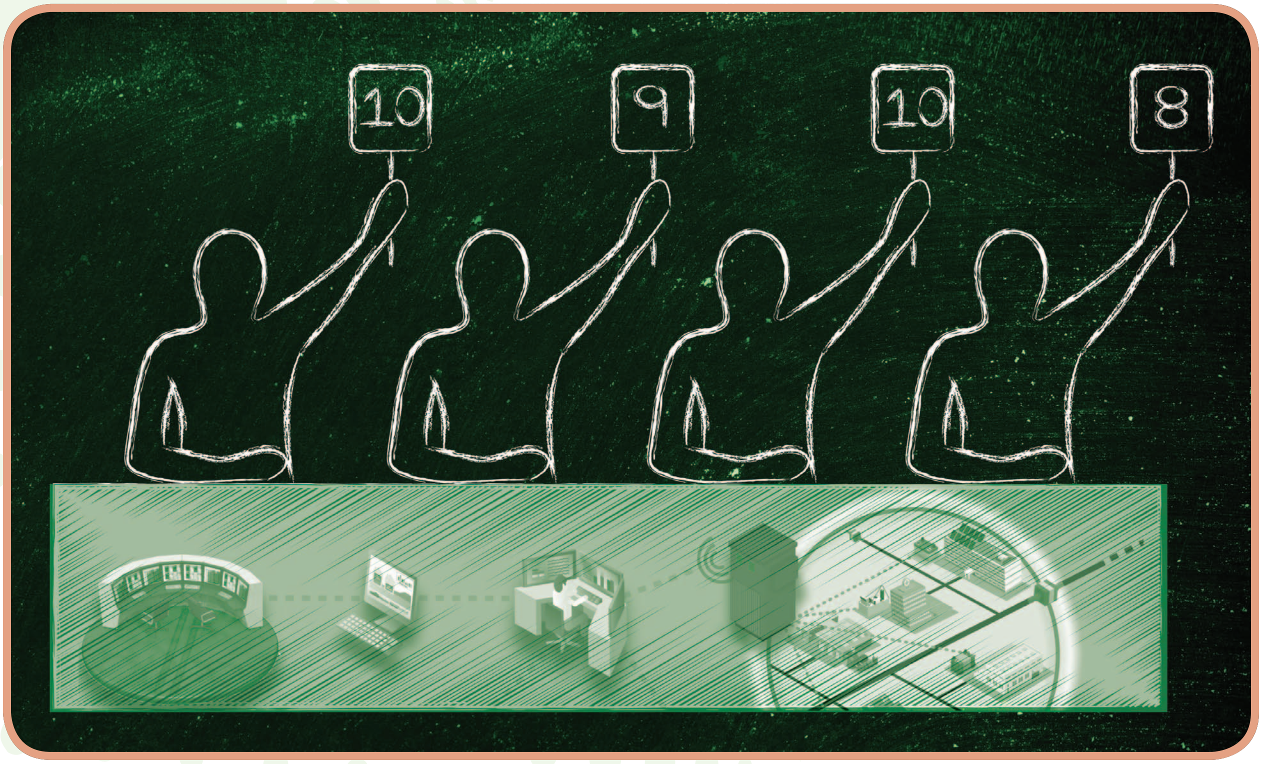

Microgrid Controllers

Expanding Their Role and Evaluating Their Performance

MICROGRIDS HAVE LONG BEEN DEPLOYED TO provide power to customers in remote areas as well as critical industrial and military loads. Today, they are also being proposed as grid-interactive solutions for energy-resilient communities. Such microgrids will spend most of the time operating while synchronized with the surrounding utility grid but will also be capable of separating during contingency periods due to storms or temporary disturbances such as local grid faults. Properly designed and grid-integrated microgrids can provide the flexibility, reliability, and resiliency needs of both the future grid and critical customers. These systems can be an integral part of future power system designs that optimize investments to achieve operational goals, improved reliability, and diversification of energy sources.

The key components of a microgrid are the isolating device at the point of interconnection (POI); the electric and thermal

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loads; the distributed energy resources (DERs), including solar photovoltaics (PVs), batteries, combined heat and power and load management systems; and the local microgrid controller, as shown in Figure 1. In North America, DERs contained within a microgrid must comply with IEEE Standard 1547-2003 (*Standard for Interconnecting Distributed Resources with Electric Power Systems*), one of the primary interconnection standards for distributed resources. The standard provides guidance on voltage and frequency control, overcurrent protection, effective grounding, islanding prevention, and synchronization thresholds, among other issues relevant to the microgrid while connected to the utility grid through the grid interface.

There are five major types of microgrids:

- ✔ *Commercial/industrial*: These are generally built to reduce demand and costs during normal operation, although the operation of critical functions during outages is also important, especially for data centers.
- ✔ *Community/utility*: These are generally designed to improve reliability and promote community participation.
- ✔ *Campus/institutional*: Many college, industrial, and hospital campuses already have distributed generations, with microgrid technology linking separate loads together. They are usually large and may sell excess power to the grid.
- ✔ *Military*: Military microgrids focus on cyber and physical security, both for fixed and forward-operating bases.
- ✔ *Remote*: Remote microgrids are permanently disconnected from other grids, continuously operating in island mode. Many already use diesel generation so microgrids offer a way to incorporate renewable energy.

