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Networked Microgrids Scoping Study

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EXECUTIVE SUMMARY

Much like individual microgrids, the range of opportunities and potential architectures of networked microgrids is very diverse. The goals of this scoping study are to provide an early assessment of research and development needs by examining the benefits of, risks created by, and risks to networked microgrids. At this time there are very few, if any, examples of deployed microgrid networks. In addition, there are very few tools to simulate or otherwise analyze the behavior of networked microgrids. In this setting, it is very difficult to evaluate networked microgrids systematically or quantitatively. At this early stage, this study is relying on inputs, estimations, and literature reviews by subject matter experts who are engaged in individual microgrid research and development projects, i.e., the authors of this study

The initial step of the study gathered input about the potential opportunities provided by networked microgrids from these subject matter experts. These opportunities were divided between the subject matter experts for further review. Part 2 of this study is comprised of these reviews. Part 1 of this study is a summary of the benefits and risks identified in the reviews in Part 2 and synthesis of the research needs required to enable networked microgrids.

NETWORKED MICROGRID PROGRAM GOALS

The following two goals and associated sub goals are qualitatively consistent with the individual settings considered in this report. The quantitative aspects of these high-level goals are based on best estimates from the individual settings described in this report.

As compared to a baseline of individually designed and operated microgrids, networked microgrids will achieve the following goals:

Goal #1: During extreme event outages, improve customer-level reliability and resilience by:

- Extending duration of electrical service to critical loads by at least 25%
- Maintaining electrical service for all critical loads during a single generator contingency in any microgrid
- Lower capital expense by at least 15%

Goal #2: During normal distribution grid operations

- Reduce the utility cost of serving the microgrids by at least 10%

RESEARCH AND DEVELOPMENT OUTCOMES—SUMMARY

Achieving these program goals requires research into and development of tools and technology for design and planning of networked microgrids and for the operations of networked microgrids. Within these two broad areas, the developed tools and technology should enable the following outcomes:

DESIGN AND PLANNING

- Regulatory environment—The study of the general classes of regulatory environments and their impacts on the networking and networked control of microgrids to guide the research and development in many of the other areas listed below.
- Business case evaluation—Within several classes of regulatory environments, the evaluation of business cases for networked microgrids to identify economically advantageous capabilities and services networked microgrids may provide to the microgrid owner, host utility, and utility/owner beyond those provided by a similar set of microgrids operated individually. The identified capabilities may inform architectural designs and network controller capabilities.
- Architecture design and use cases—The design and analysis of enabling physical, control, and information architectures to support the most advantageous business cases identified. Potential architectures should address all aspects internal to the networked microgrids and important external interactions (e.g., markets and utility distribution management systems). Researchers should document architectures via use cases for the microgrid controller and specify how relevant optimization, control, and protection actions are implemented across all necessary time scales.
- Dynamical system interactions—The analysis of dynamical interactions of a high penetration of microgrids and networked microgrids, including small signal stability, transient stability and voltage collapse, following both planned and unplanned disturbances in the bulk and distribution power systems.

SYSTEM OPERATIONS

- Network controller development—The development of networked microgrid controllers that incorporate and maximize the benefits within the identified business case opportunities, operate within the identified potential architectural designs, and perform the full range of use cases.
- System and network state estimation—The development of autonomous networked microgrid controllers to estimate the state of utility-owned circuits so that these controllers avoid taking actions that may create safety issues or damage equipment, especially in cases of physical damage to utility systems where such information may not be available from the utility.

RESEARCH AND DEVELOPMENT—FUNCTIONAL REQUIREMENTS AND TECHICAL CAPABILITIES

The outcomes discussed above require many new modeling, simulation, optimization and control functions. The details of these functions are discussed in the body of the report. The technical capabilities required to achieve these functions are discussed in the Appendix

PART 1: SCOPING STUDY APPROACH AND SUMMARY[1]

INTRODUCTION

The goals of this scoping study are to provide an early assessment of the benefits of, risks created by, and risks to networked microgrids. The intent is to provide input to potential research and development investments to enable the development and deployment of networked microgrids and achieve the goals and benefits described in this report.

RELATIONSHIP TO INDIVIDUAL MICROGRIDS

Individual microgrids are beginning to demonstrate their value to their owners and to host utilities including, but not limited to:

- Resilience benefits when microgrids are able to serve their loads when the host power system has suffered severe physical damage[2]
- Reliability benefits and/or deferral of upgrade costs by serving specific load pockets with poor reliability metrics
- Mitigation of the effects of intermittent renewable generations[3]

As owners and host utilities realize the benefits of individual microgrids, it is natural to ask if networking microgrids at the physical layer, control layer, or both will expand these benefits or capture benefits that cannot be achieved if microgrids are operated individually. This scoping study estimates the potential benefits and risks associated with networking microgrids and identifies the research needs to enable networking of microgrids. These tasks are approached by considering several possible opportunities for microgrids networked at the physical layer, the control layer, or both.

WHAT IS A NETWORKED MICROGRID?

Microgrids may be “networked” at the physical layer, the control layer, or both. For physical networking, microgrids are connected by the distribution grid, which may occur via primary or secondary voltage conductors that are utility or privately owned. The microgrids may not always be networked, but become networked after the closing of one or more normally open switches. This switching may be associated with an off-normal event that results in an outage or, possibly, physical damage to the distribution grid.

For control networking, independent local controllers may manage the microgrids. Another controller that has some visibility into each of the networked microgrids coordinates the

[1] Primary author: Scott Backhaus, Los Alamos National Laboratory
[2] http://www.tecogen.com/Collateral/Documents/Common/2012.11.05%20Providing%20Utility%20Independence%20with%20photos.pdf
[3] https://www.smartgrid.gov/files/SRJ_DOE_Final_Report_Submitted_20140717.pdf

objectives and operations of these independent controllers at a higher level. Figure 1 shows one possible reference architecture consistent with the discussion above.

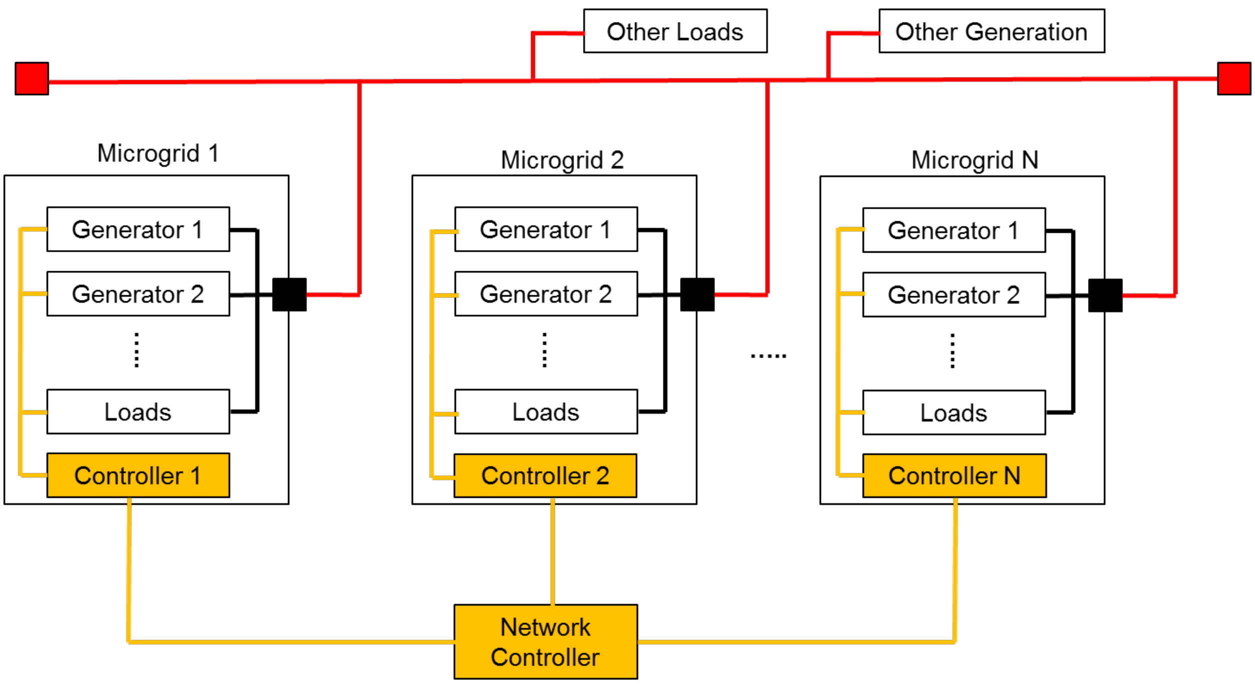

FIGURE 1. ONE POSSIBLE REFERENCE ARCHITECTURE FOR NETWORKED MICROGRIDS AT BOTH THE PHYSICAL AND CONTROL LEVELS

SCOPING STUDY: APPROACH AND STRUCTURE

Much like individual microgrids, the range of opportunities and potential architectures of networked microgrids is very diverse, however, there are very few, if any, examples of deployed microgrid networks. In addition, there are very few tools to systematically or quantitatively simulate or otherwise analyze the behavior of networked microgrids. In this setting, it is very difficult to evaluate the benefits of, risks created by, and research needs required to enable networked microgrids. At this early stage, this study relies on inputs, estimations, and literature reviews by subject matter experts who are engaged in individual microgrid research and development, i.e., the authors of this study.

The structure of this study was determined by gathering input from the subject matter experts about the potential opportunities provided by networked microgrids. These opportunities were divided between the subject matter experts, requesting that they:

1. Describe the opportunity
2. Describe one or more possible networked microgrid architectures that would enable the opportunity
3. Discuss the potential benefits provided by the networked microgrids above and beyond

that provided by the microgrids operated individually

4. Discuss the potential risks created by the networking of microgrids and the potential risks that may prevent the deployment of networked microgrids
5. Discuss the challenges to be overcome to realize the potential benefits previously identified.

Each of these individual evaluations is included in Part 2 of this report. Part 1 summarized the results of the individual evaluations and synthesizes these into set of research goals, outcomes and requirements to enable the development and deployment of networked microgrids.

POTENTIAL FOLLOW-ON STUDIES

Several national laboratories are developing design and analysis software tools that partially address some components of the quantitative evaluation of economic, reliability, and resilience benefits of networked microgrids. These studies are expected to be completed in calendar year 2016 and will provide a companion report to this study.

SUMMARY OF THE BENEFITS AND RISKS FROM PART 2

Detailed discussion of the benefits and risks of each opportunity for networking of microgrids is given in Part 2. Here, we provide a summary of the benefits and risks.

POTENTIAL BENEFITS OF NETWORKED MICROGRIDS

The benefits of networked microgrids may be very different, depending on the investment and operational environments and if these environments are coordinated with the host utility. These environments include 1) both investments and operations coordinated with the host utility, 2) customers drive the investments but the utility coordinates operations, and 3) customers drive the investments and coordinate with each other as possible.

Within each of the investment and operational environments, there are several potential benefits to consider:

<u>Interoperability</u>—Developing networked microgrid systems will promote standardization and significantly enhance interoperability of microgrids and their technologies. However, within the scope of this study, it is extremely difficult to quantify the benefits this type of standardization.

<u>Reliability</u>—Individual microgrids are already expected to improve the reliability of electrical service to loads they serve, well beyond typical utility reliability metrics.[4] Networking of microgrids is expected further improve reliability to microgrid-native loads by reducing the utility outages not mitigated by the locally-serving microgrid. The value of eliminating these residual outages should be balanced against the cost of microgrid networking, however, there

[4] Microgrid Research, Development, and System Design. Funding Opportunity Number: DE-FOA-0000997

may be capital cost benefits via pooling of backup generation across networked microgrids (discussed below) or reliability benefits to other loads not within the microgrids themselves but connected nearby via the distribution grid.

Pooling of backup generation resources—Networked microgrids support shared generation resources for critical loads, which reduces the aggregate investment costs for backup generation. General sizing guidelines suggest the peak of the critical load should be approximately 80% of capacity of the backup generator.[5] For example, we make a naïve assumption that two microgrids have a critical load with a peak-to-average ratio of approximately 2:1 (1 megawatt (MW) peak and 500 kilowatt (kW) average) and that the peaks of the two microgrids are not coincident. Instead of buying two generators, each with 1 MW/0.80 = 1.25 MW of capacity (or a total capacity of 2.5 MW), the total capacity of the networked system is 1.5 MW/0.80 = 1.88 MW. The reduction in capacity of 620 kW is equivalent to approximately $186,000 at a roughly estimated installed cost of $0.30/W for a diesel generator.

