Topic 3: Building Blocks for Microgrids

Co-Authored by Topic 3 Team

Chen-Ching Liu (Co-Lead and Point-of-Contact for Topic 3)
Virginia Polytechnic Institute and State University

Madhu Chinthavali (Co-Lead)
Oak Ridge National Laboratory

Rob Hovsapian (Co-Lead)
National Renewable Energy Laboratory

Hannah Burroughs
Lawrence Livermore National Laboratory

Sigifredo Gonzales
Sandia National Laboratory

Francis K. Tuffner
Pacific Norwest National Laboratory

Miguel Heleno
Lawrence Berkeley National Laboratory

Ravindra Singh
Argonne National Laboratory

Adam Mate
Los Alamos National Laboratory

Dushan Boroyevich
Virginia Polytechnic Institute and State University

Herbert Ginn III
University of South Carolina

Acknowledgments

The co-authors would like to thank Yashodhan Agalgaonkar and Mayank Panwar, National Renewable Energy Laboratory, and Chensen Qi, Virginia Tech, for their contributions. We greatly appreciate the helpful comments and suggestions from Dan Ton, DOE; Venkat Banunarayanan, National Rural Electric Cooperative Association (NRECA); Rick Meeker, The Florida Alliance for Accelerating Solar and Storage Technology Readiness (FAASSTeR); John Wang, ABB; Amrit S. Khalsa, American Electric Power (AEP); and Mike Gravely, California Energy Commission (CEC).

Executive Summary

This white paper is the third in a series of seven white papers in support of the Microgrid R&D Program, and accordingly summarizes the findings of the papers as they concern the overall program objectives. The program vision is to facilitate the nation's transition to (1) a more resilient and reliable, (2) more decarbonized electricity infrastructure, in which (3) microgrids have a reduced cost and implementation times, while ensuring that microgrids support an equitable energy transition through prioritized provision of at least 40% of microgrid benefits going to disadvantaged communities in a secure manner. These three enumerated strategic goals are developed in the context that the United States' electricity system is becoming more distributed in nature, and that disruptions to the electricity delivery system (EDS) are occurring more frequently and with greater severity. The vision statement follows.

> *By 2035, microgrids are envisioned to be essential building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability. Microgrids will be increasingly important for integration and aggregation of high penetration distributed energy resources. Microgrids will accelerate the transformation toward a more distributed and flexible architecture in a socially equitable and secure manner.*

The vision assumes a significant increase of DER penetration during the next decade, reaching 30-50% of the total generation capacity. In that context, the Microgrid R&D program seeks to accomplish these three goals:

Goal 1: Promote microgrids as a core solution for increasing the **resilience and reliability** of the EDS, supporting critical infrastructure and reducing social burdens during blue and black sky events.

Goal 2: Ensure that microgrids serve as a driver of **decarbonization** for the US EDS by acting as a point of aggregation for larger number of DERs, with 50% of new installed DER capacity within microgrids coming from carbon-free energy sources by 2030.

Goal 3: **Decrease microgrid capital costs** by 15% by 2031, while reducing **project development, construction, and commissioning** times by 20%.

To achieve the three primary goals, the Microgrid R&D Program works in three categories:

Category 1: Technology development,
Category 2: Analysis and tools for planning, and
Category 3: Institutional framework.

This white paper, *Building Blocks for Microgrids*, describes R&D and technology, analysis, and tools that fall into Category 1 and Category 2.

The concept of building blocks for microgrids is essential for modular design and implementation and enhances reliability and cost-effectiveness. Microgrid Building Blocks (MBBs) integrate the main functions of a microgrid in a hierarchical structure. The first MBB workshop in 2019, hosted by Virginia Tech with participants from Department of Energy (DOE) and national labs, proposed MBB functions and requirements. The proposed MBB functions include power conversion, microgrid control, protection, islanding and reconnection, and storage. The MBB requirements include stability, interoperability, security, and scalability. As an example, an MBB can be created to integrate the functions of power conversion, switching with the utility grid (and/or other microgrids), and microgrid control and communication. The modular MBB with power conversion and microgrid control/communication capabilities can be connected to generation and load components and control devices to form a microgrid.

There is not a universal type of MBB; it will be modularized to meet the needs for different application environments. The common structure of the MBB is to integrate the system-wide functions of power conversion, communication, and control. The MBB is connected to the components in the microgrid through different types of interfaces to generation, load, energy storage, microgrid, or a combination of them. A hierarchical structure exists for a distribution system with multiple microgrids that may be standalone or networked. In a simple case, if a microgrid is standalone without connection to a utility system, there would not be power conversion between the microgrid and the utility system. However, power conversion is performed at generation, storage, or load nodes and communication and control functions are needed for the MBB. In a complex operating environment, a systems approach is needed for design, operation, control, and protection of the microgrids.

The functions and performance requirements of an MBB are described in this paper. Segmentation (e.g., smart islanding involving load shedding and/or critical load service) is critical for survivability and resiliency of the microgrid under abnormal operating conditions such as a fault or loss of communication. Power electronic solutions are needed to enhance the efficiency and performance. At the system level, microgrid control requires communications to acquire measurements from (and deliver control commands to) generation, load, storage, and control devices. The microgrid controller serves to dispatch real and reactive power, manage energy, and maintains the frequency and voltages within normal limits. Control, protection, and intelligence capabilities can be modularized as hardware and/or software blocks, resulting in a plug and play platform. Protection of the microgrids in the context of MBBs requires new concepts and technologies fundamentally different from traditional distribution protection. Requirements include steady-state and dynamic performance, reliability, resiliency, storage capability, as well as interoperability, modularization, and cyber security.

For strategic microgrid development and deployment, this paper proposes a vision of MBBs for the future electric energy distribution systems. The vision includes the development of advanced power electronic interfaces for the grid. To enhance the grid metrics, a holistic design approach is proposed to integrate the control, communication, protection, and intelligence capabilities. The approach is crucial to designing interoperable, scalable, and modular systems. The power electronic interfaces with the grid are supported by the development of advanced subcomponents for the advanced grid interface to improve the performance metrics such as efficiency and cost.

Commercialization of the proposed MBB is critical for the future of microgrids. To this end, standardization of the interfaces and interconnects will enable large-scale manufacturing and deployment of the MBB-based microgrids.

A roadmap is proposed with the technical milestones and expected solutions. The fundamental step is to design comprehensive specifications for every building block for the microgrid application. Then the interfaces for every MBB will be designed. A particular MBB, depending upon its technical capability, may participate in a variety of microgrid services. Once MBB interfaces and services are defined, the next step is to develop the global microgrid control architecture. Each MBB service will contribute to a microgrid control function, e.g., blackstart and voltage stability. Based on the use case and test setup requirements, the communication and control architecture will be developed. It is proposed that MBBs at the distribution system levels of power and voltage be designed, implemented, and field tested for technology transfer and commercialization. To achieve the goal, technical issues concerning the power, control and communication devices and systems will be addressed. MBBs with grid forming and grid following capabilities provide critical control functions in coordination with the microgrid controller.

Through the proposed roadmap, several objectives will be met. A universal controller is developed with a very fast local control system to handle and enhance the latest grid codes. This also contains a fast communication link to a central microgrid controller to coordinate the system in real-time. An MBB evaluation platform is established leveraging state-of-the-art technology for testing distributed programmable control for microgrid converter applications. After completion of unit and integrated testing of MBB, the field validation is performed. Furthermore, a reprogrammable universal controller is completed, enabling plug-and-play of diverse generations and loads, such as EVs, and storage.

Based on this study, this paper provides recommendations for R&D on MBBs in the next 5-10 years. An emphasis is placed on the importance and impact of MBBs on the reliability, security, resiliency, and cost-effectiveness of the future power grid. Our recommendations for the future R&D include:

R1: MBB Implementation and Field Test with Integration of Conversion, Communication, and Control
R2: Development of MBB Low Voltage at-Scale Validation Platform
R3: MBB Design and Validation to Demonstrate MBB Features in Emulated Real-World environment.
R4: MBB-Based Microgrid Implementation and Field Test
R5: Development of Building Block Architectural Approaches
R6: Modular, Scalable Integrated Software Platform with Real-Time Control Capabilities
R7: Modular, Scalable Design and Implementation of MBB Communication and Control Systems
R8: Smart Reconfigurable System for Any Microgrid Systems

R9: Demonstration of Market Participation in a Distribution System Environment

These R&D recommendations are focused on areas where we believe DOE funding is critical and justified. MBB is a novel, foundational technology upon which commercial products and tools can be built. The potential impact on the future large-scale deployment of microgrids is high. Without leadership and initiatives from DOE, it is difficult for the power industry or manufacturers to invest in the development of fundamental technologies.

The future of MBB will depend on the cost-benefits of the new technology. Use cases for the MBBs and the associated economics are discussed in this paper. By incorporating modularity and flexibility into existing microgrid architectures, the MBB technology significantly contributes to: Reducing uncertainty at the planning and operational stages, Standardizing the design of microgrids, Enabling innovative horizontal market approaches, Facilitating the integration of behind-the-meter distributed energy resources, and Enhancing the reliability and resilience of power distribution networks. These impacts translate into economic benefits at the microgrid level and to the electricity subsector.

For practical deployment of MBB technologies, partnership with industry, national laboratories, and academic institutions are important to take advantage of the best talents and available resources. Future commercialization of the MBB-based technologies will require field testing and validation from power grids, especially distribution utility systems.