Each microgrid is designed to meet specific goals. The Electric Power Research Institute (EPRI) has developed a four-stage design evaluation process, also referred to as the Integrated Grid Benefit-Cost Analysis Framework for Microgrids, to guide the technology selection and sizing of DER assets for a given set of microgrid goals. This techno-economic analysis can be imagined as sequentially layering on a microgrid's assets and functions, evaluating the incremental costs and incremental benefits at each layer. The EPRI analysis framework was applied to inform the design of the Buffalo Niagara Medical Center (BNMC) microgrid in Buffalo, New

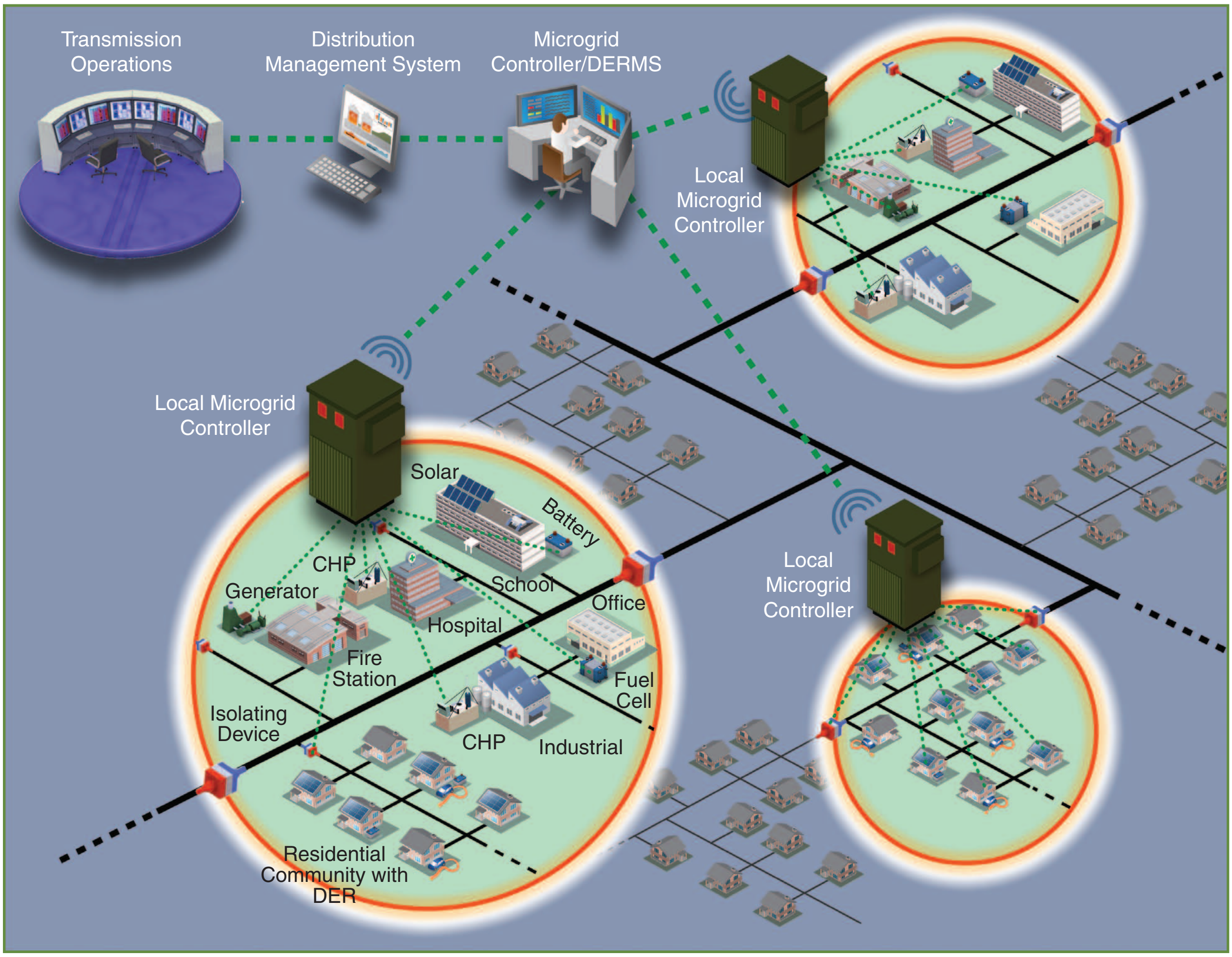

figure 1. A grid-interactive microgrid controller for resilient communities. DERMS: distributed energy resource management system; CHP: combined heat and power.

York. The analysis starts with stating the goals assigned to the microgrid, its desired capabilities, and the expected benefits for the BNMC community. A mathematical optimization (deterministic-based) model is formulated and run with identified site constraints (e.g. existing infrastructure, physical space, and utility interconnection) to determine requirements with respect to DER sizing and dispatch. The analysis details the selected system setup and its associated costs and benefits in each layer. This techno-economic analysis evaluates a broad, comprehensive strategic plan that seeks to meet resiliency needs at multiple scales, including individual BNMC member institutions, the BNMC as a whole, and the greater Buffalo region.

Microgrid Controller Requirements and Attributes

The microgrid controller manages its assets to meet the objectives of the operator, which may be a community, utility, campus, or industrial facility. A key objective is the resiliency benefits that enable continuous power for critical loads during islanded conditions. Secondary objectives may also include the reduction of operating costs, increased DER penetration and utilization, limited greenhouse gas emissions, and improved local grid reliability. In addition, microgrid controllers may be required to interface with higher-level entities [e.g., distribution management systems (DMSs), DER aggregators, or market operators] and provide local as well as bulk-level grid services to external parties, as shown in Figure 1.

IEEE Standard P2030.7 (*Standard for the Specification of Microgrid Controllers*) specifies two core control functions for microgrid controllers: transition and dispatch. These two functions enable the microgrid to operate as a system that can manage itself— autonomously or with the grid—and connect or disconnect from the distribution grid. The core control functions also ensure that the microgrid satisfies interconnection requirements, coordinates with existing grid protection schemes, and enables the exchange of power and the supply of ancillary services at the POI.