Resilience— For the depth and purposes of this study, the benefits to resilience are expected to somewhat parallel the benefits to reliability. Individual microgrids are already expected to improve the resilience of the electrical service to loads they serve during extreme events. Networking of microgrids will enable the pooling of generation resources between microgrids and with nearby loads in the distribution grids, which may lead to additional resilience and potentially lower capital costs.

Bilateral (out of market) transactions—Networked microgrids may be able to exchange power over utility lines or, alternatively, behind a common or virtual utility meter, outside of utility or wholesale markets. If the net energy metering transitions to a situation where energy fed back to the utility system is paid at a wholesale rate (i.e., at the avoided cost) while energy consumed is paid at a retail rate, bilateral transactions would allow networked microgrids to avoid energy exports and continue to receive, in aggregate, the retail value of the energy produced. In many regions, this price spread can amount to $50/MW-hour.[6] For example, if several 1-MW capacity networked microgrids are able to avoid a 1-MW export of overproduction for 4 hours each day (e.g., from photovoltaic (PV) generation of higher capacity than native load), increase in value to the aggregate microgrid system is $73,000/year.

Resource aggregation to enable wholesale market participation—Networked microgrids enable generation and reactive power support pooling to meet minimum capacity requirements for participation in utility wholesale energy and ancillary service markets. In some market areas, this pooing could amount to a major benefit by enabling microgrids to tap into revenue streams that individual microgrids would be too small to capture. However, reductions in the minimum capacity bids in ancillary service markets[7] and emergence of third-party aggregators[8] may make

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[5] Siemens, "Generator Sizing Guide," 2011, www.downloads.siemens.com/download-center/Download.aspx?pos=download&fct=getasset&id1=BTLV_40972 .
[6] U.S. Energy Information Administration, "Average Retail Price of Electricity to Ultimate Customers. by End-Use Sectors 2003 through 2013 (Cents per kilowatthour), www.eia.gov/electricity/annual/html/epa_02_04.html.
[7] http://www.pjm.com/~/media/documents/manuals/m11.ashx
[8] Enabla, www.greentechmedia.com/articles/tag/enabla.

this benefit less relevant.

RISKS ASSOCIATED WITH NETWORKING OF MICROGRIDS

There are several risks to the networking of microgrids and several risks introduced by networking of microgrids, which we divide into the following categories:

- Business Model
  - Economic risk—The competing economic interests of different microgrid owners and the host utility (which may also be a microgrid owner) over different timescales may discourage the networked control of microgrids.
  - Utility business model risk—Capturing economic benefits may require alternative metering arrangements that are not available in all areas, e.g., virtual aggregation of utility revenue metering across multiple microgrids.
  - Integrated resource planning—Customer-driven microgrid installations may invalidate the assumptions of utility Integrated Resource Plans affecting the accuracy of these plans and the profitability of the utility.
- Technical—Power Systems
  - Safety risk—Microgrid networking over utility-owned distribution-voltage circuits potentially introduces public safety issues by allowing microgrid controllers to make decisions regarding energizing conductors.
  - Equipment damage risk—Networking of microgrids, especially in islanded situations, raises the possibility that actions in one microgrid, e.g., generation tripping, load tripping, load changes, or bulk grid reconnection., may induce damage or unacceptable wear to equipment in another microgrid
  - Reliability risk—Interactions of the microgrid controllers and the network-level control may lead to an increased risk of cascading outages from impacts to bulk power system stability over a wide range of time scales, including voltage stability, small signal stability, and transient stability. The impacts may be magnified by insufficient understanding and modeling of the tripping and ride-through capability of microgrids and networked microgrids.
  - Urban networks—The meshed structure of low-voltage urban networks makes the isolation and reconnection of a smaller networked microgrid via network switching difficult. Network protectors in these low-voltage networks also limits the ability of networked microgrids to exchange power.
- Technical—Interoperability
  - Inter-microgrid communications and control—Without adequate and sufficiently early standards, there is significant risk that individual microgrid communications, protocols, and control systems will be incompatible with each other and create a large impediment to subsequent coordination via network-level controllers.

- Microgrid-utility communications and control— Similar issues apply to standards and interoperability between network-level microgrid controllers and utility SCADA or other legacy utility equipment.

- Technical—Communications
  - Communications failure and continuity of operations—The architectures proposed in this study require additional communications for control and optimization. The cost of these communications is one risk, but the loss of these communications may create undesirable effects on the power system.
  - Cybersecurity—The additional layers of communications increases the control system attack surface creating additional vulnerabilities
- Regulatory
  - Disallowed transactions—Networking of microgrids and the exchange of power over utility-owned distribution-voltage circuits likely requires adaptation of regulatory frameworks to allow for these transactions.
  - Quality of Service—Significant penetration of network microgrids may affect the quality of service to surrounding customers in a manner that is outside of the control of the host utility, even though the host utility has responsibility for quality of service in this environment
  - Emissions—The emissions of fossil-fired generation potentially contained within a microgrid contributes the overall emissions of the host power system, but the responsibility for accounting for and managing these emissions would likely fall to the host utility.

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Goal #2: During normal distribution grid operations

- Reduce the utility cost of serving the microgrids by at least 10%

RESEARCH AND DEVELOPMENT—OUTCOMES

Achieving these program goals requires research into and development of tools and technology for design and planning of networked microgrids and for the operations of networked microgrids. Within these two broad areas, the developed tools and technology should enable the following outcomes:

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- Business case evaluation—Within several classes of regulatory environments, the evaluation of business cases for networked microgrids to identify economically advantageous capabilities and services networked microgrids may provide to the microgrid owner, host utility, and utility/owner beyond those provided by a similar set of microgrids operated individually. The identified capabilities may inform architectural designs and network controller capabilities.
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RESEARCH AND DEVELOPMENT—FUNCTIONAL REQUIREMENTS

The R&D objectives and functional requirements described below focus on off line planning and evaluation tools to develop validated system designs that will achieve the high-level goals discussed above. Real-time, industrial-grade operational tools require considerations and capabilities typically beyond those addressed by national laboratories. However, the foundation laid by the R&D described below would support the subsequent development of operational tools by industry, potentially in partnership with DOE and national laboratories.

Realization of the potential benefits of networked microgrids requires significant research, development and validation of modeling, simulation and optimization tools. These tools may be created by adapting existing tools developed by DOE for distribution networks and individual microgrids and integrating them to address networked microgrids. For some aspects, new development of modeling, simulation and optimization is required to fully address the complexity of network microgrids. Overall, the research and development should yield a suite of validated tools that address a wide range of functional requirements for optimal design, optimal operations, and system simulation:

- Under "normal" grid operational situations where operations are primarily driven by economic considerations, the evaluation of networked microgrid business cases and the impacts of different operations and control paradigms on those business cases. It is anticipated that networked microgrids may be operated in a range of paradigms including completely independent microgrids, centrally coordinated via the distribution system operator, and distributed optimization and control. Business case evaluation and optimization should account for both market and non-market settings.
- Under "normal" grid operational situations where component failures are limited in scope, the evaluation of system-level and customer-level reliability and system design to improve reliability.
- Under "extreme" grid operational situations where component failures are extensive, the evaluation of the resilience posture of networked microgrid systems and the distribution network they are integrated into and coordinated system design to improve resilience.
- Combined design of individual microgrids (e.g. generation and storage assets, system layout, etc) and the integrating distribution network to maximize and balance the economic, reliability and resilience benefits to the microgrids and distribution network while minimizing the construction and integration costs.
- Aggregation and joint management of uncertainty for improved control of variable and stochastic resources in distribution networks.
- Evaluation of the dynamic feasibility of microgrid operations and control. In contrast to the bulk power system or even traditional distribution systems, both microgrids and networked microgrids have lower generation and surge/inrush capacity. Intentional switching or protection-driven operations create dynamical transients that have severe impacts on generation assets. The feasibility of these transients must be properly accounted for to avoid overly optimistic system design and operations that bias the evaluation of business models

- The low inertia of microgrids and tight coupling via distribution networks creates faster dynamical transients. The optimal designs and operations must account for the latency and reliability of communications and controls in the assessment of dynamical stability, protection, and survivability of networked microgrids.
- The networking of microgrids creates simultaneous interaction of many communications, dynamical, control and optimization effects. Although each may be accurately modeled accurately, the interactions between them can lead to destabilizing effects. Controller In the Loop (CIL) and/or Hardware In the Loop (HIL) testing via RTDS or other similar means is needed to validate the modeling of these interactions and the resulting stability boundaries of switching and protective actions. Validation of the solutions provided by the optimal design and operations tools will provide confidence in the tools when applied to more general settings.

POTENTIAL PATHWAYS TO ACHIEVE FUNCTIONAL REQUIREMENTS

A range of planning, operations, and simulation tools relevant to networked microgrids have been developed by DOE, other agencies, and private industry; however, these tools generally only address a subset of the objectives and challenges discussed above. Here, we summarize the general qualities of the individual design tools and suggest one pathway for leveraging these tools by integrating them into a single Networked Microgrid Optimal Design and Operations (OD&O) tool.

EXISTING PLANNING, OPERATIONS AND SIMULATIONS TOOLS

These individual tools can be grouped into several general categories:

Microgrid design tools seek to find advantageous configurations of microgrid generation in an individual microgrid.[9] Generally, these tools seek to maximize the economic value of a single microgrid by maximizing microgrid revenue (e.g., by minimizing the microgrid energy bill) while minimizing the capital expenditure on generation assets. Although there a few exceptions,[10] these design tools do not directly consider reliability or resilience of the microgrid. They also do not consider the interaction of multiple microgrids over a distribution network or the different optimization and control paradigms possible in this networking environment.

The Office of Electricity within the Department of Energy is funding new distribution network design tools[11] that seek to improve the resilience of distribution grids to extreme events where multiple components of the distribution network are out of service. These design tools optimize the hardening or redundancy upgrades of the distribution network while modeling microgrids as single-node components with generation capacity. Without the ability to resolve generation dispatch inside the microgrid, these tools are limited in that they cannot evaluate or optimize the

[9] DER-CAM: https://building-microgrid.lbl.gov/projects/der-cam , HOMER: http://www.homerenergy.com/ , MDT: file:///C:/Users/146840/Downloads/MDT_Factsheet_SAND2015-10341O_FINAL.pdf c

[10] Design tools currently in development in the DOE Office of Electricity ROMDST program: http://www.netl.doe.gov/File%20Library/Business/solicitations/RC-ROMDST-2015.pdf

[11] For example, the Resilient Distribution Design Tool (RDDT) [Grid Modernization Laboratory Consortium project GM0057]

generation configuration inside the microgrid for economic purposes during normal operations or evaluate or optimize the long-term operations of generation during extreme event outages.

Distribution network simulators[12] model both the quasi-static power flow and dynamical transients of distribution networks and connected distributed energy resources, including different generation types. These simulators are able to evaluate the dynamical stability and trajectory feasibility of the network and generation assets following intentional switching, protective actions, or other similar fast time scale events. However, as simulators, these tools are not adequate for finding optimal distribution network design or microgrid generation configuration design. Also, these simulators generally do not models communications or its impact on dynamical transients.

Hardware In the Loop (HIL) or Controller In the Loop (CIL) testbeds enable the co-simulation of communications, controls and power systems components (including protective elements and switching). By using actual communications and control components or realistic digital emulators of these components, HIL/CIL is able to accurately capture the interfaces between important components and subsystems of distribution networks and microgrids. However, these testbeds are simulators. They are extremely useful for validation of component and system models, but do not provide any guidance relative to optimal system design for resilience, reliability, or economic performance.

POTENTIAL INTEGRATIONS OF EXISTING TOOLS AND ASSOCIATED CHALLENGES

No single class of tool described in the previous section fully address the functional requirements discusses above. However, previous DOE investment in these tools may be leveraged by integrating them into a planning, operations, and simulation suite for networked microgrids. Figure 2 shows one potential approach to achieve this integration to create an optimal design and operations tool for network microgrids that also accounts for system dynamics. Not shown in Figure 2 is a HIL/CIL testbed simulation of the resulting design and operations to validate the solutions.