The remainder of this white paper is organized as follows. Section 1 is an introduction of the Microgrid Building Block concept and the state-of-the-art of the related subjects. The vision of future MBB development is discussed in Section 2. Based on the vision, the roadmap for the MBB technology development is presented in Section 3. The future of MBB development will depend on the cost-benefits and use cases of MBB; a discussion of these topics is given in Section 4. Related enabling technologies that are available for MBB development are summarized in Section 5. Finally, based on the findings of this study, our recommendations of the future R&D to the DOE are stated in Section 6.

1. Introduction

This white paper is the third in a series of seven white papers in support of the Microgrid R&D Program, and accordingly summarizes the findings of the papers as they concern the overall program objectives. The program vision is to facilitate the nation's transition to (1) a more resilient and reliable, (2) more decarbonized electricity infrastructure, in which (3) microgrids have a reduced cost and implementation times, while ensuring that microgrids support an equitable energy transition through prioritized provision of at least 40% of microgrid benefits going to disadvantaged communities in a secure manner. These three enumerated strategic goals are developed in the context that the United States' electricity system is becoming more distributed in nature, and that disruptions to the electricity delivery system (EDS) are occurring more frequently and with greater severity. The vision statement follows.

> *By 2035, microgrids are envisioned to be essential building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability. Microgrids will be increasingly important for integration and aggregation of high penetration distributed energy resources. Microgrids will accelerate the transformation toward a more distributed and flexible architecture in a socially equitable and secure manner.*

The vision assumes a significant increase of DER penetration during the next decade, reaching 30-50% of the total generation capacity. In that context, the Microgrid R&D program seeks to accomplish these three goals:

Goal 1: Promote microgrids as a core solution for increasing the **resilience and reliability** of the EDS, supporting critical infrastructure and reducing social burdens during blue and black sky events.

Goal 2: Ensure that microgrids serve as a driver of **decarbonization** for the US EDS by acting as a point of aggregation for larger number of DERs, with 50% of new installed DER capacity within microgrids coming from carbon-free energy sources by 2030.

Goal 3: **Decrease microgrid capital costs** by 15% by 2031, while reducing **project development, construction, and commissioning** times by 20%.

To achieve the three primary goals, the Microgrid R&D Program works in three categories:

Category 1: Technology development,
Category 2: Analysis and tools for planning, and
Category 3: Institutional framework.

This white paper, *Building Blocks for Microgrids*, describes R&D and technology, analysis, and tools that fall into Category 1 and Category 2.

1.1 Concept of MBB

The concept of building blocks for microgrids (MGs) is essential for modular design and implementation and enhances reliability and cost-effectiveness. Microgrid Building Blocks (MBBs) integrate the main functions of a microgrid in a hierarchical structure. The first MBB workshop in 2019, hosted by Virginia Tech with participants from Department of Energy (DOE) and national labs, proposed MBB functions and requirements. The proposed MBB functions include power conversion, microgrid control, protection, islanding and reconnection, and storage. The MBB requirements include stability, interoperability, security, and scalability. For microgrid design and development, there is not a unique, widely adopted definition of an MBB and its scope of functionality. However, to achieve the goal of modular design, it is important to develop a simplified approach to design and implementation of a microgrid from the users' point of view. Here the users include power grids as well as industries, commercial entities, and communities that require reliable and resilient electricity service through the deployment of microgrids.

To achieve a modular development approach, an MBB can be created to integrate the primary functions of power conversion and switching (with the utility grid and/or other microgrids) as well as microgrid communication and control. The integration of microgrid conversion, control, and communication functions into a module as an MBB simplifies the microgrid design. Indeed, a user who is interested in developing a microgrid has available generation resources, such as distributed generators (DGs), renewable generations, and energy storage devices. The user also has a set of electrical loads that will be served by the microgrid, which will sustain service to critical load when the utility system becomes unavailable due to extreme weather conditions or other events. The modular MBB with power conversion and microgrid control/communication capabilities can be connected to generation/load components and control devices to form a microgrid. There are two types of connections: electrical and communication. Electrical connections form the electrical network configuration between utility and microgrid energy resources and various load devices. On the other hand, communications are needed for data acquisition and delivery of control demands, which can come from a microgrid control center or microgrid controller (MGC), or a cluster of distributed and decentralized control devices. As a result, the design of the microgrid consists of three major tasks: MBB implementation, electrical system configuration, and communication and control system structure.

Power electronics (PE) based MBB will enhance the resiliency of inverter interfaced renewables. The inclusion of power electronics based MBB with the classical equipment will enhance the resiliency of microgrids and is an all-encompassing approach. By integrating a microgrid controller with PE-based MBBs, the maintainability of the system will be enhanced.

Microgrid Building Block (MBB)

As shown in Figure 1, the proposed MBB integrates the power processing, communication and control functions that may exist at a microgrid node and connects to other components in the microgrid or to other MBBs, through standardized power and communication interfaces. There is not a universal type of MBB; it will be customized to meet the needs for different application environments. Major microgrid components could each interface to the microgrid network through customized MBBs, e.g., sink-MBB for load clusters, source-MBB for generation (PV, wind, CHP, …), and sinks/source-MBB for energy storage or to interface to the utility grid.

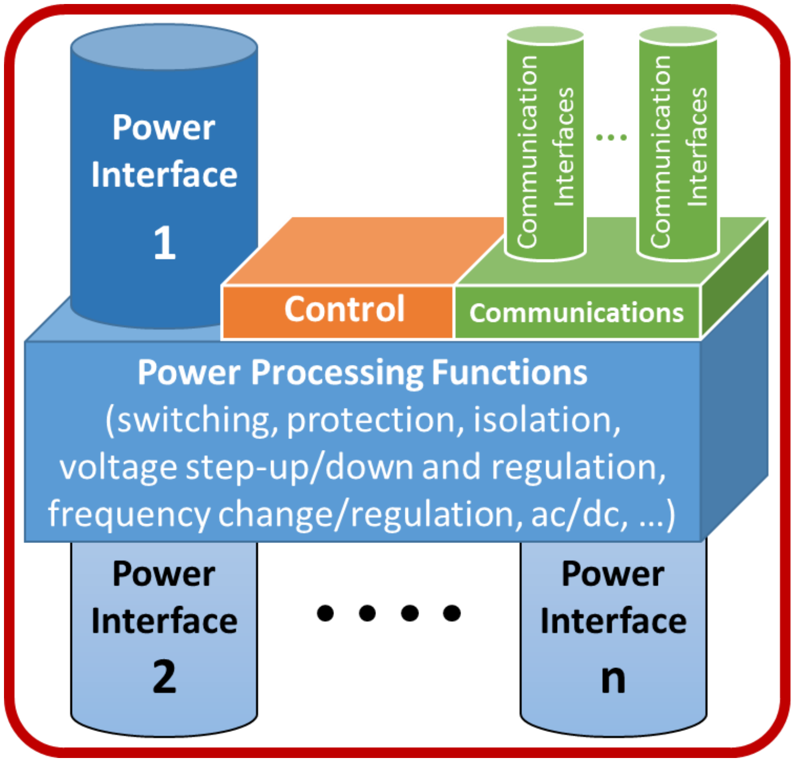

Figure 1: MBB with Power Processing, Communication, and Control Functions

The most straightforward example of an MBB is integration of all substation functions at the Point of Common Coupling (PCC) of the microgrid to the utility grid. In such a simple form, the MBB will have one Power Interface connected to the higher voltage utility grid and the other Power Interface(s) connected to the lower voltage microgrid, in addition to the multiple Communication Interfaces to major microgrid components and to the SCADA system of the utility operator. The electromechanical Power Processing Functions will include power transformer for voltage level adjustment and ground isolation, fault protection on both power interfaces, as well as various switchgear for disconnecting, re-closing, and reconfiguration. The MBB will incorporate a microgrid controller, which will provide microgrid supervisory control such as voltage regulation using the microgrid DER and demand response, as well as control the power processing inside MBB for islanding, resynchronization and reclosing, fault handling and recovery, etc. The power control is bi-directional; hence, the power flow can come from the utility system and, in some scenarios, the microgrid can also serve power to the utility system through electricity trading arrangements if the microgrid is not owned by the same utility company. More complex microgrids can also incorporate variable frequency AC and DC subsystems; in such cases the power processing block must include power electronics converters with varying complexity of functions and controls, depending on applications. The major advantages of using power electronics converters include universality (increased flexibility) and reprogrammability, significant size reduction, much smaller fault currents, etc., at somewhat increased costs and losses.

A generic architecture of the MBB concept is illustrated in Figure 2. There are specialized functions each block needs to perform. For example, the block on the far right, Power Transfer, interfaces with some form of external grid, such as another microgrid or the utility power system. This block needs to be able to communicate with synchronization requirements to the overall MBB-based grid. It needs to be able to set a desired frequency and a voltage reference for the entire microgrid to operate smoothly with the external grid. This block is also responsible for executing the breaker or switch operation, or arming of a synch-check relay, when reconnection is desired and feasible.

