ELECTRIC POWER
RESEARCH INSTITUTE

A SMART AND FLEXIBLE COMMUNITY MICROGRID WITH DYNAMIC BOUNDARY

December 2020

Introduction

The microgrid concept is not new. While the term microgrid is sometimes used to describe a number of applications involving distributed generation, the U.S. Department of Energy (DOE) describes a microgrid as "…a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode."[1] This definition covers a range of different system types from remote systems that are permanently disconnected from utility grids to systems utilizing smart grid technology where sections can operate with and without connection to the main distribution network.

Emerging lower-cost distributed energy resource (DER) technologies, environmental considerations, utility grid modernization, and a growing customer desire for more resilient electric service are increasing the potential value and application of microgrids. At the same time, several states are also undertaking regulatory efforts to improve the resilience of the electric grid. For example, the California Public Utilities Commission has recently directed utilities to improve the interconnection process for resiliency projects and modernize tariffs to maximize social resiliency benefits. Regulators in Connecticut, Hawaii, and DC are likewise considering resilience in their grid modernization proceedings. When combinations of these drivers are present, a well-designed microgrid may offer a cost-effective option to enable a more modern grid; provide low-cost, efficient, and clean power; enhance integration of DER; reduce peak loads; promote customer participation; and significantly improve reliability and resiliency of the power grid.[2]

In the early stages of microgrid adoption, the majority of projects were for demonstration purposes, customized for special sites, such as military bases, university or business campuses.[3] With lower DER costs and more standard designs, microgrid deployments in the U.S. began to see significant growth in 2017. According to a recent survey,[4] a record 546 microgrids were installed during 2019 as shown in Figure 1. Most of those projects were below 5 megawatts – a trend that started in 2017 – with smaller, more modular projects accounting for most of the growth each year. Clearly, microgrids are beginning to play a greater role, creating new opportunities for how utilities design and operate the grid and deliver value to the communities they serve. Rather than relying solely on utility-driven smart grid programs to improve reliability and power quality, microgrids embedded within utility transmission and distribution systems can increase flexibility and offer a number of economic, environmental, and reliability improvements.

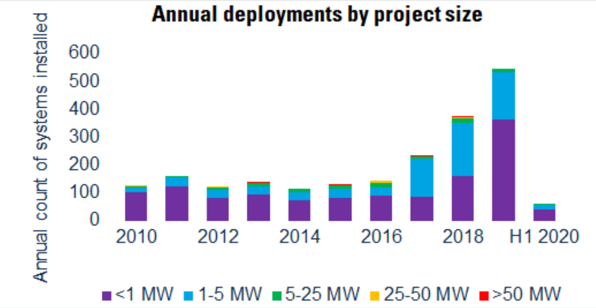

Figure 1. Annual microgrid deployments by project size (source: Wood Mackenzie)

Recognizing these emerging trends, the Advanced Research Projects Agency-Energy (ARPA-E), began working with industry to sponsor research investigating microgrid designs that would more readily facilitate expansion and duplication to communities across

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This white paper was prepared by EPRI.

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[1] D. T. Ton, M. A. Smith, "The U.S. Department of Energy's Microgrid Initiative," *The Electricity Journal*, vol. 25, no. 8, 2012, pp. 84-94.

[2] *Microgrids: Expanding Applications, Implementations, and Business Structures*. EPRI, Palo Alto, CA: 2016. 3002008205.

[3] *Program on Technology Innovation: Microgrid Implementations: Literature Review.* EPRI, Palo Alto, CA: 2016. 3002007384.

[4] Wood Mackenzie Investor Landscape, Q3 2020.

the country. Key considerations were utilization of existing smart grid technology (distribution automation and management systems, high-speed communication, and customer distributed generation) that may already be deployed on the grid and non-proprietary controller designs based on general purpose hardware to enable lower cost implementation.

This report describes an ARPA-E project with the University of Tennessee - Knoxville (UTK), Electric Power Board of Chattanooga (EPB), National Instruments (NI), Green Energy Corporation (GEC), the Tennessee Valley Authority (TVA) and the Electric Power Research Institute (EPRI) to apply and demonstrate these design concepts on the EPB power grid.[5,6] A key feature of this project is the utilization of EPB's advanced smart grid features and to explore scenarios to dynamically adjust - expand or contract - the microgrid boundary based on available power generation and loads at the time of the outage event.

Motivation and Objective

The host site for the microgrid, Chattanooga EPB, has over 180,000 customers, a service territory of approximately 600 square miles, and is one of the largest publicly-owned power distributors in the U.S. EPB has built a highly-resilient communications and electric network including 100% fiber enabled communication network and dense distribution automation powered by 1200 S&C IntelliRupter® smart switches. These infrastructure investments have been responsible for a 45% reduction in system outage time, by promptly isolating faults and transferring the loads to other feeders through automated control.[7]

However, further improvement is desired. Severe weather events continue to cause system-wide disturbances. For example, a tornado outbreak in 2011 interrupted power for 23 hours to three quarters of the customers as well as critical loads at the City of Chattanooga Metropolitan Airport. Recognizing the opportunity to utilize the existing 2.1 MW (later expanded to 2.8MW) local PV generation to help serve the critical load, the project team selected the airport as the demonstration site for the microgrid. In addition to serving some portions of the critical load at the airport, the microgrid also has the potential to support approximately 66 neighboring commercial and industrial customer loads, by adjusting the microgrid boundary when the PV generation is sufficient.

