2020 Microgrid R&D Program
Peer Review Meeting

Resilient Operations of Networked Microgrids (RONM)

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Sandia National Laboratories

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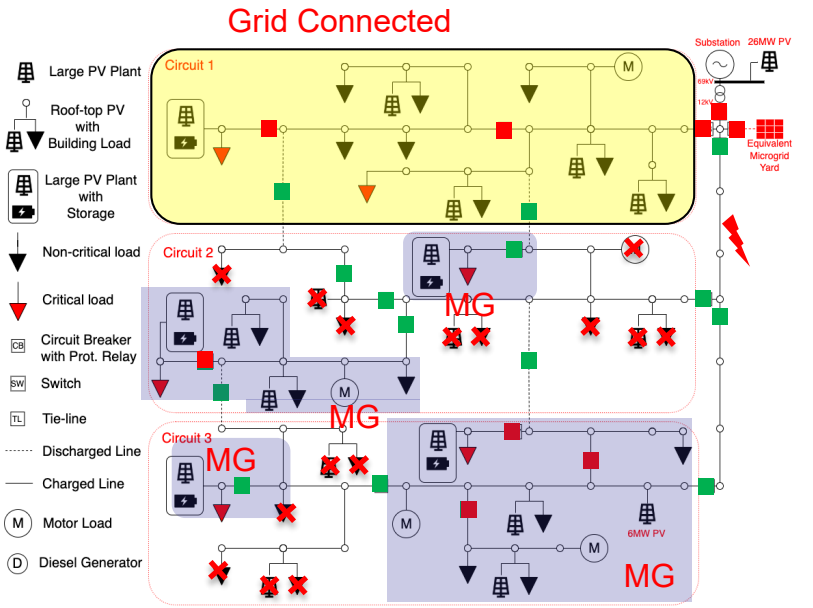
NREL NATIONAL RENEWABLE ENERGY LABORATORY

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 which includes key engineering constraints associated with system recovery after extreme events



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 coordinated HIL evaluation framework for implementing networkable microgrid use-cases and testing resilient operations and recovery algorithms

Funding Summary ($K)

FY19 & prior, authorized	FY20, authorized	FY21, requested
0K	1866K	1866K

Significance and Impact

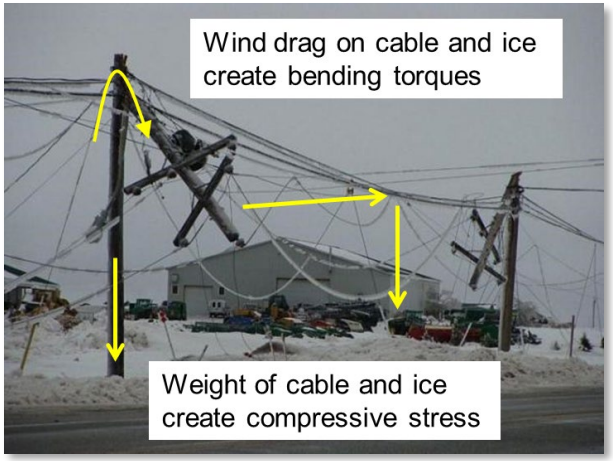
Industry Needs and Significance

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

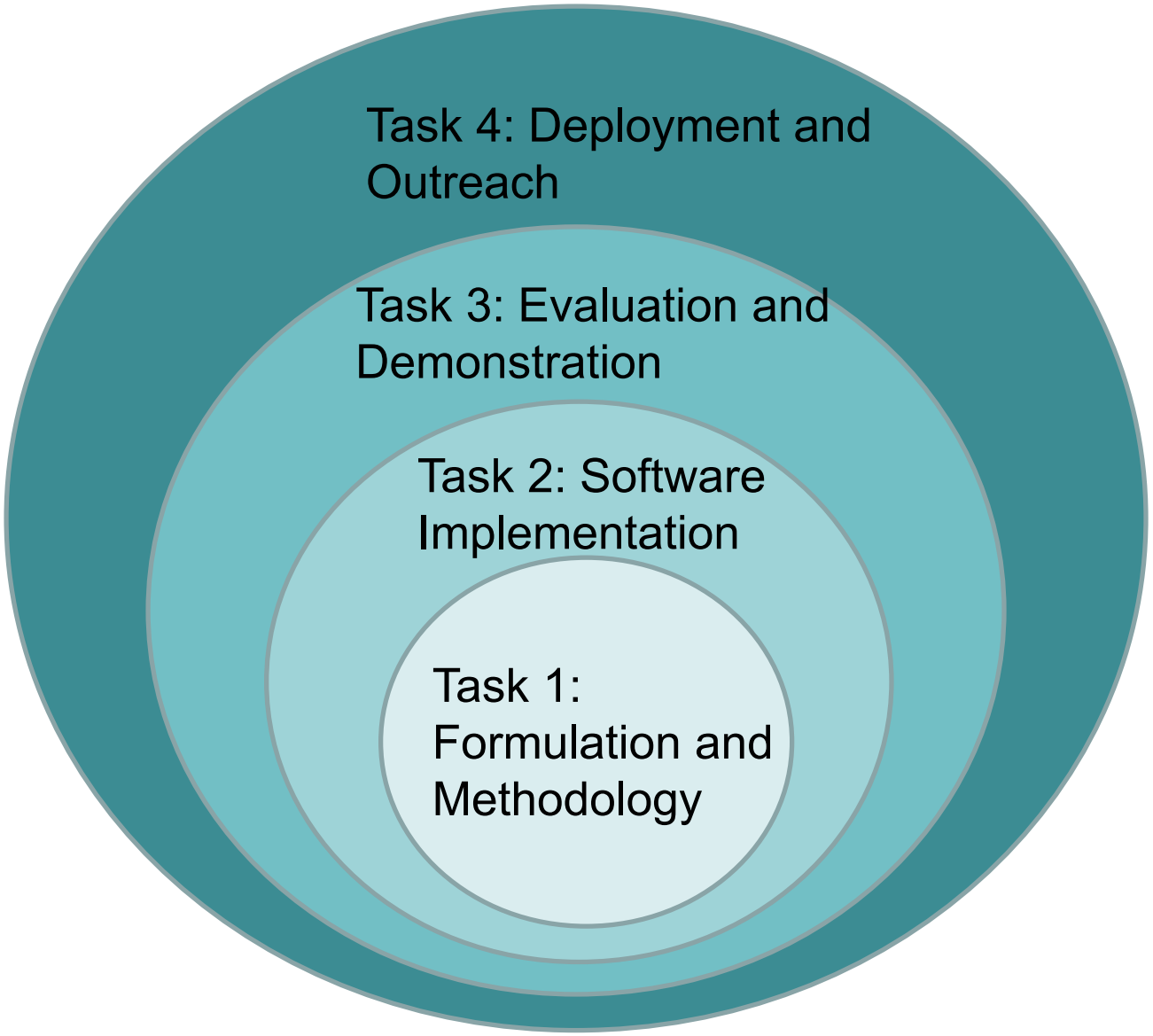
Source: Reuters

Targeted Advances

- Quantify the resiliency value of networking microgrids during extreme conditions.
- Build algorithms which enable self-healing grids through advanced black start restoration, network reconfiguration, and distributed energy resource (DER) management.
- Demonstrate 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).
- Evaluate and validate the viability of RONM solutions on practical distribution networks modeled within advanced HIL evaluation platforms.



Approach

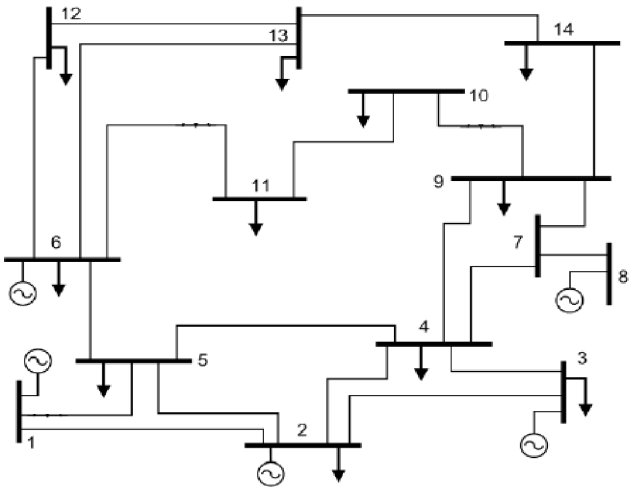


Layered Organization

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

Approach

Task 1—Formulation and Methodology



Overview

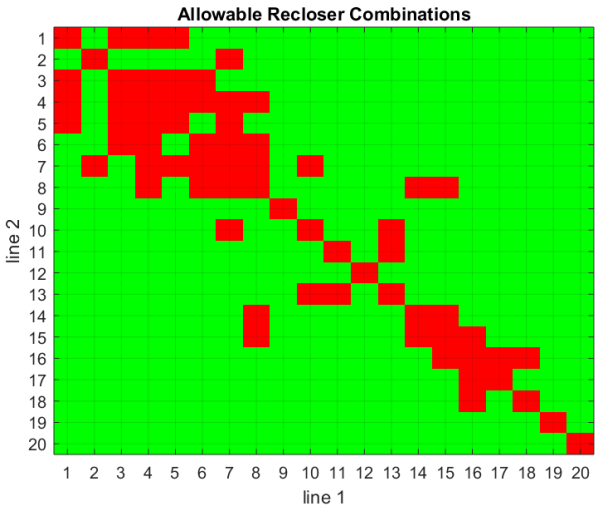
- Develop the core formulation for combining resilient reconfiguration algorithms and restoration algorithms to handle extreme events
- Develop first-of-kind advanced engineering objectives and constraints on system stability, device protection, regulatory restrictions, and economic considerations