The Networked Microgrid Optimal Design and Operations (OD&O) tool is a Distribution Network OD&O tool nested with individual Microgrid OD&O tools in a feedback loop. The distribution network OD&O stage finds optimal network hardening and topology and microgrid capacities to achieve a desired system-level reliability and resilience performance against a set of prescribed reliability and resilience events. At each iteration of the design and operations optimization, a distribution network simulator is executed to check the dynamical feasibility of the topology changes and guide the optimization.

The microgrid capacities from the Distribution Network OD&O are passed to individual Microgrid OD&O tools which optimize the generation configuration and “normal” system operations of each microgrid placed in the network. The optimization yields the economic and technical performance of each microgrid and a system-level economic and technical

[12] Gridlab-D: http://www.gridlabd.org/

performance. These result are aggregated with the system-level reliability and resilience performance and fed back to the Distribution Network OD&O for another iteration of the Distribution Network OD&O.

Although the process in Figure 2 is described in terms of optimal design, components of the process can be used to assess optimal operations and to evaluate business cases for particular configurations of networked microgrids.

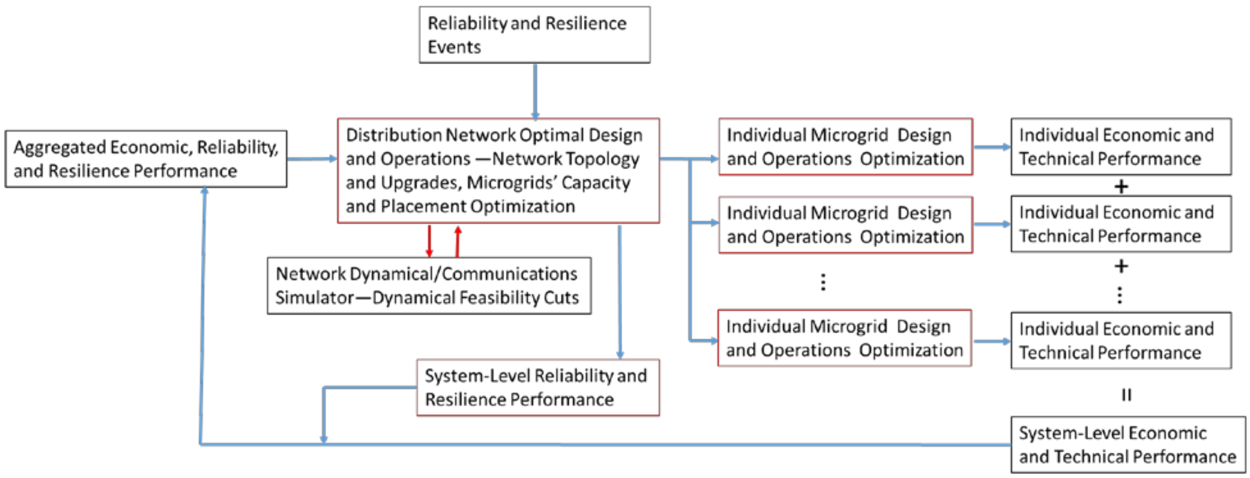

FIGURE 2. SCHEMATIC OUTLINE OF ONE POSSIBLE ITERATIVE DESIGN LOOP THAT INTEGRATES NETWORK-LEVEL DESIGN AND OPERATIONS, MICROGRID-LEVEL DESIGN AND OPERATIONS, AND SYSTEM DYNAMICAL FEASIBILITY ASSESSMENT. THESE THREE CLASSES OF TOOLS ARE SHOW IN RED BOXES. THE OUTPUTS OF THESE TOOLS ARE SHOWN IN BLACK BOXES. THE FINAL DESIGN AND OPERATIONAL PROPERTIES ARE COMPARED AGAINST A HIL/CIL TESTBED (NOT SHOWN) TO VALIDATE AND IMPROVE THE ACCURACY OF THE MODELING, SIMULATION AND OPTIMIZATION TOOLS.

RESEARCH AND DEVELOPMENT—TECHNICAL REQUIREMENTS

The technical requirements that form the basis for the functional requirements discussed above are included in the Appendix.

PART 2: EVALUATION OF INDIVIDUAL OPPORTUNITIES FOR NETWORKED MICROGRIDS

NEW YORK OPPORTUNITIES: REFORMING THE ENERGY VISION AND RELATED DEVELOPMENTS[13]

Opportunity

Under the New York Reforming the Energy Vision (REV), utilities in New York State (NYS) are experiencing an unprecedented transformation in distribution system design, planning, and operation.[14] A principle vision of the REV process is the development of the distributed system platform (DSP), wherein the local utility would act essentially as a balancing authority and utilities will be incentivized to flatten the peak demand for their service territory. This goal would be accomplished by animating the markets at the distribution layer. Developing markets at the distribution layer will lead to increasing deployment of distributed energy resource (DER) (including renewables, energy storage devices, combined heat and power (CHP) generation, etc.) and the interconnection of microgrids. Microgrids would represents a class of DER that could act as load, generation, or both.

Another key objective of the REV is to deploy a more resilient electricity distribution system wherein microgrids are expected to play an important role. One of the NYS REV policy initiatives is the NYPrize Competition, an initiative to develop a number of microgrids statewide. The aim of the competition is to learn more about the value propositions for microgrid development. In addition to the Investor Owned Utilities, NYS municipal utilities are also exploring the value propositions associated with municipal microgrids to manage costs and provide more resilience to their communities. In some cases, these microgrids would encompass the entire municipality.

NYS will need to consider every benefit that a microgrid may offer. A wide spectrum of opportunities related to microgrids include networking, system optimization with networked microgrids, economic optimization, reliability, resilience, and recovery. Market structure is a key issue for incentivizing third-party development of DER, particularly locational and time of day pricing. Assessing these opportunities also requires new valuation tools for DERs, including microgrids.

Architecture

Because distribution network structures in NYS are very diverse, i.e., meshed networks in New York City and radial networks in many other places, there will be different topologies and architectures for networked microgrids. Microgrids may be networked and coupled weakly in the

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[13] Primary authors: Meng Yue and Patrick Looney, Brookhaven National Laboratory

[14] See New York State Department of Public Service, "Reforming the Energy Vision," http://www3.dps.ny.gov/W/PSCWeb.nsf/All/CC4F2EFA3A23551585257DEA007DCFE2?OpenDocument.

sense that radial-feeder-based microgrids are connected at the distribution substation. Alternatively, microgrids may be coupled at multiple points if they are built based on meshed distribution networks. The complexity of coupling at physical layers will pose more challenges and add complexity in the controller layers.

This networking must occur at both physical and control layers to enable the wide range of benefits from resilience to economic optimization and market participation.

Proposed NYPrize projects under consideration are interconnected at sub-transmission, down to primary distribution including low-voltage urban networks, demonstrating the need for physical networking at all voltage levels.

A microgrid can be considered as a balancing authority and networked microgrids are analogous to North American Electric Reliability Corporation (NERC) regions or interconnections. A network controller will need the same control layers that control NERC regions, namely primary (droop control, seconds), secondary (automatic generation control (AGC), minutes), and tertiary controls (economic dispatch, approximately every 30 minutes). Because the inertia in many microgrids is low and any disturbances inside a microgrid may represent a significant fraction of total load or generation, the time resolution needed for primary control in networked microgrids is expected to be fast, i.e., subsecond. Secondary and tertiary control is expected to be on the same time scales as in a NERC region.

To address the automatic or autonomous and interoperable features of networked microgrids, a hierarchical structure of controllers, namely the primary, secondary, and tertiary controls,[15] is suggested, as shown in Figure3.

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[15] W. Bower et al, "The Advanced Microgrid: Integration and Interoperability," SANDIA REPORT, SAND2014-1535, March 2014.

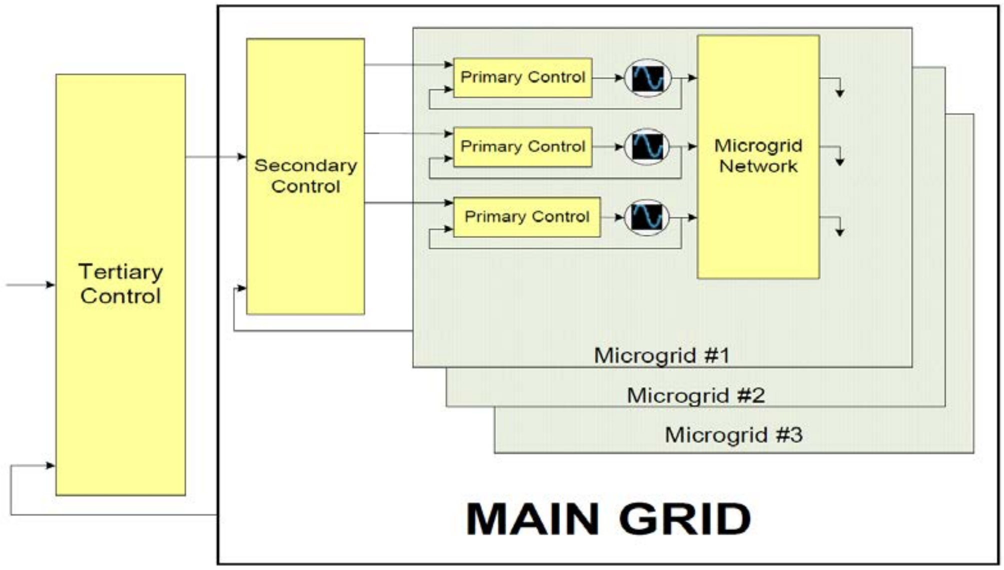

FIGURE 3. CONTROL STRUCTURE OF NETWORKED MICROGRIDS

This architecture is very similar to the frequency control hierarchy in the transmission network. The primary controls are exclusively localized targeting operation of individual devices within the microgrid, e.g., generators, based on local measurements. An energy management system may play the role of the secondary control responsible for generation dispatch, load management, operational mode switching, etc. Market signals also directly impact the amount of power exchange over wires between individual microgrids and therefore, the AGC in the secondary control of networked microgrids. The role for the tertiary control is to coordinate interactions between multiple microgrids and interactions between the microgrids, utility grids, and market/DSP operators by performing, e.g., economic dispatch.

Benefits

The positive impacts or benefits of networked microgrids include:

- Enhanced distributed and renewable energy resources integration: Networked microgrids provide additional flexibility to manage the real and reactive power imports and exports of microgrids, including those that also incorporate intermittent renewable generation. This capability enables the distribution utility to better regulate voltage in radial distribution circuits, but there may be significant value in controlling exports from networked microgrids in meshed urban networks when such exports are detrimental to system operation. The additional flexibility may also enable CHP resources to run more often and more efficiently.
- Grid reliability and resilience enhancement: Networked microgrids can share generation resources for critical loads, thereby reducing the aggregate investment costs for backup generation.
- Resource aggregation: Networked microgrids enable generation and reactive power

support pooling to meet minimum capacity requirements for participation in utility markets.

- Grid modernization and interoperability: Development of new solutions to microgrid technologies and codes and standards will significantly enhance the integration of microgrids and interoperability of multiple smart-grid interconnections and technologies.

In addition, new innovations for networked microgrids can be applied to provide secure and advanced automated or dispatched controls for the legacy electric grid. Networked microgrids will initiate changes to the grid that will contain nearly self-healing sectors in the event of natural disasters or other massive grid failures. Quantification of these benefits will require further research.

Possible Risks

There exist potential negative impacts and one of the major concerns is the possibility for cascading instability of microgrids, which may propagate beyond the distribution systems and enter the transmission system. Networked microgrids in the distribution system that provide significant generation capacity increase the complexity of the power system, bringing additional uncertainty to its stability and potentially increased susceptibility to cascading outages, e.g., via potential disconnections of a large number of microgrids within a short time window and the loss of generation and ancillary support to the grid.

Challenges

Challenges are present on many fronts, including:

- Complexity of communication schemes and networked microgrid controller designs that must operate at multiple levels, i.e., within a single microgrid, between networked microgrids, and between microgrid network controllers and utility distribution management systems
- Resolving the economic and resilience priorities of multiple microgrid owners
- Development of market mechanisms or incentives for third-party investment in microgrids and the networking of microgrids

IMPROVED UTILIZATION OF GENERATION ASSETS[16]

Opportunity

Economic optimization of microgrids entails unit commitment and economical dispatch as well as economical demand response under normal grid-connected operation and while islanded.[17] Compared with microgrids that are operated independently, networked microgrids have the potential to improve economic dispatch of resources in the distribution network, increase utilization of generation assets including renewable energy sources (RES) and energy storage systems (ESS), and reduce the overall operating cost of the distribution network.