A core goal of this project is to utilize the existing PV system as well as the available smart grid capabilities within EPB's network, including automatic switches, smart meters, and fiberoptic communication links. By incorporating the existing smart grid infrastructure and capabilities, the proposed design is expected to have enhanced flexibility, reliability, and cost-effectiveness, while also being more replicable by other utilities with similar smart grid capabilities. The following objectives were considered during the design of the microgrid:

1. Improve system energy efficiency by >20% from the baseline case (without microgrid/DER).
2. Reduce carbon dioxide emissions by >20% compared with the baseline case (without microgrid/DER).
3. Reduce System Average Interruption Duration Index (SAIDI) of critical load by >98%.
4. Limit the critical customer interruption time due to extreme weather or external attack to 15 minutes.
5. Fully utilize the existing PV generation to reduce the SAIDI for the adjacent community.

To achieve the design objectives, a battery energy storage system (BESS) and a backup generator system were sited and sized to consider critical loads, existing renewable energy profiles, and the adjacent communities. The probability and duration of stochastic extreme weather event were considered to make sure that the critical customer interruption time could be improved.[8] Auxiliary equipment such as grounding transformer and capacitor banks were included in the design. Flexible protection schemes suitable for both grid-connected and islanded operation were also developed.

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[5] ARPA-E program introduction, "Smart and flexible microgrid". Available at: https://arpa-e.energy.gov/?q=slick-sheet-project/smart-and-flexible-microgrid.

[6] *A Smart and Flexible Microgrid with Dynamic Boundary and Intelligent Open-Source Controller*. EPRI, Palo Alto, CA: 2018. 3002014310.

[7] "Annual Report 2012," Chattanooga Electric Power Board: Chattanooga, TN, Dec. 2012.

[8] J. Dong, L. Zhu, Y. Su, Y. Ma, Y. Liu, F. Wang, L. M. Tolbert, J. Glass, and L. Bruce, "Battery and backup generator sizing for a resilient microgrid under stochastic extreme events," IET Generation, Transmission & Distribution, vol. 12, no. 20, pp. 4443 - 4450, 2018.

Dynamic Boundary Concept

One of the most important and unique features of the microgrid design is the dynamic boundary.[9,10] This is achieved by manipulating the sectionalizing smart switches across the medium voltage distribution network. Thus, the proposed design works best in a medium voltage distribution circuit feeder or a part of it. In this section, the operating principle of the microgrid will be explained on an example feeder, with some features generalized for illustration purposes. The concept of connecting to the utility through multiple grid interfaces – one feeder serving as a primary and two backups – to provide additional resiliency features is also illustrated.

The basic operation is as follows. After a fault, the smart switches take action to isolate the fault. The microgrid next chooses a healthy source feeder to connect to, if available, or otherwise disconnect from the grid and go to islanded operation supported by available DER. In islanded operation, the microgrid boundary is dynamically defined by load, DER generation and status of the smart switches.

In the figures below, the energized circuits within the base microgrid are highlighted in black, while the de-energized circuits as well as branches and loads of other feeders are distinguished by gray. The base case is highlighted with gray background.

Grid-Connected Operation

In normal grid-connected mode, shown in Figure 2(a), operation of the microgrid is no different than a traditional system. It is capable of economic dispatch to optimize utilization of the renewable power for local loads and provide grid support functions such as voltage regulation. The microgrid boundary in this case is regarded as the base case and is shaded in gray.