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

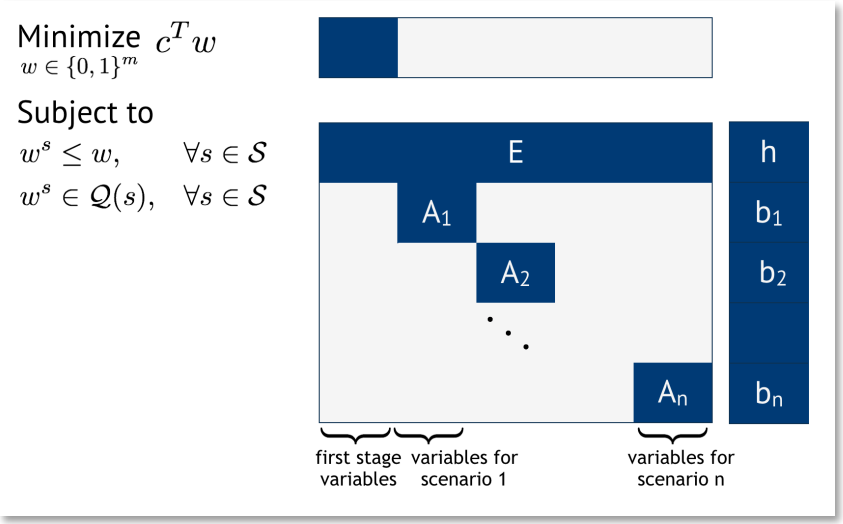
- Methodology for evaluating the design and operations of networked microgrids for different classes of extreme events



Example: Protection Constraints

Approach

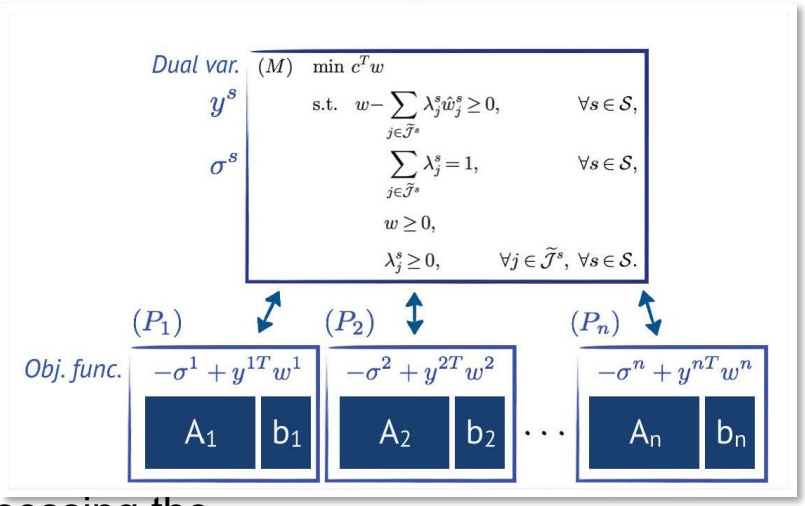
Task 2—Software Implementation



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 I Networked Microgrids (ODO), LPNORM, and Cl DERMS 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



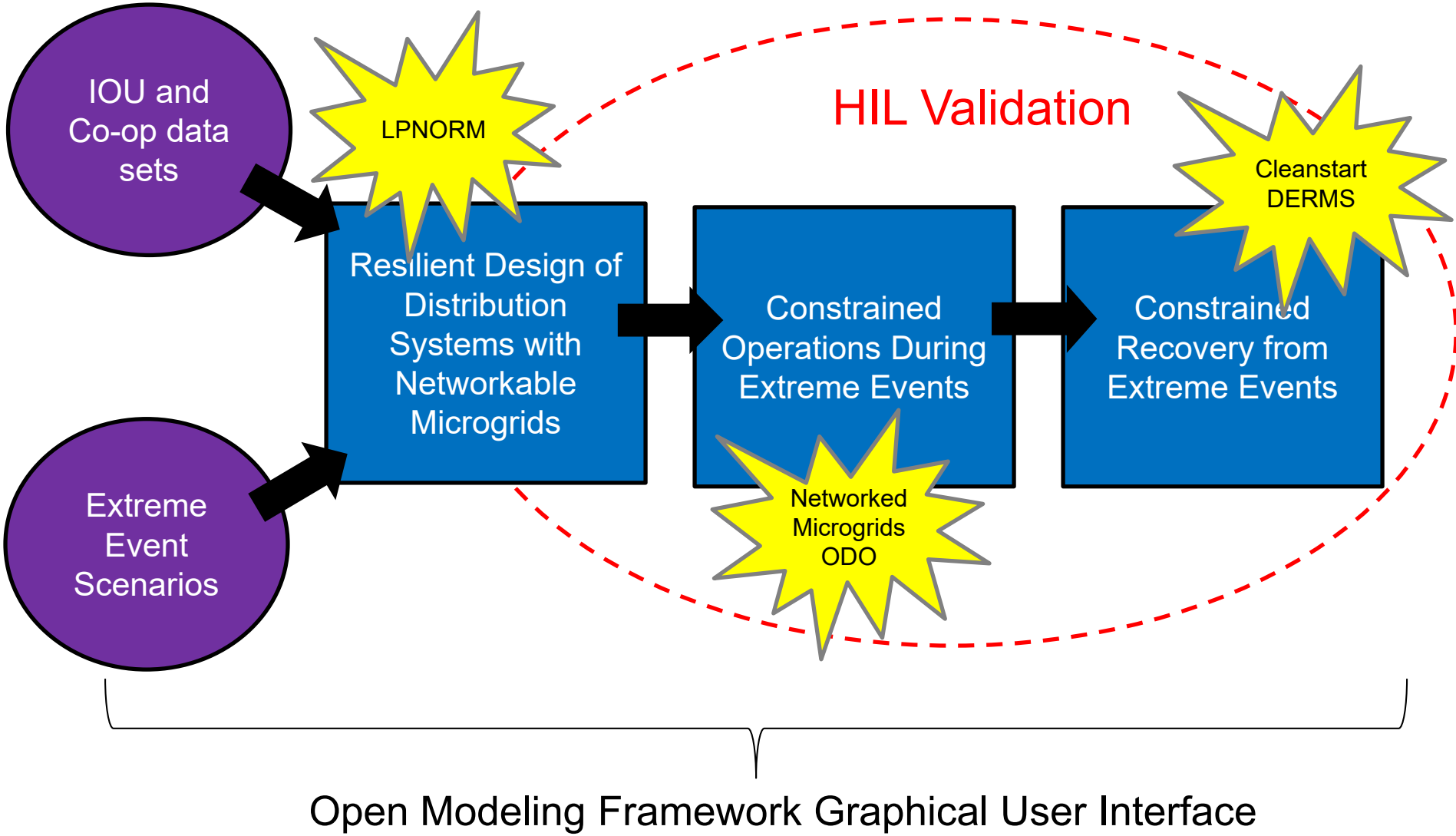
Innovation

- 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

Approach



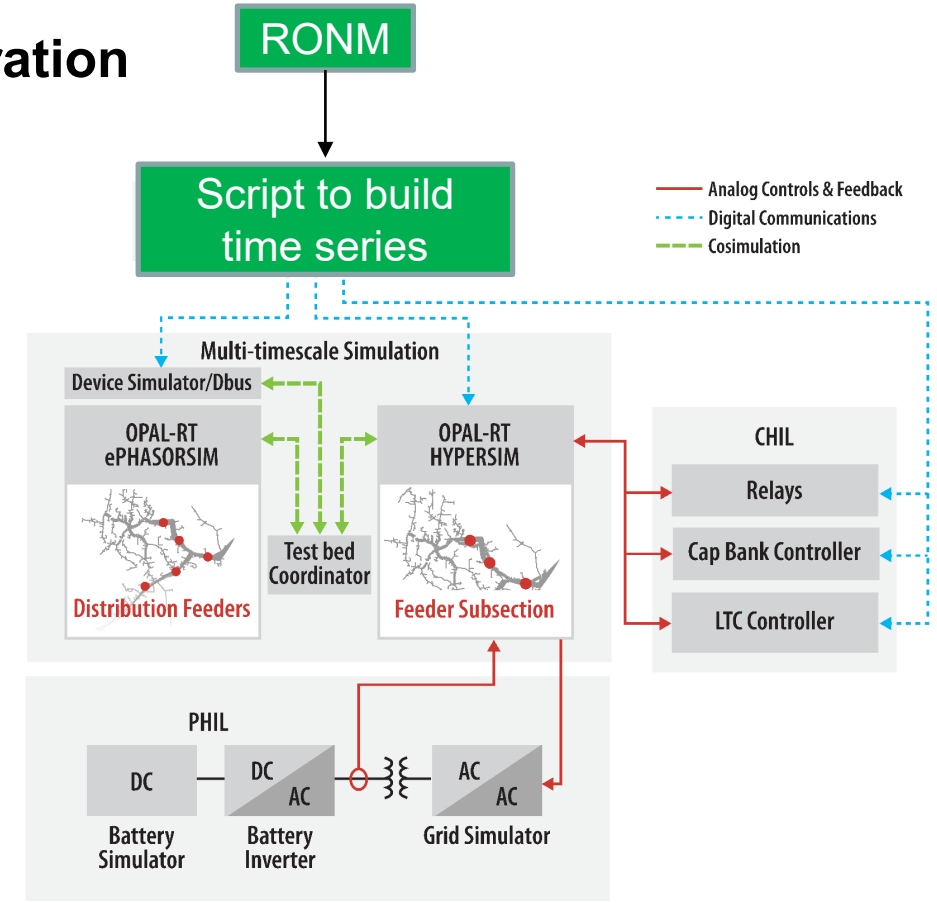
Leverage capabilities developed by prior projects

Approach

Task 3—Evaluation and Demonstration

Overview

- Use distribution system models adapted from NRECA and SDG&E to evaluate 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).