Beyond the functions that are required to be performed by microgrid controllers, other desirable attributes of microgrid controllers include

- ✔ standardized
  - a control platform that is modular and reconfigurable to promote wide-scale adoption
  - a commercially available controller that utilizes open communication protocols
  - a functionality-driven controller that focuses on a modular approach to the implementation of the functional requirements.
- ✔ customizable and interoperable
  - a controller that is able to coordinate/operate a diverse set of DER technologies of varying sizes and quantities
  - a controller that enables a simple configuration, deployment, and operation of microgrid systems interfacing with a conventional supervisory control and data acquisition system and other DMSs.
- ✔ scalable and robust
  - a controller that enables users to add, remove, or edit assets within the connected system
  - a controller that operates as a distributed energy resource management system (DERMS) in grid-tied mode and takes on generation-load balancing authority in islanded mode.

Microgrid Controller Performance Evaluation

The performance of microgrid controllers should be evaluated in a relevant environment prior to field deployment. The evaluation of a microgrid controller in a laboratory setting allows for testing under various operating conditions and asset limits, e.g., worst-case testing, without impacting the grid and connected customers. The evaluation comprises several different goals, including compliance with standard specifications, evaluation of multiple controllers under the same conditions, and evaluation with respect to site-specific requirements.

The first goal of the laboratory evaluation is to determine whether a microgrid controller performs as specified. This is addressed in IEEE Standard P2030.8 (*Standard for the Testing of Microgrid Controllers*), which focuses on testing the functional and performance requirements. It includes the control functions specified in IEEE P2030.7:

- ✔ functions for managing local resources and loads
- ✔ functions for control in grid-connected mode, including power-flow management and supply of ancillary services for the local distribution system and potentially the bulk system
- ✔ functions for control in islanded mode (autonomous), including management of local generation, storage, and loads to optimize performance
- ✔ ability to seamlessly connect and disconnect from the grid, based on specified parameters
- ✔ additional local functions may be specified for specific circumstances (such as renewable resource management, load prioritization, and support of grid reliability and automation functions).

The second goal of the evaluation is to characterize performance by subjecting several microgrid controllers to the same tests. This type of evaluation is important to help microgrid developers and/or operators make informed decisions when selecting a microgrid controller that meets their specific needs, and it informs vendors on their product's performance. The U.S. Department of Energy's (DOE's) Office of Electricity Delivery and Energy Reliability (OE) supported an effort led by the Massachusetts Institute of Technology's Lincoln Laboratory to develop a real-time hardware-in-the-loop (HIL) simulation platform to evaluate commercial microgrid controllers. This allows microgrid controller hardware to be integrated with commercial genset controller hardware, paired with the real-time simulation of a microgrid system with critical and noncritical loads, DERs, and other conventional power sources. This platform is being extended to include power hardware, including a PV inverter, battery-based storage, and an electric vehicle, at the National Renewable Energy Laboratory (NREL) with support from the DOE's National Laboratory Impact Initiative under the Microgrid Controller Innovation Challenge. However, this approach does not provide insight into how a microgrid controller will perform for the *specific* microgrid being designed.

Therefore, the third goal of the evaluation is that of site-specific performance assessment and compliance. This goal addresses the question of whether a specific microgrid controller is capable of managing a unique portfolio of microgrid assets to meet utility interconnection and customer requirements.

All three goals of laboratory evaluations described herein require testing in the context of an overall microgrid system. The microgrid controller will need to be customized for the specific laboratory setup that will be used to model the actual microgrid. Therefore, close cooperation between the laboratory staff performing the evaluation and the microgrid controller provider is required for successful evaluation.

Site-Specific Microgrid Controller Evaluation

Several options are available for evaluating a site-specific microgrid controller in a laboratory setting, as illustrated in Figure 2. The first approach [Figure 2(a)] shows pure simulation, where all components are represented in simulation. While such an approach may be used by microgrid controller developers in the early stages of product development, the challenge here is that the microgrid controller needs to be recreated with the simulation software used by the laboratory performing the evaluation. Therefore, a more popular option is controller-HIL (CHIL) simulation, where the microgrid controller hardware is interfaced with a simulated microgrid and assets [see Figure 2(b)]. A transient simulation, with a time step in the range from tens to hundreds of microseconds, is able to be performed using either a commercial real-time simulator—available from vendors such as Opal-RT, Real-Time Digital Power System Simulation (RTDS), Typhoon, or Speedgoat—or a custom-built real-time simulator. It is sometimes necessary to simplify the electric power system model with respect to the microgrid, based on the capability or capacity of the real-time simulator. However, if properly developed, the reduced-order model characteristics (e.g., short circuits or voltages) and performance will be similar to that of the full model. A CHIL simulation setup requires significant effort to implement, especially regarding the communication interface between the microgrid controller hardware and the simulation platform.