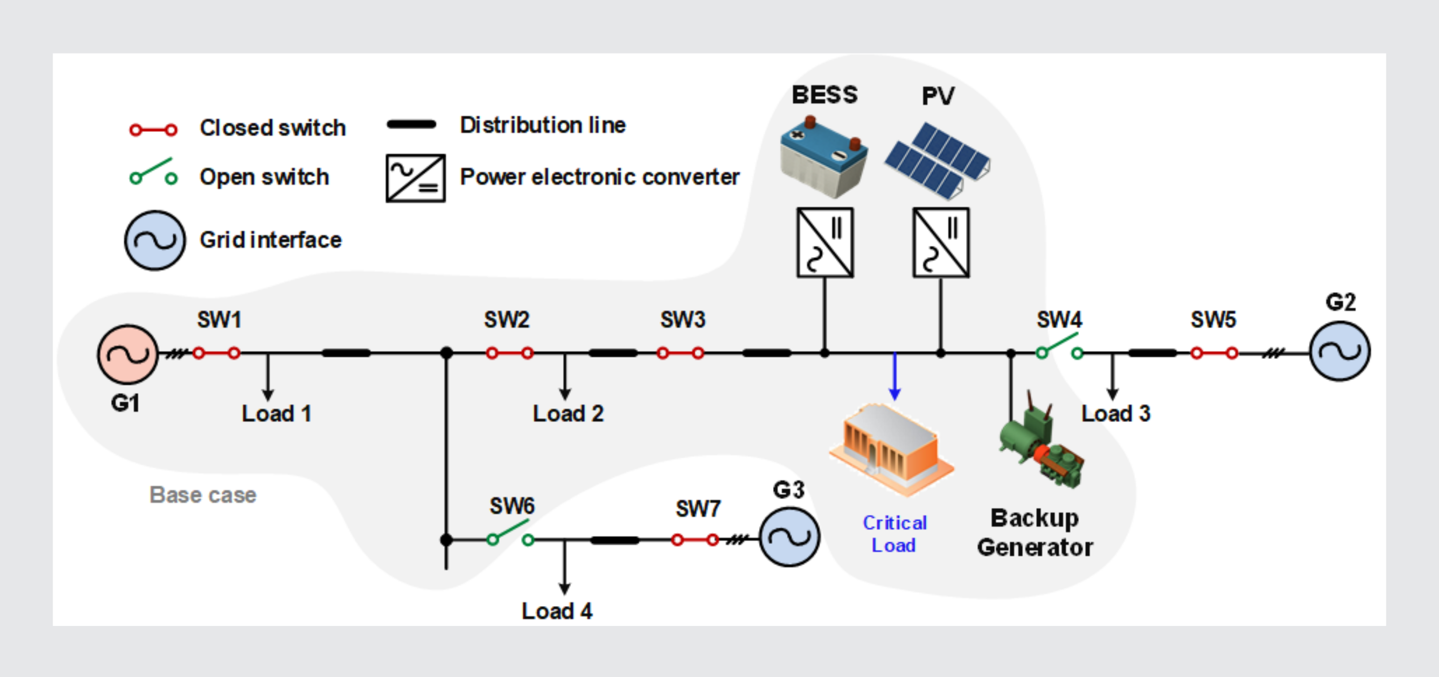

Figure 2(a). Grid-connected operation – Base case

Enabled by multiple source feeders and the automated smart switches, the distribution circuit can quickly isolate a fault, and reconnect to another healthy utility feeder, if available. By doing this, the interruption time of loads can be minimized. The smart switches are equipped with sophisticated protection algorithms which are capable of autonomous fault isolation and grid reconnection. These

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[9] Y. Ma, X. Hu, H. Yin, L. Zhu, Y. Su, F. Wang, L. M. Tolbert, and Y. Liu, "Real-time Control and Operation for a Flexible Microgrid with Dynamic Boundary," in Proc. IEEE ECCE, 2018.

[10] F. Wang, X. Shi, L. M. Tolbert, Y. Ma, Y. Liu, and L. Zhu, "Microgrids with dynamically configurable boundaries including multiple main grid feeder coupling locations and methods of operating the same," United States Patent 10447038B2, Granted 10/15/2019.

switches are monitored and controlled by distribution SCADA system and accessible to the microgrid central controller. An example of reconfiguring the microgrid to an alternate feeder is shown in Figure 2(b), where a fault happens between SW1 and SW2, and the microgrid area could re-connect to G2 for grid service.

The switch configuration and microgrid boundary may also change in normal operation, for loss reduction, voltage profile improvement, or other economic purposes, as shown in Figure 2(c), where loads 3 and 4 are transferred from G2 and G3 to G1.