Architecture

Networked microgrids can support each other with local generation capacities to minimize the overall operational cost of networked microgrids. This can be achieved both in the grid-connected mode or when they are interconnected while islanded from the main grid. Each microgrid coordinates with others to fulfill its economic and reliability objectives, while maintaining the overall objective at a higher level in the distribution network.

To derive economic optimization benefits, networked microgrids should be networked at both the control layer and the physical layer. In grid-connected mode, the physical-layer networking already exists and the physical network connection is via points of common coupling (PCC) for power exchange. Therefore, only the control layer networking is needed for networked microgrids, but the control layer may also require a virtual meter at the PCC that allows aggregation of load across different microgrids. In islanded mode, the control layer and physical layer are both needed. The control layer network should include two-way communication capabilities, and it may include controllers connected in a hierarchical or distributed manner, each with different objectives.

Economic optimization is not affected by the voltage level of the physical network connection, however, networking at higher voltage levels increases the need for virtual metering of similar solutions to enable the aggregation of generation and load across different microgrids.

For controllers connected in a hierarchical manner, as shown in Figure 1, the network controller is at a higher level than the upper most level of control for individual microgrids, often referred to as tertiary control.[17] An appropriate time resolution is required for the network controller to coordinate the individual microgrid controls with the distribution grid control, which depends on the control scheme of the individual microgrid controllers.

For example, there are three control levels in the Illinois Institute of Technology microgrid:[17]

1) Primary control (time resolution in seconds), which implements droop control for sharing the microgrid load among distributed energy resource (DER) units;
2) Secondary control (time resolution in minutes), which performs corrective action to

[16] Primary author: Annabelle Pratt, National Renewable Energy Laboratory

mitigate steady-state errors introduced by droop control; and

3) Tertiary control (time resolution of one hour), which determines the optimal dispatch of DER units in the microgrid, and manages the power flow between the microgrid and the utility grid.

In this case, the economic optimization may need an hourly time resolution for the network controller.

In general, the limited available literature discusses two control schemes for networked microgrids.[17,18,19,20,21,22,23,24,25] The first scheme is hierarchical control,[17,18,19] as shown in Figure 1, where independent local controllers manage individual microgrids with objectives, such as operational cost and/or voltage deviation minimization. A network controller that has some visibility into the distribution network and each of the networked microgrids coordinates and aggregates the objectives of the individual microgrid controllers at a higher level.

A microgrid aggregator or a distribution network operator usually owns the network controller. The objective of the network controller is to minimize the overall operating cost of the distribution network while maintaining the power flow below the respective power ratings of lines and maintaining the voltage across the distribution network within a predefined range. The overall operating cost may include revenue from participation in real-time markets, including demand response. Note that market participation will require time resolution in minutes from both the individual microgrid controllers and the network controller. In addition, the network controller can directly control some generation assets and loads owned by the microgrid aggregator or distribution network operator. Hierarchical control would have lower control complexity compared to centralized control at the distribution level.

The other scheme is distributed control.[20,21,22,23,24] In distributed control, there is no network controller and each individual microgrid controller communicates with its neighboring counterparts. This scheme is of low complexity for communication and control, because only local communication and power support between neighboring microgrids are involved.

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[17] M. Shahidehpour and M. E. Khodayar, “Cutting campus energy costs with hierarchical control: The economical and reliable operation of a microgrid,” *IEEE Electr. Mag*., vol. 1, no. 1, pp. 40–56, Sep. 2013.
[18] Z. Wang, B. Chen, J. Wang, M. Begovic, and C. Chen, “Coordinated energy management of networked microgrids in distribution systems,” *IEEE Trans. Smart Grid*, vol. 6, no. 1, pp. 45–53, Jan. 2015.
[19] A. K. Marvasti, Y. Fu, S. DorMohammadi, and M. Rais-Rohani, “Optimal operation of active distribution grids: A system of systems framework,” *IEEE Trans. Smart Grid*, vol. 5, no. 3, pp. 1228–1237, May 2014.
[20] J. Wu and X. Guan, “Coordinated multi-microgrids optimal control algorithm for smart distribution management system,” *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 2174–2181, Dec. 2013.
[21] G. E. Asimakopoulou, A. L. Dimeas, and N. D. Hatziargyriou, “Leader–follower strategies for energy management of multi-microgrids,” *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1909–1916, Dec. 2013.
[22]] M. Fathi and H. Bevrani, “Adaptive energy consumption scheduling for connected microgrids under demand uncertainty,” *IEEE Trans. Power Del*., vol. 28, no. 3, pp. 1576–1583, Jul. 2013.
[23] Z. Wang, B. Chen, J. Wang, and C. Chen, “Networked microgrids for self-healing power systems,” *IEEE Trans. Smart Grid*, in press.
[24] E. Dall'Anese, H. Zhu, and G. B. Giannakis, "Distributed Optimal Power Flow for Smart Microgrids", IEEE Transactions on Smart Grid, vol. 4, no. 3. pp. 1464-1475, Sep. 2013.
[25] S. Backhaus, G. W. Swift, S. Chatzivasileiadis, W. Tschudi, S. Glover, M. Starke, J. Wang, M. Yue, and D. Hammerstrom.,“DC Microgrids Scoping Study—Estimate of Technical and Economic Benefits”, DOE Report, Available at http://energy.gov/oe/downloads/dc-microgrids-scoping-study-estimate-technical-and-economic-benefits-march-2015

Benefits

Based on the DC microgrids scoping study,[25] the performance of networked microgrids in terms of economic optimization can be estimated and compared using the metrics below:

- Operating Costs—Present value of total variable cost (primarily energy use, but also including ancillary revenue streams, maintenance, etc.) for a power system to serve an end-use function. The operating cost benefits should be shared among the individual microgrid customers and operators and the microgrid aggregator or distribution network operation that serves multiple microgrids.[25]
- Environmental Impact—The total CO2 emissions produced by the marginal electricity generator used to deliver the net electrical needs at the interface of the microgrid and the local power system.[25]

Models[18,19,20,21,22,23] various methods to show the improvement of control strategies or optimization algorithms on decreasing microgrid operating costs or to show improvements in computational speed from previous algorithms. However, there is little research effort to date that clearly shows the benefit of microgrid networking on the economic optimization. We expect that any reduction in operating costs primarily results from the opportunity to utilize more cost-effective generation sources across multiple microgrids. The networked capacity of DERs would provide more flexibility to adjust the time of energy imports from the grid, which, in turn, reduces costs against a time-of-use tariff, demand charge, or other time-dependent pricing schemes. Networked microgrids may also increase revenue from participating in markets, because of higher generation capacity and diversity to schedule in response to market need. The market structure within which the microgrids operate will have a significant impact on the savings that can be achieved

Control across the networked microgrids could also improve the condition of the distribution system by managing load distribution across the circuits. A network controller with visibility into the networked microgrids with significant renewable generation may achieve substantial operating cost savings by coordinating the aggregate dispatch of fossil generators and battery storage to improve the overall efficiency of operations and reduce aggregate emissions.

Other potential benefits may include:

- Reduction in peak load and/or peak electricity price in the distribution network by sharing the generation capacity in the networked microgrids and decreasing energy imports from the distribution network.
- Creation of new market opportunities for demand side participation. There are minimum bidding requirements in the wholesale markets, e.g., regulation bids. The distribution network operator or microgrid aggregator might participate in the wholesale markets to generate revenue through aggregating multiple microgrids. A microgrid network controller may enable more economic demand response to generate higher revenue. The economic incentive may also give rise to an increasing level of demand side

participation.

Two simple examples below demonstrate how sharing generation capacity in networked microgrids would improve utilization rate of generation capacity and reduce the operating cost.

Example 1: Consider three microgrids with loads of 375 kW, each with a 750-kW generator with a 500-gallon fuel tank. If the microgrids are islanded or if the cost of purchasing power from the utility exceeds the cost of providing power from the generators, the loads are powered by the generators. Without networking, all three generators are dispatched at 375 kW with a capacity utilization rate of 50%. With networking, only two generators are dispatched, each at 562.5 kW with an approximate capacity utilization rate of 75%. Assuming a typical fuel consumption rate of 27.4 gallons/hour at 50% utilization and 39.3 gallon/hour at 75% utilization,[26] the overall fuel consumption rate will be reduced from 82.2 gallons/hour to 78.6 gallons/hour, resulting in fuel cost savings of 4%, or an increase in run time of 50 minutes (if islanded).

Example 2: Consider two microgrids, each with a critical load of 200 kW. One microgrid has 400 kW of renewable DERs and the other has only non-renewable DERs. Assume that the cost of serving 1 kW with non-renewable DERs is $1 per hour, and that for the time period under consideration, the renewable DERs can produce 400kW. In islanded mode, without networking, 200 kW from renewable DERs is utilized in one microgrid; the other microgrid would have to use its own non-renewable DERs to serve the load. The total operational cost in this case is $200 per hour for the microgrid with non-renewable DERs. With networking, the renewable DERs from the first microgrid can serve both microgrids. Assuming that the microgrid with the renewable DERs charges 50 cents per kWh to provide power to the other microgrid, then the first microgrid could earn $100 per hour and the other microgrid's operational cost would be reduced by $100 per hour. In grid-connected mode, consider a situation where the price to purchase electricity from the utility has risen to $2/kWh, but the utility pays only $1/kWh for power generated by DERs. Without networking, the microgrid with renewable DERs would earn $200 per hour, and the microgrid with non-renewable DERs would choose to operate its DERs to reduce the cost to $200/kWh. With networking, assuming that the microgrid with renewable DERs charges $1.50/kWh to provide power to the other microgrid, the first microgrid could earn $300 per hour and the other microgrid's operation cost would be reduced to $150 per hour.

Discussion of possible risks

There is risk related to the need for updated regulations to allow virtual metering. The examples discussed above clearly show the need for virtual metering, and regulatory changes will be required to ensure that virtual metering solutions are allowed

Challenges

The complexity in control and optimization is the primary challenge with economic optimization of networked microgrids. Addressing energy management, market participation, dynamic architecture of the network, and the security and resilience of electricity distribution networks with a high penetration of networked microgrids will require a multi-timescale (day-ahead, hour-ahead and real time), hierarchical optimization and control framework.

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[26] http://www.dieselserviceandsupply.com/Diesel_Fuel_Consumption.aspx

To fully realize the economic benefits of networked microgrids, a wholesale market where networked microgrids from the distribution network are able to actively participate in the bulk power market is required. The new market design should facilitate the integration of components in distribution networks, not only to provide ancillary services, such as peak shaving, demand response, and frequency regulation under normal conditions, but also to introduce new critical services in conceivable local electricity markets, such as black start services and their corresponding pricing and settlement mechanisms. Due to a lack of clear methods for quantifying costs and benefits, business models and incentives for microgrid owners to participate in a microgrid network must be developed. Networking of microgrids also requires developing virtual metering solutions that will allow utilities to aggregate the demands of the individual microgrids on time scales consistent with the tariffs or markets.

IMPROVING UTILITY "NORMAL" OUTAGE METRICS[27]

Opportunity

In networked microgrids, DERs can be shared among the individual microgrids, providing a higher level of redundancy in case of DER outages. Compared to the alternative of power supply delivery from the macrogrid, power supply delivery from a neighboring microgrid in a networked microgrid system shortens the distance between the generation and demand, potentially leading to fewer line outage events. In addition, when outages happen, networked microgrids can offer smart reconfiguration and self-healing. Networked microgrids provide reliability enhancement through higher redundancy, lower outage events, and self-healing and reconfiguration.

Architecture

Increased reliability requires networking at both physical and control layers. The physical layer network is needed to share DERs and provide higher resource redundancy, as well as to enable reconfiguration. The control layer networking facilitates the information sharing required for load sharing and reconfiguration.

The interconnection voltage level will not have a significant impact on the reliability opportunity; however, networking via the utility secondary voltage circuits will increase the risks and challenges.

Very fast control times will not be required from the network controller. Considering a hierarchical control system (see Figure 1) with primary, secondary, and tertiary control levels, we expect that primary frequency control will occur at the individual generator level. Only secondary and tertiary-level controls, with time scales from minutes to hours and used for load-generation balancing and reconfiguration for restoration, will be implemented in the network controller.