Adding a power-HIL (PHIL) simulation to the CHIL simulation, as shown in Figure 2(c), allows for the use of actual hardware, either the exact model planned for the microgrid site or a representative model with similar characteristics. Utilizing real hardware components reduces modeling inaccuracies, especially because proprietary controls of various vendors embedded within the power hardware, such as PV inverters,

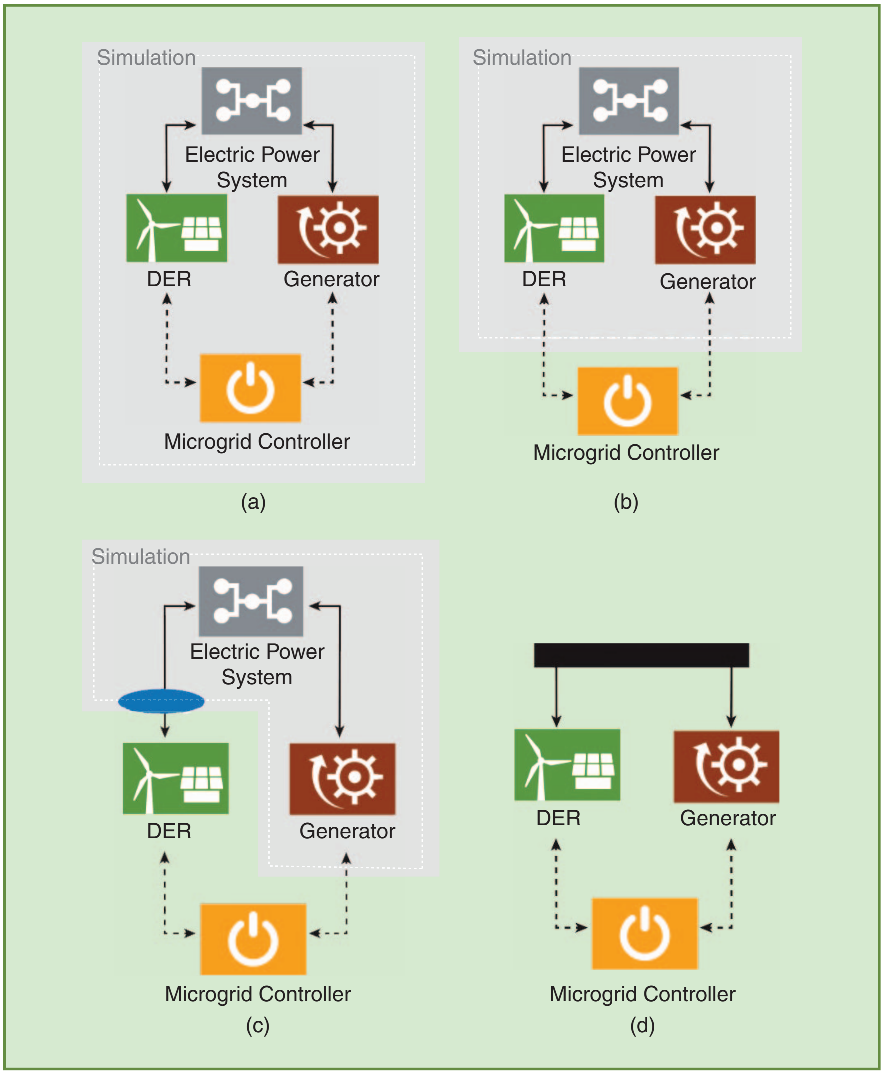

figure 2. Options for laboratory evaluations of microgrid controller compliance with site-specific requirements: (a) pure simulation, (b) CHIL, (c) CHIL and PHIL, and (d) hardware only.

cannot always be accurately modeled. At the same time, interfacing power hardware with the real-time simulator introduces far more complexities and challenges compared to a CHIL-only setup. If the interfaces—which are indicated by the blue oval in Figure 2(c)—are not properly designed and configured, the simulation can become unstable; therefore, the interfaces should also include compensators to ensure stability and accuracy.

The final option is full hardware testing, excluding any simulated components [see Figure 2(d)]. As with PHIL, either the same hardware or representative hardware of the microgrid may be used; however, this type of evaluation is limited by the inability to represent the electric power system of the microgrid.

Examples of Site-Specific Microgrid Controller Evaluation

Several examples are provided here to further illustrate these site-specific evaluation approaches. The first is the evaluation of the Spirae Wave microgrid controller, discussed earlier, that was conducted for the BNMC campus microgrid. Spirae first tested the microgrid controller functionalities at their InteGrid test facility using a hardware-only approach, as shown in Figure 2(d). The test setup consisted of its Wave microgrid controller managing several representative assets connected to a single bus: two synchronous generators, a PV inverter, a wind turbine simulator, and a synchronous condenser. The controller was then evaluated by NREL at the Energy Systems Integration Facility using a combined PHIL and CHIL approach as shown in Figure 2(c), which includes a simulation of the BNMC electric power system that interconnects the different microgrid assets. This work was funded by the OE under Funding Opportunity Announcement DE-FOA-0000997-Amendment 0002 (FOA 997).

The testing at both sites was conducted under scenarios including grid-connected operation, disconnection, maintaining an island, resynchronization, and black start. Results from the test scenarios were compared to performance metrics specified by DOE for the following functional requirements:

1) disconnection, evaluated by determining whether the microgrid disconnects from the utility within the time specified when a voltage or frequency threshold is reached or when an unintentional island is created
2) resynchronization and reconnection, evaluated by determining whether reconnection occurs only when the grid voltage, frequency, and phase angle differences between the utility and microgrid are within a specified range (as defined in IEEE 1547 and ANSI C84.1, *Electric Power Systems and Equipment—Voltage Ranges*)
3) steady-state performance in islanded mode, evaluated based on whether the microgrid controller is able to maintain the voltage and frequency within the ranges specified
4) protection, evaluated by simulating external and/or internal faults and determining whether the microgrid controller provides adequate control to serve and manage critical loads in both grid-connected and islanded modes of operation, assuming that the faults will be cleared by the microgrid's protection scheme
5) dispatch, evaluated by determining the microgrid controller's ability to utilize resources to serve critical loads when islanded.

