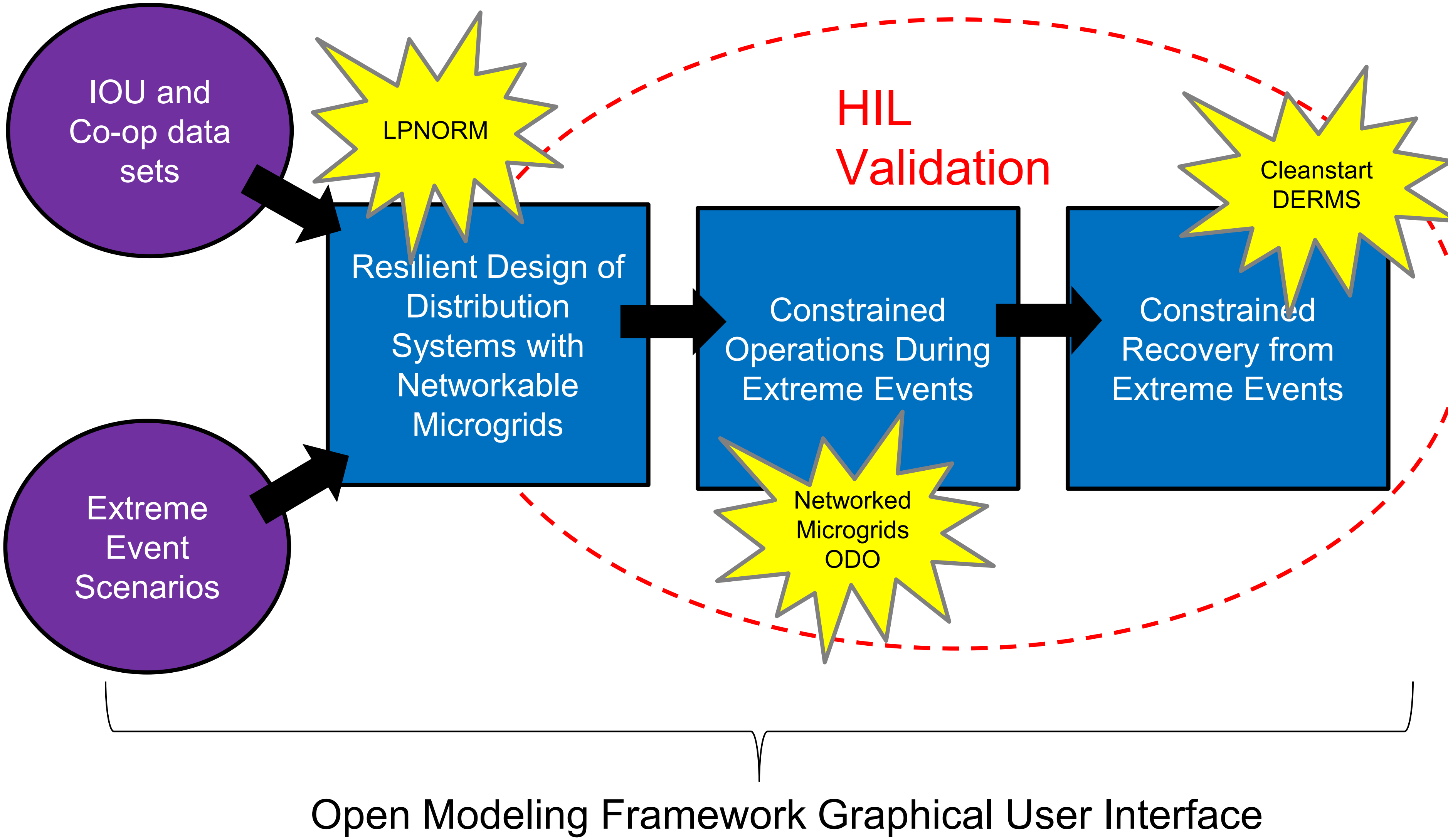
Innovation

- A first-of-kind detailed planning tool for distribution utilities to assess the resilience benefits of networking microgrids

Expected Outcome

- A comprehensive application software stack for assessing the resiliency benefits of networked microgrid technologies.
- Deployment on NRECA's OMF web platform

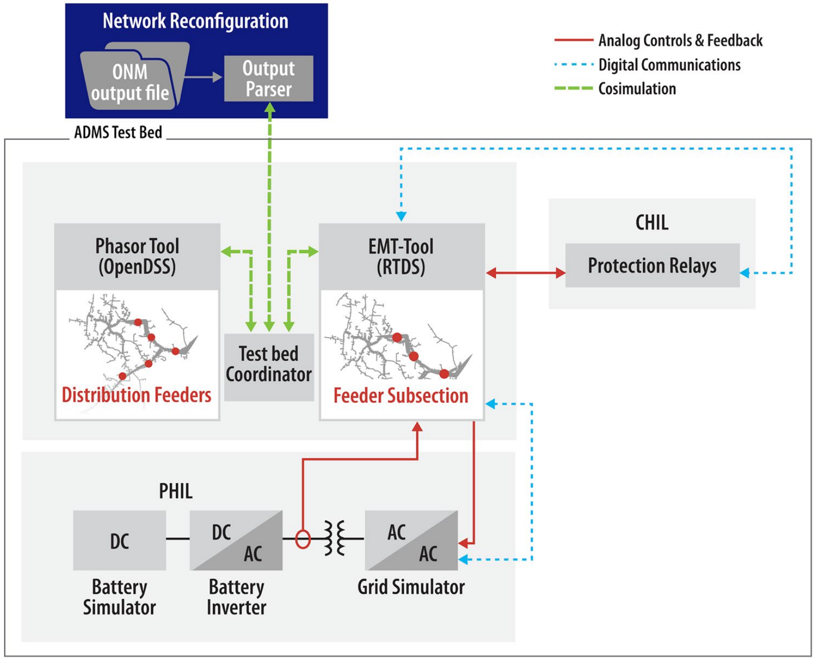
RONM Technical Approach



Leverage capabilities developed by prior projects

RONM Technical Approach

Task 3—Evaluation and Demonstration



<u>Overview</u>

- Use distribution system models adapted from NRECA and SDG&E to evaluation the RONM solutions for reconfiguration and restoration of distribution systems after extreme events.
- Validate in software simulation and then validate on a HIL evaluation platform to demonstrate that the solutions do not violate key physical and engineering constraints associated with system operations in the distribution circuit.
- Annual vetting by an Industry Advisory Board (IAB).