Innovation

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

Expected Outcome

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

Approach

Task 4—Deployment and Outreach

Overview

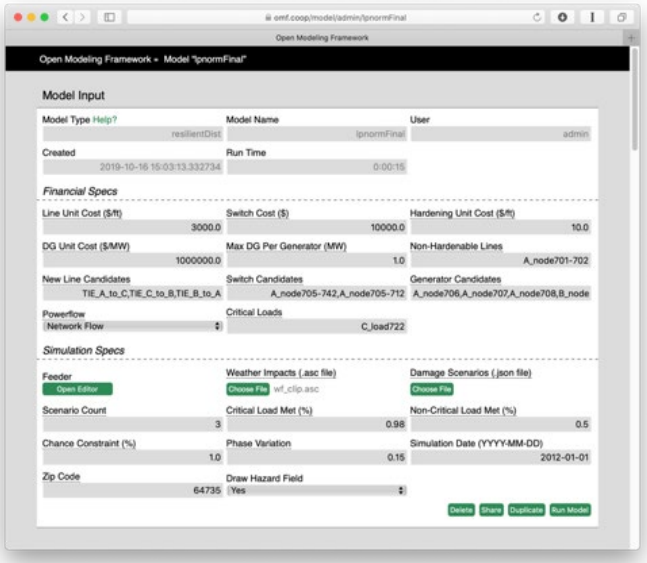
- Deploy RONM software on NRECA's open modeling framework (OMF) platform
- Release open access software
- Regular interaction with utility partners to solicit feedback on the project's progress

Innovation

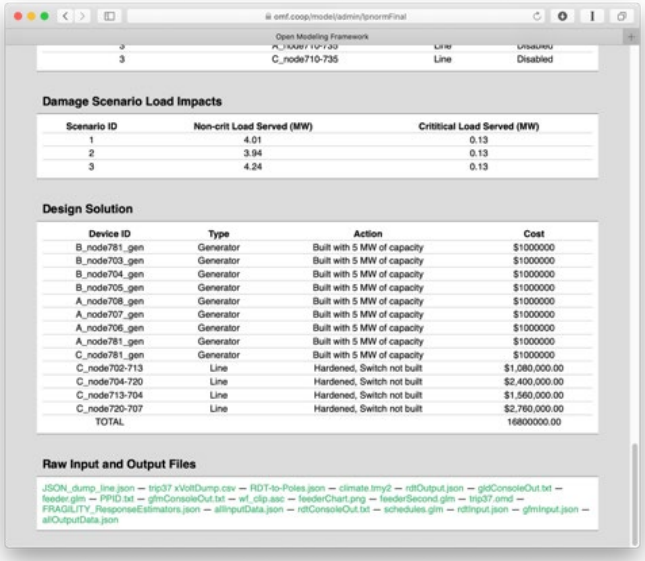
- A combination of software libraries for use by utilities to incorporate resilience into their networked microgrid planning and a graphical user interface for interacting libraries.

Expected Outcome

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



Model Inputs



Recommended resilience improvement detail

Progress and Results – FY19

Project start: Dec 2019—Precursor projects and technology

DOE Advanced Grid Research Project: Networked Microgrids—This project developed key software capabilities for modeling N-1 reliability criteria and N-k resilience criteria when operating distribution feeders.

DOE GMLC Project: 0057 LPNORM—This project developed key software and algorithmic capabilities for designing microgrid based systems to be resilient to extreme events and operate these systems (reconfiguration) immediately post event prior to restoration activities.

DOE GMLC Project: CleanStart DERMS—This project developed black start restoration methodologies for distribution feeders. In RONM, we will extend these approaches to include advanced engineering objectives and constraints such as stability criteria, device protection, regulatory restrictions, and economic considerations.

DOE GMLC Project: 1.2.1 Grid Architecture—RONM will leverage this project's architectural development concepts to inform planning and design within and between electric cooperatives and extend the methodology to investor-owned utilities and municipally-owned electric utilities.

DOE GMLC Project: 1.5.2 Radiance—The Radiance project developed and tested networked microgrids for Alaskan Communities and informed the need for the advanced engineering constraints that will be developed under this project.

DOE GMLC Project: 1.5.6 SC-SECURED—The SC-SECURED project developed models of microgrid technologies which can be used to improve the resilience of distribution systems.

DOE GMLC Project: 0237 ADMS Testbed—This project developed a test bed to evaluate the performance of existing and emerging advanced distribution management systems (ADMS) or specific applications of such systems. The testbed provides a realistic laboratory test setting, including detailed modeling of the power system, controller and/or power hardware, and industry-standard communication protocols. We will utilize this testbed to validate RONM algorithm generated solutions meet the physical and engineering requirements of distribution feeders.

DOE GMLC Project: 1.4.15 HELICS—This project developed a co-simulation framework which is used within the ADMS testbed.

DOE Advanced Grid Research Project: ROMDIST—This project developed key precursor algorithmic capabilities of RONM associated DER planning for microgrid systems

Progress and Results – FY20

Task 1—Formulation and Methodology

Constraints on Protection

Fault Study → Optimal Protection Coordination → Feasible Configurations

LANL Fault Study
Calculates post-fault voltages and currents on a network for every

1. System state: switch & generator status
2. Fault bus location
3. Fault type: phase A line-ground, phase AB line-line, etc.

Inputs

1. Electrical model: impedance matrix, gen location
2. System state

Output
Fault voltages and currents for each state

SNL Algorithm
Determines optimal protection settings given network configuration

Inputs

1. Electrical model
2. Protection locations & types
3. System state
4. Fault currents for each state

Output

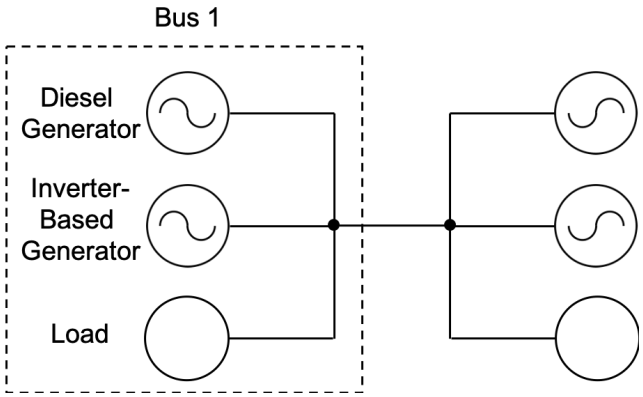
1. Set of protection settings if solution found
2. Null set if no solution found

Table of Feasible Configurations
Input of feasible configurations for RONM operational algorithm

Switch 1	Switch 2	Gen 1	Gen 2
Closed	Open	On	On
Closed	Closed	On	On
Open	Closed	On	On
Closed	Closed	Off	On
Closed	Closed	On	On

Progress and Results – FY20

Task 1—Formulation and Methodology



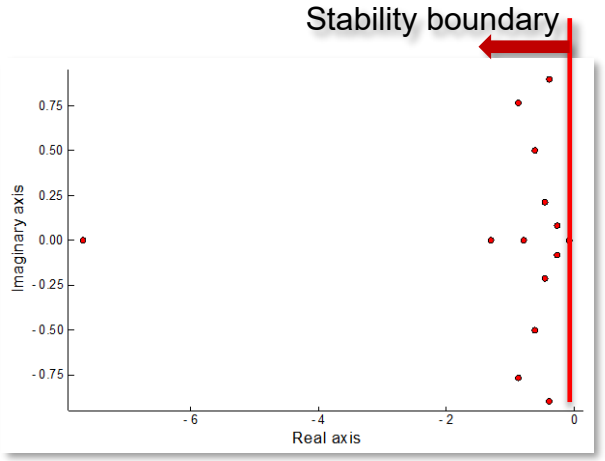
Topology of controlled components in the analysis

Constraints on System Stability

- Evaluate if a microgrid can regain a stable operating equilibrium point after a disturbance
- Stability is required for designing microgrids to operate reliably around a steady-state operating point.
  - Smaller size makes microgrids more vulnerable to instabilities than grid-connected systems.
- Focus on how changes in network parameters such as topology, line impedances and loads affect system stability.

Progress

- We have constructed a set of differential equations $\dot{x} = A(\lambda)x$ for diesel generators and inverter-based generators—implemented based on load flow data formats like OpenDSS.
- Given $\dot{x} = A(\lambda)x$, x is state vector of phase angle, frequency and voltage magnitude at generator terminals and λ contains parameters like droop gains, line impedances, generator set points, and steady-state operating point.
- We have developed a Lyapunov-based eigenvalue formulation for state-space matrix, $A(\lambda)$, for assessing stability.



The microgrid is small-signal stable *if and only if* the eigenvalues of the system matrix $A(\lambda)$ lie on the left-half plane.

Progress and Results – FY20

Task 1—Formulation and Methodology

Potential Regulator Constraints

- Understand current regulatory barriers for networked microgrid system (NMS) deployment
- NREL identified seven main barrier categories and analyzed the severity of each barrier category for utility NMS.
- In the table, barrier severity marked in green represent a low-level barrier for utilities to overcome, yellow intermediate, and red barriers that would deter development. Regulatory barriers in general are difficult to quantify mainly because there is almost no precedent for NMS deployment across U.S. jurisdictions.
- ONM tool will show a warning to the user, including information regarding relevant statutes and regulations and, if possible, precedents.
- Published one article in T&D World and a technical paper (see slide on Technical References)
- Example: first case, California