The PHIL and CHIL evaluation of the Wave microgrid controller was subsequently performed at NREL using the laboratory setup illustrated in Figure 3. A reduced-order model of the BNMC electric power system, including most of the generators and DERs, was simulated using an RTDS system, which solves the model in real time and generates measurement signals that emulate an actual microgrid. These measurement signals are received by the microgrid controller, which acts on them and produces control commands for the microgrid's controllable assets, thus closing the control loop.

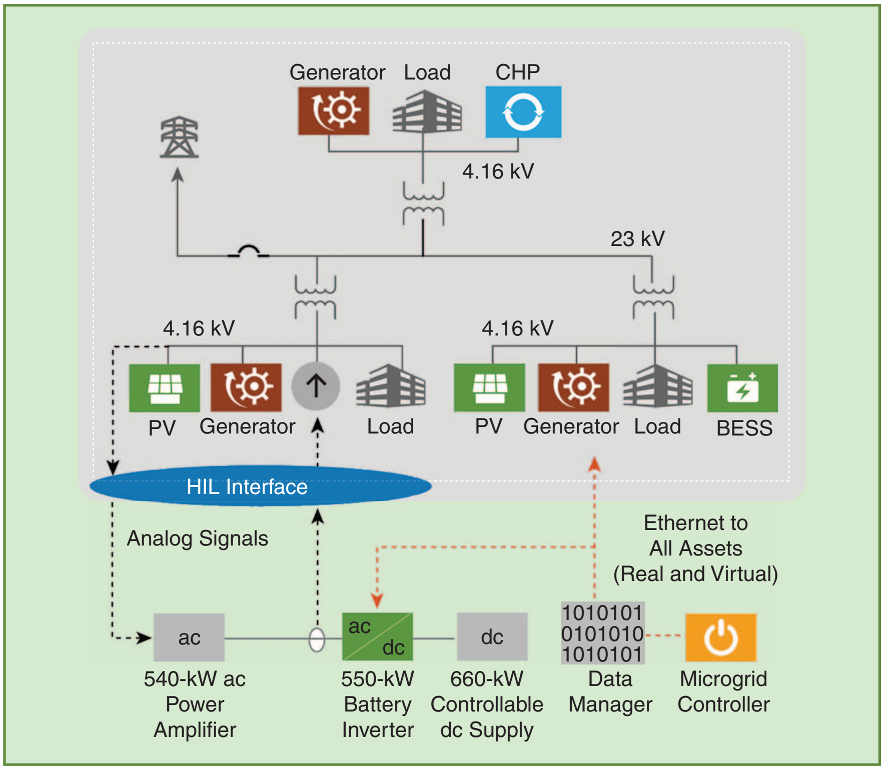

figure 3. The laboratory setup for PHIL and CHIL evaluations of the Spirae Wave microgrid controller for BNMC.

The microgrid controller is interfaced to the RTDS through a data manager that performs protocol-translation and data-concentrator functions.

One of the battery energy storage systems (BESSs) is represented in power hardware by a 480-V/540-kW three-phase battery inverter. An ac power amplifier—a controllable, bidirectional ac source—is used to create the interface between the power hardware and virtual parts of the model. The RTDS controls the ac power amplifier to follow the (scaled) voltage on the simulated bus to which the BESS is connected. The current output of the BESS is measured and reflected in the RTDS model as a (scaled) current source, closing the PHIL loop. A controllable, bidirectional dc supply is controlled to act as a battery.

The PHIL interfaces include digital-to-analog (and analog-to-digital) conversions and appropriately designed compensators to ensure that the time delays introduced by these conversions do not result in an unstable experiment. They also include compensators to ensure accuracy.

Figure 4 shows the simulation results during a microgrid planned islanding event, which may be performed prior to a scheduled grid-outage event or in response to degrading electric grid power quality. In Figure 4, (a) shows the disconnect signal issued by the microgrid controller, (b) is the voltage on the microgrid side of the breaker at the POI, (c) shows the current through the POI breaker, and (d) is the output current of the hardware battery inverter. The POI breaker current is low prior to islanding because the microgrid controller reduces the power flow across the POI to nearly zero to ensure a smooth transition. The microgrid voltage and battery inverter current waveforms confirm that a smooth transition occurred.

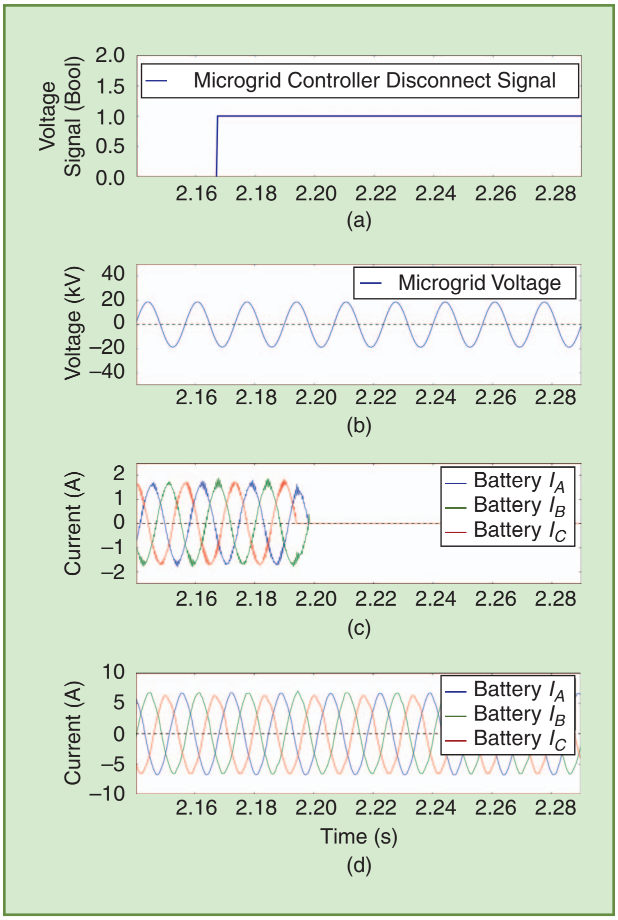

figure 4. PHIL and CHIL test results of the Spirae Wave microgrid controller for a planned islanding event: (a) control signal, (b) microgrid voltage, (c) circuit breaker current, and (d) current output of battery inverter.