<u>Innovation</u>

- Rigorous verification and validation of RONM methodology and approach for assessing resilience of networked microgrid distribution systems

<u>Expected Outcome</u>

- Verification that RONM solutions are relevant to different classes of distribution feeders

RONM Technical Approach

Task 4—Deployment and Outreach

Overview

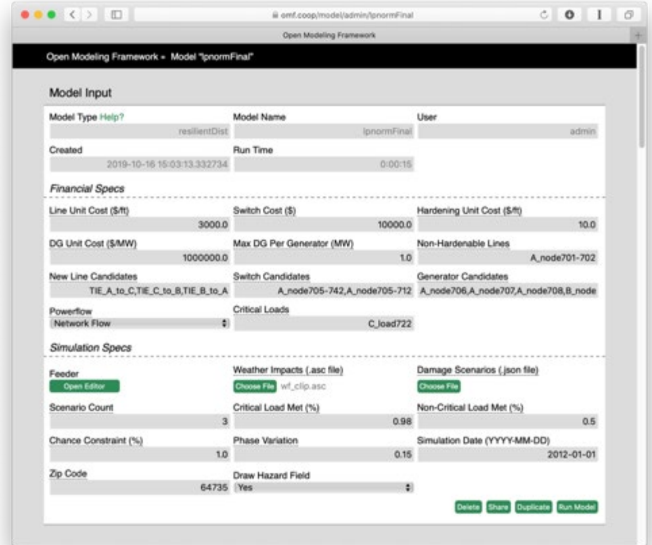
- Deploy RONM software on NRECA's open modeling framework (OMF) platform
- Release open access software
- Regular interaction with utility partners to solicit feedback on the project's progress

Innovation

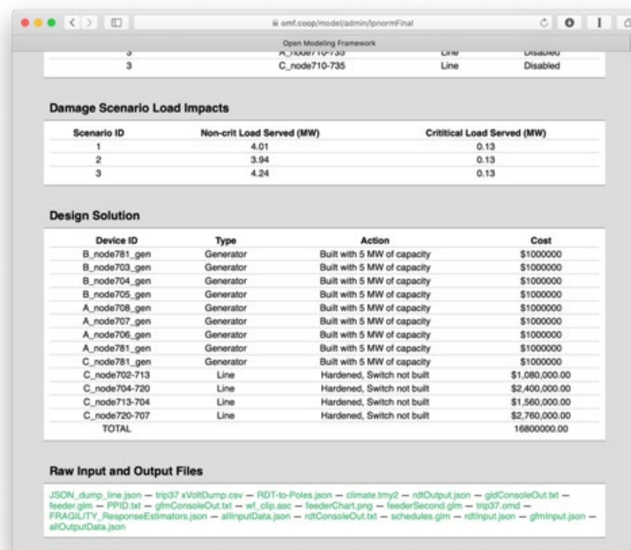
- A combination of software libraries for use by utilities to incorporate resilience into their networked microgrid planning and a graphical user interface for interacting libraries.

Expected Outcome

- Software platform which is available for use by the nation's distribution utilities.



Model Inputs



Recommended resilience improvement detail

Progress and Results

Summary and Highlights

Formulation and Methodology

- Formulation documented as a technical report (2020)

Software Implementation

- Developed a formal lifecycle development plan (2020)
- Core algorithms implemented and released as open source (v3 in 2022)
  - https://github.com/lanl-ansi/PowerModelsONM.jl
- Extensive software documentation
  - https://lanl-ansi.github.io/PowerModelsONM.jl/stable/
- Novel algorithm to adaptively adjust protection settings for network reconfigurations

Evaluation and Demonstration

- Approach demonstration on industry provided data sets with 1000+ nodes
  - SDG&E (IOU)
  - Cobb, EMC (co-op)
- Estimate resilience and economic value of networking microgrids
  - **Example Evaluation:** In one use case, we showed that in isolation, the micorgrids support ~22% of the total load in the system, all within the microgrid boundaries. In sharp contrast, when the microgrids are networked together, close to 66% of the load can be supported

Deployment and Outreach

- Packaged as part of NRECA's open modeling framework web-based front end
  - https://github.com/dpinney/omf