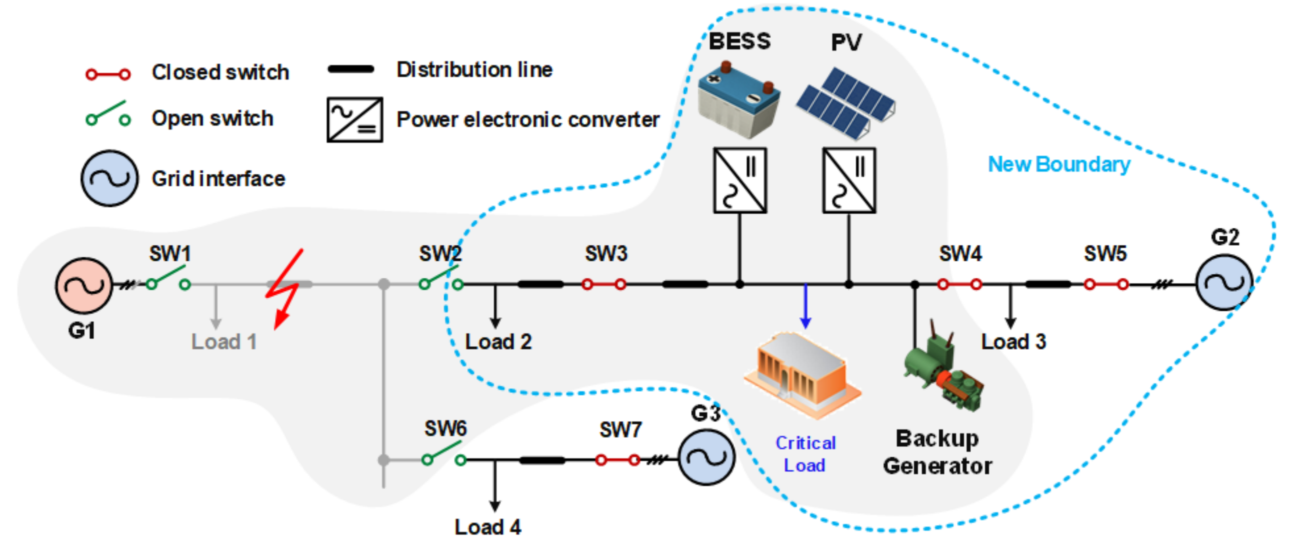

Figure 2(b). Grid-connected operation – Network reconfiguration after a fault

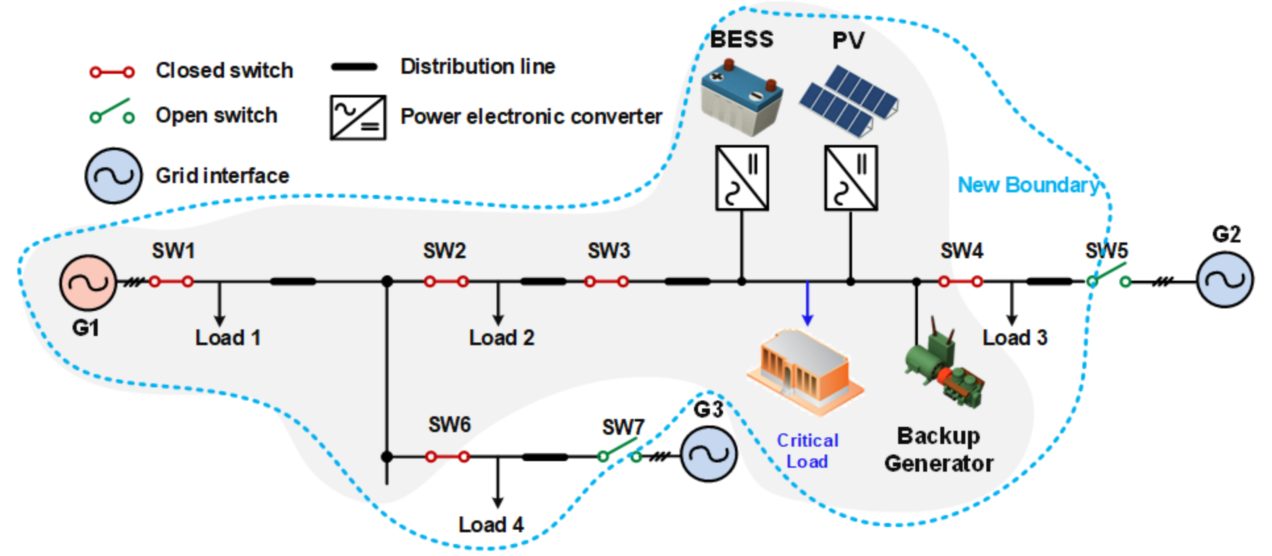

Figure 2(c). Grid-connected operation – Load transfer network reconfiguration

Islanded Operation

During a grid outage, when no healthy grid source is available, DER becomes the only energy resource, and loads may need to be shed or restored according to the available power generation. The smallest microgrid boundary in islanded operation is shown in Figure 3(a). In this case, PV is assumed to have very low power generation. The microgrid can only support the critical load with the battery or backup generator. Given that the BESS or backup generator is generally sized to serve the critical load uninterrupted, all non–critical load (load 1 and 2) are shed. On the other hand, if excess power is generated by PV, the microgrid can serve not only its own non–critical loads (load 1 and 2), but also the loads previously served by other feeders (load 3 and 4). When all loads are picked up, the microgrid has its largest boundary, as shown in Figure 3(b). Active and