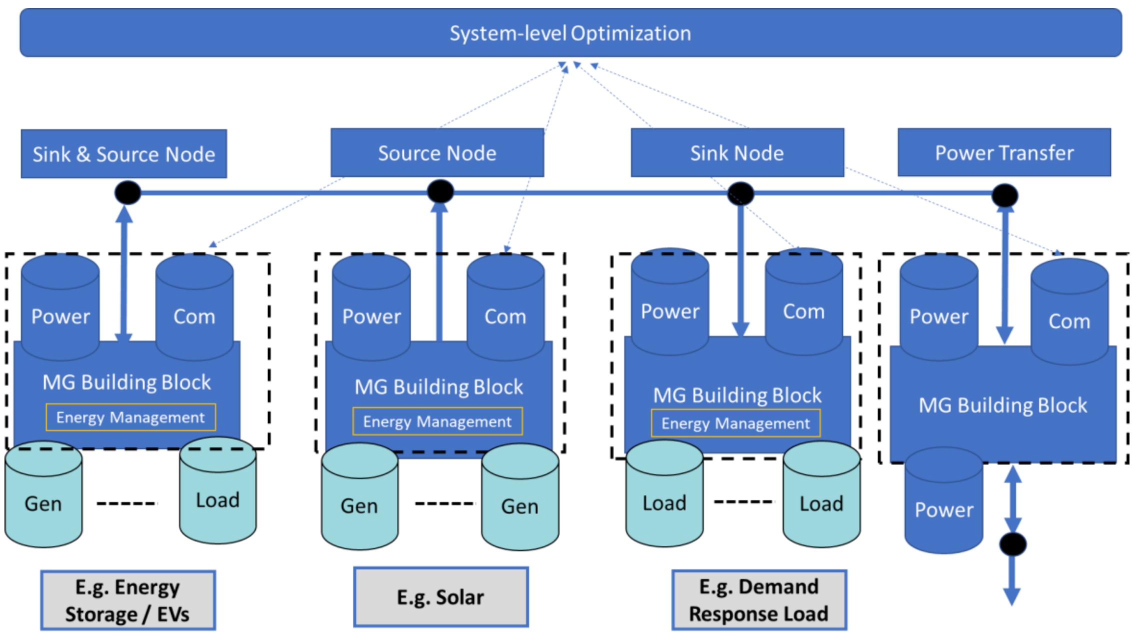

Figure 2: Typical Microgrid Building Block (MBB) Based Architecture

Another example of specialized capability, the "Sink Node" and the "Sink & Source Node" MBBs also require specialized controls. The MBB devices need to coordinate and represent any demand-response signals or direct controls to load devices connected. The specifics of how and when these controls are activated will vary with different operating conditions, but MBB enables their capability on the microgrid.

The communication system serves data acquisition as well as control commands for the entire microgrid as a cyber-power system. The microgrid controller provides functions similar to those of a control center in a power grid. However, control commands can be issued from a remote location by system operators or the commands may be autonomous within the microgrid. Communications can be wired, wireless, or a combination of both, depending on the microgrid environment. The centralized microgrid controller has the capability to calculate the appropriate control actions based on the data/information acquired from various nodes in the microgrid in a real time environment. In contrast, in a distributed control structure, software/hardware agents at different nodes share data/information and collaborate in the control tasks.

The proposed MBB concept in Figure 1 is not unique; other visions of microgrid building blocks are possible. As mentioned, building blocks may be developed for power conversion, microgrid control, protection, islanding and reconnection, or storage. However, standardized building blocks should be able to integrate and interface with existing microgrid functions.

Electrical System Configuration

As shown in Figure 1, each MBB has two or more Power Interfaces that connect the power processing inside the MBB to the outside world. The Power Processing Functions include switching and reconfiguration, fault protection on all Power Interfaces, isolation, voltage step-up/down, voltage regulation, frequency synchronization, and could include frequency change and regulation, as well as AC to DC conversion, or vice versa, if power electronics conversion is used. MBBs power terminals should have standardized Power Interface connectors and ratings to simplify microgrid construction and operation.

An illustrative list of possible MBB Power Interface characteristics, suitable for smaller microgrids, is shown in Table 1. Probably no MBB would ever have all these power terminals. For example, the PCC-to-utility Power Transfer MBB discussed above could have Power Interface A on the utility side, B connected to the microgrid loads and the C connected to the microgrid DERs and other loads. Inside the microgrid, a Source-MBB could connect on one side to the microgrid distribution bus through the Power Interface C, while using D for connecting to a Combined Heat and Power (CHP) variable-speed generator and multiple G Connectors for several PV arrays. Another Sink/Source-MBB would also use C for connecting to the same microgrid bus, while on the other side using a couple of Power Interfaces E for the battery storage, F for a specialized industrial load, and an H for the Power Transfer with a small DC nanogrid.

Table 1: Illustrative Examples of Possible Standardized MBB Power Interface Characteristics

Connector	**Type**	**# wires**	**Frequency**	**Voltage** (rms)	**Power**	**Direction**
A	3-phase AC	3-wire	60 Hz	13.8 kV line-line	2 MVA	bi-dir.
B	3-phase AC	3-wire	60 Hz	4.16 kV line-line	1 MVA	output
C	3-phase AC	4-wire	60 Hz	2.4 kV phase-neutral	1 MVA	bi-dir.
D	3-phase AC	3-wire	25-100 Hz	1- 4 kV line-line	500 kW	input
E	Bipole DC	3-wire	0	± 400 V	250 kW	bi-dir.
F	3-phase AC	4-wire	50 Hz	220 V phase-neutral	250 kW	output
G	DC	2-wire	0	+ 400 V	125 kW	input
H	DC	2-wire	0	+ 400 V	125 kW	bi-dir.

The electrical system connects the generation resources to the loads. The configuration may be radial or meshed depending on the reliability and redundancy requirements. A radial configuration is common in distribution systems for ease of protection design with respect to overcurrent conditions due to line faults. However, as protective devices are actuated to isolate the faulted sections or components, there will be an outage area that needs be restored by back-up generation sources. On the other hand, a meshed electrical network has built-in redundancy that allows the load to be served by available power sources.

Traditionally distribution system protection is provided by circuit breakers and protective relays in the substations as well as reclosers and fuses installed on the primary feeders and laterals served by the primary feeders. Microgrids connected to a utility distribution system are no longer a radial system as there are multiple generation sources to serve the load. As a result, protection design for radial configurations is not effective. Instead, protection schemes and/or relays can be used to detect a fault on an electrical component (or a group of components) and isolate the faulted portion of the microgrid, allowing loads in other portions of the microgrid to be restored quickly with the available generation resources. The faults involving DERs will necessitate coordination with the interface inverter algorithms. Due to different short circuit currents and electrical behaviors, protection for a microgrid operating grid-connected as part of the electrical system differs from protection for an islanded microgrid.

Communication and Control System Structure

The stable operation of a microgrid is dependent not only on the performance of the control system but also on reliability of the communication or cyber system on which the control signals are routed. A good cyber system must be robust, reliable, and secure. To design a realistic cyber model, three pieces of information are needed: cyber elements of the network, topology of these cyber components, and technology that could model these cyber elements. The cyber elements of a microgrid are the devices involved in communication or remote control. These may include the microgrid controller (MGC), local controllers (LCs), and the PCC. The communication structure among the cyber elements determines the topology. In some microgrids, a centralized communication system is employed and the MGC acts as the brain of the microgrid. In such a system, a master-slave architecture is preferred. In a distributed (de-centralized) system; however, LCs and other intelligent devices interact with one another directly. Thus, the cyber system is peer-to-peer. There can also be a hybrid approach with centralized and distributed control functions. A centralized communication and control system configuration is illustrated in Figure 3. In the configuration, each local controller has a remote terminal unit (RTU)/Gateway for communication and control purposes.

The microgrid controller maintains system steady-state and dynamic performance in response to load and generation variations and faults, intentional islanding, and major contingency events such as generator outages or unplanned islanding of the microgrid from the utility system. In these scenarios, the control system needs to maintain the frequency and voltage within the acceptable limits. The control functions include generation dispatch, frequency and voltage regulation, and stabilization of the microgrid following disturbances. At a generation or load node in the microgrid, there may be local power conversion and control of the voltage and frequency. The microgrid controller is an additional system-level (secondary) control that maintains system stability during normal load variations and when the system undergoes a contingency event such as loss of generation or load and line faults.