Progress and Results

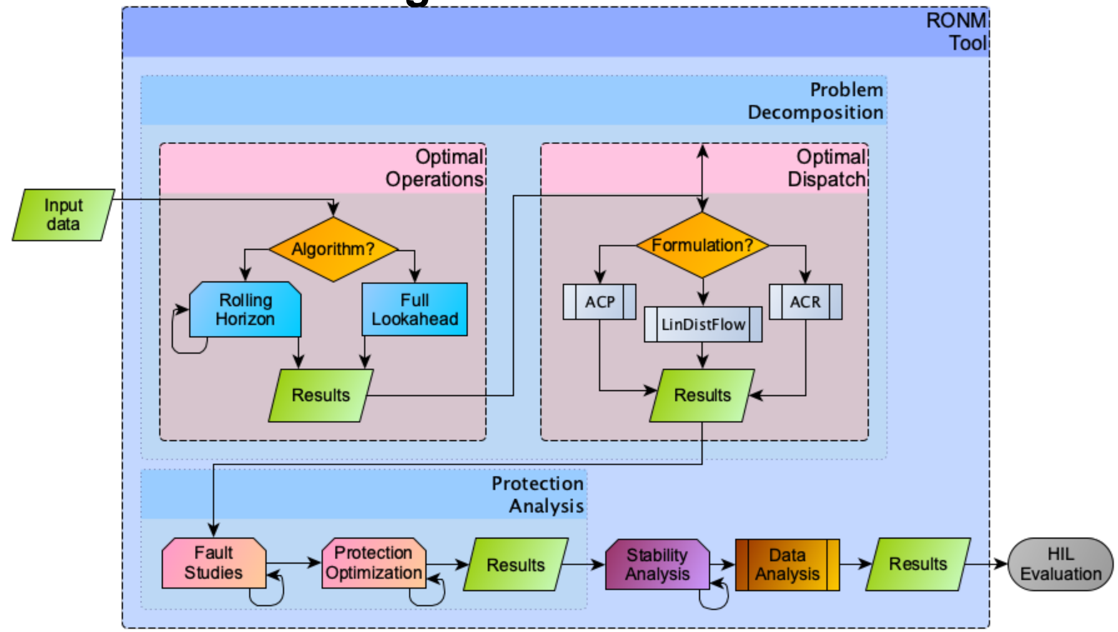
FY22 Milestones

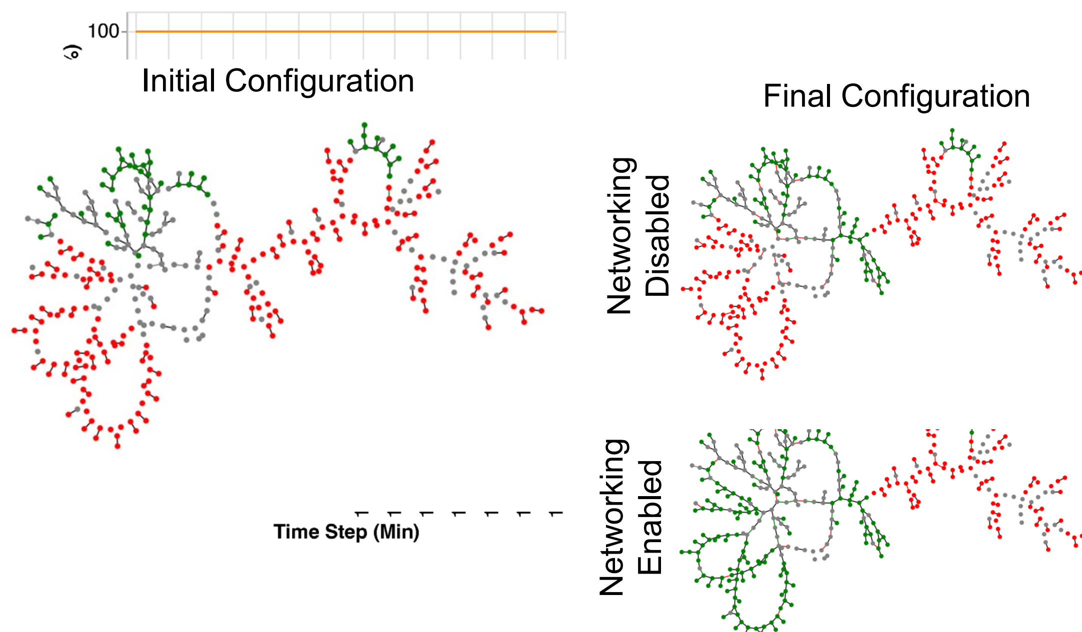
NRECA feeder model in OpenDSS format validated against model in format provided by utility.	10/15/21	**Complete.** Report provided to DOE on 10/15/21
Demonstration of RONM methodology on an NRECA system with more than 100 nodes. **Criteria: Feasibility of solution validated with HIL.**	11/30/2021	**Complete.** Report provided to DOE on 11/30/21. Briefing provide to DOE on 12/14/21
Report describing progress towards meeting milestone *.	1/15/2022	**Complete.** Report provided to DOE on 1/15/22
Draft paper on algorithm for resilient operation and recovery of distribution systems through utilization of advanced networked microgrid technologies.	1/15/2022	**Complete.** Draft paper provided to DOE on 1/15/22
Demonstration of networked microgrid protection optimizer interfacing with RONM for fault currents from PowerModelsProtection.jl and settings returned in RONM output	1/15/2022	**Complete.** Protection optimizer only uses inputs from RONM for fault currents and topology, and returns the protection settings in the RONM output
Paper submitted for peer-review on algorithm for resilient operation and recovery of distribution systems through utilization of advanced networked microgrid technologies.	2/15/2022	**Complete.** Paper submitted to IEEE Transactions on Smart Grid on 2/15/2022.
* Demonstration of RONM capabilities on one IOU distribution system with more than 1000 nodes.	4/1/2022	**Complete.** Report submitted to DOE on 4/1/2022.
Industrial Advisory Group Meeting	4/30/2022	**Complete.** Meeting conducted on 4/12/2022.
Inclusion of advanced networked microgrid protection schemes beyond time overcurrent into RONM	9/30/2022	On track
Deployment of RONM Version 2 on NRECA's Open Modeling Framework.	9/30/2022	On track

Progress and Results

Algorithm and Modeling

- Operations and Dispatch are decomposed from MINLP to MIP and NLP problems
- Operations (Optimal Switching)
  - MIP using LinDist3Flow
  - Rolling horizon vs full lookahead
  - Phase Unbalanced OPF +
    - Switch control
    - Spanning forest (radiality)
    - Grid-forming inverter assignment
    - Storage output balance
    - Load block isolation
    - Tap control
    - Capacitor control
    - Microgrid networking prevention (optional)
- Dispatch (OPF)
  - NLP using, e.g., ACR/ACP
  - Phase Unbalanced OPF +
    - Fixed topology (from Operations)
    - Tap control
    - Capacitor control
- Protection Optimization (Sandia)
- Stability analysis
- HIL Evaluation



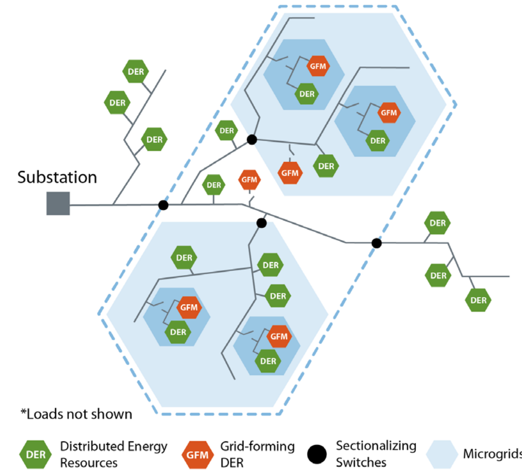


Progress and Results

Protection

A significant barrier to the adoption of networked microgrids is the protection system

- Multiple microgrid points of interconnection and range of configurations – number of possibilities for direction of current flow
- Range of sizes of microgrids and diversity of sources of generation – fault current magnitudes could be smaller in some configurations than the load flow in another configuration
- Pre-configured adaptive protection using setting groups will not work



Optimal Adaptive Protection

- Determines if each state can be protected and the settings for all protective devices
- Optimize settings (protection function 50P/G, 51P/G, 51V, 67, 21, thresholds, curve type, time dial, and pickup current) based on the capabilities of each protective device to minimize the sum of the relay operating times for all possible faults
- Ensure coordination for all fault types at various locations and resistances (including fast and slow curve recloser coordination with fuse minimum melting and total clearing time)

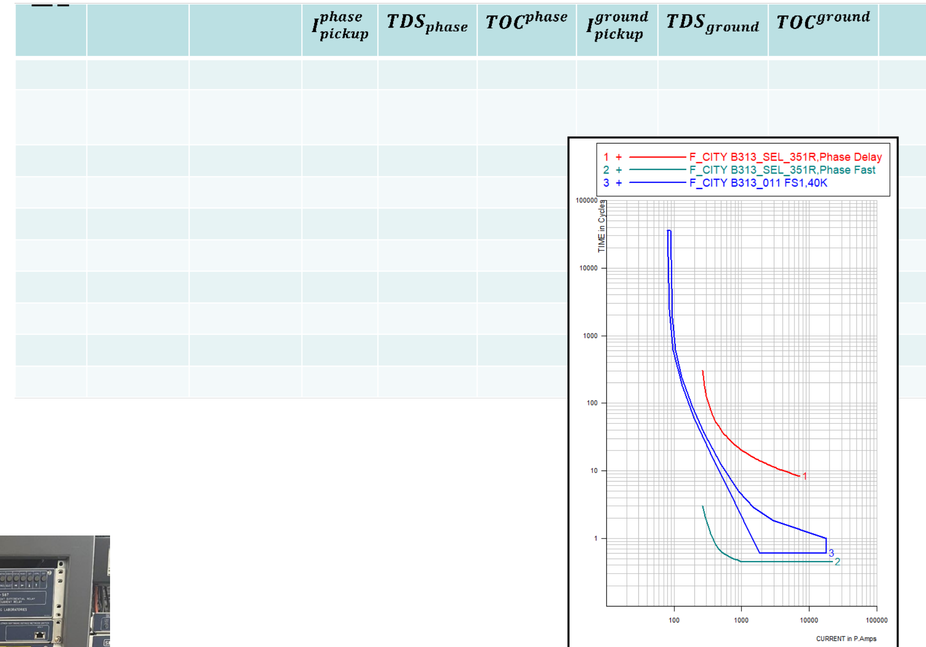
Determine System Configuration
Import Data → Path Tracing
Determine Relay Pairs → Fault Simulations → Optimize Relay Settings