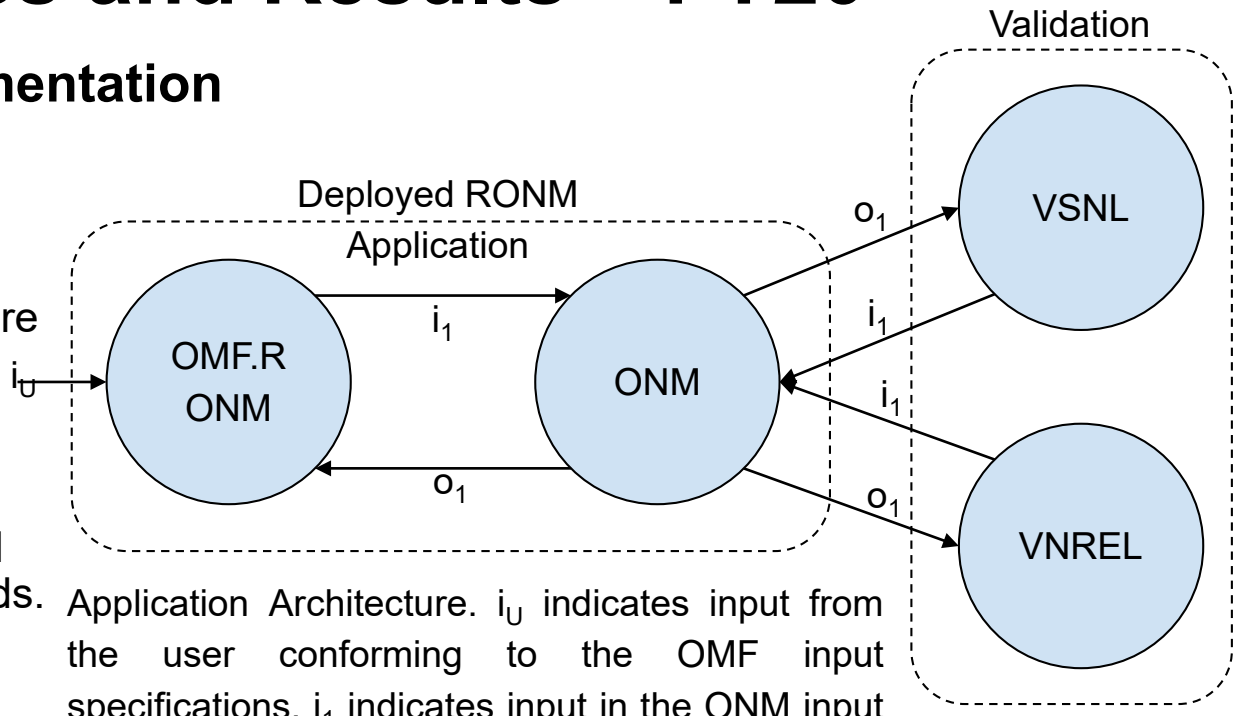
Potential Barriers	Barrier Severity for Utilities in CA	Exp
Barriers exclusive to utility-owned NMS		SB dis pri mi
Utility DER Ownership		In tra bid an bla ow
Lack of microgrid definition		SB me
The following barrier categories apply across the U.		
Right of way (ROW)		NM cu
Franchise agreements		Fra
Regulated as utility		Th reg
Interconnection time/cost		Thi
Utility infrastructure access (particularly during outages)		Thi NM

Progress and Results – FY20

Task 2—Software Implementation

Life Cycle Development Plan

Agility: Leverage modern software development best practices to quickly test and verify new software versions. This allows RONM to rapidly release new features to the OMF platform and quickly respond to customer needs.



Application Architecture. i_U indicates input from the user conforming to the OMF input specifications. i_1 indicates input in the ONM input format; o_1 indicates output in the ONM output format.

Open-Access: All of the core components of the RONM software are made available as open-source. This maximizes the impact of the RONM capability to the broader community and enable external review of the implementation details.

Best Practices: Collaborative Implementation and Version Management, Code Quality Management, Code Quality Management, Process Automation via Continuous Integration

Scrum.org

agile

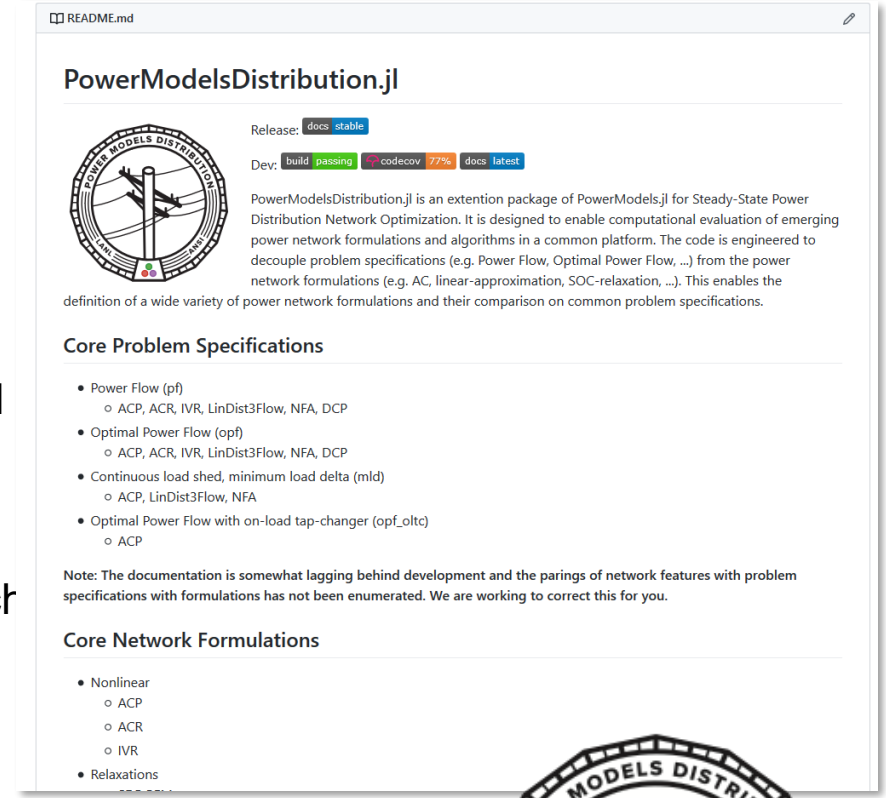
Progress and Results – FY20

Task 2—Software Implementation

Software Releases

- PowerModelsDistribution.jl v0.9
  - https://github.com/lanl-ansi/PowerModelsDistribution.jl
  - Add support for data fields required to model stability, regulatory, protection, and economic constraints
  - Support for modeling fault currents
  - Support for time series—multi-period data sets and optimization problems which include PV and Storage
  - Support for modeling industrial data sets, including models for multi winding transformers, a variety of load models, DER, etc.

- PowerModelsProtection.jl
  - https://github.com/lanl-ansi/PowerModelsProtection.jl
  - Software extension for modeling protection and its interactions with fault currents


README.md

PowerModelsDistribution.jl

Release: docs stable

Dev: build passing codecov 77% docs latest

PowerModelsDistribution.jl is an extention package of PowerModels.jl for Steady-State Power Distribution Network Optimization. It is designed to enable computational evaluation of emerging power network formulations and algorithms in a common platform. The code is engineered to decouple problem specifications (e.g. Power Flow, Optimal Power Flow, ...) from the power network formulations (e.g. AC, linear-approximation, SOC-relaxation, ...). This enables the definition of a wide variety of power network formulations and their comparison on common problem specifications.

Core Problem Specifications

- Power Flow (pf)
  - ACP, ACR, IVR, LinDist3Flow, NFA, DCP
- Optimal Power Flow (opf)
  - ACP, ACR, IVR, LinDist3Flow, NFA, DCP
- Continuous load shed, minimum load delta (mld)
  - ACP, LinDist3Flow, NFA
- Optimal Power Flow with on-load tap-changer (opf_oltc)
  - ACP

Note: The documentation is somewhat lagging behind development and the parings of network features with problem specifications with formulations has not been enumerated. We are working to correct this for you.

Core Network Formulations

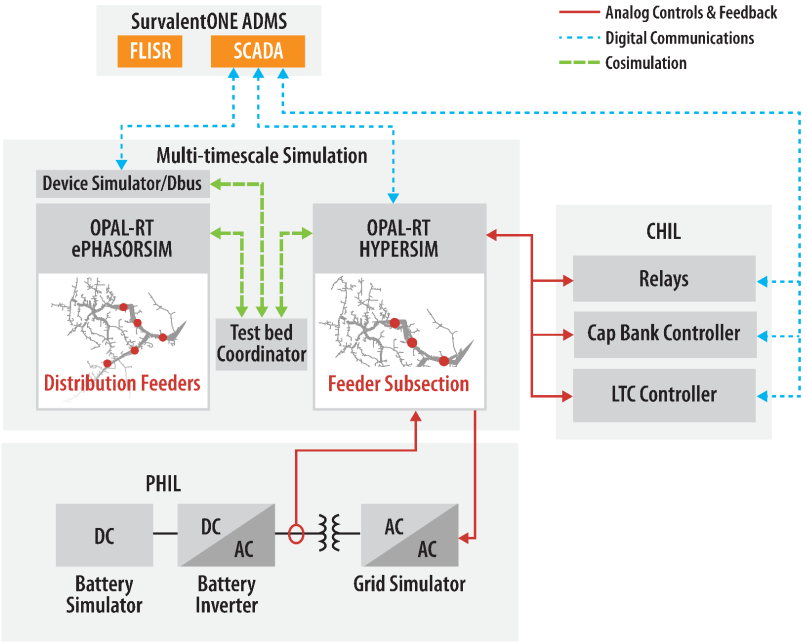
- Nonlinear
  - ACP
  - ACR
  - IVR
- Relaxations

Progress and Results – FY20

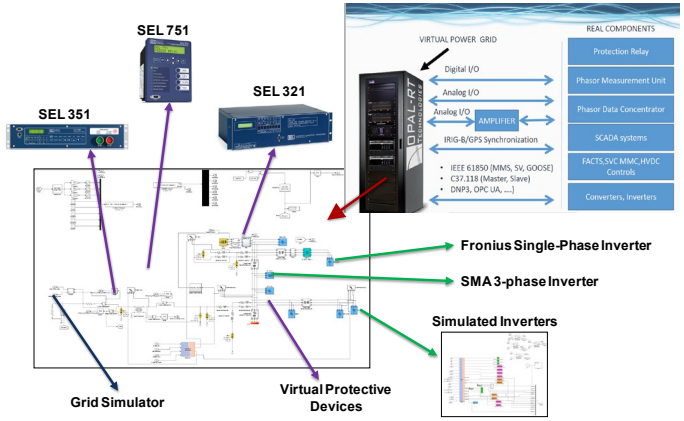
Task 3—Evaluation and Demonstration

HIL Evaluation Platform Design

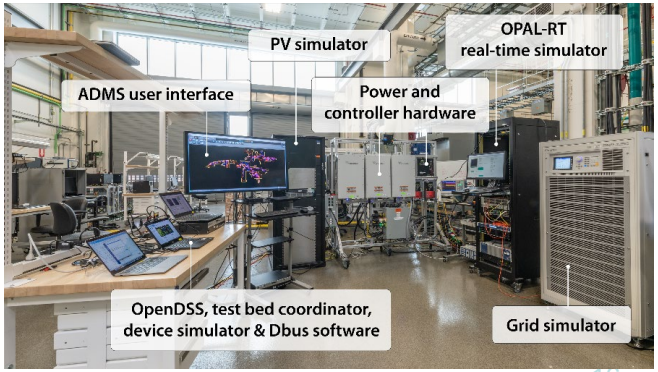
- Identified the desired capabilities of the evaluation platform for verifying RONM solutions
- Selected simulation tools based on requirements: Opal-RT ePHASORSIM (electromechanical) & HYPERSIM (EMT)*