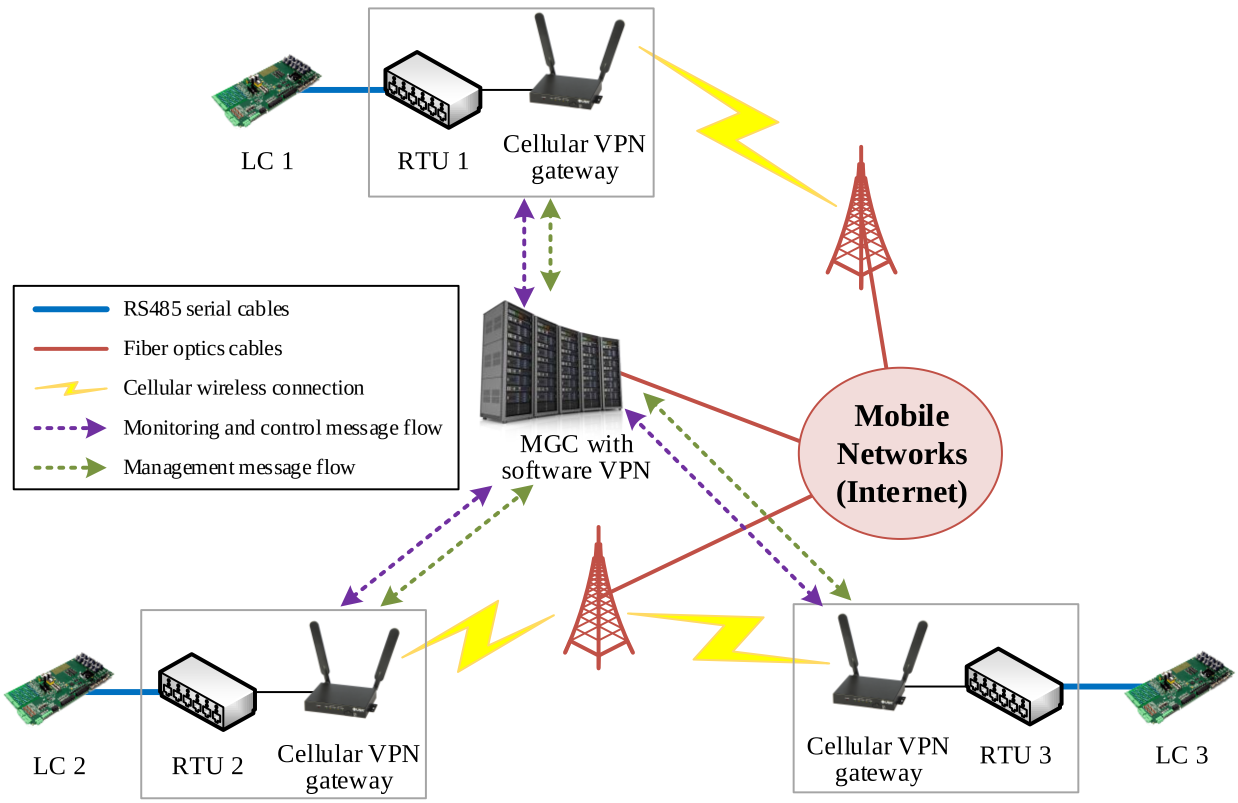

Figure 3: Centralized Communication and Control System Structure for the MBB

A hierarchical structure exists for a distribution system with multiple microgrids that may be standalone or networked. In the complex operating environment, a systems approach is needed for operation, communication, control, protection, and planning of the microgrids. In this case, there are multiple MBBs in the system that requires an appropriate centralized or decentralized communication and control structure. Refer to Figures 2 and 3.

A centralized secondary control scheme is shown in Figure 4. In each round of control, the MGC collects the active and reactive power outputs of all distributed generators, as well as the frequency and voltage at the point of common coupling (PCC) and other nodes. Using the collected data, the MGC as part of the MBB computes setpoints for the next sampling period, including the desired active and reactive power outputs and the deviation of PCC frequency and voltage, and dispatches them to local controllers. Upon receiving the updated setpoints, LCs will be actuated to regulate the parameters of the governor and excitation systems accordingly. MBB will be responsive to signals from both MGC and LCs. MGC is the global controller and LCs are actuated to regulate the parameters of individual MBBs. For scenarios where there is no PCC, e.g., navy shipboard application, the microgrid building block control and communication functions can be integrated with existing power system and power electronics facilities.

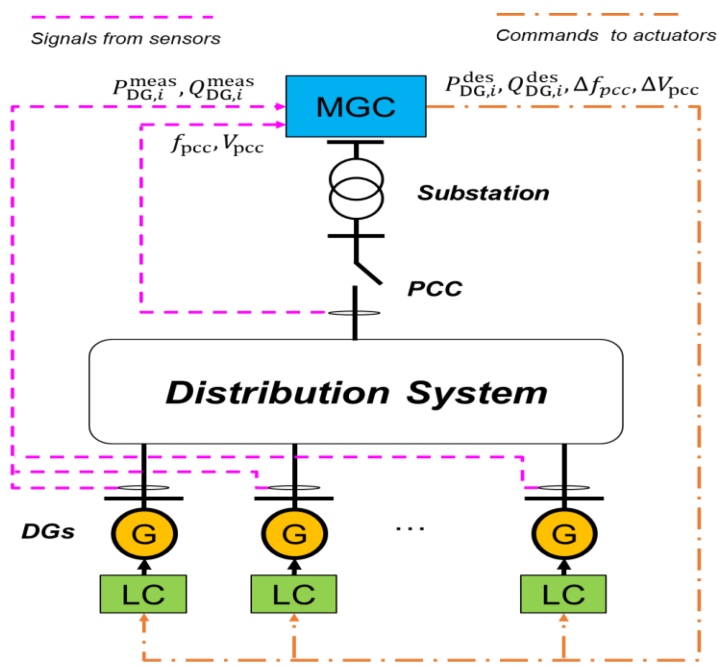

Figure 4: Microgrid Controller to Maintain System Stability

Note that the operating condition may deviate from normal conditions as a result of small and large disturbances, such as load variations or electrical faults. A systemwide secondary control system in collaboration with the local controls is needed to steer the microgrid back to a normal operating condition. For the secondary control scheme illustrated in Figure 4, many control algorithms are available for the microgrid. However, it is important to incorporate practical considerations about the performance and cost.

Practical considerations of the overall control of the MGC and MBB devices must also account for event scenarios that result in the loss of communication. Even with wireless peer-to-peer connectivity, some of the MBBs and their associated local control devices may become isolated from the systemwide coordination and control. In this case, it is important that any MBB-related control has a form of fallback operation. When the coordination mechanism for systemwide communication and control is not available, the local controllers or local MBB device should be able to operate reliably but may be at a suboptimal state. For example, another MBB or MGC may be commanding a generator to adjust its power to accommodate a generation change elsewhere on the system. Without the communication/coordination network, it should still be able to rely on local frequency measurements and droop controls to maintain grid operations, even if it is not operating at the optimum power output from a system point of view.

1.2 State-of-the-Art

MBB is a new technology concept for the development and implementation of microgrids. As a result, the literature for MBB is essentially non-existing. However, significant progress has been made over the last decades on the related technology of Power Electronics Building Blocks (PEBB) [1-3], and more recently on the Solid Sate Transformer (SST) [4-5] and Solid State Power Substation (SSPS) [6] concepts. Following the microelectronics paradigm, power electronics needed a revolution in modularity and commonality. The power electronics building block concept [1] has moved converter power hardware in that direction. A definition of the concept is given in [2] as:

> "Power Electronics Building Block (PEBB) is a broad concept that incorporates the progressive integration of power devices, gate drives, and other components into building blocks, with clearly defined functionality, that provides interface capabilities able to serve multiple applications. This building block approach results in reduced cost, losses, weight, size, and engineering effort for the application and maintenance of power electronics systems. Based on the functional specifications of PEBB and the performance requirements of the intended applications, the PEBB designer addresses the details of device stresses, stray inductances, switching speed, losses, thermal management, protection, measurements of required variables, control interfaces, and potential integration issues at all levels."

Thus, the goal of PEBB-based power systems is to make it possible to integrate identical basic building blocks as major components of the final application. Interconnecting PEBB units creates specific system configurations with various power level ratings. Together, the aggregate of these basic building blocks forms a complete power electronics converter system, including mechanical, cooling, power, auxiliary power, and controls system interconnections. Custom designed systems and installations, without the benefit of standard interfaces or PEBB concepts, cannot be upgraded without incurring significant design, development, and re-commissioning costs.

The building block approach extends to power electronic control systems. The overall control of a power electronics system is achieved by arranging rudimentary control functions to produce a desired control. When the control functions of various types of power electronic systems are examined, a significant degree of common functionality emerges, irrespective of the target application. It is possible to define hierarchical control architectures for these systems using common interface definitions between control system divisions or layers. Such definitions enable the use of common designs for multiple applications and the use of commercially available electronics and communications modules allowing cost reduction in power electronics applications. Control/protection technology is advancing rapidly and substantial improvements can be attained through cost effective upgrades. Furthermore, potential benefits from upgrading and adding new features of control are occurring on an increasingly accelerated time scale. Key to this upgrade process are well defined control partitions which will allow an individual control subsection to be removed and upgraded without impacting adjacent layers and even hardware. The move toward a standardized modular control architecture is further motivated by the rapid obsolescence of controls relative to other parts of power electronics systems. A common definition of the control layers, with defined interfaces, enables the ability for a partial upgrade [3].

Although a hierarchical partitioning may not yield the most computationally efficient design, partitioning these control functions can increase interconnectivity and reduce the engineering required for follow-on efforts. Moreover, the continuous trend of increasing microprocessor speeds and memory size, along with reduction of cost has now reached a point where the benefits of modularity can often be achievable without compromising control performance specifications.

The Solid State Power Substation (SSPS) idea, developed by the Advance Grid Research program in the DOE Office of Electricity, carries the PEBB concept further to address the electricity delivery network, especially for substations. In the recent roadmap document [6], SSPS is "defined as a substation or "grid node" with the strategic integration of high-voltage power electronic converters, [that] can provide system benefits and support evolution of the grid." As illustrated in Figure 5, SSPS is "ultimately envisioned as a system consisting of modular, scalable, flexible, and adaptable power blocks that can be used within all substation applications. SSPS converters will serve as power routers or hubs that have the capability to electrically isolate system components and provide bidirectional alternating current (AC) or direct current (DC) power flow control from one or more sources to one or more loads—regardless of voltage or frequency."