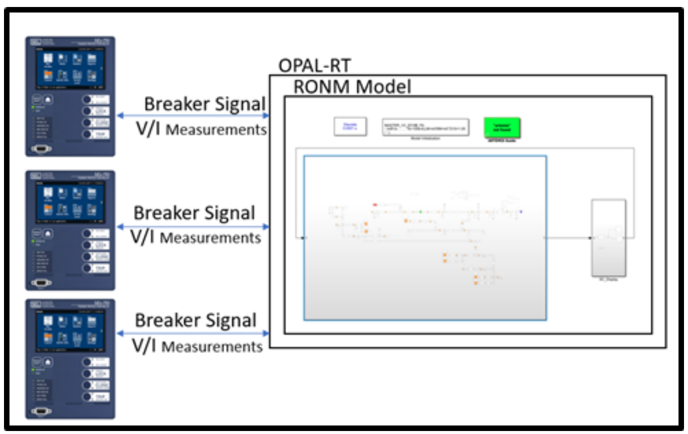
Progress and Results

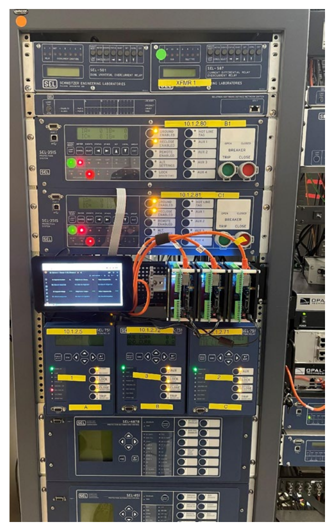
Protection

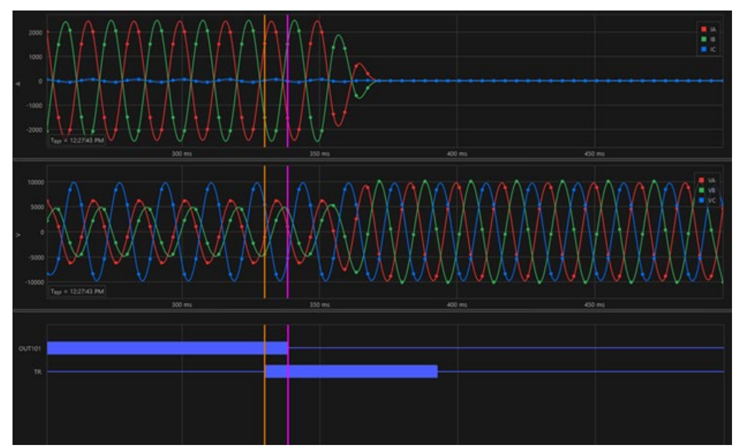
Settings table is generated by RONM for each step in the reconfiguration, restoration, networking, and dispatch of generators

Verification performed in HIL by sending the settings to hardware relays and applying faults in digital twin real-time simulation in Opal-RT









Progress and Results

Evaluation and Demonstration

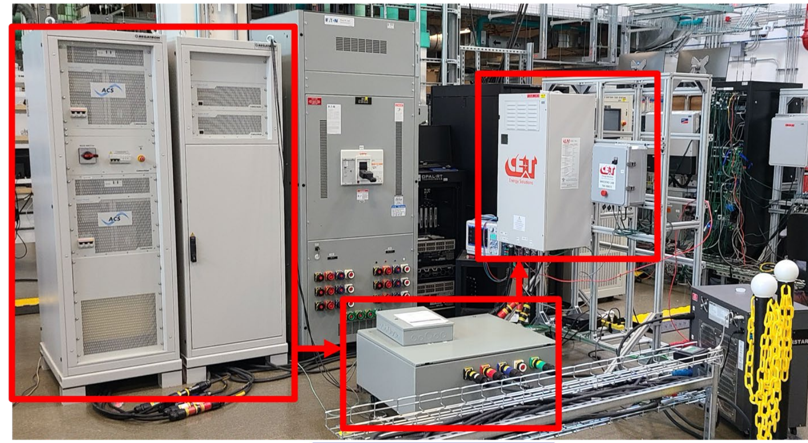
Evaluation at NREL

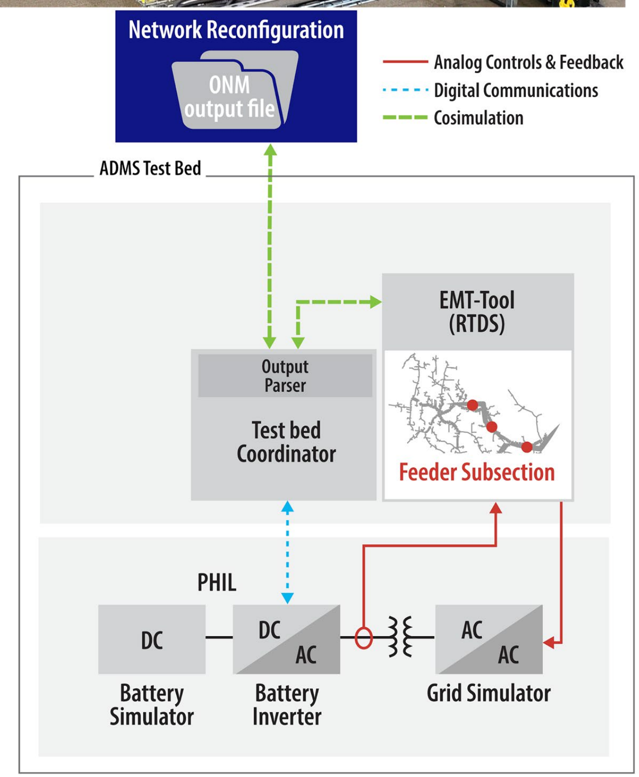
Configured ADMS Test Bed:

- RTDS for real-time simulation
  - Distribution mode for larger systems
- Two utility feeders (SDG&E and Cobb EMC)
  - Converted and validated
  - Reduced and validated
- Grid-forming inverter model in RSCAD:
  - Based on PSCAD model from NREL
  - Extended to unbalanced loads in GFM mode
- New grid-forming battery inverter hardware
  - New grid simulator & battery emulator
  - Working on new PHIL interface that allows for transitions
- Developed output parser
  - Converts offline ONM results into real-time signals

Use case simulations:

- Developed use cases for SDG&E and Cobb EMC feeders
- Completed HIL simulations of use cases