The microgrids are physically connected, although some of the connections may be through normally open switches that will only close during abnormal events. Each microgrid has a controller with its own local objectives, e.g., to lower its own operation cost and/or enhance power quality in its own network, which it attempts to achieve using its own resources or resources from other microgrids. A second objective is to benefit other microgrids.

The balance between self-benefit and other-benefit may be achieved through priority lists, and/or financial incentives. The management of the microgrids in the network can be performed using a central controller (Figure 4), which determines set-points for individual microgrids to achieve overall welfare. Alternatively, a distributed approach may be used wherein microgrids communicate with each other, instead of communicating with a central controller. Depending on the number of microgrids, complexity of tasks, and availability of communication infrastructure, the communication could be all-to-all (Figure 5), or only between neighboring microgrids (Figure 6)

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[27] Primary authors: Salman Mashayekh and Michael Stadler, Lawrence Berkeley National Laboratory

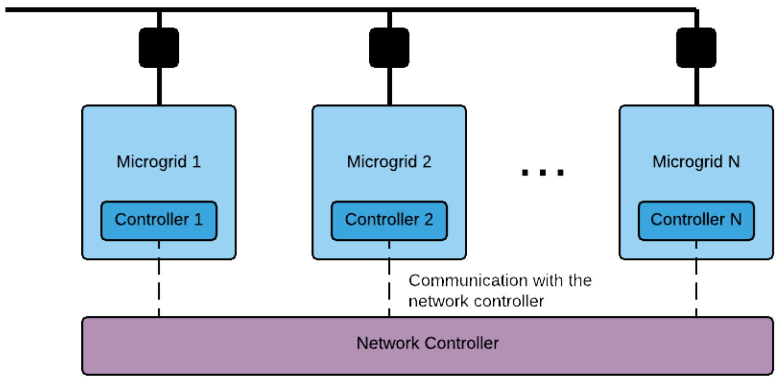

FIGURE 4. CENTRAL NETWORK CONTROLLER

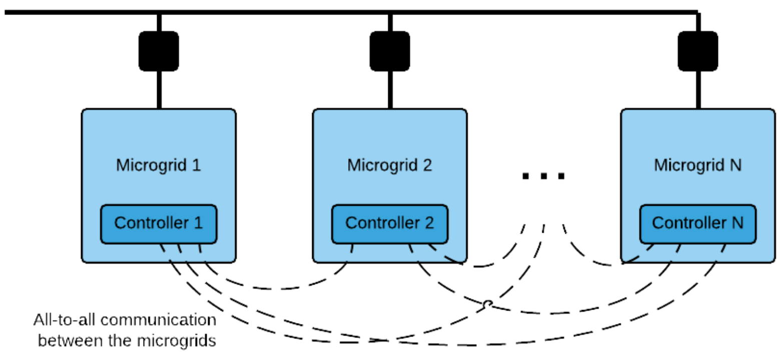

FIGURE 5. DISTRIBUTED NETWORK CONTROLLER – ALL-TO-ALL COMMUNICATION

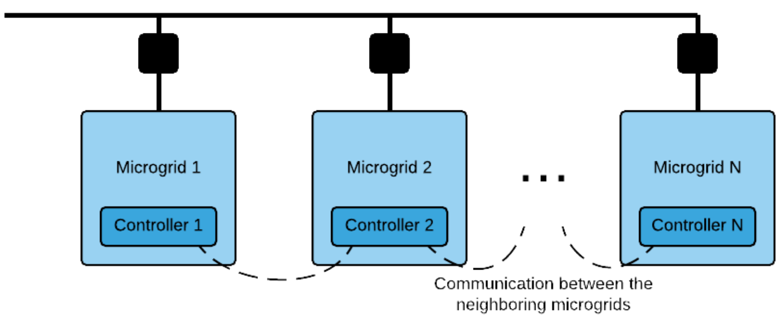

FIGURE 6. DISTRIBUTED NETWORK CONTROLLER – COMMUNICATION BETWEEN NEIGHBORING MICROGRIDS

Benefits

The reliability of electrical service at the customer level may vary greatly throughout a distribution system depending on many factors such as distance from the substation, the prevalence of underground lines, etc. To gauge the reliability benefits of networked microgrids, will use typical system-average reliability indices, such as the System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI).

Typical reliability provided by the macrogrid are SAIFI of about 1 interruption per year and

SAIDI of about 120 minutes of outage per year. Current Department of Energy targets for individual microgrids are expected to improve the effective local reliability to SAIFI ~ 0.05 interruptions per year and SAIDI ~ 5 minutes of outage per year.[28] During the reliability events when an individual microgrid is unable to serve its own loads, networking of microgrids could enable another microgrid to serve these loads and potentially decrease the effective local SAIFI and SAIDI further towards zero.

Possible Risks

In a networked microgrid, new communication links are included in the system, either between microgrid controllers and the central controller, or between microgrid controllers, adding new points of failures. This new vulnerability could be exploited by cyber hackers, or the links could simply fail due to unintentional mistakes or natural events.

Challenges

The most important challenges to address in a networked microgrid, especially if the microgrids are owned independently, are resource sharing between microgrids and load loads during conditions when not all loads can be served. As an example, consider a case where a school campus microgrid and a hospital campus microgrid are networked together. Assume the utility grid is out and the hospital campus has a generation deficit that can be supplied only if the school campus microgrid sheds some loads. In this situation, although hospital loads have higher priority, an incentive must be offered to the school microgrid owner to ensure that it would be willing to disconnect some of its loads and share its extra generation. The problem complexity increases multifold when the number of microgrids and the number of load types/priorities expand.

[28] Microgrid Research, Development, and System Design. Funding Opportunity Number: DE-FOA-0000997

RESILIENT MICROGRIDS FOR SMART CITIES/URBAN CORES[29]

Opportunity

Because of the concentration of critical loads within urban cores, there is a greater opportunity for the deployment of microgrids for resilience purposes. These deployments can leverage the numerous smart city initiatives that are currently deploying the communications and controls systems that microgrids need. It is possible that there are numerous microgrids operated by a range of stakeholders within a smart city. Under normal operations there may or may not be an economic incentive for the disparate microgrids to interact, but during an extreme weather event there are clear incentives related to resilience. By allowing multiple microgrids to coordinate in various smart city architectures, it is possible to increase operational flexibility when they are grid-connected and to increase reliability and resilience during extreme weather events.

Architecture

Because the concept of a smart city is still evolving, a range of architectures must be examined. It is clear is that during an extreme weather event, it is unlikely that a smart city will form a single massive microgrid; unless it is a small city with a load of <10 MW. Because of the limited generation assets and the complexity of controlling so many distributed devices, it is more likely that multiple smaller microgrids will be formed at various locations around the city. As a result, a wide range of operational scenarios need to be examined. These should include, but not be limited to:

- Traditional stand-alone microgrids
- Microgrids connected at the secondary level
- Microgrids connected at the primary level
- Microgrids connected via sub-transmission
- Microgrids that connect to low voltage networks

Figure 7 shows a conceptual one-line diagram of a smart cities electrical infrastructure. It shows a small city supplied by three substations served by a 230 kV and 500 kV transmission line and inter-connected by a 115kV sub-transmission ring. The three substations serve three low voltage, 120/208V, networks through 13 13.9 kV radial feeders and there are 10 additional 13.8 kV radial distribution feeders which do not serve the networks. Not shown on the one-line diagram are the normally open tie switches that connect that various radially operated feeders. The system also will have a number of distributed energy resources in the form of low-sulfur reciprocating diesel engines, fuel cells, combustion turbines, solar PV, batteries, electric vehicles, and controllable loads.

[29] Primary author: Kevin Schneider, Pacific Northwest National Laboratory

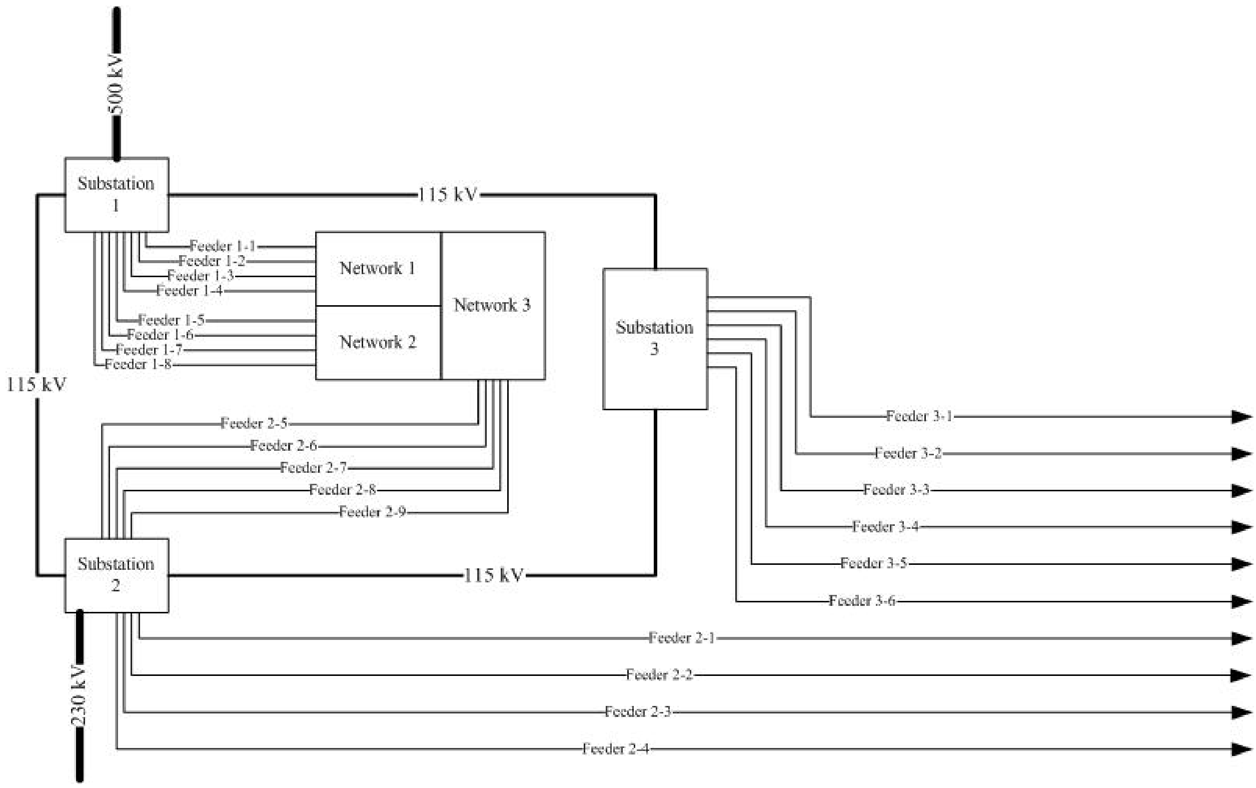

FIGURE 7. A SMALL CITY SUPPLIED BY THREE SUBSTATIONS SERVED BY A 230 KV AND 500 KV TRANSMISSION LINE AND INTER-CONNECTED BY A 115KV SUB-TRANSMISSION RING

Benefits

Individual microgrids rely only on the resources and assets within their operational boundaries. By allowing switching operations, which can interconnect these microgrids, resources and assets can be shared to increase efficiencies and support critical loads via more efficient load balancing across distributed resources as well as sharing of fuel and/or energy storage resources. These benefits can be quantified by reduced emissions, increased system-level efficiencies, and extended service to critical loads during extreme weather events.

Possible Risks

Allowing microgrids operated by various stakeholders, possibly including a municipal utility, to interconnect across utility assets will present operational and regulatory challenges. Risks include, but are not limited to:

- Uncoordinated synchronization of microgrids may lead to equipment damage
- Switching operations on de-energized network sections may lead to overload of generators and potential damage
- Effective coordination of DER across multiple stakeholders.

There are also specific risks related to networking over low-voltage meshed networks, including:

- Exporting power back into the meshed network through network protectors

- Segmenting the meshed network into small enough sections than can be served by a relatively small number of networked microgrids

Challenges

Multiple technical and regulatory challenges exist. These include, but are not limited to:

- Operational challenges of coordinating multiple microgrids
    - Segmenting and reconnection of low-voltage meshed network systems
    - Managing in-rush during switching transients
    - Management of distributed assets
- Coordination of microgrids owned by different stakeholders

FLEXIBLE-ADAPTIVE NETWORKS FOR SERVING LOAD AFTER EXTREME DAMAGE[30]

Opportunity

A networked microgrids have advantages in reliability and flexibility over independent microgrids or existing grid infrastructure. The use of generation technologies, such as combined heat-and-power systems, distributed energy storage devices and flexible interconnection of infrastructure gives the networked microgrid approach great advantages and opportunities. One opportunity is the ability of networked microgrids to automatically reconfigure and continue to serve load after the network of the power systems and potentially the microgrids network have suffered extensive physical damage.