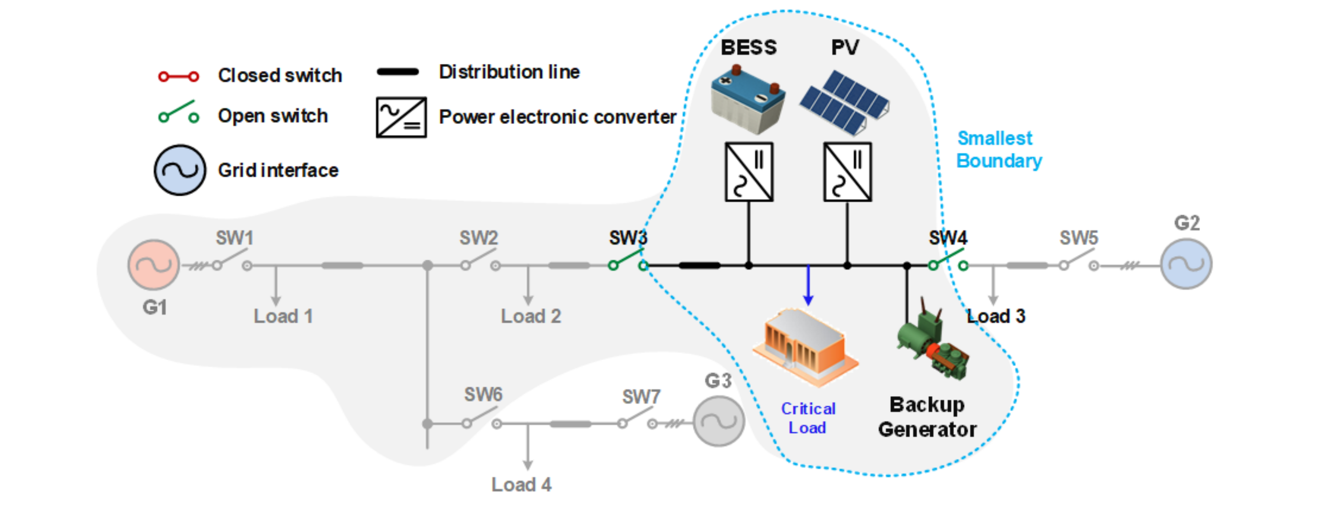

Figure 3(a). Microgrid boundary during islanded operation - Smallest boundary

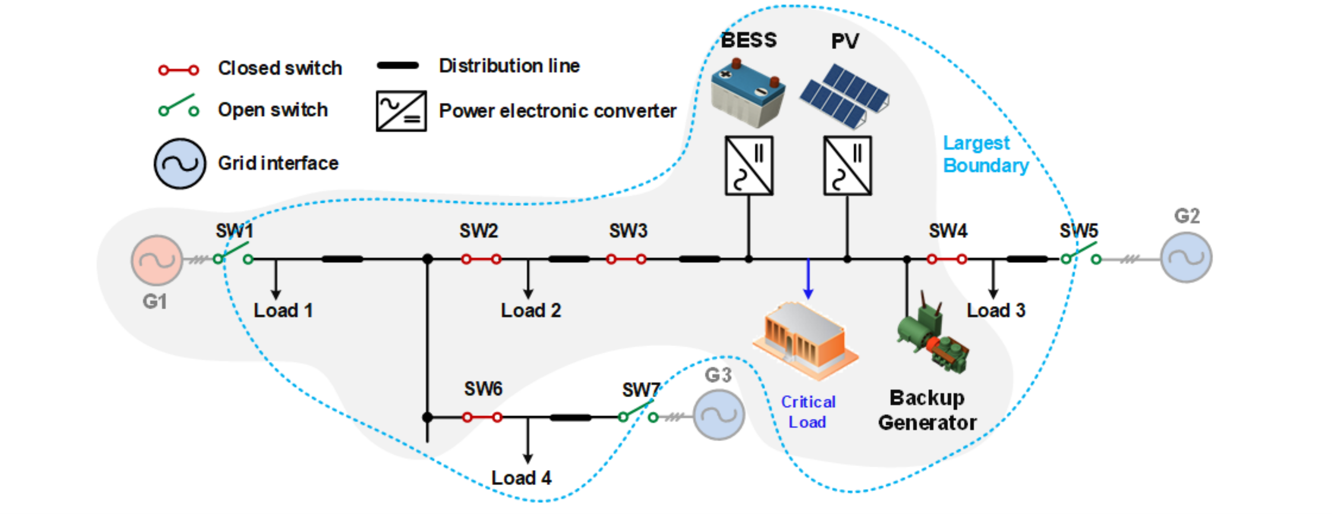

Figure 3(b). Microgrid boundary during islanded operation - Largest boundary

timely monitoring and boundary management control are essential to ensure power balance and acceptable voltage/frequency deviation in islanded operation.

Faults may also occur during islanded operation conditions, but they lead to similar reduction in the boundary. In some cases, the renewable output power may need to be curtailed to maintain the real-time power balance. Note that due to the limited current generation capability of power electronic converters, the fault current level during islanded mode may be much less than that in the grid-connected mode, so protection schemes, including adaptive relay settings, proper coordination among various protective devices and protection methods, etc., should be well-designed and implemented.

Microgrid Controller

Controller Design

In order to fully utilize the existing communication infrastructures, a two-level hierarchical control architecture was employed, with a microgrid central controller (MGCC) that interfaces with the utility distribution management system (DMS) and local controllers with the DERs at the site. As shown in Figure 4, the MGCC communicates with the utility SCADA system through two channels. A VRTU (virtual remote terminal unit) was configured in the EPB SCADA system so that the MGCC may issue commands to, and receive status of the EPB smart grid assets (IntelliRupters, smart meters, etc.) in real time. The MGCC also updates its operational status and receives commands from SCADA, such as black start requests. The local controller is responsible for monitoring and controlling the DER. Control signals such as power setpoints and islanding status are issued to the DER through its corresponding local controller.

The microgrid controller is based on the general-purpose NI hardware (CompactRIO) and LabVIEW software platform. This platform offers a robust and flexible development and implementation environment. Control algorithms for both the MGCC and local controllers were developed to meet the functional requirements for both grid-connected and islanded modes, mode transition, and protection. The interactions of the control modules are shown in Figure 5.

Several control modules were designed and implemented in the microgrid controllers to achieve the dynamic boundary, shown in the red boxes. The *Online Topology Identification* function analyzes the switch status within the microgrid area, and then generates the system topology matrices based on the algorithms of graph theory.[11] The generated matrices are then used to identify switches that form the microgrid boundary, and differentiate load sections within or outside of it. Using generated topology matrices, the *Active and Re-*

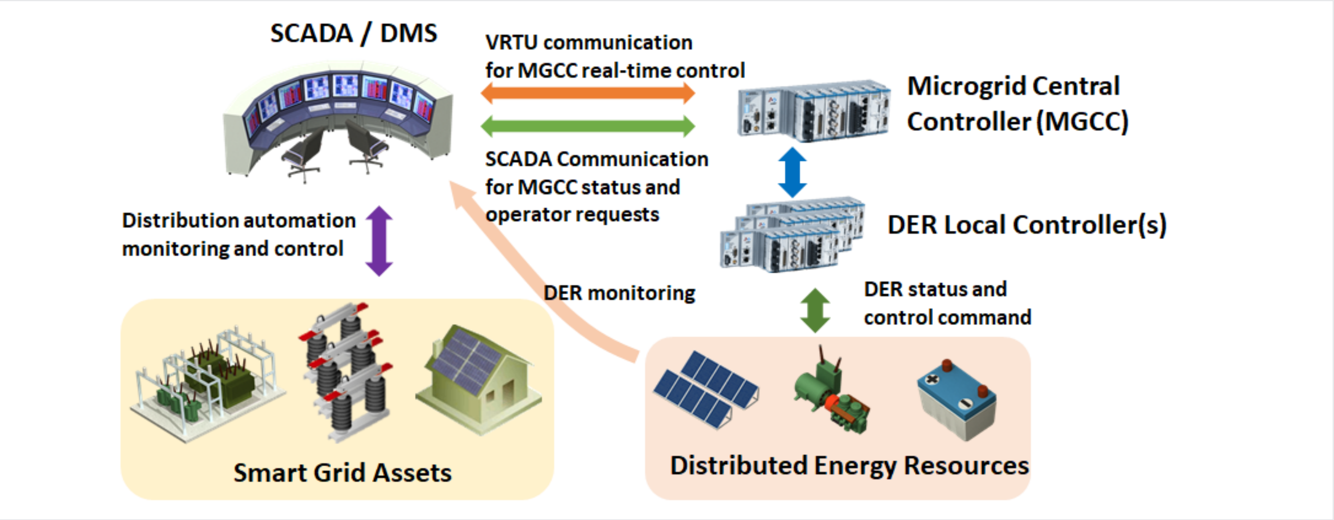

Figure 4. Illustrative microgrid controller communication structure

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[11] https://en.wikipedia.org/wiki/Kruskal's_algorithm.