Leverage Microgrid Protection Test Bed at SNL



Leverage ADMS Test Bed at NREL

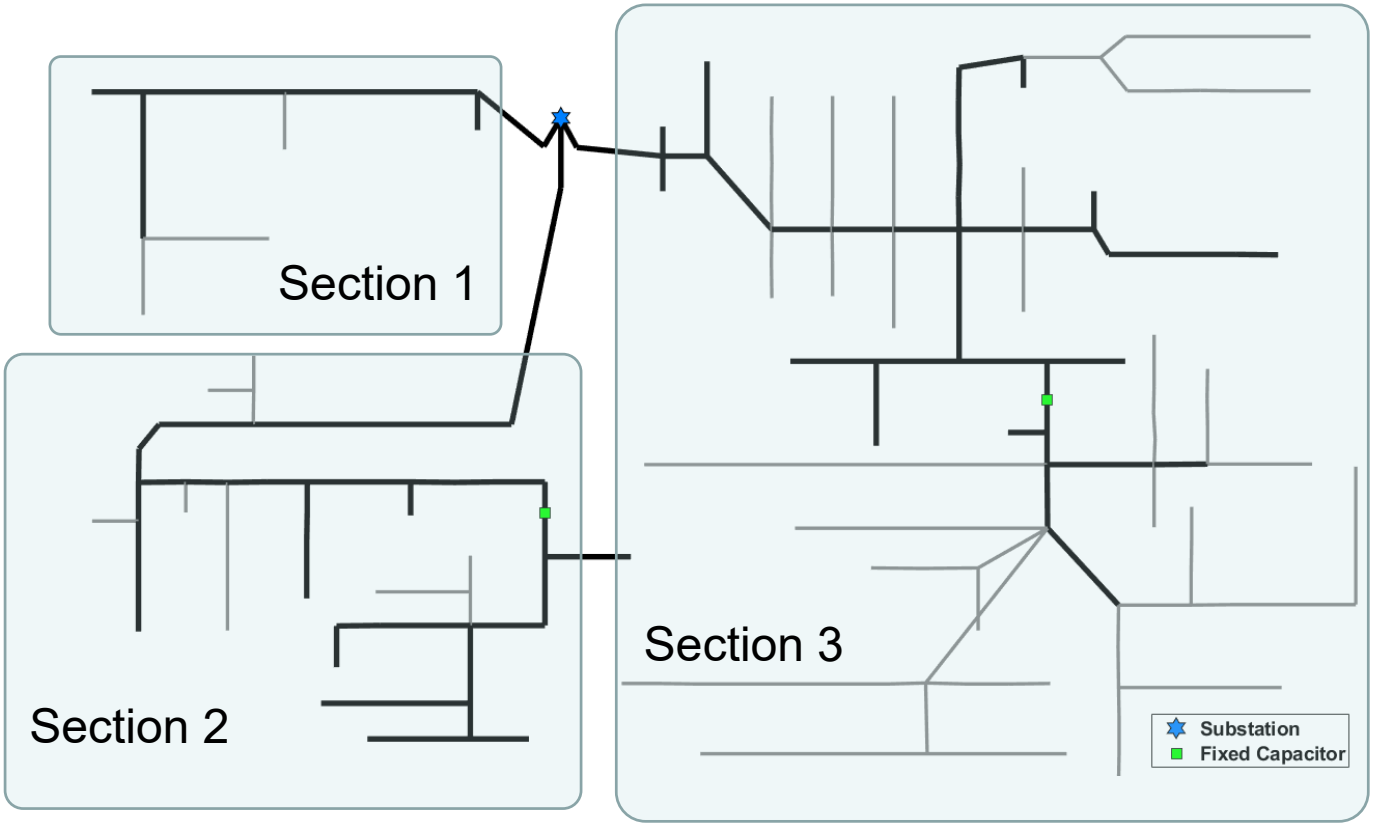


Progress and Results – FY20

Task 3—Evaluation and Demonstration

- Original test feeder has 915 nodes
- System Load: 1.2MW + 0.23MVAr

- Multiple networking opportunities between neighboring (feeder) sections



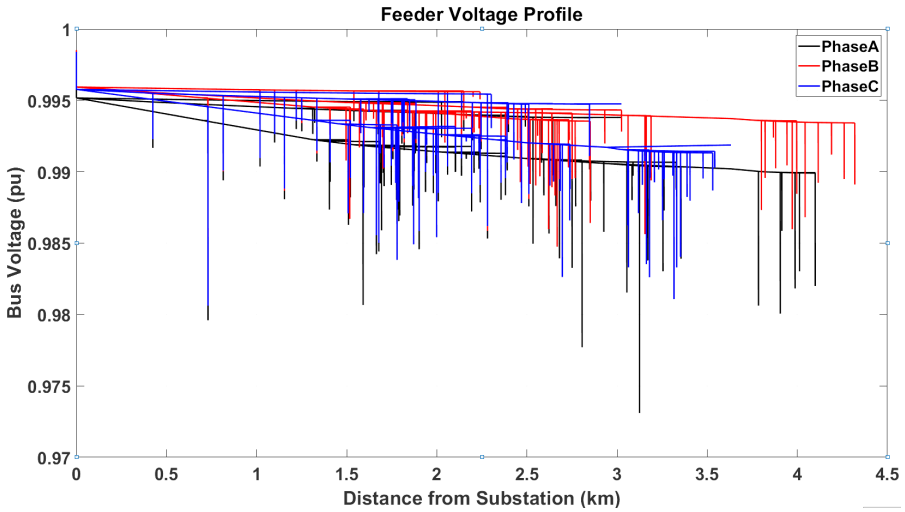
The 240-bus Iowa Test Feeder

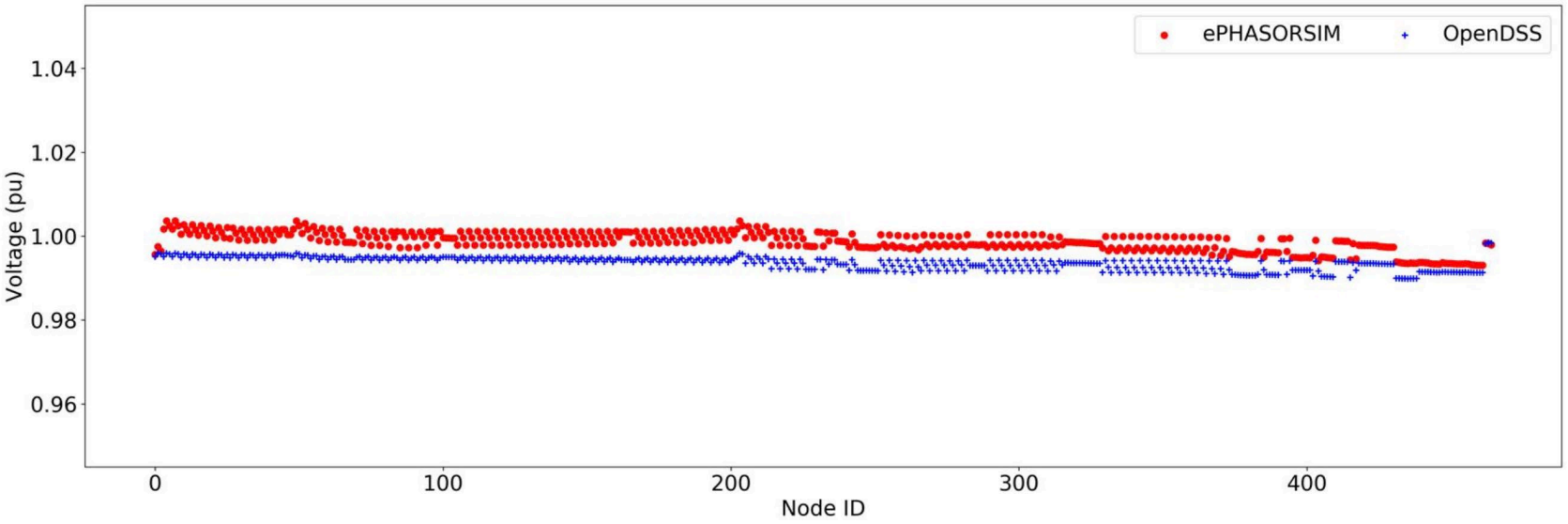
Progress and Results – FY20

Task 3—Evaluation and Demonstration

Validation for Real-time Modeling

- Reduced Distribution Feeder without the secondary transformers: 472 Nodes
- Node voltages between the steady state and real-time dynamic phasor models are within 1%.