Architecture

Networked microgrids that experience extreme damage to their physical networks are also likely to suffer damage to a centralized control system communications network. We anticipate that a robust system that can reconfigure the physical network layer will require a decentralized control architecture to enable self-adapting and self-healing capabilities. One way to achieve this performance is through an intelligent informatics/agent strategy combined with an energy storage layer. Once the network has reconfigured, the newly arranged system will need a real-time capability to self-assess and determine if the new configuration is dynamically stable and to reassign energy storage systems and remaining generation to support critical loads.

The distributed control we are suggesting would require networking only in the physical layer, however, we anticipate that control layer networking will also be required to achieve other economic benefits. The distributed control capability considered here would be in addition to any control system networking.

Networking at the primary voltage level may introduce regulatory issues and risks. Therefore, networking and interconnections and re-configurations between microgrids is likely more feasible at secondary voltage levels.

A distributed and hierarchical control structure will likely require a time separation in control to be able to implement different functionality. For example:

- Microsecond to seconds primary control for servo level actuation of equipment such as generators, inverters and storage devices. This control will be highly distributed onto the individual assets.
- Seconds to minutes secondary control may be more centralized and will be used to correct short term operational actions such as load sharing commonly part of an energy management system.
- Minutes to days tertiary control will likely be even more centralized to calculate long term or "forecasting" optimal operational and economic dispatch of assets.

Benefits

[30] Primary author: Steve Glover, Sandia National Laboratory

Following an extreme event such as a hurricane, utilities are in damage assessment mode and are not actively restoring power for 24-48 hours. After a major hurricane, utility personnel may be able to restore power for up to two weeks. The primary benefit of flexible, autonomous reconfiguration of networked microgrids is the potential for faster restoration of electrical service to critical loads, in the absence of utility crews, following extreme physical damage to electric power systems, including the microgrids themselves

Possible Risks

Technical risk—The primary technical risk is found in the automated reconfiguration of networked microgrids. State estimation errors by the microgrid controller may lead to reconfiguration that energizes downed power lines that endanger the public or utility workers. Related controller errors may also lead to reconfiguration that causes and instability or damages microgrid equipment and further reduces its ability to serve critical loads.

Regulatory risk (see also the Section "Networked Microgrids to Manage and Optimize Distributed Energy Resources within High-penetration Scenarios")—King investigated several legal and regulatory issues in his comprehensive, survey-based study of microgrids. [31] Many of his findings are also relevant to networked microgrids. One of his findings is that a microgrid is likely to be legally viable as long as it does not attain utility status. Although potentially legal, he also describes numerous regulatory barriers that could lead to excessive risk to the investors and operators making microgrids and networked microgrids an unattractive solution. King describes the regulatory space as being "murky" and cites "the existence and relevance of utility service territories; utility services and tariffs; and interconnection procedures and technical requirements" as being the primary sources of uncertainty.

A primary motivation for exclusive service territories is to reduce the financial risk to the utility to make long-term infrastructure investments. King's state survey indicated that the need for this exclusivity would drive the illegal status of microgrids should they attain utility status. That is, creating a competitive market within a service territory. It is important to note that even if a networked microgrid did not attain utility status, its existence would likely be challenged by the utility if it operates within the utility's service territory while attempting to compete with the utility. In summary, any action that a networked microgrid takes that creates a competitive environment with the utility may lead to investment uncertainty due to legal challenges.

Fair procedures have been developed in many states for providing interconnects for distributed generator owners with a focus on maintaining stability and safety. King's survey of regulatory officials indicates a mixed message for the interconnection of microgrids. They could be classified as something other than distributed generation and, thus, existing distributed generation interconnection rules would not apply. This classification would likely give more authority to the utility to set the rules for networked microgrid interconnection leading to the burden of proof to lie more heavily on the networked microgrid operator.

Challenges

[31] D. E. King, The regulatory environment for interconnected electric power microgrids: insights from state regulatory officials," *Carnegie Mellon Electricity Industry Center Working Paper CEIC-05-08*, May 2008. [Online]. Available: https://wpweb2.tepper.cmu.edu/ceic/pdfs/CEIC 05 08.pdf.

Microgrids allow for local control of the distributed generation units and for the flexibility to operate autonomously during disturbances and damage in the bulk power system. To further leverage this flexibility by enabling autonomous reconfiguration of networked microgrids raises several challenges:

- In the case of system damage, potentially dangerous areas need to be automatically detected, isolated and de-energized to prevent direct human exposure.
- It is foreseen that reconfiguration and switching network connections will trigger large transients in the network. Therefore, the hardware and control need to be designed and implemented such that transients such as inrush currents and large step changes in load will not cause, or at least minimize, disruption in service.
- Before an AC connection can be closed, the voltages must be synchronized. This is made all the more difficult to implement if the microgrid is under distributed control where there is no one reference controller for frequency, phase and magnitude. Therefore, a strategy to synchronize isolated microgrids for reconfiguration is critical. Using DC microgrids or DC interconnections between AC microgrids can simplify or eliminate many of these synchronization challenges.

BLACK START RESOURCE FOR DISTRIBUTION-CONNECTED INVERTER-BASED DISTRIBUTED GENERATION[32]

Opportunity

Networking of microgrids may enable additional microgrids to operate during a utility outage by sharing black start capabilities throughout the network. The sharing of black start resources may reduce outage times and lower capital costs by limiting the number of microgrids requiring black start capability.

Architecture

Both physical and control layer networking are required for black starting with inverter-based distributed generation. One option for black starting includes starting up multiple microgrids in parallel, and then syncing the microgrids at their point of common coupling (Case 1). This process involves starting each microgrid with its respective voltage/frequency (V/f) controlled source, then coordinating the voltage magnitudes, phase angles, and frequencies at the PCC. This requires that each of the networked microgrids have the ability to separately black start. Initially, this method requires no networking of physical or control layer. However, during the synchronization period between the microgrids, networking between both the physical and control layers is necessary.

Another option for black starting networked microgrids is black starting a single microgrid and using this microgrid to provide power to the other networked microgrids (Case 2). For example, consider the topology in Figure 8. The primary microgrid initiates black start, closes the PCC to the secondary microgrid, and commissions the secondary microgrid. Instead of commissioning, the secondary microgrid could also initiate a separate predetermined black start sequence without a V/f source. This methodology requires networking of the physical and control layer from the beginning of the black start sequence.

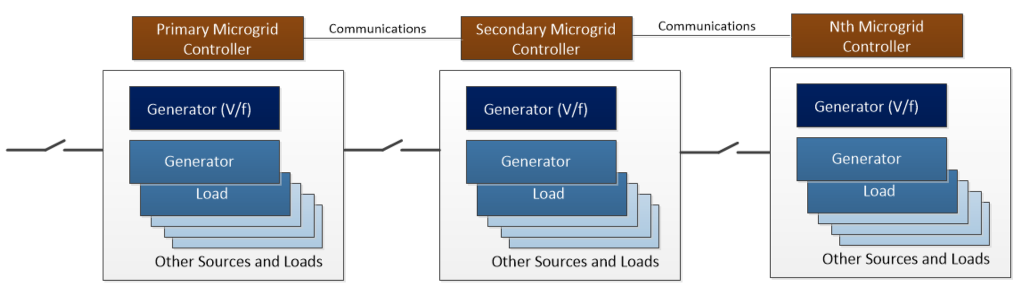

FIGURE 8. BLACK START WITH NETWORKED MICROGRIDS

Networking at primary voltage is preferable. A distribution feeder secondary could be in a single or split-phase configuration. Black start from a single phase system (secondary side) would be difficult as this would require coordination of single phase systems to create the three phase power, voltage, and frequency needed to black start. Furthermore, the sources on this side are not

[32] Primary author: Michael Starke, Oak Ridge National Laboratory

expected to be large.

In Case 1 mentioned above, the time resolution for the network controller would have to be subsecond. The controller requires awareness of PCC switch closure, particularly the PCC between the two operating black started microgrids. The controller would then need to deactivate one of the two V/f sources to avoid any undesirable controller interactions. This will typically need to happen in less than 10 cycles at 60 Hz.

In Case 2, the time resolution is less critical. The networked microgrids can start up in a pre-defined black start sequence and this can be defined and communicated in advance.

Benefits

A scenario wherein a storm passes through a distribution network causing a substation breaker to open, resulting in 1,000 customers losing power. Sensing the fault, relays operate to isolate completely the faulted section of line, restoring power to 300 customers. The remaining 700 customers fed by two separate microgrids, one with 400 customers (MG1) and the other with 300 customers (MG2). Because the fault is isolated, it is possible to black start and operate both of these microgrids. MG1 has enough stored energy (from batteries or fuel tanks) to operate for 1 hour. MG2 has enough energy to operate for 10 hours. The local utility estimates that it will take 4 hours to restore the grid to all 1,000 customers.

In Case 1, both microgrids black start independently, providing power to the 700 customers and decreasing their outage time. Both microgrids operate independently for 30 minutes. The MG1 controller notices that it will not be able to operate for much longer on its current energy reserves. It issues a request to MG2 to connect the microgrids and share resources to avoid a shutdown of MG1. MG2 accepts the request and begins the synchronization process. The PCC closes, and both microgrids operate as one microgrid, serving the 700 customers for the entirety of the 4 hour outage. By synchronizing, the utility has avoided 72,000 customer outage minutes (400 customers in MG1 * 180 hours MG1 would have been shut down) had the microgrids not been able to network.

In Case 2, a black start scheme has been previously developed which would a) black start one of the microgrids completely, then close in the PCC and continue the black start procedure until both microgrids are operating together, or b) close the PCC and then black start as if the two microgrids were one large microgrid. The microgrids share resources and operate the entirety of the 4 hour outage. The utility avoids the same number of minutes as in Case 1, if the microgrids were not able to be networked.

Possible Risks

Each case has a possible risk. In Case 1, if the delay between the PCC closing and one of the V/f sources being deactivated is sufficiently large, then both microgrids could become unstable and return to an outage state. This could also damage microgrid resources and lead to extra switching operations for relays.

In Case 2, it is possible that the generation resources in MG1 are not sufficient to serve both its own load and the loads of the second microgrid, causing instability and a potential return to an outage state. This could also damage microgrid resources and lead to extra switching operations for relays.

Challenges

Technical challenges include the following:

- Communication latency between controllers needs to be sufficiently small to avoid instabilities, especially in case of synchronization
- Standardized information exchange will be crucial for microgrid controllers to exchange the necessary information
- Coordinated control of load control will be critical during black start of connected microgrids to maintain stability and avoid generator overloads

BLACK START RESOURCE FOR TRANSMISSION-CONNECTED GENERATION[33]

Opportunity

By networking microgrids, black start generation capabilities within various microgrids can be gathered to energize relatively long sections of transmission lines and bring cranking power to non-black-start generating units in the transmission system, which may not be achievable by using any single microgrid.

Architecture

Networking of microgrids to use as black start resource will require both physical and control layers. The connection in physical layer shares the available generation capability in each microgrid, while the control layer connection, via either a centralized network controller or peer-to-peer communication between microgrid controllers, helps manage all generation capabilities. An ad hoc solution may be used for preset black start strategies, however, a network level controller (or a distributed coordination mechanism) is still necessary to handle unexpected scenarios. Due to uncertainties in load demand and power generated by intermittent distributed generation, it is very difficult to predetermine strategies for all possible scenarios.

Networking at primary voltage level may be preferable because during the black start process, power will be sent from networked microgrids to the transmission system. If the microgrids are networked in the secondary side, a transformer will be needed to transform the secondary voltage into primary voltage level which increases the already large in-rush current when energizing the transmission lines.

If the black start strategies are preset, the network controller will only need to send commands at much lower time resolution to each microgrid and monitor the status of microgrids. The local controller for each microgrid will capture in-rush dynamics with a subsecond time resolution and respond properly; however, the network controller must still update the status of microgrids continuously. For example, if a microgrid disconnects itself from the network for protection purposes, the network controller should capture the event and respond immediately. Therefore, we still need a small time resolution for the network controller. The schematic shown in Figure 1 works for the black start purpose.