NREL is also supporting a distinct project funded by the California Energy Commission (CEC) with PHIL and CHIL testing to evaluate microgrid controller technology. Borrego Springs, California, is a desert community served by one 30-mi radial transmission line that extends across mountains and deserts, where the circuit is susceptible to severe weather and fires. The CEC awarded a project grant to San Diego Gas & Electric to expand an existing DOE-funded microgrid demonstration project to cover the entire Borrego Springs community of 2,800 metered customers. The goals are to provide customers with greater reliability and resiliency—and to leverage more local renewable energy to power the community. The expanded microgrid includes a large PV plant that enables the community to operate during the day, solely on renewable energy. NREL's test setup includes a microgrid controller and two genset controllers as the CHIL, and it includes a representative battery inverter and the actual PV inverter that is used in the field as the PHIL. The CEC requires evaluation of similar functional requirements as those in the funding opportunity announcement Microgrid Research Development, and System Design as well as additional tests.

Microgrid Controller Integration with DERs and Distribution Management Systems

In the future, microgrid controllers are expected to play a significant role in the management of electric distribution systems, especially where DERs connected to a distribution system are located within microgrids. An integrated approach is required to allow a microgrid controller to work in harmony with a DMS to effectively manage the electric distribution system. Over the past few years, industry activities to create standards for DERs have focused on the behaviors of individual DER units and open communication protocols over field networks that connect directly to these end devices. To better integrate and manage increasingly diverse distributed resources, EPRI has been developing functional requirements and communication protocols for DERMS operating in a grid-tied mode. Management of the electrical distribution grid has occurred without the expansion of DMS functions, accounting for the proliferation of DERs and microgrids on existing electrical distribution systems. Currently, the DMS, DERs, DERMS, and microgrid controllers are managed as separate entities with minimal communication, let alone coordination, among them.

The DOE's OE office has been investigating such an integrated system under its project Structuring a Demonstration Project to Integrate DER, Microgrid, DERMS, and DMS. The objective of this project is to develop a deep and comprehensive understanding of integrated control and management systems for distribution systems with high penetrations of renewable energy generation. Recent publications from EPRI and Argonne National Labs provide guidelines on potential architectural variations of an integrated system as well as establish the relationships between the different components and identify core DMS applications. The overall architecture for integrating a DMS with DERs, DERMS, and microgrid controllers varies based on circuit topology, utility operation practices, and connected distributed generation. This project includes a site-specific evaluation of the integrated operation of a DMS and microgrid controller, and the microgrid site needs to be modeled along with the distribution network to which it connects. This requires model size beyond what transient real-time simulators can usually handle.

For these reasons, reduced, multitimescale simulations are required, as shown in Figure 5. A physical DMS and microgrid controller will interact with select power hardware components and each other through the simulation platform. This test bed development will draw upon the foundational capabilities necessary for a multitimescale test bed being developed under the advanced distribution management system test bed project, also supported by DOE through its Grid Modernization Laboratory Consortium.

The beneficial integration of microgrids within distribution systems requires communications between the microgrid controller and DMS to plan and manage the transitions between grid-connected and islanded modes and coordinate the grid support microgrids that provide electricity generation to the distribution system when functioning in grid-tied mode. DER group functions can be used to structure these communications. Since 2012, EPRI has facilitated a focus group of industry experts that is developing a library of standard DER group functions to monitor and manage groups of DERs. Microgrids are examples of DER groups operated by a single managing entity.

Microgrid transitions fall within three possible categories: planned islanding, unplanned islanding, and reconnection. The microgrid controller and the DMS can coordinate planned islanding and reconnection events through use of the connect/disconnect function, one of the DER group functions available (see Figure 6). Any of the two entities