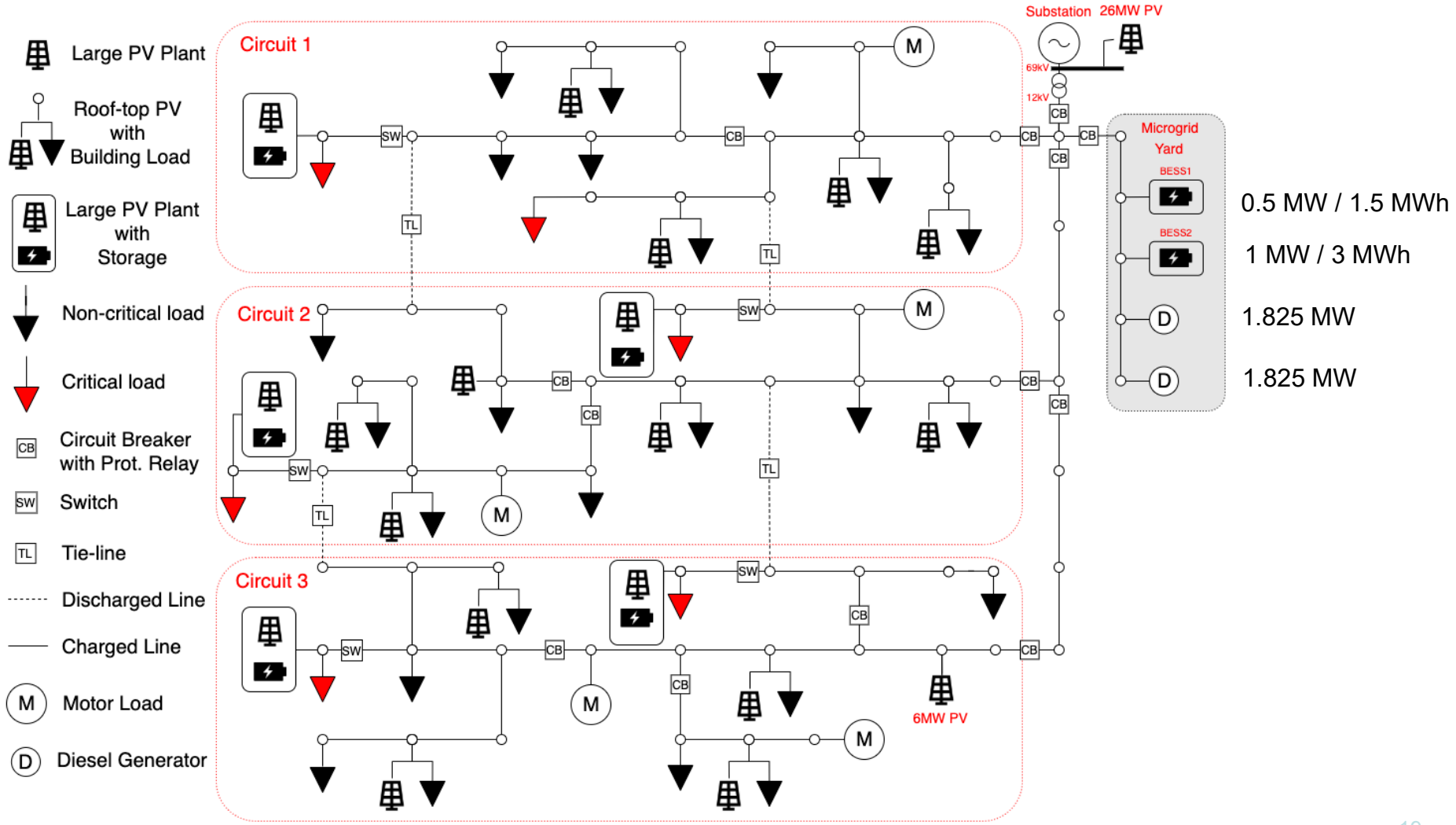


Comparison: Voltage profiles between ePHASORSIM and OpenDSS

Progress and Results – FY20

Task 3—Evaluation and Demonstration

Develop Industry Use Case

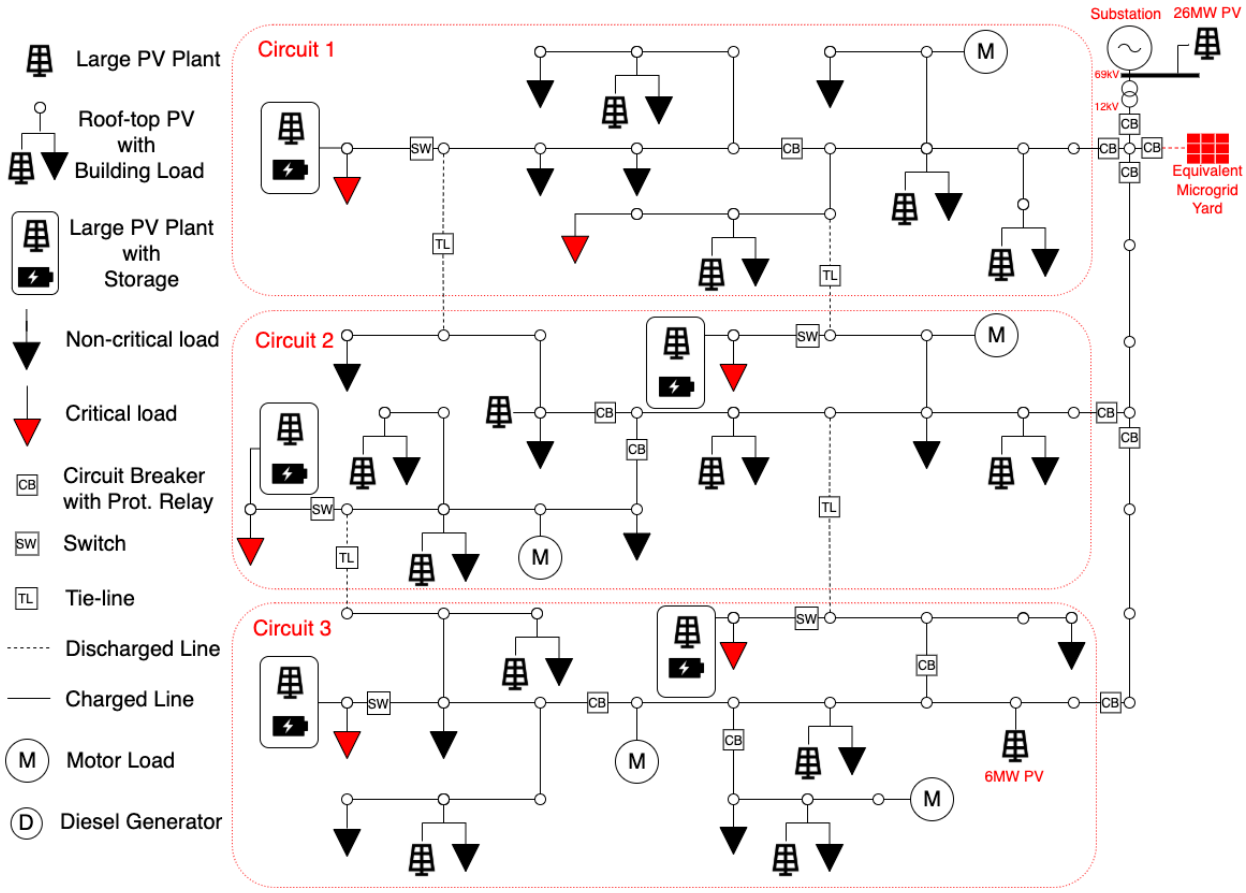


Progress and Results – FY20

Task 3—Evaluation and Demonstration

Default Configuration

- Sample distribution system with multiple radial sections
- Available DERs, roof-top PVs, and/or storage
- Tie-lines for interconnecting the radial sections
- Circuit breakers (include protection devices which can operate on fault detection)
- Switches (to isolate a section for islanded mode operation) – only for critical loads

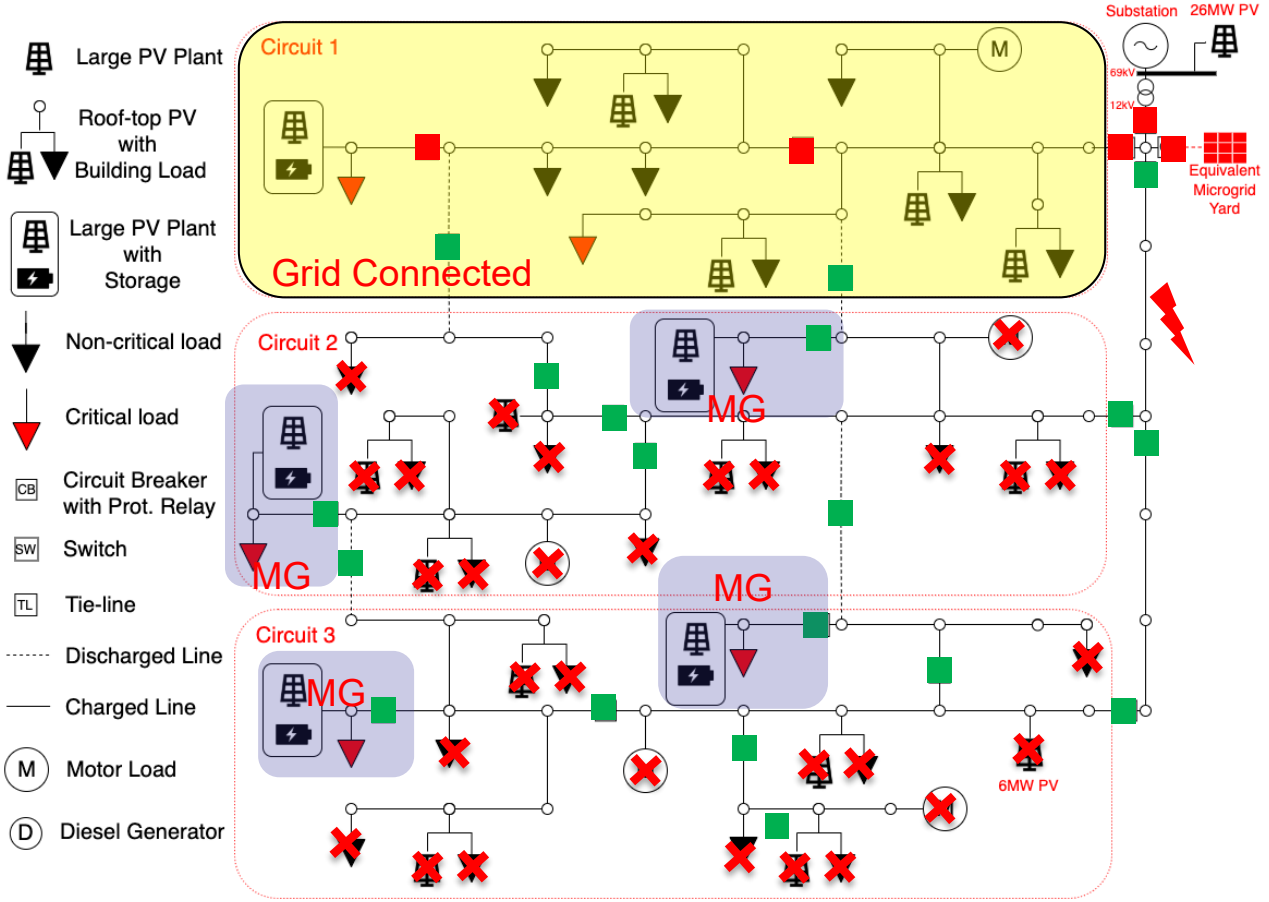


Progress and Results – FY20

Task 3—Evaluation and Demonstration

Use Case 1—Fault downstream from Circuit 1

- Circuit 1 is grid connected
- Portions of Circuit 2, 3 are operating as intentionally islanded microgrids
- Roof-top PVs and associated loads are tripped to avoid forming unintentional islands
- A power system section can be charged when all the non-controllable loads in the section can be supported.
- Given the available power, only (some of) the critical loads in Circuits 2, 3 can be supported.