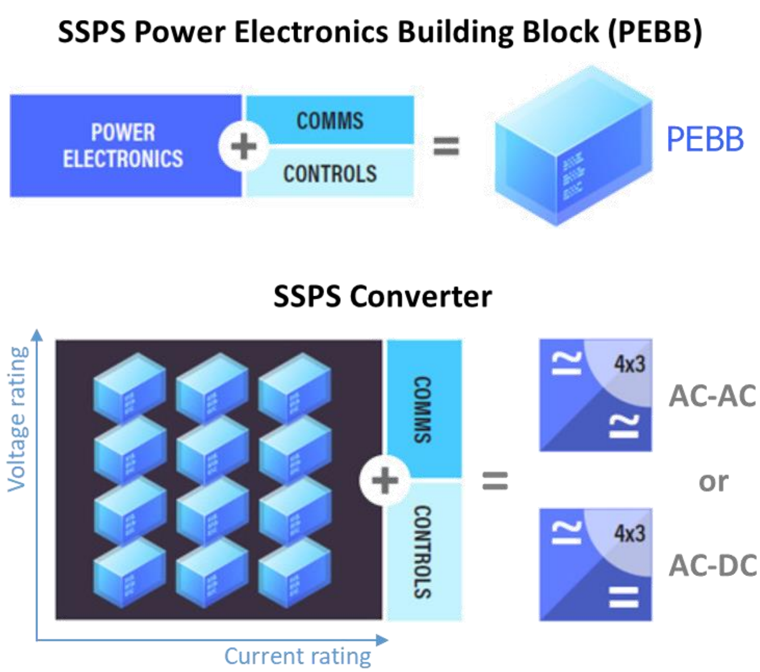

Figure 5: Vision for SSPS Converters (adapted from [6])

Although there are similarities between these concepts, they are significantly different. The PEBB concept is clearly focused on modular implementation of power electronics converters, for any applications. SSPS technology looks further down towards Intergrid [7] when electricity will be collected, transported, and delivered through AC/DC network of electronic energy routers at low voltage level (SSPS 1.0), medium voltage level (SSPS 2.0), and high voltage level (SSPS 3.0). All these concepts integrate power processing, control, and communications functions. However, PEBB and SSPS use exclusively power electronics converters for the power processing functions, whereas MBB may use power electronics or more traditional electromechanical components or a combination of both, depending on specific needs and maturity of the underlying technologies. Additionally SSPS sits only at the Power Transfer nodes between different sub-networks, while MBBs can additionally provide standardized interconnectivity of different generation (Source), storage (Sink/Source), and load (Sink) devices.

2. Vision for the Future

Microgrids have existed on geographical islands and in the Arctic region over the past century. Their ability to withstand extreme weather and provide reliable electricity led to widespread constructions in numerous inland locations as well, where connection to bulk energy systems may be available. By now, microgrids are found all around the world: from remote villages in Alaska to community microgrids in many Asian and European countries, and from islands surrounding Australia to military bases in the United States [8-11]. Microgrids have been transitioning their generation profiles to renewable energy resources, with many already transitioned to or near 100%, leading to enhanced resilience and reliability [12-14]. With the growing interest in creating interconnected microgrids that are able to island and retain operation during disturbances, methods are being developed to seamlessly island towns as their own microgrids operate autonomously [15-16].

The MBB concept offers modularity, flexibility, as well as reduced cost, and further enhances its value for MGs by application of the universal control architecture. An MBB universal controller (MUC), which is a multi-function controller tightly integrated with lower-level control of MBB and self-configuring for different technologies, will be used. The MUC offers the advantage of reconfigurability of control algorithms as well as dynamic reconfiguration based on awareness of topology or state of the MBB. A MUC can continue operating intelligently by detecting the faulted part of MBB and dynamically reconfigure in a degraded mode while providing guidance for full restoration. Having a universal microgrid controller and building block approach can serve diverse technologies such as solar PV, energy storage, fuel cells, and electrical vehicles (EVs) in both AC and DC-coupled architectures. The building block and a universal controller will simplify integration of these high-tech devices in a tightly interconnected environment. The building block approach improves modularity, flexibility, and reliability at the device level, microgrid level, as well as distribution system connectivity level. Benefits of a building block approach include:

- Enhanced resiliency, reliability of interconnecting microgrids through electrical and communication connectivity,
- Holistic consideration of microgrid resiliency considering cyber physical threats for building block approach and universal controller,
- Improves modularity, maintainability, scalability for future expansion, and standardization for both power and control for rapid recovery and reduced downtime,

- Reduction in balance of system (BOS) cost with standardization of the interfaces and interconnects, and
- Reduction of operation & maintenance (O&M) costs with advanced features such as online health monitoring, and cyber physical security.

To maximize the grid functions from the microgrids employing the MBBs, and to promote rapid integration and optimization, the MBBs are to be categorized/segregated by functionality as: AC load building block, DC load building block, AC source building block, and DC source building block. An MBB can be viewed as a power conversion stage with input and output ports to which load devices or assets can be connected. Given that the operating power of an MBB can range from tens of kW to MW based on application, the architecture of MBBs should support cascading or paralleling of Modular Power Stages (MPS). MPSs can be considered as the fundamental building blocks of MBBs. To support interoperability, scalability, and plug and play capability, both the MBB and MPS are to be designed with communication, control, intelligence, advanced algorithms, and protection. The associated hierarchy in control, communication, protection, intelligence etc. needs to be identified. Unlike a smart inverter, MBB can be preconfigured and the design optimized to support predefined grid functions as discussed above. Thus, MBB and MPS should be designed to improve the grid metrics, including resiliency, reliability, power quality, security, efficiency, and cost. The vision of MBB development is summarized in Figure 6.

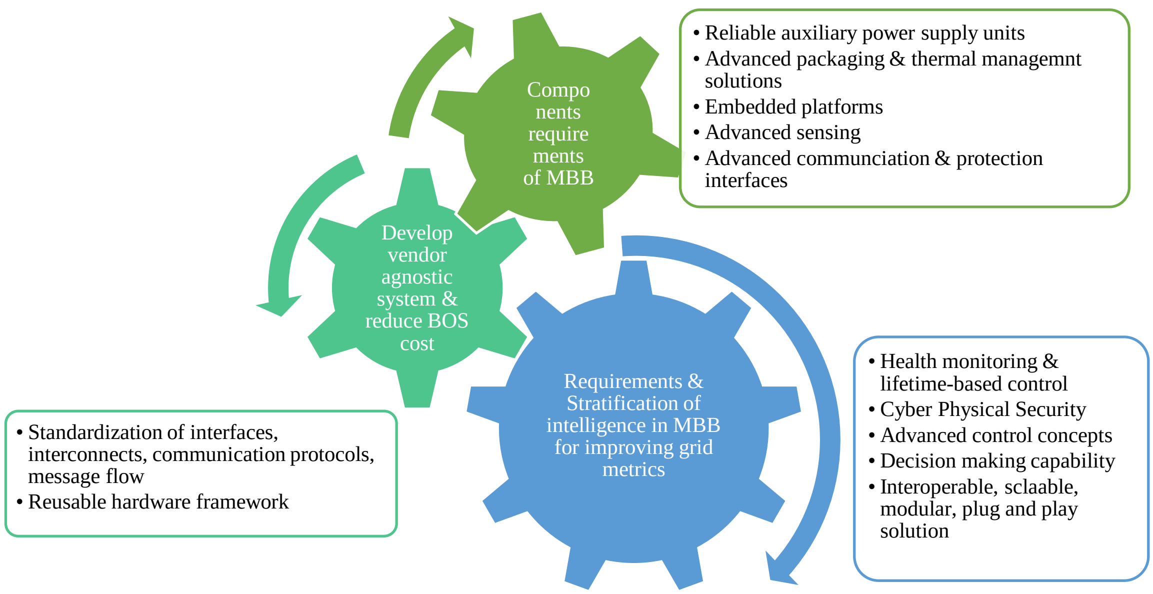

Figure 6: Vision for Development and Commercialization of Building Blocks

Vision 1: Development of Advanced Power Electronic Interfaces for the Grid

To enhance the grid metrics, the fundamental blocks must be designed to be robust and resilient and this calls for a holistic design with control, communication, protection, and intelligence. The holistic design approach is crucial to designing interoperable, scalable, and modular systems. Interoperability, scalability can be further enhanced with the inclusion of advanced features (listed in Table 2), including cyber-physical security, diagnostics, and advanced control algorithms. Together, these features will make the grid interface more reliable and resilient, i.e., minimize failures and downtimes and alleviate the impact of cyber threats. Such advanced building blocks can be used to demonstrate a microgrid with advanced functionalities.

Table 2: MBB Features and Corresponding Grid Impact

MBB features	System Level Impact	Metrics
1. Interoperability	- Easy integration and reduction in BOS costs	Economics
2. Embedded intelligence and decision-making capability with a flexible scalable platform	- Improved voltage profile at the point of connection (POC) - De-rated/continuous operation during failure events	Reliability, Grid Support, Power Quality
3. Diagnostics	- Allows maintenance to be pre-planned - Prevents loss of the inverter from affecting the overall system - Increases lifetime	Reliability, Economics & Reduced Downtime
4. Embedded optimization & transactive functionality	-Cost benefits to the consumers -Market for ancillary services	Economics
5. Cyber-physical security	- Improved protection against cyber threats	Reliability, Resiliency, and Economics
6. Limp home capability	- Sustained operation in the event of failures	Reliability

For example, after minor failure events the microgrid could continue to operate for extended periods of time in a "de-rated" mode using demand response or even automatic rolling load-shedding. On the other hand, after catastrophic failures, when a shutdown becomes necessary, it would be of great interest for the microgrid to have "limp home capability" to inform the critical loads of impending power outage and to set-up the system configuration and prepare all MBBs for the upcoming black start after the repair or removal of the failure cause. An example of such capability would be to retain a reserve level of energy storage and to keep the control and communication units running in all MBBs ("maintain the brain while the body recovers").