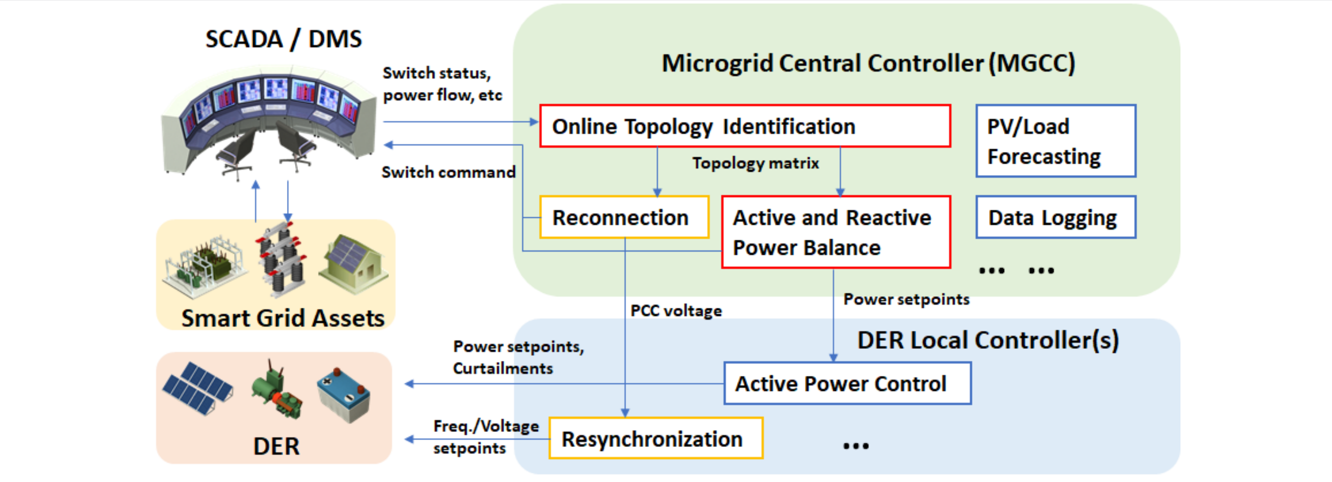

Figure 5. Microgrid controller function modules

active Power Balance function commands switches to open or close to adjust the microgrid boundary and/or change the setpoints of the DER, through a deliberate optimization algorithm, to maintain the balance between the generation and loads in real time.

In addition, some control functions were enhanced to accommodate the unique capability of the dynamic boundary, highlighted in the yellow boxes. For example, the *Reconnection* function was adapted to receive the information from the boundary switch, which varies for a microgrid with a dynamic boundary. With the available information, the resynchronization function can instruct the DER to synchronize with the grid to be connected, in the same way as traditional microgrid controllers. Other essential functions such as *PV/Load Forecasting, Data Logging* and *Active Power Control* were also developed and included as part of the controller codebase, but function remains the same as for fixed boundary microgrid controllers, shown in the blue boxes.

Although the microgrid controller was developed for a specific application, the algorithm was generalized to be applicable and scalable for community microgrids with different geographic areas, load sizes, and distributed generation number and types within an area grid. Except for dynamic boundary related functions, the codebase developed in this project is open-source released at Github.[12] The hardware-in-the-loop (HIL) simulation circuit and an application guideline were also released along with the code.

Controller Lab Testing

Microgrid controller operation was validated before field deployment using two platforms: 1) real-time controller HIL simulation using OPAL-RT and 2) real-time hardware emulation using real inverters.

For the HIL simulation, the EPB feeder circuit was simulated in the Opal-RT real-time HIL simulation platform, including necessary communication signals exchanged between the HIL and physical controllers, as well as between the local controllers and MGCC (both physical). The performance of the microgrid controller – in terms of reliability, interoperability, and robustness - was then evaluated through various operation scenarios, including large transients and fault conditions.[13]

HIL simulation has limitations, since details of the simulated system are generally difficult to model, such as measurement errors, mechanical or control delays, non-linear characteristics of inverters and transformers, switch behaviors, etc. A unique test facility at UTK

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[12] https://github.com/GeniusMicrogrid/DynaMic_Basic.

[13] H. Yin, Y. Ma, Y. Su, F. Wang, Y. Liu, L. M. Tolbert, X. Hu, and J. Glass, "A Hierarchical Control System for a Flexible Microgrid with Dynamic Boundary: Design, Implementation and Testing," *IET Smart Grid*, 2019.

called the grid-emulation Hardware Testbed (HTB)[14,15] was utilized to test the controller in a more realistic environment. In the HTB, power electronic converter based emulators are utilized to represent the BESS, PV, loads and grid interfaces. The distribution lines are represented by the physical inductors, and smart switches are represented by the contactors. By using real inverters and switches, the characteristics that cannot be fully captured by HIL simulation were accurately reproduced.[16]

During the tests, several issues of practical implementations of control algorithm were found and rectified, including the impact of measurement error and interoperability of different control modules.

Field Testing

After the lab verification, the controllers were installed and tested in the field. To accommodate the microgrid controller, the following software and facilities of the EPB distribution system were upgraded. The VRTU and a data ingestion engine were set up in the SCADA system. The BESS and grounding transformer were installed at the demonstration site, and protection profiles were updated in the smart switches. The following field tests have been successfully performed:

- Communication among the MGCC, BESS local controller, and EPB SCADA to make sure that the DNP3 command and status can be sent and received.
- Microgrid control of the BESS, switches, and other equipment during grid connected operation, including functions such as PV forecasting and economic dispatch.
- Microgrid control during islanded operation with the BESS as the only source, including boundary expansion and reduction, with local loads.
- Microgrid controller automated control sequences.