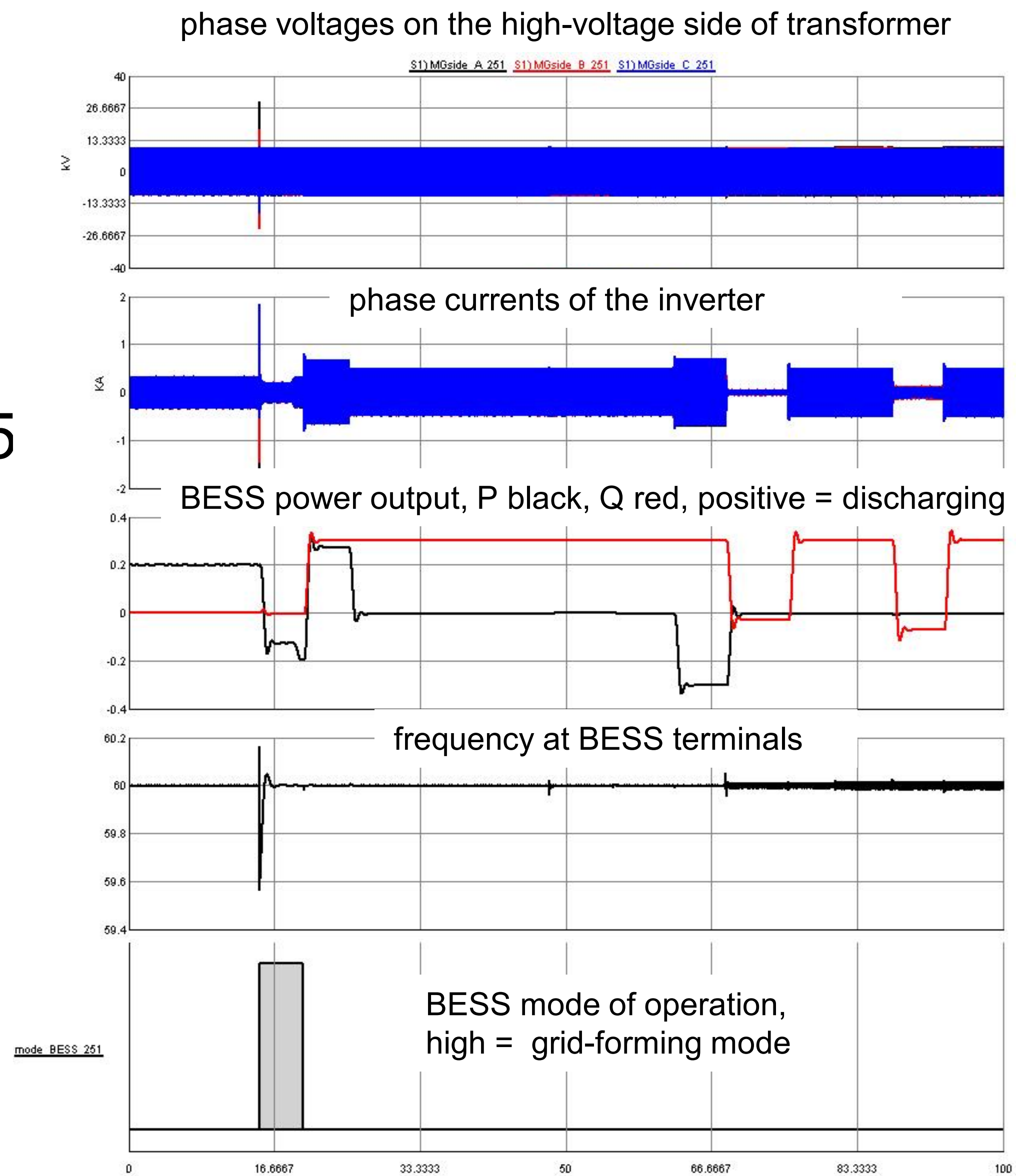


Progress and Results

HIL Evaluation

MG 1 Results

- High PV, so BESS1 charges
- Networked with MG5 at first step
- MG5 has larger DER, so BESS1 becomes GFL