Vision 2: Development of Advanced Subcomponents for the Advanced Grid Interfaces

With the vision to develop advanced power electronic interfaces for the grid, the R&D efforts should align to improve metrics such as power density, efficiency, and cost minimization. To this end, emphasis should also be on the development of advanced subcomponents required to realize features such as high bandwidth and noise immune sensing units, fault tolerant and reliable auxiliary power supply units, and embedded platforms for hosting advanced algorithms. R&D efforts are also required in the domain of packaging and thermal management to improve the system power density and efficiency.

Vision – 3: Commercialization of Proposed MBB Concept

Standardization of the interfaces and interconnects will enable mass manufacturing and commercialization by reducing the balance of system costs. Standardization of the interfaces and interconnects will eventually lead to vendor agnostic systems and a streamlined supply chain. The end goal is to hasten commercialization and adoption of such intelligent grid interfaces, nodes, or hubs to support modernization of the power grid with resultant improvement to reliability, resiliency, power quality, economic, efficiency, and security metrics.

Although product standards are finally developed, adopted, and implemented by industry, it is essential that the development of standardization framework starts immediately and is developed concurrently with the research on the MBB concept. As MBB is a new technology, there are no adequate standards that will enable interoperability, modularity, scalability, and plug-and-play, and hence its commercialization will be highly dependent on early adoption of a standard reference framework. The situation is similar where inter-computer communications were 40 years ago: The Internet concept could not take off until the Open Systems Interconnection Reference Model (ISO/OSI) was adopted and TCP/IP standard accepted.

3. Roadmap - MBB Technology Development

MBB Design, Implementation, and Testing

The building block can be defined as a common interface that allows for the interoperable integration of sources (generators) and sinks (loads) into a microgrid. A typical building block is envisioned to have power and communication interfaces and standardized control functions. The fundamental step in the roadmap is to design comprehensive specifications for every building block for microgrid application.

At the system level, the MBB performs the functions of energy management, communication, and control, as well as system-level optimization. The functions are shown in Figure 7. The next step in the roadmap is to design interfaces for every MBB. A particular MBB depending upon its technical capability may participate in a variety of microgrid services. Typically, each MBB can contribute to reliability services, resiliency services, and flexibility services depending upon its technical characteristics. A source MBB may have additional services such as black start, voltage support, frequency support apart from acting as a power source. A sink if constituted with controllable load may contribute to functions such as demand response, frequency stability, and voltage stability. Thus, the definition of services and interfaces will constitute the first phase of the building block development roadmap.

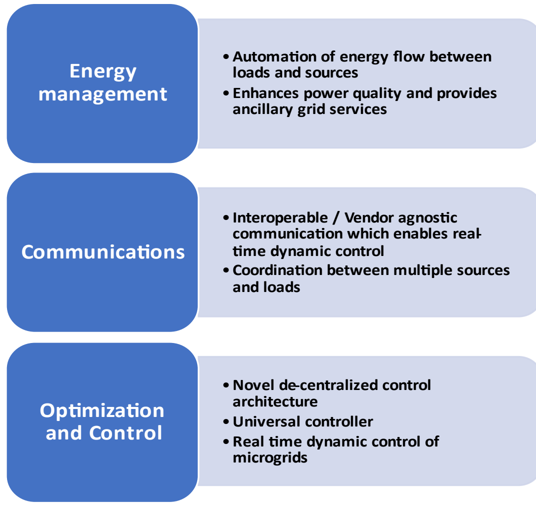

Figure 7: System Level Functions of an MBB

The design, development, and testing of an MBB is illustrated in Figure 8. Once MBB interfaces and services from each MBB are defined the next roadmap phase is to develop global MG control architecture. Each MBB service will be contributing to a microgrid control function. These control functions can be black start, voltage stability, etc. Accordingly, the microgrid control architecture will be defined. The MBB will be required to meet certain performance requirements to achieve a global microgrid control. A typical performance criterion could be how fast/reliable/stable each function needs to be. The MG control architecture design phase and the building block development phase are iterative in nature.

As MBB is a new technology, it will be critical to demonstrate how a modularized MBB can help to simplify and reduce the cost for development, installation, and maintenance of a microgrid. One good example is to start with a basic utility/campus/community distribution system and use the MBB technology to develop the microgrid capability in the distribution system. This will demonstrate how the microgrid increases the resiliency and create new opportunities such as ancillary services.

It is likely that there are a lot more small microgrids than large ones. Modular design will make a greater impact if many microgrids can show benefits from the MBB technology. Therefore, it could be the most appropriate for the program to develop the first MBBs for smaller microgrid systems, with power ratings similar to the Power Interface characteristics shown in Table 1.

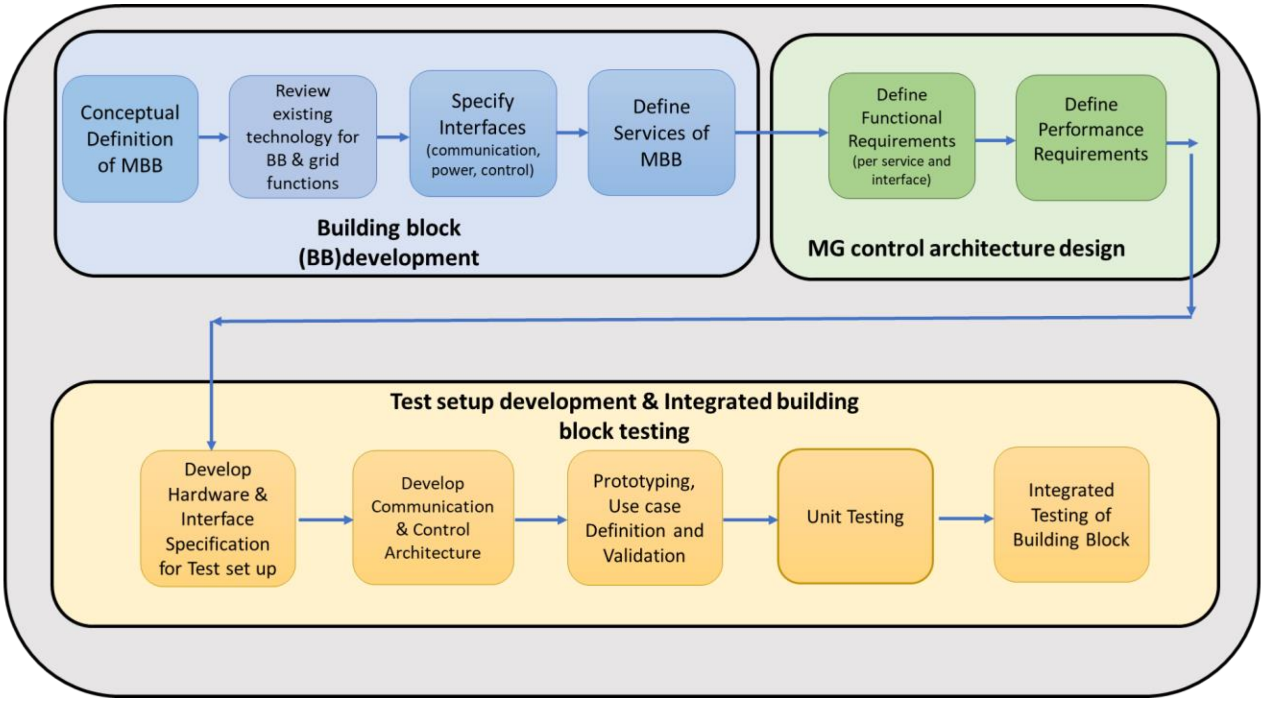

Figure 8: Design, Development, and Testing of an MBB

.

A microgrid developed with MBB design philosophy will be tested in the next step of the roadmap. In order to validate the value proposition of MBB, a test setup will be developed. Hardware & interface specification for a test setup will be designed in the subsequent step. Based on the use case and test setup requirements the communication and control architecture will be developed. MBB block prototype required for a particular use case validation will be designed. MBB testing will be performed in two phases. An MBB unit testing for a particular service and integrated functionality and interoperability testing of multiple MBBs will validate the value proposition of MBBs for a microgrid application. A detailed procedure and roadmap for MBB design, implementation, and testing is given in Figure 8. The process starts with a study of the generation and load profiles for the microgrid. The functional requirements are incorporated, considering the grid performance indicators. After the architecture of the MBB is designed, the implementation, testing and validation tasks will follow. Through this roadmap following foremost objectives will be achieved:

- Development of a universal controller with a very fast local control system to handle and enhance the latest grid codes. This also contains a fast communication link to a central supervisor to coordinate the system in real-time. A modular power grid-connected inverter package capable of high efficiency and switching frequency serves as the power converter interface for microgrid applications.