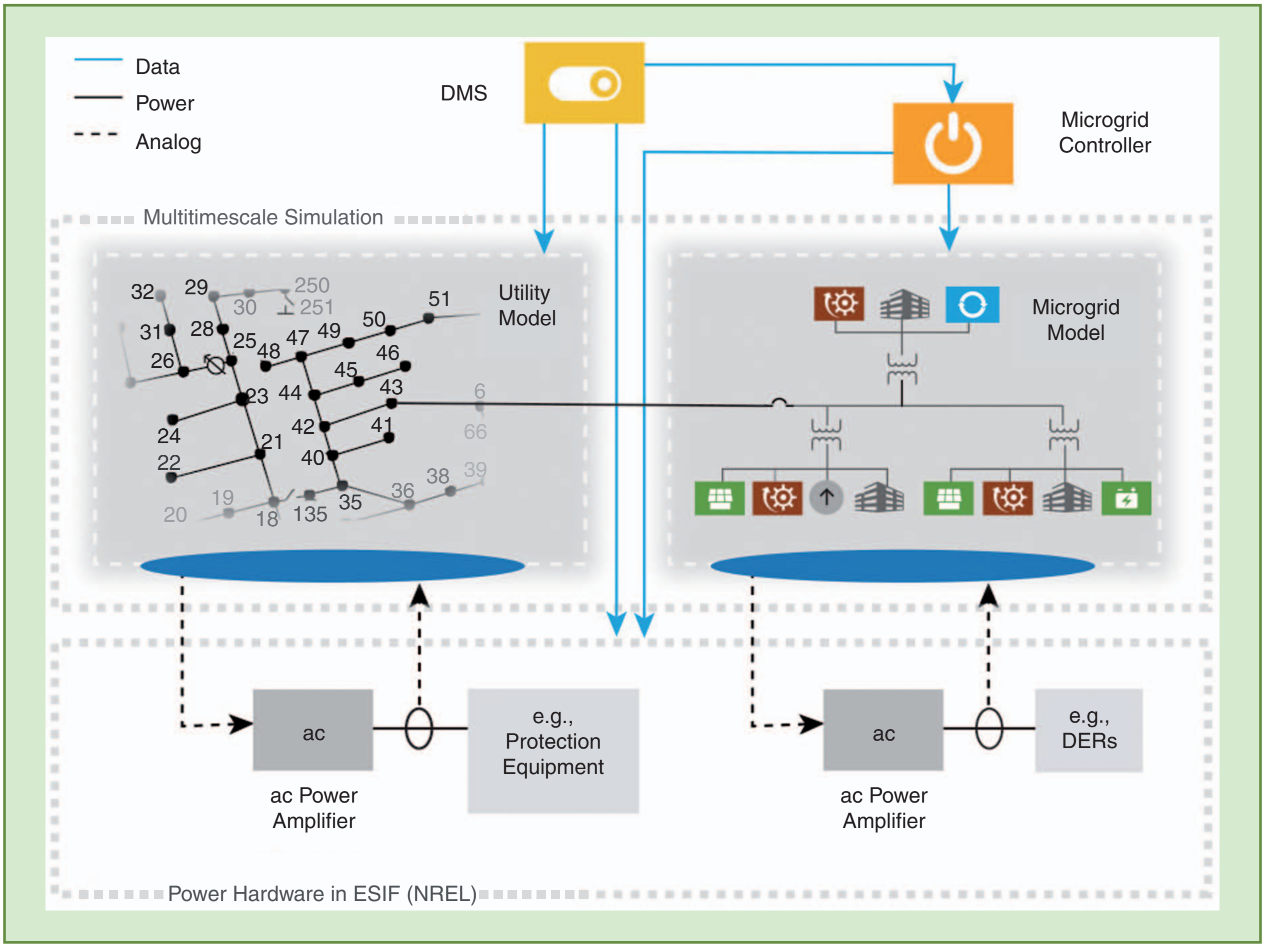

figure 5. A diagram of a multitimescale test bed to evaluate DMS-microgrid controller integration.

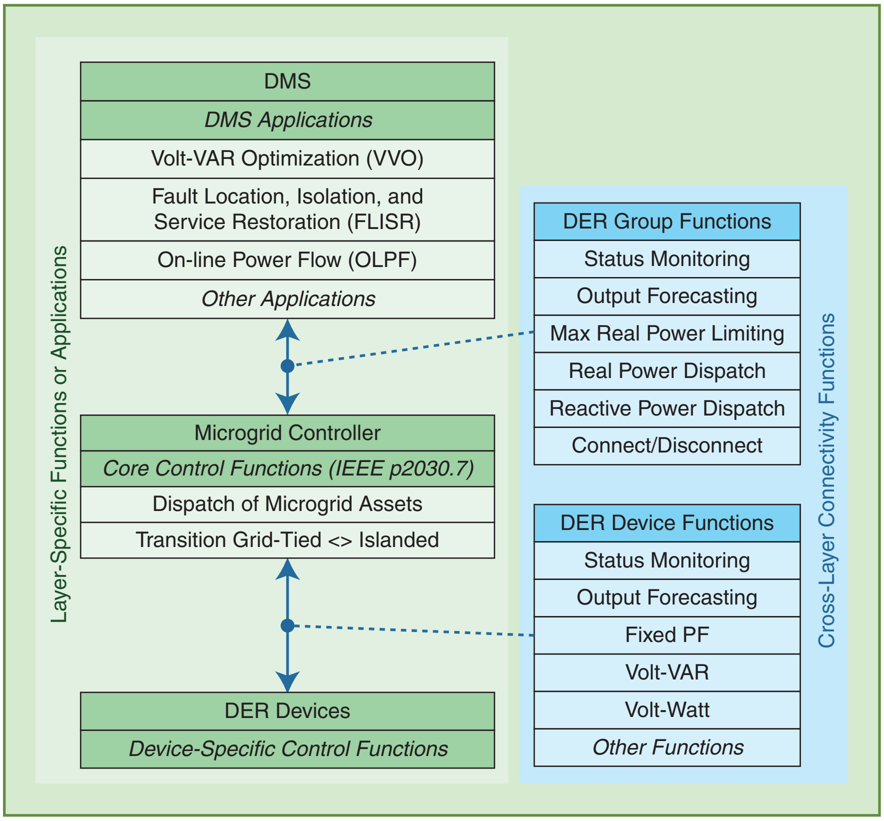

figure 6. A comparison between functions and applications *internal* to each control layer and functions enabling connectivity *between* control layers.

can send the other a request for executing a planned transition at a certain time. When agreement is reached between the two, the microgrid controller initiates islanding or reconnects at the time agreed upon with its two core control functions, transition and dispatch, as defined in IEEE P2030.7. This involves executing a series of internal control steps to bring the voltage, phase, and frequency at the POI within certain limits specified by the distribution system. Unplanned islanding is different; it is triggered automatically by abnormal conditions at the POI without any prior communication between the microgrid controller and DMS. The distribution system operator may require the microgrid controller to report any unplanned islanding events to the DMS to facilitate the execution of contingency actions for the distribution system.