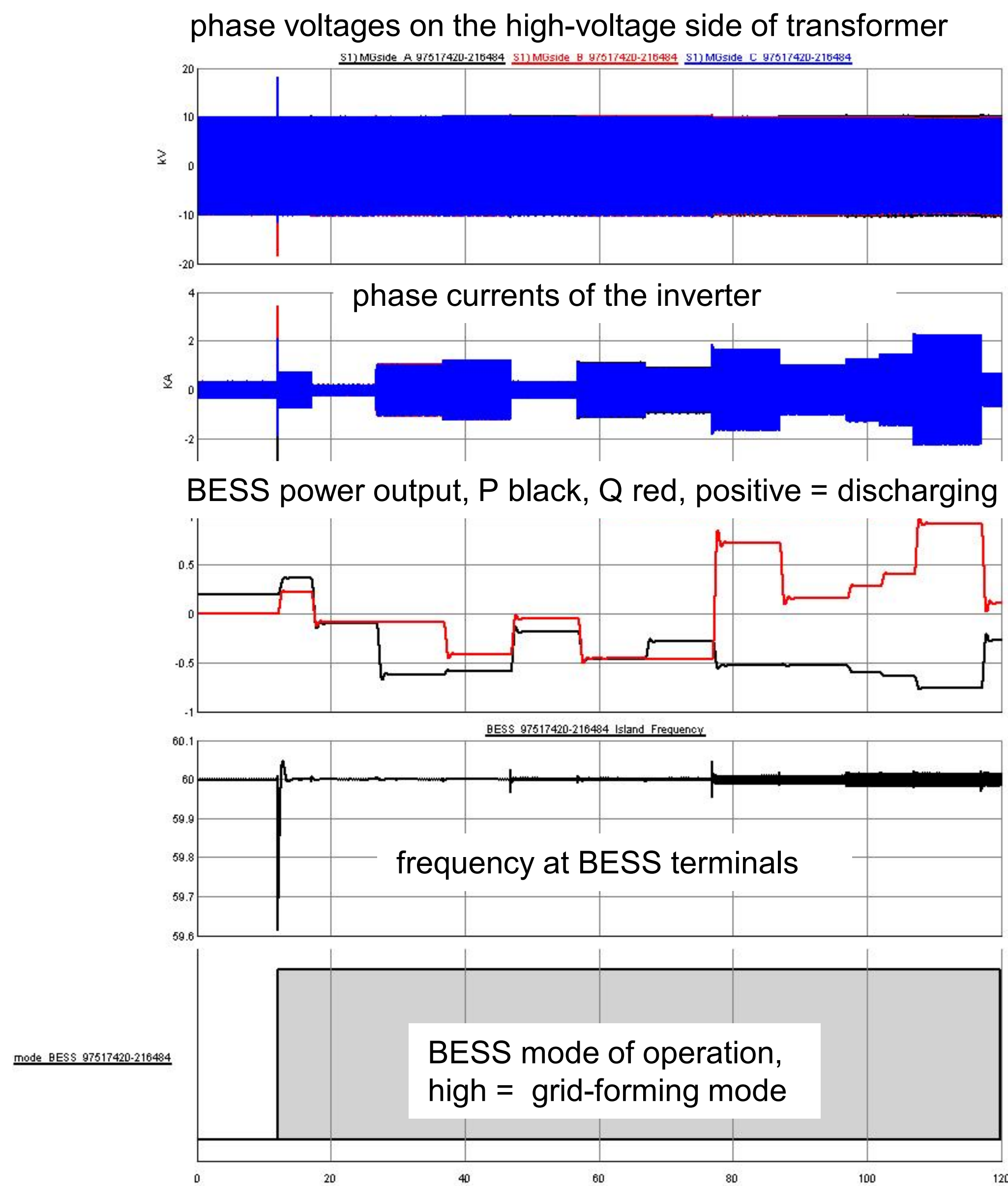


Progress and Results

HIL Evaluation

MG 5 Results

- Largest DER, so GFM entire duration



Progress and Results
HIL Evaluation

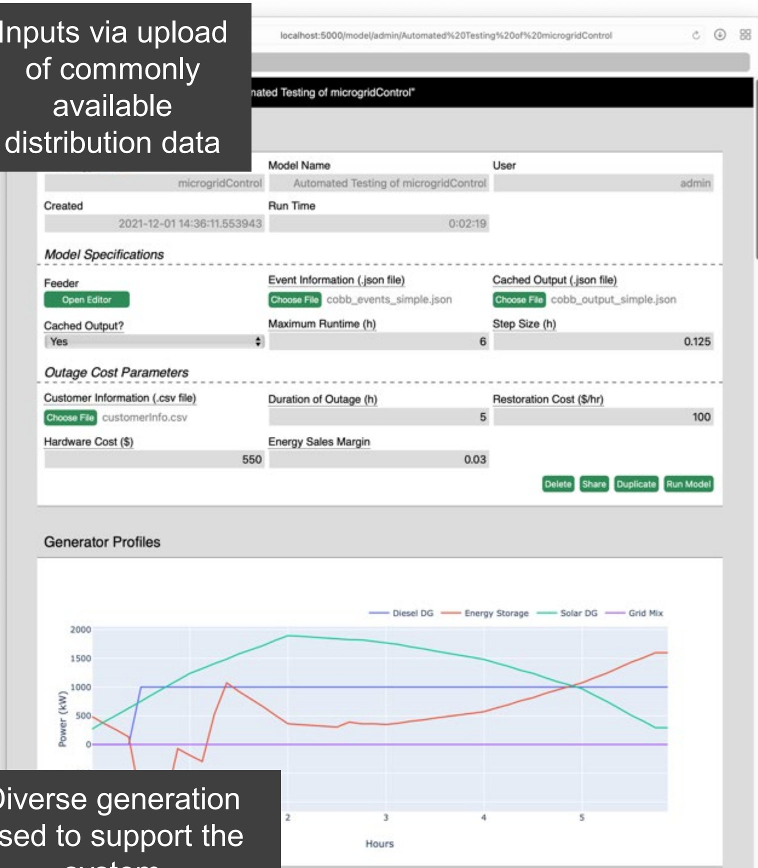
- Stable networking of microgrids
- Some oscillations in the frequency as the load on the BESS increase & unbalance in load also increases
  - RSCAD inverter model could not yet handle unbalanced setpoints at time of simulations (Nov 2021).
  - Have since extended controls to address this.

- Significant reactive power setpoints from RONM
- Suspect due to unbalanced load that requires reactive power to manage the voltages. Will be studied more.

Progress and Results

OMF.coop Web Interface

Inputs via upload of commonly available distribution data



Diverse generation used to support the system

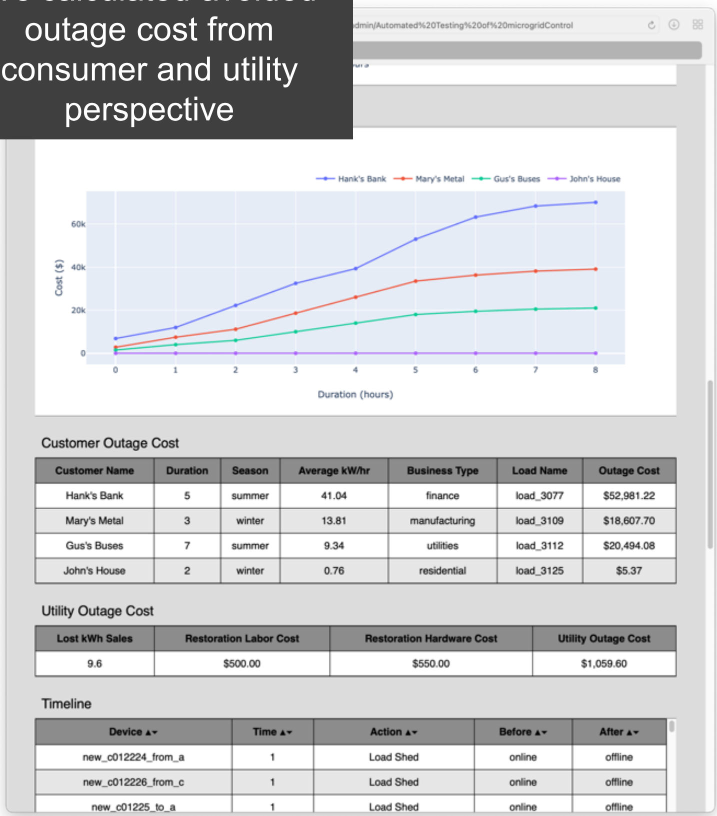
Voltages well regulated (optimization constraint)

Microgrid reaches outside its boundary to support 60% of feeder load during outage

Progress and Results

OMF.coop Web Interface

We calculated avoided outage cost from consumer and utility perspective



Customer Outage Cost

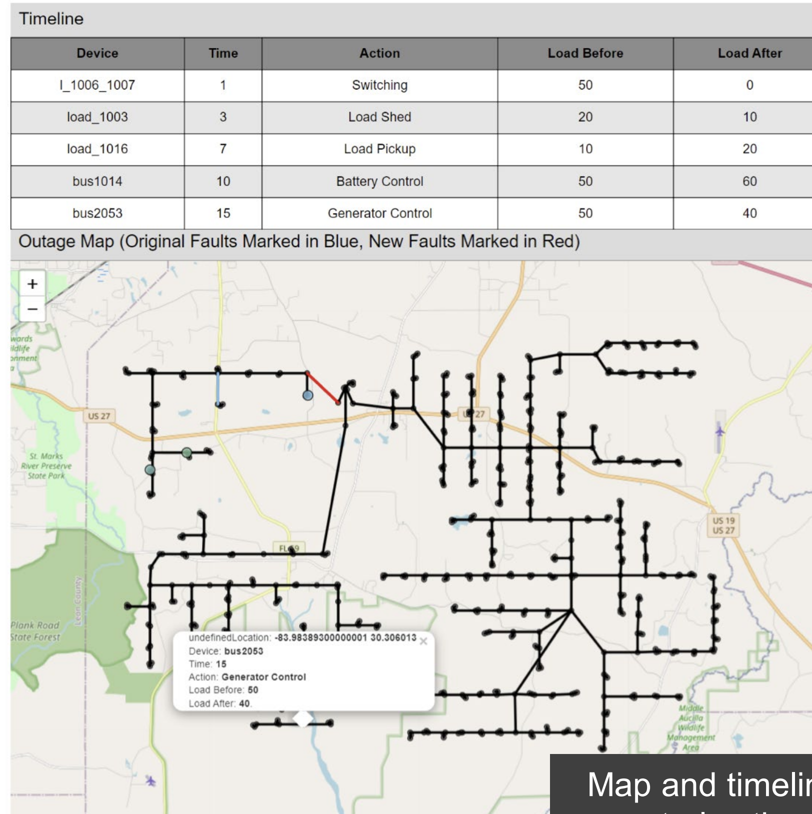
Customer Name	Duration	Season	Average kW/hr	Business Type	Load Name	Outage Cost
Hank's Bank	5	summer	41.04	finance	load_3077	$52,981.22
Mary's Metal	3	winter	13.81	manufacturing	load_3109	$18,607.70
Gus's Buses	7	summer	9.34	utilities	load_3112	$20,494.08
John's House	2	winter	0.76	residential	load_3125	$5.37

Utility Outage Cost

Lost kWh Sales	Restoration Labor Cost	Restoration Hardware Cost	Utility Outage Cost
9.6	$500.00	$550.00	$1,059.60

Timeline

Device	Time	Action	Before	After
new_c012224_from_a	1	Load Shed	online	offline
new_c012226_from_c	1	Load Shed	online	offline
new_c01225_to_a	1	Load Shed	online	offline



Timeline

Device	Time	Action	Load Before	Load After
l_1006_1007	1	Switching	50	0
load_1003	3	Load Shed	20	10
load_1016	7	Load Pickup	10	20
bus1014	10	Battery Control	50	60
bus2053	15	Generator Control	50	40