- A low voltage at scale test platform is envisioned at national laboratories as demonstrated in Figure 9. An MBB evaluation platform leveraging state-of-the-art technology for testing distributed programmable control for microgrid converter application will be developed. After completion of unit and integrated testing of MBB, the field validation will be performed in collaboration with other academic institutions. A field validation set up illustrating MBB for distribution system is shown in Figure 9.

- A reprogrammable universal controller that does plug and play of diverse generators, loads such as EVs, and storage. A multi-functional controller with online learning/adaptation capabilities allows various hybrid configurations.

- A plug-and-play (PnP) approach is adopted, which is a smart reconfigurable system for various storage technologies.

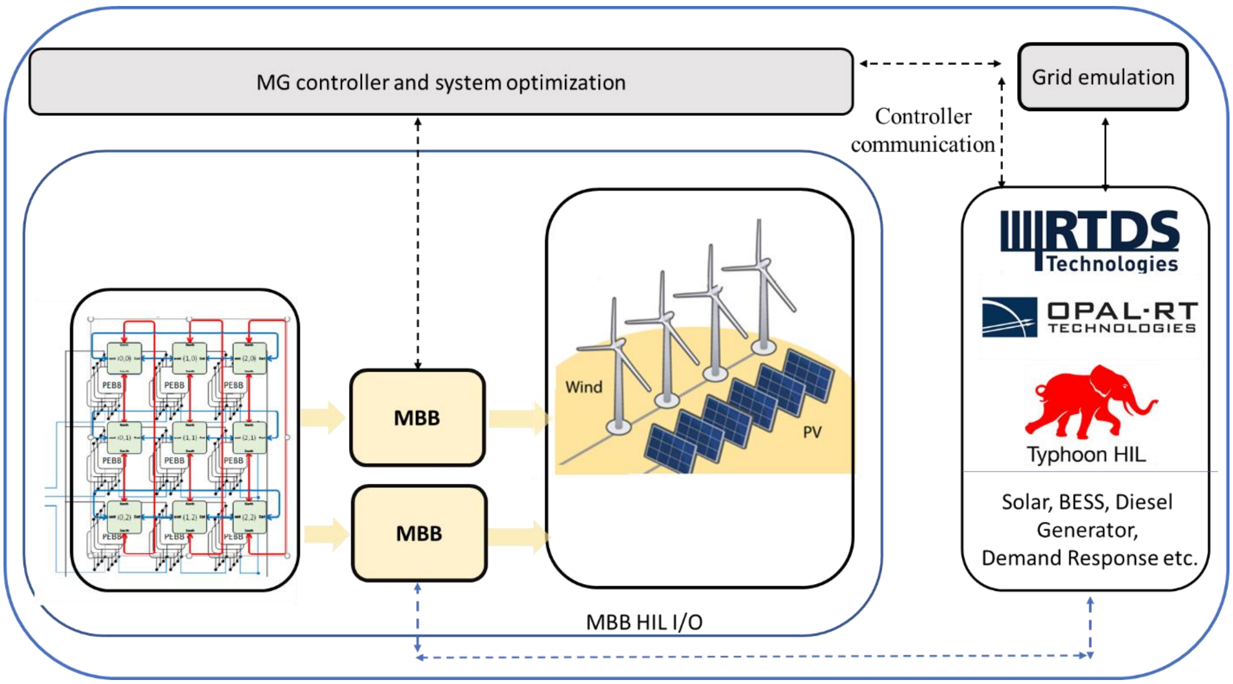

Figure 9: MBB Low Voltage Evaluation Platform Using RTDS at Oak Ridge National Laboratory, Sandia National Laboratory, and National Renewable Energy Laboratory

Issues to be addressed include interoperability and standardization (e.g., interfaces and controls). For wide deployment, the resulting building blocks should not require highly advanced knowledge and skills for installation, operation, and maintenance.

4. Cost-Benefits/Economics and Use Cases

4.1 Cost-Benefits and Economics

By introducing modularity and flexibility into existing microgrid architectures, the MBB concept can significantly contribute to (1) eliminating uncertainty at the planning and operational stages, (2) standardizing the design of microgrids, (3) improving the exchange of flexibility services at the distribution level, (4) enabling innovative horizontal market approaches, (5) facilitating the integration of behind-the-meter distributed energy resources, as well as (6) improving the reliability and resilience of power distribution networks. It is important to note that the MBB concept enables these capabilities; however, every MBB element does not have to encompass the full range of capabilities, as they may not be necessary for the operation and may increase the cost. With the MBB concept, certain functions may be coordinated by another MBB controller or device elsewhere in the system, e.g., a microgrid controller. These impacts translate into economic benefits at the microgrid level and to the electricity subsector.

Cost-Benefit Balance of Modularity

Microgrid building blocks and the inherent standardization of communications, control, and power interfaces may impact microgrid costs. It is anticipated that this concept requires an independent layer of control for each block, which should be interoperable and robust to support multiple types of connections to other blocks, in order to address different microgrid deployment scenarios. Consequently, it is possible that the MBB modular framework leads to an increase of Information and Communications Technology (ICT) infrastructure costs for microgrids. However, it is important to stress that communications and control infrastructures are a small portion of the overall microgrid costs, ranging from 2% in community and campus microgrids up to 10% in utility-owned microgrids [17].

One the other hand, the modular and standardized aspects of MBB can also bring benefits to the electricity subsector, especially in terms of operational costs reduction. In fact, the modular communications and control architecture of MBBs allows for better identification of component failures, improves troubleshooting, contributes to isolate outages, and minimizes repair-times and loss of load, which reduces the overall economic losses of a microgrid. At the same time, the standardization of microgrid components reduces the need for specialized operation at the device-level. It also decreases maintenance costs and improves interoperability of devices and systems, which expands the market choices and increases competitiveness among vendors and manufacturers. Finally, standardization can also benefit the microgrid project phase by simplifying the design process, reducing commissioning costs, and mitigating the investment risk and related financial costs.

Asset management or renewal of microgrid installations or their components is an important consideration. The MBB concept, if properly executed, would support long-term renewal of microgrid installations. However, it should be noted that electronic/control components may have a shorter expected life than the power generating components. Modularity is a key element to facilitate the asset management and upgrading strategy for the microgrids.

Value of Flexibility

The increasing penetration of renewable distributed generation, together with dynamic behaviors at the building level, increases the long-term and short-term netload uncertainties in the nodes of microgrids. This uncertainty leads to unpredictable imbalances in the bulk power system, which poses new challenges to microgrid and distribution grid operation, introduces new requirements of network reinforcement and operational flexibility, and increases the overall costs of planning and operation. Utilities and microgrid operators currently manage these uncertainties through conservative strategies, such as over-investments in network capacity, active curtailment, or interconnection limitations to renewable-based resources, resulting in significant economic losses.

By introducing a new source of flexible control at the microgrid level, the MBBs can locally address the impact of uncertainty, leading to decreased operational and planning costs that derive from unmanaged uncertainty. In fact, due to the control architecture, the MBB concept can guarantee robust netload limits in the interface between blocks (e.g., via control setpoints), which significantly contributes to mitigation of the impact of uncertainty. Consequently, the controllability and flexibility functions have the potential to reduce the investment costs in new lines and cables, as well as provide guarantees to microgrid owners in the participation markets and dynamic price programs. Additionally, when acting as a block in the overall operation of the distribution network, MBBs give microgrids the potential to avoid the propagation of uncertainty across different areas of the utility network and to the bulk power system. This represents significant economic gains in terms of decreased operational costs, better integrated renewable generation, reduced losses, greater resources commitment, and deferred investment.

To unlock these uncertainty management capabilities of MBBs, innovative supervisory control functions are required. These functions can include, for example, new microgrid economic dispatch methods that are compatible with the MBB architecture and able to provide netload guarantees at the block level for different risk-aversion operational conditions. On the other hand, to capture the value of MBB in cost reduction, existing microgrid/distribution grid optimal capacity planning, economic operation, and valuation tools should be updated to model the added flexibility provided by the MBB architecture.

Value of Resilience

Power distribution is vital for the life and safety of our communities, requiring microgrids to be reliable and resilient. Routine failures of network components together with high-impact low-frequency events (HILF), e.g., wildfires, floods, hurricanes, can entail significant risks to reliability and resilience. Traditional grid investment strategies, such as line hardening and topology redundancy establishment, are expensive forms of guaranteeing security and continuity of electricity supply to the consumers. Consequently, the flexibility introduced by the MBB concept can be a cost-effective form of maintaining overall network reliability and resilience, minimizing the microgrid loss of load during routine equipment failures, mitigating the impacts of HILF events, and protecting critical infrastructures.

To determine the additional reliability and resilience value of MBBs, it is important to evaluate the impacts of different block configurations on outage mitigations, namely in 4 dimensions: (1) reducing the magnitude of disruption, (2) extending duration of resistance, (3) reducing duration of disruption, and (4) reducing duration of recovery. The analysis should apply a consistent approach to modeling the sequence of events and their impact at the block level and capture the overall contribution of different blocks for reliability and resilience. Probabilistic simulation methods across various microgrid topologies, compatible with MBB architecture, are needed to capture costs, values, and key reliability and resilience performance of microgrids.