When grid tied, microgrids have potential to provide grid support to the distribution system to help maintain grid reliability or rectify abnormal grid conditions. The DMS specifies and coordinates the type and level of support requested from the grid-tied microgrid. To that end, the standardized DER group functions enable the DMS and microgrid controller to exchange information on current and forecasted grid conditions as well as the microgrid capacity to provide support. DER group functions also enable the DMS to send specific support requests to the microgrid controller. For example, when executing its volt-var optimization (VVO) application, the DMS can make use of its monitoring and forecasting group functions to evaluate the present and forecasted support capability of a given microgrid. This information is used as input to the VVO optimization engine that determines how to best leverage the support capabilities available from the microgrid to help meet the VVO objectives. The desired settings can be set points or ranges and relate to the real and/or reactive power exchanged at the microgrid POI. Once the desired settings have been determined, the DMS sends a corresponding support request to the microgrid controller through use of the maximum reactive power limiting real power dispatch, and/or reactive power dispatch group functions (see Figure 6). The microgrid controller disaggregates this DMS request into specific set points assigned to each of the DER assets it manages, using the *dispatch* core function. Finally, the DER device functions can be used to communicate the individual set points to the DER assets, and each asset responds by executing its own internal control functions accordingly.

Enterprise-Level Integration

Finally, the topology of an integrated system is shown in Figure 7 with the DMS, DERMS, DERs, and microgrid controllers working together along with other management, a geographic information system, and an outage management system. All of these systems integrate at the enterprise level and also require interface specifications through standards like the Common Information Model. In a system where microgrids are present, a microgrid controller is used to manage the DERs within it. The prediction of DER output power can be done by either the microgrid controller or the DMS. A microgrid controller can communicate directly with DERs or through a DERMS to DERs within the microgrid. A microgrid controller can also communicate directly with the DMS or through a DERMS to the DMS. The architecture for integrating a DMS with microgrid controllers and a DERMS needs to be considered in the context of the specific DMS applications that interact with these systems. Many of these applications will also require interfaces with other enterprise-level systems. This becomes part of an overall systems level specification for the microgrid controller and its required interfaces.

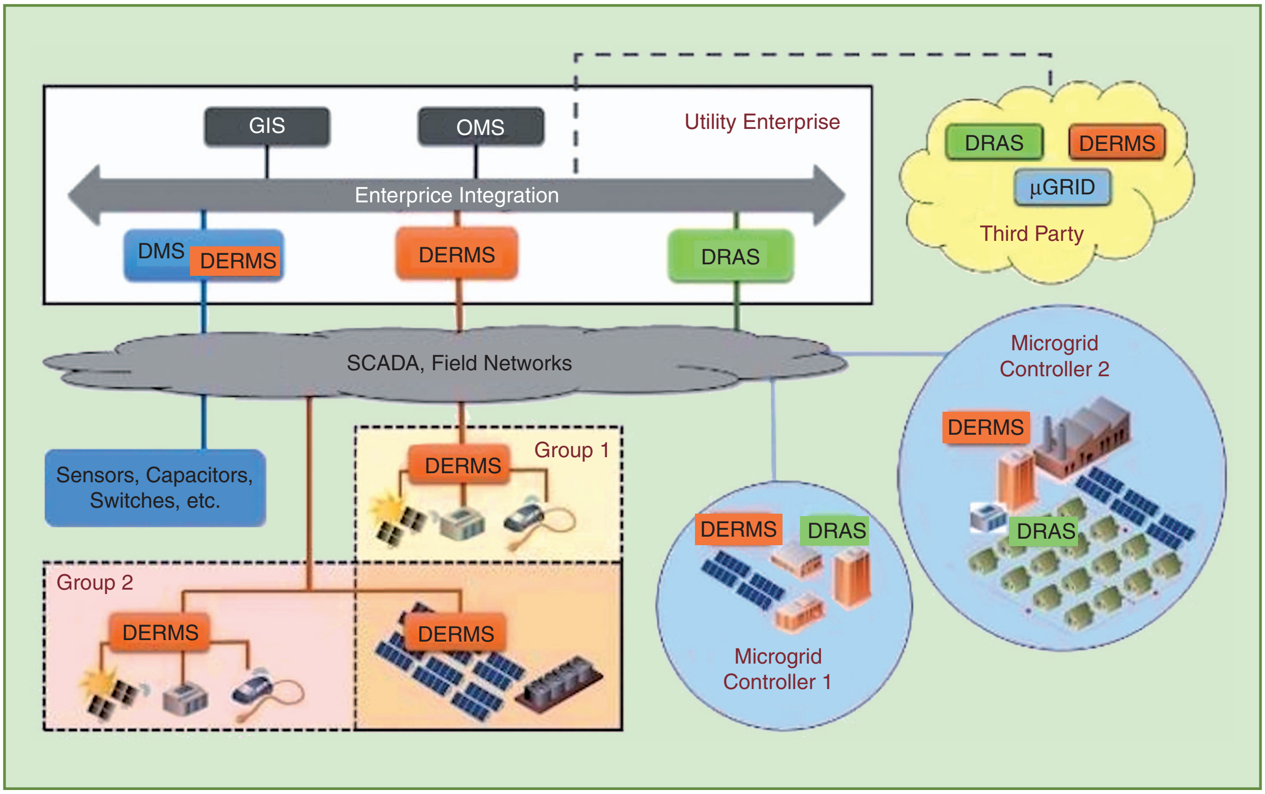

figure 7. A utility high-level architecture.

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For Further Reading

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