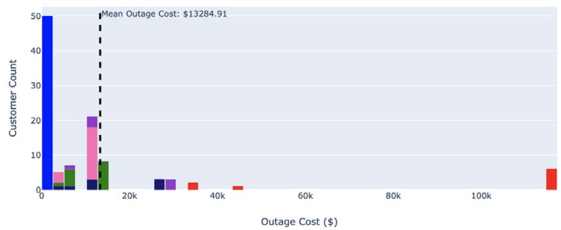
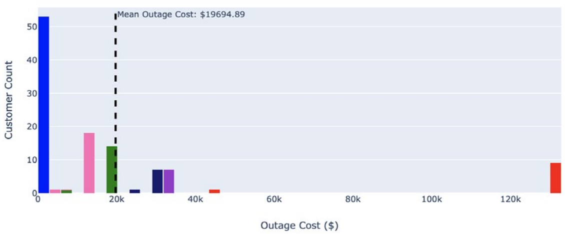
Outage Map (Original Faults Marked in Blue, New Faults Marked in Red)

Map and timeline of control actions to guide restoration and microgrid planning

Progress and Results

OMF.coop Web Interface

Comparing the networking microgrids case vs no-networking microgrids case for the Cobb model, we can see that there is a substantial benefit to networked systems:

<table>
<tr><th></th><th>Networking Microgrids</th><th>No Networking Microgrids</th></tr>
<tr><td>Total Customer Outage Cost</td><td>$1,408,200</td><td>$2,205,827</td></tr>
<tr><td>Average Customer Outage Cost</td><td>$13,284</td><td>$19,694</td></tr>
<tr><td>Outage Duration</td><td>3.7 hours</td><td>5.6 hours</td></tr>
<tr><td>Bonus Load Served</td><td>~41% of demand</td><td>~4% of demand</td></tr>
<tr><td>Outage Cost Histograms</td><td>
</td><td>
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Progress and Results
Resilience Cost-Benefit Calculator

- **Cost-Benefit Calculation**
  - **Compares the cost** of enabling networking of microgrids, i.e., the cost of adding resilience, **to the benefits**, i.e., financial losses avoided by customers when they allow microgrids to network
  - For **costs**, consider capital investments to enable networking (DERs, switches, controls, etc.)

Progress and Results

Resilience Cost-Benefit Calculator

Resilience Annual Average Financial Value

- **Benefit calculated as the difference between two values:**
  - Customer value lost to outages in base case (independent microgrids)
  - Customer value lost to outages in resilient system (networked microgrids)
  - Uses outage cost results from OMF
  - Five outage durations simulated: 1, 2, 4, 6 and 12 hours
  - 1, 2 or 3 switching actions allowed per time step, use average
  - Calculated value lost on an annual basis
    - Single outage scenario (loss of substation)
    - Single loading condition

Progress and Results

Resilience Cost-Benefit Calculator

Resilience Annual Average Financial Value

- **Annual Average**
  - Resulting from multiplying the financial value in each outage duration times the probability of an outage of that duration occurring in one year

Duration (hr)	Customer financial benefit	Estimated average occurrences per year	Annual average
Momentary	$0.00	5	$0.00
1	$ 44,062.09	2	88124.18
2	$ 100,333.03	1	$100,333.03
4	$ 337,408.36	0.75	$253,056.27
6	$ 751,173.74	0.5	$375,586.87
12	$ 358,806.92	0.01	$3,588.07
Total			$820,688.42

Progress and Results

Resilience Cost-Benefit Calculator

- Net present value of estimated costs and benefits
- Cost of adding resilience (i.e., networking) to independent microgrids
- Present value of annual benefits on a 25-year period, 10% discount rate
- Networking cost: - $1,169,883
- Resilience Benefits: $10,404,312
- Net Benefit: $9,234,429

Project Collaborations and Technology Transfer

Publications (12)

- David M Fobes, Harsha Nagarajan, and Russell Bent, *Optimal Microgrid Networking for Maximal Load Delivery in Phase Unbalanced Distribution Grids: A Declarative Modeling Approach*, IEEE Transactions on Smart Grid, under review.
- A. Summers, T. Patel, R. Matthews, and M. J. Reno, *Prediction of Relay Settings in an Adaptive Protection System*, IEEE Innovative Smart Grid Technologies (ISGT), 2022.
- A. K. Summers, R. C. Matthews, T. Patel, and M. J. Reno, *Power System Protection Parameter Sensitivity Analysis with Integrated Inverter Based Resources*, IEEE Photovoltaic Specialists Conference (PVSC), 2021.
- M. J. Reno, S. Brahma, A. Bidram, and M. E. Ropp, *Influence of Inverter-Based Resources on Microgrid Protection: Part 1: Microgrids in Radial Distribution Systems*, IEEE Power and Energy Magazine, 2021.
- R. C. Matthews, T. R. Patel, A. Summers, M. J. Reno, and S. Hossain-McKenzie, *Per-Phase and 3-Phase Optimal Coordination of Directional Overcurrent Relays Using Genetic Algorithm*, Energies, 2021.
- Arthur K. Barnes, Jose Tabarez, Adam Mate, and Russell W. Bent. *Optimization-Based Formulations for Short-Circuit Studies with Inverter-Interfaced Generation in PowerModelsProtection.jl*. Energies, 14(8), 2160, 2021.
- Flores-Espino, and A. Pratt, *The Regulatory Path Forward for Networked Microgrids*, T&D World, May 21, 2020.
- R. C. Matthews, A. Summers, and M. J. Reno, *An Algorithm for Placement of Directional and Nondirectional Time-Overcurrent Relays in a Fully Protected Network*, IEEE PES General Meeting, 2020.
- H. Yang, H. Nagarajan; *Optimal Power Flow in Distribution Networks under Stochastic N-1 Disruptions*, Power Systems Computation Conference (PSCC), 2020.
- D. M. Fobes, S. Claeys, F. Geth, C. Coffrin. *PowerModelsDistribution.jl: An Open-Source Framework for Exploring Distribution Power Flow Formulations*, arXiv:2004.10081, Power Systems Computation Conference (PSCC), 2020.
- A. Barnes, H. Nagarajan, E. Yamangil, R. Bent, and S. Backhaus. *Resilient Design of Large-Scale Distribution Feeders with Networked Microgrids*, Electric Power Systems Research, 171: 150-157, 2019.
- R. C. Matthews, M. J. Reno, and A. Summers, *A Graph-Theory Method for Identification of a Minimum Breakpoint Set for Directional Relay Coordination*, Electronics, 2019.

Project Collaborations and Technology Transfer

Invited Talks (2)

- A. Pratt, *Addressing Challenges for Single Microgrids and Networked Microgrids at Large Scales*, panel presentation at *IEEE GreenTech,* April 8, 2021.
- Matthew Reno, *Controls and Fault Response of Inverter-Based Resources*, Panel Talk for IEEE PES General Meeting, 2021.
- David M Fobes, *Optimizing operations of networked microgrids in response to severe contingencies*, invited session, INFORMS Annual Meeting, October 2022.

Open Source Software (5)

- Protection System Modeling - https://github.com/lanl-ansi/PowerModelsProtection.jl
- Distribution System Modeling - https://github.com/lanl-ansi/PowerModelsDistribution.jl
- Networked Microgrids Operations - https://github.com/lanl-ansi/PowerModelsONM.jl
- Open Modeling Framework - https://github.com/dpinney/omf
- Distribution Transformation Tool (DiTTo) - https://github.com/NREL/ditto.