With the basic functionality of the microgrid controller verified in the field, the project team is aiming to make the microgrid fully operational. Additionally, a backup generator is being installed to the microgrid, and further tests are planned: parallel operation of the generator and BESS, microgrid operation during the daytime when PV generation varies, and autonomous dynamic boundary adjustment.

Lesson Learned

Through development and field testing, there have been a number of lessons learned, summarized below, which may be helpful to technology developers and distribution system planners.

Microgrid design considerations - There are several items that were not fully considered during the initial microgrid design stage, but later discovered or refined during project execution. One of the benefits of the dynamic boundary microgrid is that it can expand and serve much more load than its own critical load if the renewable generation is sufficient. However, larger loads could introduce more transient conditions that need to be supported by the DER. This may cause issues if not properly considered in the planning stage. A guideline summarizing the holistic design effort and all considerations will be made available to the public in the future.

Cyber security considerations - It is imperative that the microgrid control system be resilient to cyber-attacks. To achieve that, the microgrid controller and all other components in the microgrid need to be considered, including communication network devices and even protocol translators. Measures, such as limiting physical access, disabling non-essential service such as FTP, and splitting network into segments may need to be employed to enhance the system security. The project team has mapped the requirements from IEC 62443-3-2.[17] Security techniques may also have unintended consequences. For example, the EPB microgrid controller was placed on the utility internal network for added security, but that prevented access to the external weather forecasts, negating the PV forecasting function. As a work-around, the project team utilized real-time PV irradiance data, as well as manual weather information input from the system operator.

Black start capability - A basic microgrid feature is to black start during a grid outage. This is conducted by having the generator or BESS running in grid-forming mode to provide steady voltage to the islanded system. However, the control power and communication system to the generator or BESS must be un-interrupted. In the first islanded test, a network device lost power preventing control of the

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[14] L. M. Tolbert, F. Wang, K. L. Tomsovic, K. Sun, J. Wang, Y. Ma, and Y. Liu, “Reconfigurable Real-Time Power Grid Emulator for Systems with High Penetration of Renewables,” *IEEE Open Access Journal of Power and Energy,* 2020.

[15] Hardware Test-bed https://curent.utk.edu/files/8414/8709/3719/Tolbert_Fact_Sheet_Web.pdf.

[16] D. Li, Y. Ma, C. Zhang, H. Yin, I. Ray, Y. Su, L. Zhu, F. Wang, and L. M. Tolbert, “Development of a converter based microgrid testing platform,” in Proc. *IEEE ECCE,* 2019.

[17] IEC 62443-3-2:2020 Security for industrial automation and control systems - Part 3-2: Security risk assessment for system design.

BESS. This was resolved with a battery uninterruptible power supply on the network device, and the rest of the tests were successful.

Microgrid control coordination with existing automation system - For utility owned and operated microgrids, system assets such as smart switches or BESS may be controlled by both system operator and microgrid controller at the same time. Under a system event such as short circuit fault, the existing grid automation may engage and start the network reconfiguration, while the microgrid controller may start an unplanned islanding process. Control conflicts may lead to system issues. Such events must be carefully examined and considered in control schemes. For the EPB microgrid, control actions, such as black start or reconnection, must be requested by the system operator. Unplanned islanding is not permitted. Upon request, the microgrid controller would assume the authority, and disable all automatic restoration function from the smart switches. The system operator does not control the microgrid until system shutdown or reconnection is requested and completed. For other microgrids, the solution would vary according the detailed needs and expectations. Also, the desired system response will have to be designed case by case.

Going Forward

The microgrid with dynamic boundary concept stems from the case when the DER sources are situated closely together. However, it is not uncommon for critical loads and DER to be spread in different locations along the feeder. With DER generation or storage located at multiple locations, the concept of dynamic boundary can be extended to even more use cases. Figure 6 gives an illustrative example of microgrid design, where a backup generator and PV serve critical load 1, and a BESS serves critical load 2.

During low PV generation period, the sources only supply the critical loads with smallest boundary, as shown in Figure 6(a). When PV starts to generate power, the boundary may extend, and the two small islands may merge to form a larger area, shown in Figure 6(b). In this case, the PV may also charge the BESS for future use. If PV power continues to grow, the boundary may extend further to serve all loads (load 1 – load 3), forming the largest boundary similar to Figure 3(b).