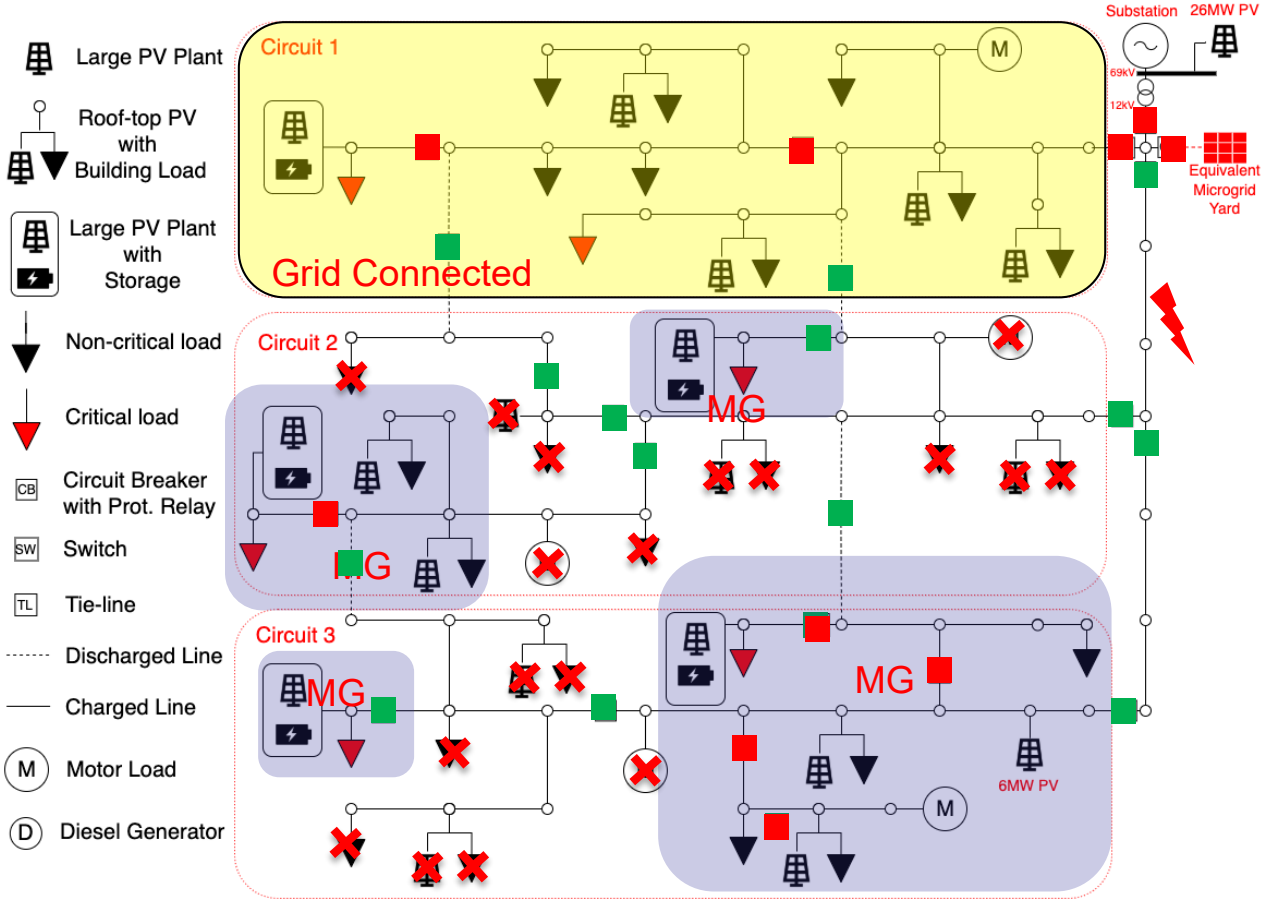


Progress and Results – FY20

Task 3—Evaluation and Demonstration

Use Case 1—Fault downstream from Circuit 1

- Forming the largest possible non-networked microgrid
- Circuit 1 is grid connected
- Portions of Circuit 2, 3 are operating as intentionally islanded microgrids
- Some microgrids pick up load outside of the MG results. These MGs were able to close the respective switches
- For other MGs, closing the PCC switch doesn't result in supporting all the non-controllable loads. Hence, the switch remained open.

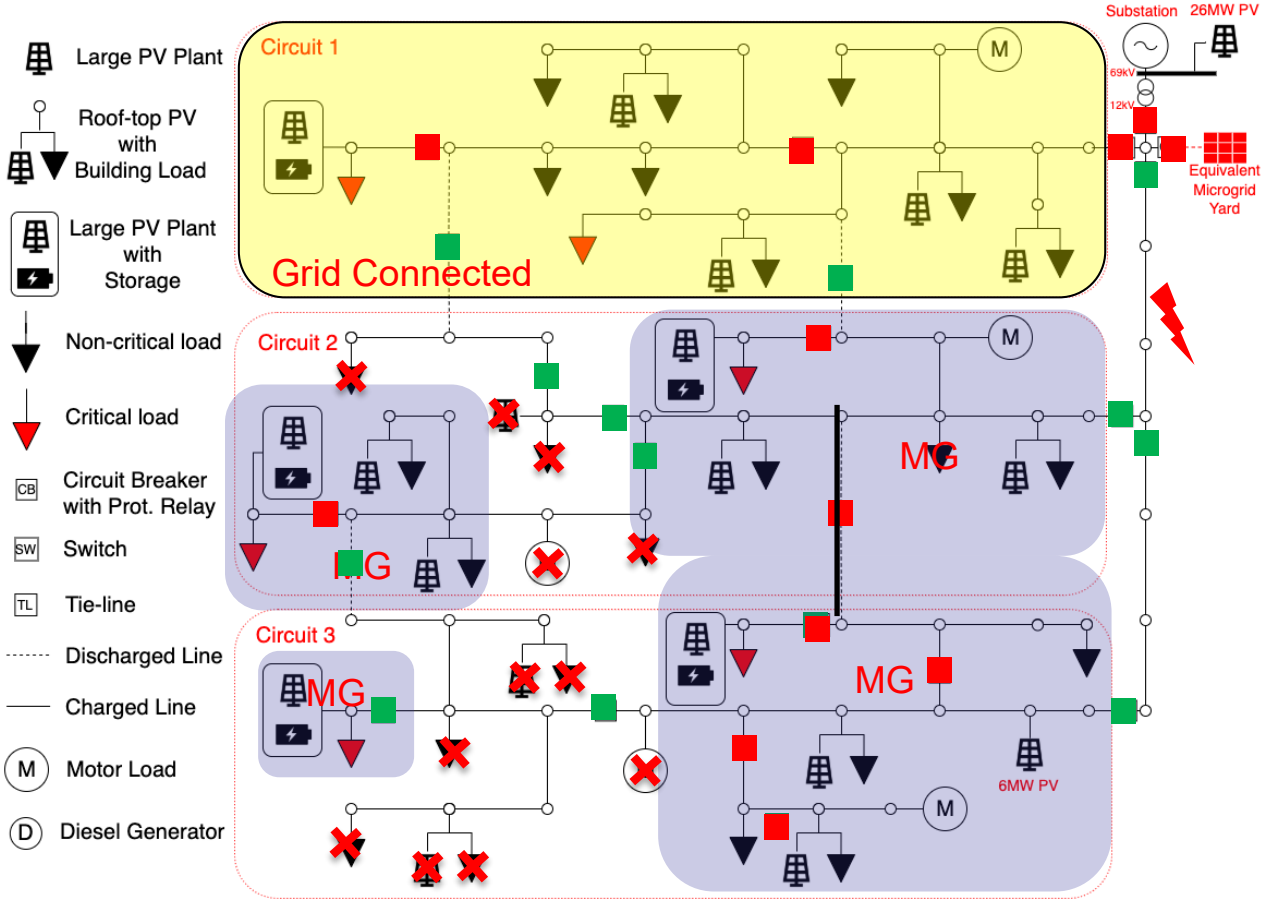


Progress and Results – FY20

Task 3—Evaluation and Demonstration

Use Case 1—Fault downstream from Circuit 1

- Circuit 1 is grid connected
- Portions of Circuit 2, 3 are operating as intentionally islanded microgrids
- For some of the microgrids, picking up load outside of the MG results in supporting more non-controllable loads. These MGs were able to close the respective switches
- For other MGs, closing the PCC switch of an existing MG doesn't result in supporting all the non-controllable loads. Hence, the switch remains open.