Reports (9)

- Trupal Patel, David Fobes, Ronald Matthews, Matthew Reno. *Integration of RONM tool output with protection settings optimizer.* 2022.
- Matthew Reno, Adam Summers, Trupal Patel, Ronald Matthews. *Resilient Operation of Networked Microgrids (RONM) May 2021 - Integration of Relays into HIL for Validation* Report
- Trupal R. Patel, Ronald C. Matthews, Matthew J. Reno. *Algorithm and Formulation for Operational Protection Constraints for Networked Microgrids*, Sandia Technical Report. 2021.
- Annabelle Pratt, Rishabh Jain, Soumya Tiwari. *HIL Evaluation Platforms for Resilient Operation of Networked Microgrids (RONM)*, 2021.
- S. Hossain-McKenzie, M. J. Reno, R. Bent, and A. Chavez, *Cybersecurity of Networked Microgrids: Challenges, Potential Solutions, and Future Directions*, Sandia National Laboratories, SAND2020-13723, 2020.
- F. Flores-Espino, J. Giraldez and A. Pratt, *Networked Microgrid Optimal Design and Operations Tool: Regulatory and Business Environment Study*, Technical Report NREL/TP-5D00-70944, May 2020.
- Russell Bent, Carleton Coffrin, Tarek Elgindy, David Fobes, Shamina Hossain-McKenzie, Rishabh Jain, Ronald Matthews, David Penny, Annabelle Pratt, *Resilient Operation of Networked Microgrids Software Development Life Cycle Plan.* 2020.
- Russell Bent, Art Barnes, David Fobes, Smitha Gopinath, Hassan Hijazi, Ronald Matthews, Harsha Nagarajan, Matt Reno, Jose Tabarez, Haoxiang Yang. *Resilient Operations of Networked Microgrids Formulation Report.* 2020.
- K. Schneider, H. Nagarajan, A. Pratt, M.J. Reno, B. Ollis, F. Tuffner, et al, *Preliminary Design Process for Networked Microgrids*, 2020.

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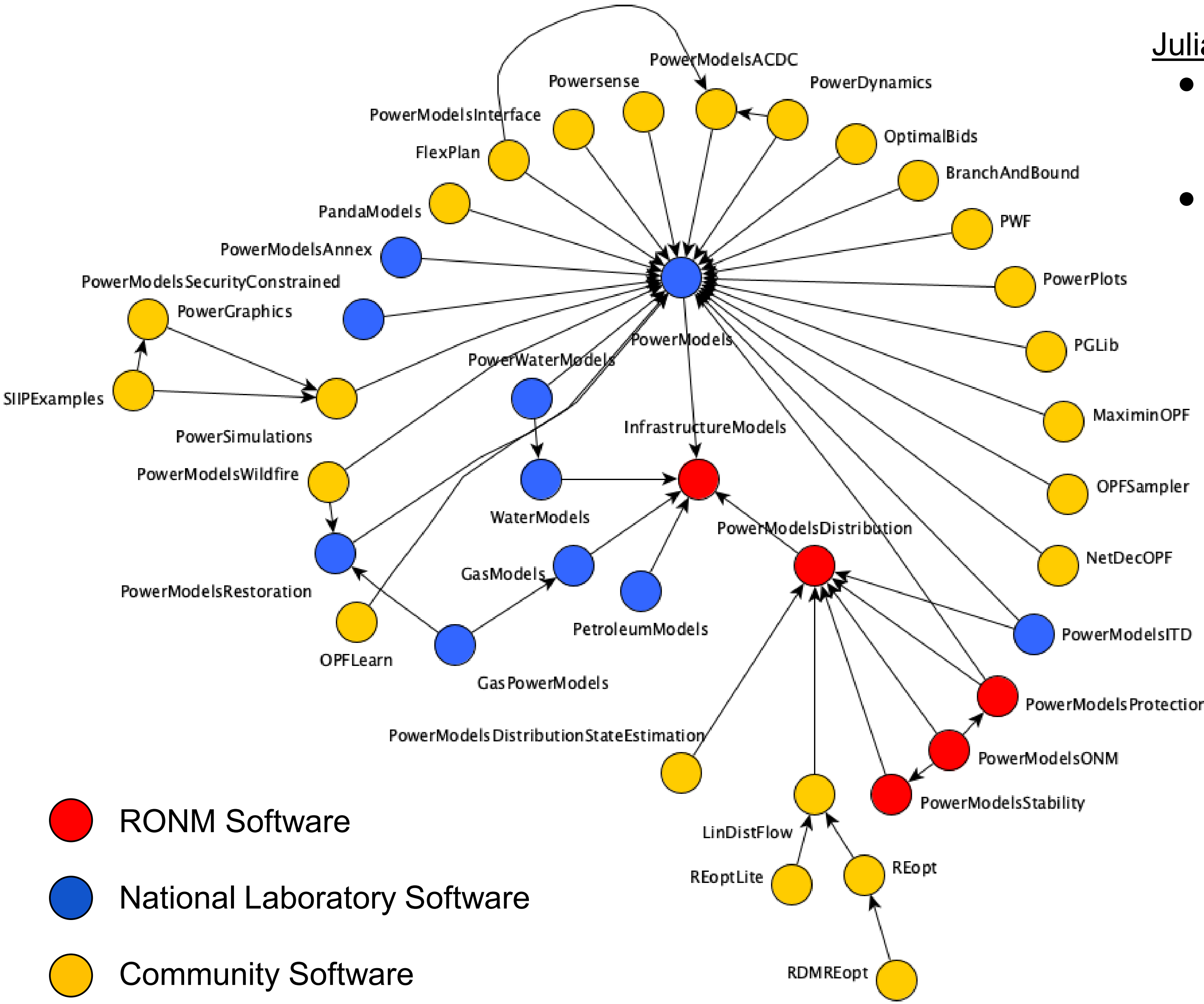

<u>Julia Software Ecosystem</u>

- Arrows denote direction of dependency
- RONM leveraging a wide range of laboratory and community developed tools

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Industrial Advisory Board

- Invaluable source of feedback, a sounding board for project focus, and identification of industry needs
- Examples of comments (use cases discussion)
    - IAB saw opportunities for using the capability to better understand requirements on storage sizing and microgrid sizing
    - IAB saw opportunities to model operations in islanded mode and to mitigate disturbances.
    - IAB suggested including some modeling of the capabilities of the controllers and modeling what happens when a third party owns the microgrid
    - IAB incorporating temporal aspects of requirements when going from grid following to grid forming (5-minute delay to deliver power after an outage requirement for legacy solar). Also asked about how the availability of solar is modeled.
- Examples of comments (tools that are needed by industry discussion)
    - Tools for capital investment analysis and evaluation of tradeoffs between capital costs and saved costs in outage avoidance.
    - Reliability under microgrid networking
    - Storage sizing analysis

Our Favorite Comment: RONM was one of the most advanced tools the IAB has seen so far.

Conclusions

Key Contributions

- An open-source planning tool to evaluate the resilience benefits of networking microgrids
- New modeling and algorithmic approaches for incorporating key requirements of microgrid networking (e.g., protection)
- Evaluation of feasibility of software solutions through sophisticated HIL simulation and engagement with industry partners
- Robust deployment of capability through OMF

Future Work

- Introduce capabilities recommended by the IAB (evaluate design and capacity options, such as storage)
- Introduce capabilities to model metrics in sustainability
- Use case demonstration on remote and/or disadvantaged communities
- Develop training material and conduct training sessions to encourage tool adoption and usage.
- Key implementations and modeling approaches are being transitioned into projects like Dynagrid

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