Benefits

Networked microgrids can serve as a better black start resource than a single microgrid by providing higher capability to manage in-rush current and reactive power to energize longer transmission line sections relative to individual microgrids.[34] For example, consider two microgrids, each with a 500 kVar reactive power absorption capacity and capable of energizing a 115 kV transmission line section of 21 miles or shorter. By networking the two microgrids, a

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[33] Primary author: Chen-Ching Liu, Washington State University

[34] The estimate in the above discussion is based on the nomogram proposed in the following paper: K. P. Schneider, F. K. Tuffner, M. A. Elizondo, C.-C. Liu, Y. Xu, and D. Ton, "Evaluating the Feasibility to Use Microgrids as a Resiliency Resource," Accepted for publication on *IEEE Trans. Smart Grid*.

total reactive power absorption capability of 1000 kVar will be available. The networked microgrids can energize a 115 kV transmission line section of 26 miles or shorter.

Possible Risks

Possible risks include:

- In-rush current may cause damage to distributed generators.
- Underestimates on the amount of reactive power that needs to be absorbed may lead to damage of distributed generators.
- Improper real/reactive power sharing among different microgrids may result in overloading of some microgrid in the network.

Challenges

The need for offline dynamic and transient simulation capabilities for comprehensive evaluation of the potential risks by control room personnel presents a technical challenge, but these capabilities are not expected to be required for the network controllers.

AC/DC NETWORKED MICROGRIDS[35]

Opportunity

Networked microgrids allow coordinated control and energy management across both AC and DC microgrids. They provide an effective architecture to meet the requirements of increasing penetration level of AC and DC microgrids into the distribution system. The power electronic converters used to link DC microgrids to the distribution system can be aggregated by using the interface converters between the common buses in AC sub-grid and DC sub-grid in the networked microgrid configuration. This aggregation may lead to more effective use of the converter apparent power capacity thereby lowering over capital cost, increasing the ability to provide reactive power support, and increasing converter loading and efficiency

Architecture

The opportunity requires networking at both physical and control layers. The physical connection among multiple AC and DC microgrids should be provided to achieve power exchange. Meanwhile, the networking at the control layer ensures the coordinated control and management among multiple microgrids.

Considering that the AC and DC microgrids are typically connected to distribution systems, the preferred voltage should be similar to those used for conventional microgrids and distribution systems, which ranges from several hundred volts to several thousand volts. However, commonly available equipment is typically in the 300–400 V_{DC} range, and this is the expected voltage of the interconnection.

The network controller should be implemented considering multiple time scales. In particular, in the primary control level, the time scale should be smaller to achieve the device level control, e.g., several milliseconds or tens of milliseconds, while in the secondary or higher control levels, the time scale should be longer to achieve system level coordinated control, e.g., several seconds or even minutes. Figure 9 shows a schematic of a potential AC and DC hybrid networked microgrid.

[35] Primary authors: Jianhui Wang, Argonne National Laboratory

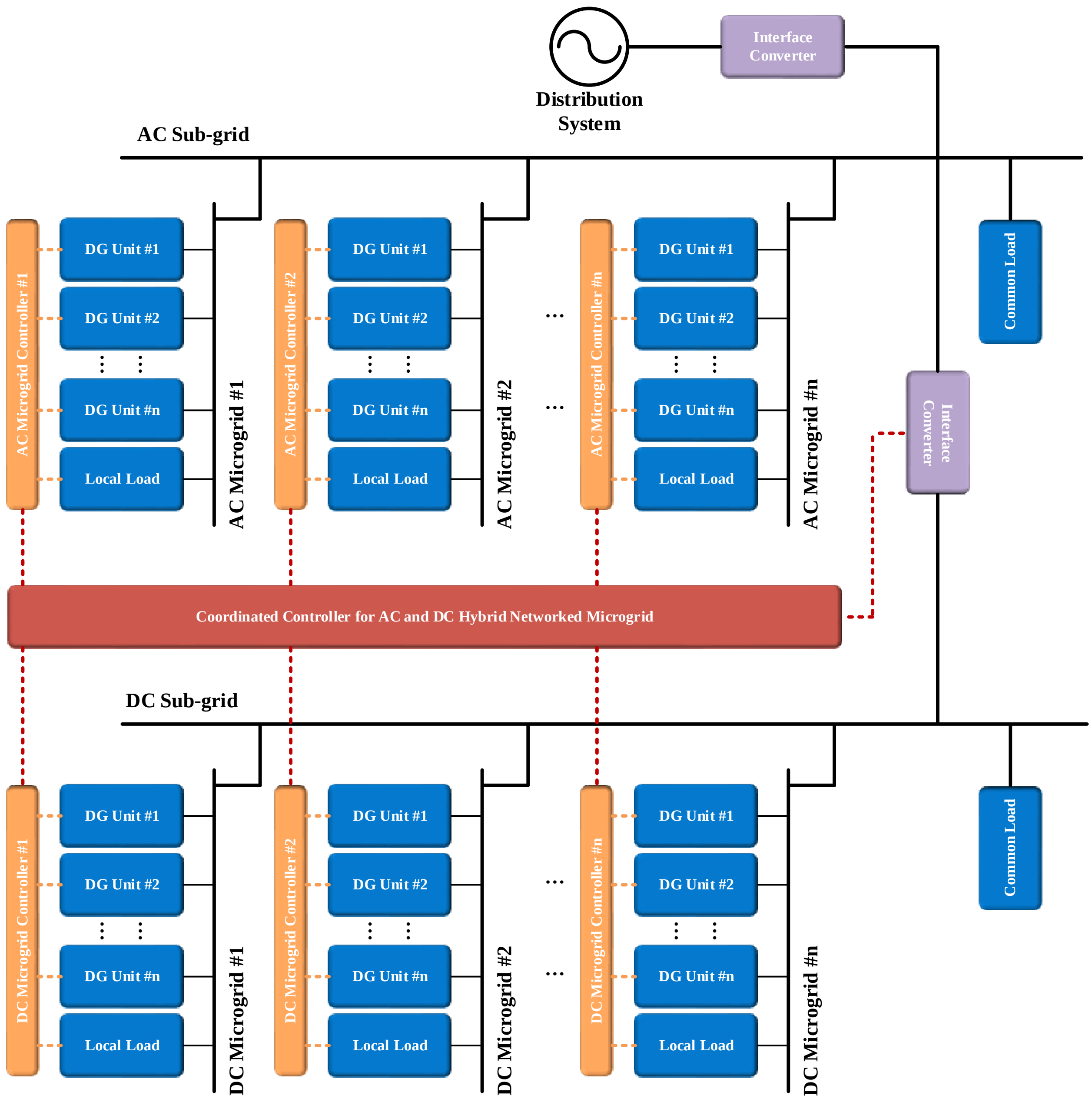

FIGURE 9. SCHEMATIC OF POTENTIAL AC AND DC HYBRID NETWORKED MICROGRID

Benefits

The benefits of networked microgrids with both AC and DC sub-grids can be summarized in two aspects. From the aspect of physical layer, the flexibility of integrating multiple renewable energy sources and loads can be enhanced. The sources and loads feature different electrical couplings. For example, wind turbines and distributed generators commonly have AC couplings, while PV panels and batteries have DC couplings. By using AC and DC hybrid networked microgrids, different components can be easily integrated in a more flexible manner. Meanwhile, the interface converters that are used to connect DC microgrid to distribution system can be aggregated, and fewer converters are needed to connect the common buses in both AC sub-grid and DC sub-grid. For example, assume that 'm' DC microgrids are taken into account, and one interface converter is needed to connect each DC microgrid to the distribution system, thus, 'm' converters are needed in total. When using networked microgrids, the AC microgrids are aggregated to form an AC sub-grid, and the DC microgrids are aggregated to form a DC sub-grid. Only one interface converter is needed to connect the common buses in AC and DC sub-grids. It should be also noted that by using coordinated control, the power exchange between AC and DC sub-grids can be minimized. The power rating of the interface converter linking the AC and DC sub-grids can be reduced, which reduces the capital cost and increases its operational efficiency.

From the aspect of the control layer, the coordinated energy management can be easily implemented among both AC and DC sub-grids using networked microgrid configuration. Meanwhile, some common components can be shared by different sub-grids, e.g., energy storage units, common loads, etc. These components can be regarded as energy assets participating into frequency/voltage regulation. By sharing these units in AC and DC networked microgrids, the overall investment cost of the system can be lowered down by using fewer components and devices, e.g., energy storage.

Possible Risks

When AC and DC microgrids are networked in a hybrid system, several potential risks arise:

- If there are multiple AC-DC microgrid interfaces, the network controller may drive circulation of active and reactive power between the AC and DC microgrids increasing losses
- Instability may result from poorly understood interactions between AC and DC microgrids in a hybrid system
- High-frequency harmonics in the DC microgrid may affect the AC microgrid

Challenges

The technical challenges for realizing the benefits and avoiding the risks include:

- Developing a controller that can simultaneously optimize and control coupled AC and DC microgrids
- Development of theory to predict the stability of AC and DC hybrid networked microgrids
- Development of software tools to perform optimal design of integrated AC and DC microgrids, especially for energy storage units and backup generators
- Lack of a systematic methodology to manage the power quality of AC and DC networked microgrids in terms of active/reactive power circulation, harmonics, stability, etc.

MANAGING DISTRIBUTED ENERGY RESOURCES WITHIN HIGH-PENETRATION SCENARIOS[36]

Opportunity

Based on its aggressive energy and environmental policies, California is witnessing exponential growth in DER — a growth that has already impacted its load duration curve and is fundamentally changing the dynamics of power supply and demand, with significant potential impacts to the grid.[37] Facing a future with highly distributed, two-way flows of information and energy, California is developing a framework for utility DER planning and valuation.[38] This framework aims to establish for its investor-owned utilities uniform, consistent and verifiable methods for evaluating distribution system DER Integration capacity (distribution line/feeder hosting capability), optimal location benefits, DER locational net benefits and high DER growth scenarios for its investor-owned utilities. Critical elements of this framework also include the development of (1) distribution resources plans; (2) well-structured demonstrations to test and validate the methods; and (3) policies and procedures for data sharing between utilities, customers, and DER owners/operators/service providers. In carrying out the California Public Utility Commission's (CPUC) order, investor-owned utilities are explicitly required to address the cost-effectiveness and strategic siting of microgrids to maximize value and minimize incremental costs to the macrogrid.

This DER valuation and planning framework could tangibly contribute to the market development of advanced microgrids and networked microgrids, not only as a "multi-function" grid resource that provides services to system operators, such as reliable, dispatchable energy, ancillary services, load-shedding, storage for overgeneration, economic optimization, resiliency and outage recovery;, but also as a "community resource" that provides integrated resource solutions using intelligent energy management.

California's approach provides a significant opportunity to develop and demonstrate the cost-effectiveness of networked microgrids as grid and community resource because these measures will (1) employ a uniform, consistent and verifiable means of quantifying and comparing the net benefits of networked microgrids to utility distribution system capital investment options and alternative DER investment strategies;[39] (2) support investment in DER interoperability and integration to help standardize the use by utilities of distributed and demand-side energy resources as part of overall power system planning, grid operations and power market trading; and (3) enable the development of an integrated smart grid designed to increase the independence, flexibility and intelligence for optimization of energy use and energy management within localized energy networks/networked microgrids ("system of systems"), as well as to integrate locally developed resources into the smart grid.[40] These measures could support the

[36] Primary author: Larisa Dobriansky, General Microgrids
[37] P. De Martini and L. Kristov, "Distribution Systems in a High Distributed Energy Resources Future," LBNL Future Electric Utility Regulation Series, October 2015.
[38] Order Instituting Rulemaking Regarding Policies, Procedures and Rules for Development of Distribution Resources Plans Pursuant to Public Utilities Code Section 769, California Public Utility Commission, Rulemaking 14-08-013, August 14, 2014. (CPUC Order)
[39] E. Martinot, L. Kristov and D. Erickson, "Distribution System Planning and Innovation for Distributed Energy Futures," Curr Sustainable Renewable Energy Report, 2:47-54, (2015). (Distribution System Planning)
[40] Electric Power Research Institute, "Needed: A Grid Operating System to Facilitate Grid Transformation," July 2011. (EPRI 3.0 Grid)

development of smarter distribution architecture that includes "networked microgrids" to (1) optimize energy availability across a larger variety of energy resources, improving economics; (2) create an infrastructure for more optimum management of overall energy requirements (heating, cooling and power); and (3) increase control and management of reliability at the local level, as well as harden critical infrastructure and improve the resiliency of the macrogrid.[41]

Architecture

The topologies and architecture for networked microgrids will depend upon conditions within utility service territories/communities, as well as the objectives to be served. Through its solicitation process, the California Energy Commission has been funding the development of microgrids to meet different types of objectives (e.g., critical infrastructure hardening, grid resiliency, renewable energy intermittency, and high DER penetrations/increased use of electric vehicles) with a view to evaluating the performance and cost-effectiveness of appropriate configurations. Potential system complexities of managing wide and dynamic sets of distributed and intermittent resources and control points are prompting California to explore the capabilities of advanced microgrids and networked microgrids–capabilities that would go beyond what two-way command and control systems could provide with smart meters, fast sensors and complex controls/management systems within utility distribution systems.