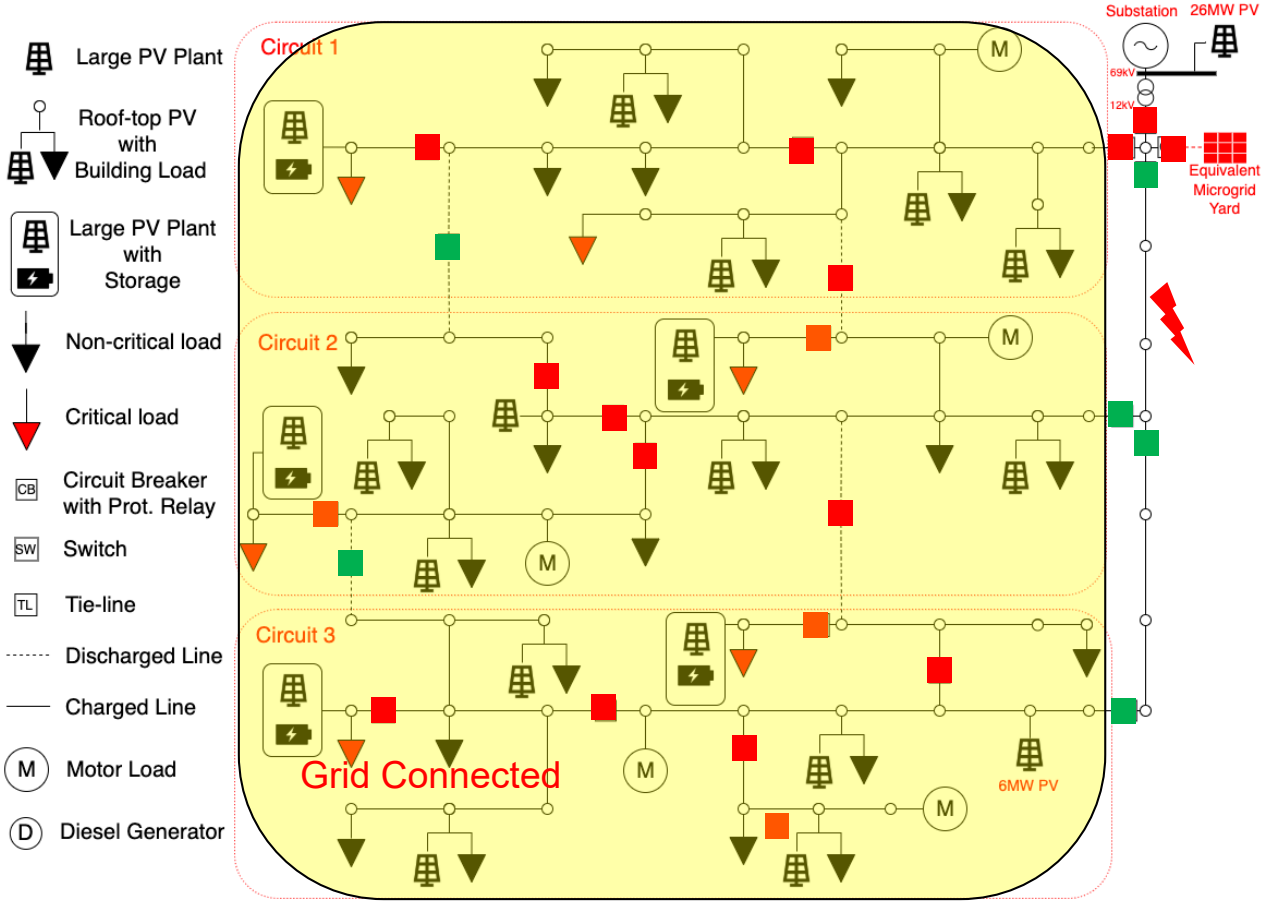


Progress and Results – FY20

Task 3—Evaluation and Demonstration

Use Case 1—Fault downstream from Circuit 1

- Largest possible system formed
- By optimizing the topology of the MGs formed incrementally, a grid connected topology is possible to support an even larger system.
- The resulting system needs to be able to operate stably and support all non-controllable loads, without violating the system limits (like voltage, or line loading)



Progress and Results – FY20

Task 4—Deployment and Outreach

Industrial Advisory Board

- June 9, 2020
- Solicit information on industry perspective and challenges faced when networking microgrids,
- Obtain critical assessment of project direction
- Identify collaboration opportunities with Citadels project

Organization	Members
San Diego Gas and Electric	Tom Bialek, Laurence Abcede, Amin Salmani
National Rural Electric Co-op Association	David Pinney
Siemens	Siddharth Bhela
Orange and Rockland	Mark Mcguire
Southern Company	Andrew Ingram
EPB	Jim Glass
Hawaiian Electric	Darren Ishimura
Today's Power	Justin McCann
Cobb EMC	Manish Murudkar
Anza EC	Kevin Short
Georgia Transmission	Christina Alston
Poudre Valley REA	Milton Geiger

Progress and Results – Milestones

Milestones, Deliverables, and Go/No-Go in FY20 and FY21

Milestone Name/Description	End Date	Type
Lifecycle Development Plan	3/15/20	Deliverable
Industrial Advisory Group Meeting	6/9/20	Milestone
Report detailing formulations of the objectives and constraints of the optimization-based recovery algorithm which are used to model requirements on system stability, device protection, regulatory restrictions, and economic considerations.	9/30/20	Deliverable
Designs completed for HIL evaluation frameworks for implementing networkable microgrid use cases.	1/15/21	Annual Milestone
Paper submitted for peer-review detailing RONM methodology for combining reconfiguration operation models with restoration models.	2/28/21	Deliverable
Demonstration of RONM methodology on one IOU system with more than 500 nodes. Criteria: Feasibility of solution validated with software simulations	2/28/21	Go/No-Go
Industrial Advisory Group Meeting	4/30/21	Milestone
Version 1 of RONM software which implements algorithm for resilient operations and recovery of networked microgrids.	6/30/21	Deliverable

Tech Transfer – Laboratory Collaboration

Los Alamos National Laboratory (LANL)—LANL leads the project and is responsible for the execution of the program plan. LANL will be heavily involved in developing the mathematical formulations, optimization-based algorithms and software development.

National Renewable Energy Laboratory (NREL)—NREL will develop electrical distribution for evaluating the optimization-based methods developed by LANL. NREL will first evaluate these methods using software simulation tools and then develop an HIL evaluation platform for demonstrating the RONM algorithms. NREL will also provide input to LANL on regulatory restrictions that need to be considered within RONM and develop cash flow models for operating networked microgrids.

Sandia National Laboratory (SNL)—SNL will develop system protection strategies and design methods to create example protection designs. In particular, SNL will demonstrate the ability of the system protection design methods to clear faults for bi-directional current flows and reconfigure the network to achieve improve resiliency metrics.

Tech Transfer – Industry Collaboration

National Rural Electric Cooperative Association (NRECA)—NRECA will provide support for the project through the development of a software interface and conduct industry outreach to demonstrate the effectiveness of the tool.

Julia Computing—Julia computing will advise on how to best integrate a Julia software stack into the established platform and provide work arounds and bug fixes for core-Julia issues that are identified during the deployment process.

San Diego Gas and Electric—As part of the use case development process, SDG&E will provide distribution system models, access to microgrid technology data, and voltage information for validation. SDG&E will also provide guidance on extreme event models of concern to the distribution systems.

Solcast—Access to solar forecasting and estimated actuals data products which will support modeling of renewable energy sources in microgrid during restoration activities.

Emera Technologies—DC microgrid modeling support and access to DC microgrid models.

Gurobi—Software licenses for the Gurobi optimization software to support the ROMN project

Industrial Advisory Board—EPB, Hawaiian Electric, Southern Company, Orange and Rockland, Siemens

Tech Transfer - Technical References

Publications

- A. Barnes, J. Tabarez, R. Bent, M. Reno, S. Hossain-McKenzie, R. Matthews. *PowerModelsProtection.jl: A Julia Package for Representing Protection in Power Systems Optimization Problems*, Western Protective Relay Conference, 2020, under review.
- K. Schneider, H. Nagarajan, A. Pratt, M.J. Reno, B. Ollis, F. Tuffner, et al, *Preliminary Design Process for Networked Microgrids*, submitted to IEEE Access.
- 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,
- Flores-Espino, and A. Pratt, *The Regulatory Path Forward for Networked Microgrids*, T&D World, May 21, 2020.
- G. Byeon, H. Nagarajan, R. Bent, P. van Hentenryck. *Communication-Constrained Resilient Distribution Grid Design*, INFORMS Journal of Computing, to appear.
- 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.

Tech Transfer - Technical References

Invited Talks

- R. Bent. *Advanced Distribution Modeling Panel*, TechAdvantage Conference, Feb. 2018
- G. Byeon, R. Bent, P. van Hentenryck, H. Nagarajan. *Communication-constrained Resilient Distribution Grid Design*. INFORMS Annual Meeting 2017, 2018
- H. Nagarajan. *Optimal Resilient Grid Design of Distribution and Transmission Systems*. INFORMS International Conference, June 2016, Hawaii.
- R. Bent. *Optimal Resilient Distribution Grid Design using a 3-phase Unbalanced AC Power Flow*, INFORMS Annual Meeting, Nov 2015, Philadelphia, PA.
- R. Bent. *Optimal Resilient Distribution Grid Design*. INFORMS Annual Meeting, October, 2015, San Francisco, CA.

Open Source Software

- 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.

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Key Elements to be Addressed in the Ensuing Slides

- Significance and Impact
  - Industry need/challenge being addressed by the project
  - Specific improvements/advancements targeted by the project with respect to reliability, resiliency, affordability, flexibility, security, and/or sustainability of electricity delivery
- Approach
  - Innovative aspects of the approach
  - Validity and likelihood of success of the approach in accomplishing the project's objectives/outcomes
- Progress and Results
  - Prior-year progress and results (1 slide)
  - FY20 project progress including major accomplishments, results, findings, and lessons learned
  - Key tasks, milestones, go/no-go criteria, and schedules for the remainder of FY20 and FY21
- Tech Transfer Activities
  - Industry project collaborators and role (participating and advisory)
  - Conference presentations, peer reviewed papers, articles, and other products
- Contact information (name/address/phone/email of presenter(s) and PI)

General Guidelines

- Address all key elements provided in the preceding slide, with emphasis on FY20 progress and planned activities for the remainder of FY20 and FY21.
- All projects are slotted for 40 minutes each (30 minutes for presentation + 10 minutes for Q/A).
- Don't include proprietary information in the presentation or project summary, as both will be published for open access.
- The presentation and project summary are due COB on Thursday, 4 June, to Diane Littau (diane.littau@nrel.gov). Information received as of then will be sent to all peer reviewers for review before the meeting.

Back-up Slides

Include any back-up slides you would like to provide to the peer reviewers and DOE program managers for additional information. The back-up slides will not be shared with others, unless specifically stated by the presenter.