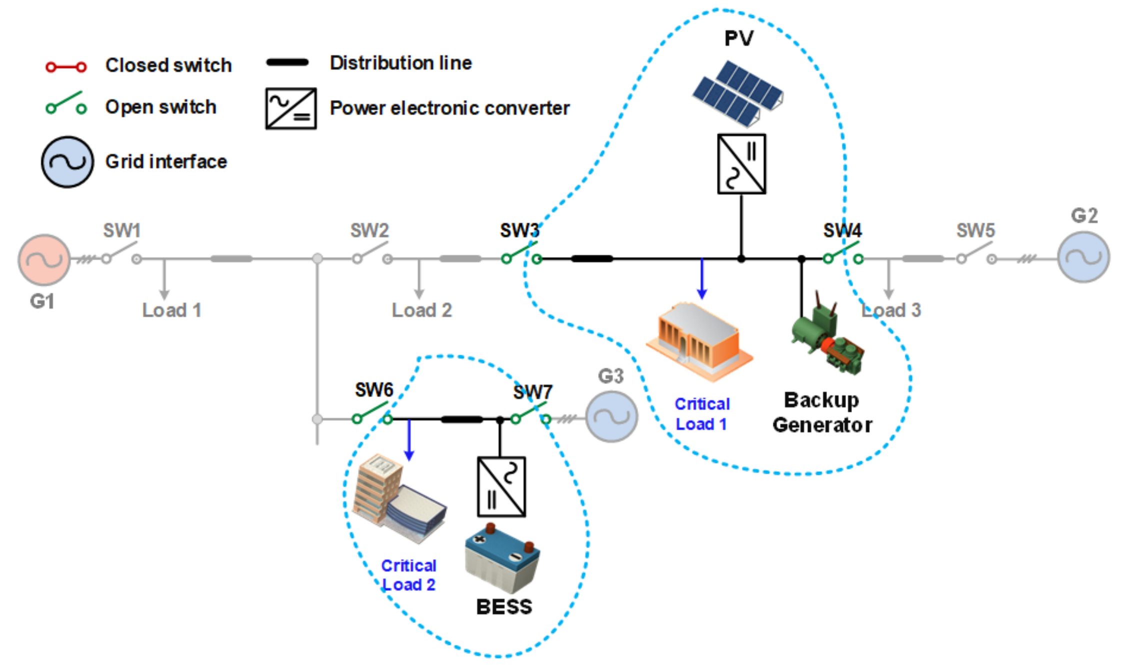

Figure 6(a). Networked microgrid boundary during islanded operation - Smallest boundary

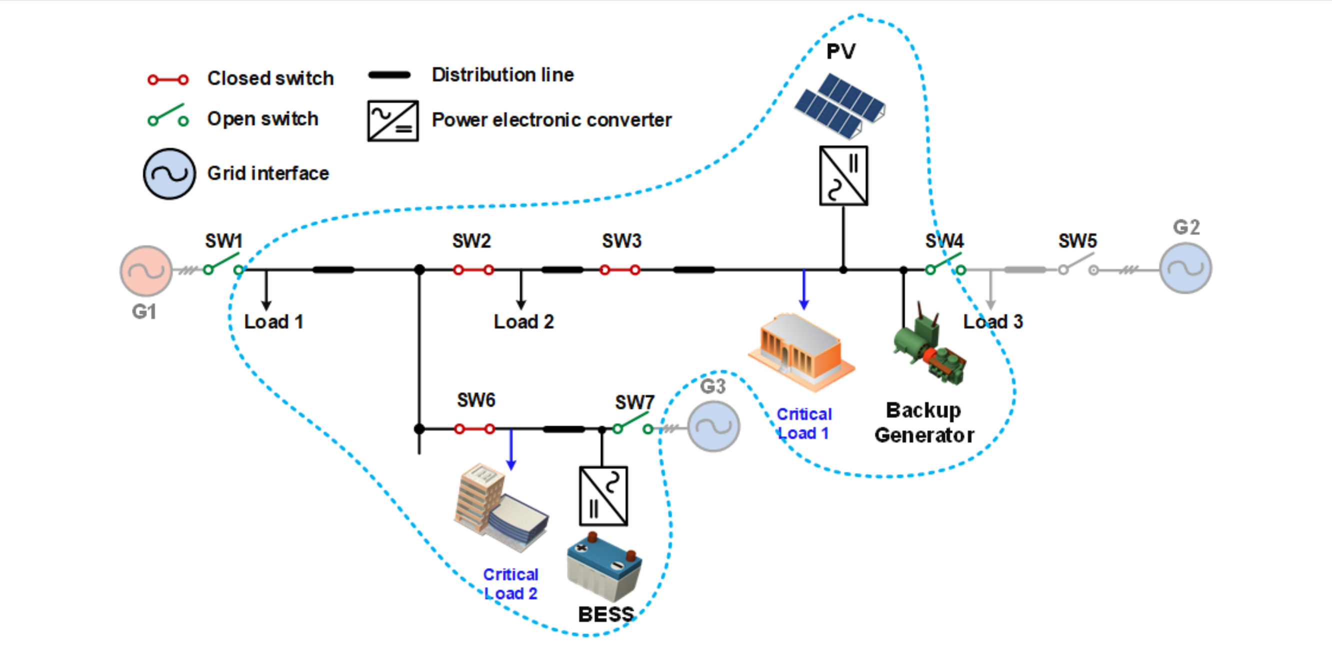

Figure 6(b). Networked microgrid boundary during islanded operation - Merged boundary

To satisfy such need, the microgrid controller has been enhanced to manage multiple sub-microgrids in a feeder. HIL and HTB tests were successfully conducted to validate the performance. Part of the updated codebase are open source released to GitHub.[10]

Final Thoughts

Microgrid designs which incorporate the smart grid capabilities being deployed by many U.S. utilities could provide a promising way to more cost-effectively accommodate the increase in renewable resources, promote the energy efficiency, and improve customer and overall system reliability and resiliency. This ARPA-E microgrid project aims to promote a microgrid design that can be applicable to many utilities with minimum adaptation.

This microgrid has been designed for and is being tested in EPB's smart community, utilizing its existing smart grid features, including intelligent switches, ultra-high-speed communication links, as well as a multiple feeder connection design. These features are fully leveraged to help achieve enhanced performance with reduced cost. The microgrid controller, based on NI's general-purpose hardware and software platform, is designed to be flexible, scalable, robust, secure and easily adopted by other microgrid applications. These features have been successfully demonstrated in the lab and through field testing at the EPB demonstration site. Upon successful completion of final field tests, the microgrid will become fully operational on the EPB system.

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