In connection with the management and optimization of proliferating distributed resources, networking would be at both physical and control layers.

There have been no limitations placed on voltage level for demonstrations of advanced microgrids. Projects that have been considered are interconnected at sub-transmission, down to primary distribution, including low voltage networks.

For purposes of demonstrations, no limitations have been placed on architectural structures, but see the NYREV paper on the need for a hierarchical structure of controllers (primary, secondary and tertiary controls)

Benefits

Overall, the CPUC is taking a course of action that can create a more level playing field for microgrids and networked microgrids in relationship with utility services within an "integrated grid." California's emerging electricity regulatory reforms are being structured to better align utility financial interests with achieving California's aggressive energy and environmental policy objectives, without compromising the reliability, affordability or safety of the electrical power system. Requiring investor-owned utilities to develop uniform, consistent and verifiable benefit/cost analytical methods is part of a larger California effort to reform ultimately the role of utility distribution companies into Distribution System Operators who are responsible for distribution network operation; have a financial interest in pursuing the most cost-effective solutions; and will optimize the efficient use of DER without regard to resource ownership.

The benefit/cost analytical framework and methods that California is developing will enable utilities, developers, service providers, and customers to evaluate and compare the cost-

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[41] Id. at 11.

effectiveness of alternative DER investments and strategies against established baselines and against each other, including networked microgrids. Using uniform, consistent, and verifiable methods and tools, investor-owned utilities will evaluate DER impacts on the distribution system at substation and feeder levels; identify optimal locations and DER combinations; deploy sensors and communication infrastructure and data collection and analysis; and simulate DER portfolios using new dynamic modeling tools and data collected from monitoring and communications systems used to determine impacts on the distribution system.

The CPUC anticipates that, based on the knowledge and databases developed, the State and utilities will be able to delineate Distributed Energy Resource Zones and define additional DER portfolios based on value optimization (analytical tools and processes to compare DER/microgrid systems/networked microgrids with traditional distribution infrastructure investments addressing operational, economic, and societal factors, including attracting stakeholder input and feedback into analytical methods).[42] In this regard, networked microgrids could offer higher value applications than a DER aggregation model or portfolios of individual DER.

Based on the development and deployment of these common analytical methods, the CPUC also contemplates stakeholder-driven development of DER procurement policy and mechanisms for investor-owned utilities, including supporting the development of non-utility distribution systems, such as advanced microgrids and networked microgrids. The CPUC framework would allow for the evaluation of networked microgrids as a cost-effective technical solution to address high DER market penetration scenarios, one that could maximize the potential benefits of DER on distribution system performance, while also mitigating adverse impacts that DER could otherwise create if the resources proliferated as standalone or dispersed resources, in uncoordinated ways.

Possible Risks

As part of California's framework for investor-owned utilities DER planning and valuation, the CPUC requires for its investor-owned utilities to address three categories of barriers to DER deployment, that would apply as well to networking of microgrids (DER used to cover all technologies): (1) barriers to interconnection/integration onto distribution grids; (2) barriers to limit the ability of DER to provide benefits to the macrogrid; and (3) barriers related to distribution system operational and infrastructure capability to enable the provision of DER benefits (i.e., needed investment in advanced technology such as advanced protection and control systems, telecommunications and sensing).

The CPUC also requires utilities to characterize the nature of the barriers within each category, whether statutory (statutory prohibitions), regulatory (regulatory rules or processes that increase the cost of DER deployment or limit DER functionalities), grid insight (lack of visibility into distribution system conditions, bulk electric system conditions or actual performance of DER that limit DER deployment of operations), standards (inadequate or undefined standards; for example, the need for enabling smart inverter functions), safety (standards related to technology or operation of the distribution circuit), benefits monetization (lack of mechanisms to monetize

[42] Supra, CPUC Order.

DER benefits; for example, inability of DERs to bid into CAISO market to provide services such as spinning reserves), or communications (lack of a communications link between DER and the utility grid operator limits deployment or benefits monetization of DER). [43] (Note: this approach, which is part of California's reform efforts, contrasts with the findings of the D.E. King survey-based study of microgrids (May 2008), referenced in the Sandia National Laboratory paper, which examined the legacy regulatory environment for interconnected electric power microgrids.)

Challenges

While the regulatory, institutional, and technical challenges under the current electricity regulatory regime remain significant, the reforms that California is undertaking represent a major push to recognize the need for investment in upgrading the distribution system to integrate cost-effective distributed resources and to pro-actively identify and remove barriers to deployment of DER. These reforms, which will be implemented in phases, will contribute to reducing uncertainties and risks surrounding investment in the networking of microgrids and create an opportunity for networked microgrids to provide functional control of proliferating distributed resources for purposes of providing real-time balancing and flexibility, as well as other services, such as reactive power and frequency control, to the local or bulk grid.[44]

Major challenges facing utilities in integrating microgrids include:

- Regulatory Challenges: Ownership of generation assets; administrative burden of regulation
- Economic Challenges: Distribution generation technologies still costly and with uncertain lifetimes; business model still undeveloped
- Technical Challenges: Bi-directional power flows; fault current contribution; unit level volt/VAR support; islanded operation

Networking of microgrids could represent an integrated approach that utilities take with respect to microgrids, with a view to achieving more cost-effective management and optimization of DER.[45]

While microgrids or individual local energy networks/networked microgrids could operate in a standalone mode, the integration into the distribution system, envisioned by California's framework for its investor-owned utilities planning and valuation, would allow interconnection and integration with technologies that could ultimately enable a modernized 3.0 operating grid.[46] Networked microgrids could operate somewhat independently, but their value would be maximized when nested together and with the bulk power system. This nesting concept could contribute to increased overall stability within the power system. Networking and the nesting concept would raise, however, new, complex regulatory issues relating to non-utility distribution system liability, the nature and extent of obligations, whether organization and operations trigger

[43] Supra., CPUC Order.
[44] Supra., Distribution System Planning.
[45] A. Maitra, Electric Power Research Institute, "Microgrids and Grid Integration: Where Microgrids stand in the Battle for our Energy Future, Infocast Forum on Next Generation Microgrids, February 27, 2014.
[46] Supra., EPRI 3.0 Grid

“utility” regulation, etc.

ACRONYMS

AGC	automatic generation control
CHP	combined heat and power
CPUC	California Public Utilities Commission
DER	distributed energy resources
DSP	distributed system platform
ESS	energy storage systems
kW	kilowatt
MW	megawatt
NERC	North American Electric Reliability Corporation
NYS	New York State
PCC	points of common coupling
RES	renewable energy sources
REV	Reforming the Energy Vision
V/f	voltage/frequency
W	watt

APPENDIX—TECHNICAL CAPABILITIES TO SUPPORT NETWORKED MICROGRID TOOLS

Part 1 of this reported discussed on potential pathway for how a Networked Microgrid Optimal Design & Operations tool may be developed by leveraging previous DOE investment in microgrid and distribution network optimal design and simulation tools. This description is not meant to restrict the options to only this process, however, it can be used to specify several technical capabilities that are expected to generally apply to all Networked Microgrid OD&O tools. The following Table provide a general summary of these capability specifications broken down by the requirements for system simulation, optimal operations and optimal design.

<table>
<tr><th></th><th rowspan="2">Capability</th><th colspan="3">Networked Microgrid Tool</th></tr>
<tr><th></th><th>Simulation</th><th>Optimal Operations</th><th>Optimal Design</th></tr>
<tr><td rowspan="10">General Power Systems Modeling</td><td rowspan="2">Power Flow</td><td colspan="3">• 3-phase unbalanced
• Full AC representation or a sufficient approximation
• Able to solve with multiple islands
• Resolved in both distribution network and microgrid</td></tr>
<tr><td colspan="2">• Radial and urban mesh networks</td><td>• Radial networks</td></tr>
<tr><td rowspan="2">Loads-Quasi static</td><td colspan="3">• Flexible modeling of loads including constant PQ, constant Z, and constant current</td></tr>
<tr><td>• Time series data inputs for load variability with 1 minute resolution or better</td><td colspan="2">• Time series data inputs for load variability with 15 minute resolution or better</td></tr>
<tr><td>Loads-Dynamics</td><td>• Resolve the phasor dynamics of important loads with AC-cycle time scale resolution (e.g. induction motors) inside the microgrids and on the network</td><td>• Account for the impact of dynamics of loads on the feasibility of dispatch and topology optimization</td><td>• N/A</td></tr>
<tr><td rowspan="3">Distributed Generation-Quasi static</td><td colspan="3">• Flexible modeling of generation including constant PV, constant PQ, and slack bus
• Include fossil-fired generation, PV, wind, and battery storage
• Include non-constant generator efficiency curves</td></tr>
<tr><td>• Time series data inputs for generation variability with 1 minute resolution or better</td><td colspan="2">• Time series data inputs for generation variability with 15 minute resolution or better</td></tr>
<tr><td>• N/A</td><td>• Operational costs</td><td>• Capital and operational costs</td></tr>
<tr><td>Distributed Generation-Dynamics</td><td>• Resolve the dynamics of important generators and associated controls with AC-cycle time scale resolution (synchronous generators, inverter coupled generation inside the microgrids and on the network</td><td>• Account for the dynamics of generators during dispatch and topology optimization</td><td>• N/A</td></tr>
<tr><td>Transmission system interface</td><td>• Simulate effects of quasi-static and dynamic changes of voltage and frequency</td><td colspan="2">• N/A</td></tr>
</table>

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		at transmission-distribution interface, e.g. faults, voltage sags, frequency fluctuations	
Controls Modeling	Load and DER	• Resolve the quasi-static and dynamic response of advanced controls for load and DER	• Resolve the quasi-static response of advanced controls for load and DER
	System Topology	• Simulate scripted topology switching sequences including dynamics	• See Unit Commitment and Economic Dispatch
	Communications	• Include the effects of latency and communications interruptions/dropped messages	• N/A
Reliability Analysis	Faults and Protection Studies	• Computes fault currents and simulates protective device actions • Simulates post-fault/post-clearing system dynamics	• N/A
	Contingency Analysis	• Automatically simulates lists of contingencies	• See Unit Commitment and Economic Dispatch
	Renewable Resource Variability	• User specified or default resource time series at 1 minute resolution or better—irradiance (W/m^2) or wind speed (m/s)	• User specified or default resource time series at 15 minute resolution or better—irradiance (W/m^2) or wind speed (m/s)

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Unit Commitment and Economic Dispatch	Objectives	• N/A	• Co-optimizes energy and ancillary services (frequency regulation, spinning reserve, VAr, Black Start)
	Contingencies	• N/A	• Includes N-1 contingency constraints for generators and critical power lines
	Topology	• N/A	• Solves for optimal topology for cost and/or resilience • Accounts for feasibility of topology switching—quasi-static and dynamics
	Uncertainty	• N/A	• Accounts for impact of generation and load uncertainty on constraints, reliability and costs
	Multi-layer optimization and control	• N/A	• Able to represent multi-layer decision making in generation dispatch and other operation optimization
	BES Market Integration	• N/A	• Able to emulate bulk energy system markets to evaluate interactions with higher-level markets
Optimal System Design	Microgrid	• N/A	• Generation type and capacity optimization • Topology optimization
	Distribution network	• N/A	• Network hardening and expansion optimization including new lines, switches, etc
	Networked microgrids	• N/A	• Integrated design and siting of networked microgrids for

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				economics, reliability and resilience
	Extreme events/Fragility modeling	• N/A		• Model component damage and network state post-extreme event
Resilience Analysis	Fragility modeling	• Ability to simulate time sequenced device/component failures for extreme events		•