Transactive Energy Management Value

Transactive energy management has emerged as a form of coordinating the multiple agents in power systems (prosumers, aggregators, retailers) while considering their particularities, priorities, interests, and autonomy. The idea is to optimize the allocation of resources (e.g., generation, controllable devices, and loads) by enabling actors to interact with each other and exchange information about consumption, generation, constraints, and preferences until an equilibrium solution is reached. There may also be a non-transactive objective to be met, e.g., costs, flexibility, environmental performance. The transactive control is naturally decentralized and entails a transparent decision-making process, promotes the participation of several small agents, increases market competitiveness, and reduces energy and flexibility costs.

When it comes to enabling these transactive solutions from a grid operation perspective, the characteristics of MBB architecture can be decisive. In fact, due to its decentralized nature, MBBs can simplify the integration of these horizontal markets and services, allowing utilities and microgrid operators to guarantee operational limits and reduce market constraints, favoring clearing mechanisms and decreasing costs. For example, MBBs can facilitate communications of peer-to-peer transactions at the intra-block level, and act as a participant in microgrid and distribution level markets.

To achieve this, expanding the MBB concept to economic and market standardization aspects is important, such as development of price elasticity functions that are able to capture the response of the individual blocks to variations in energy prices. This would allow to introduce the paradigm of "MBB as a service entity," i.e., a structured economic block integrated with the communication, control, and power layers. Additionally, to show the value of MBB as an enabler of transactive energy markets, the research effort needs to include the development and demonstration of realistic cases, which would measure the economic benefits of MBB-based transactive control in comparison with current microgrid hierarchical control approaches.

4.2 Use Cases of MBB

Microgrid as a Resiliency Source

Virginia Tech Electric Service (VTES) is a 60 MW distribution system (owned and operated by Virginia Tech), with power served from Appalachian Power (part of American Electric Power). One of the proposed VT Climate Action goals is to achieve 100% renewable electricity by 2030. To this end, large-scale solar facilities and energy storage will be developed and deployed near the campus town of Blacksburg, VA. As shown in Figure 10, the proposed MBB serves as a building block to provide functions of power conversion, communications, and control for the microgrid.

If and when the AEP system becomes unavailable due to extreme events, the VT microgrid can operate in a resiliency mode to serve the critical load on campus and in Blacksburg. The microgrid control and communications will be built upon the existing VTES grid control and communication facilities. New sensors, communication, and control components and systems will be developed to complete the microgrid design.

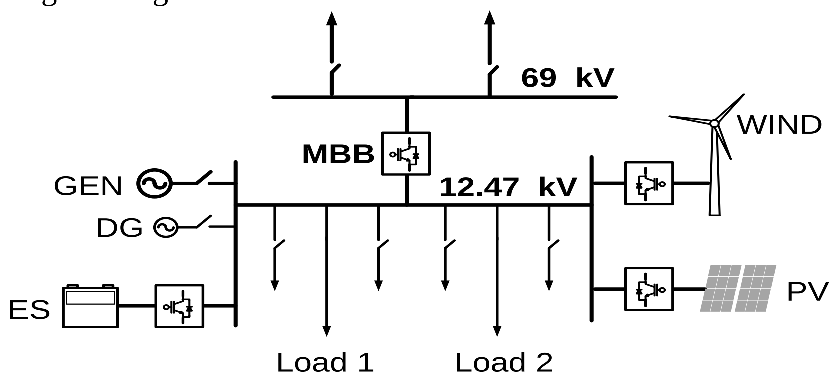

Figure 10: Illustration of MBB for Virginia Tech Electric Service Grid

A pilot study on MBB has been conducted at Virginia Tech in a project sponsored by DOE Office of Electricity and Pacific Northwest National Laboratory. The MBB at the PCC integrates the primary functions of power conversion, communications, and control for the microgrid. By modeling and simulation, the power conversion capability of the MBB demonstrates successful operation under islanding, black start, and unbalanced loading conditions. Communication and control functions of the MBB maintain the microgrid stability under the operational conditions of real/reactive power dispatch, frequency/voltage regulation, and stabilization under large disturbances.

MBB-based Microgrid in Alaska

Alaska has several rural microgrid power systems with capacities ranging from 30 kW to multi-MW levels. The generation and load mix is seasonal and variable, including dispatchable and renewable energy resources. Several of these microgrids operate as isolated rural power systems with low inertia, operate under harsh weather conditions, and pose control and stability challenges. Some ongoing DOE-funded projects are addressing control and integration challenges for resilience enhancement through various smart grid technologies, such as energy storage, advanced sensors, time-synchronized digital controls, advanced metering infrastructure, demand side management, resilience-based decision-making, and energy storage optimization and controls. Several of these methods are deployed and integrated with existing controls with conventional centralized control architecture in an AC distribution grid with individual device or subsystem controllers.

The MBB-based architecture offers flexibility and standardized approach to resilient design and control of the microgrids. The integration phases require more effort due to complexity of MBB-based system design, but offers several advantages for maintainability, modularity, flexibility, and resiliency. The MBB-based approach, in-turn, reduces the risk and cost of field deployment, operation, and maintenance by standardized building blocks and combining several subsystem controllers into a universal controller. Leveraging existing work and results on microgrid control design from DOE-funded project in Cordova, AK, an MBB-based microgrid design can be pursued. The MBB architecture can be used to design multiple potential locations with different sink & source MBBs, including a universal controller in EMT simulation, and controls prototyped in a hardware testbed environment. The actual field data from Alaska can be used to emulate and test various MBB control architectures.

To reduce the risks of MBB-based development, the performance assessment of MBB will be done using emulation and hardware testbed, and the efficacy/value of MBB can be quantified using measures/metrics by evaluating the four features listed below:

a) *Demonstrate Maintainability*

The microgrids can exist in various configurations, sites, energy mix with varying and dynamic physical, operational, and environmental conditions. The building blocks of a microgrid can be exposed to

- Harsh environment and operating conditions
- Complex system interaction and emergent behavior leading to protection/hidden failures
- Natural degradation of component health that can affect the performance[1]0.

MBB can provide high-level fault-tolerance and ease of troubleshooting through practical indications about the state of health of the system using error-codes, warnings, alerts etc., for faulty subsystems or blocks containing auxiliary states. The standardized design and integration of building blocks will ensure that there is no steep learning curve for preventive and corrective maintenance, thus providing ease of maintainability in a deterministic way. The plug-n-play architecture will ensure interoperability. The demonstration of the maintainability aspect of MBB can be achieved by using traditional metrics of reliability such as mean time to repair (MTTR), with the cause leading to failure or performance degradation specified as an event in the use case.

b) *Demonstrate Modularity*

Modularity is another aspect that is important for a standardized approach in complex systems such as electric microgrids. The MBB is assumed to be an atomic unit of a microgrid that is modular for standardized design with different configurations, capacities, and scales. Modularity conveys achieving the functionalities in a scaled-up system by coupling multiple atomic units of the same kind without additional customization for power or control logic.

[1] Deterioration due to extreme events is covered under the resilience use-case.

For example, capacity doubling may be achieved by using two tightly integrated power converter units capable of synchronized operation without affecting the system performance. In that case, two units of 1X capacity are equivalent to one unit of 2X capacity. At a very large scale, this linear or proportional behavior may become non-linear. This architecture provides a step-by-step expansion and improves overall system reliability from a device failure perspective.

c) *Demonstrate Flexibility*

A microgrid typically consists of AC generators, AC loads, and AC distribution / transmission circuits. The renewable and distributed energy resources (DERs) such as solar PV, energy storage, electric vehicles, electrolyzers, fuel cells, etc. are essentially DC and require conversion to AC for typical microgrids. The evolution of microgrids is bringing the DC distribution technology to forefront due to various benefits such as efficiency, but also poses its own challenges. Nonetheless, the capacity expansion and load growth in microgrids can result in a hybrid AC-DC design within a single microgrid and MVDC / LVDC connectivity across multiple microgrids.

Using an MBB approach provides a standardized and low-risk way to integrate hybrid AC-DC systems while reducing the risk of customization. Since MBBs are modular entities, the core functions for power exchange, communication, control, and protection will be inherent to the design and offer opportunities for demystifying and addressing the stability and protection coordination challenges in electric microgrids.

d) *Demonstrate Resilience*

Extreme events such as natural disasters (hurricanes, flooding, earthquakes, tsunamis, avalanche, wildfires, etc.), vandalism, extra-terrestrial events (solar flares), electromagnetic pulse (EMP), electromagnetic disturbance (EMD), cyber intrusion events can damage the integrity and performance of the MBB-based microgrid system. The resilience in microgrids can be multi-faceted and realized in multiple stages, such as *anticipate*, *withstand*, *recover*, of which the post-event recovery becomes important in cases of both partial and completed system outage. The *anticipate* stage is pre-event, and is largely based on analytics, forecasting, and event prediction for system preparedness, while *withstand* is the ability of a system to maintain functionalities during the event progression[2].

To demonstrate resilience against natural and cyber events, recovery can include an efficient process to safely remove and replace the compromised blocks. This aspect ties to maintainability. Another approach to supporting a resilient recovery is the development of self-healing capabilities of MBB under partial physical damage or cybersecurity breach. This can be achieved by reconfiguring the building blocks for degraded operation and/or restoring the compromised firmware with last-known trusted version.

[2] There can be a finer division and categorization of resilience based on event progression. Our consideration is coarse but general. In this paper, we focus on MBB level functionalities that can be expanded to other frameworks with alternative treatment of resilience.

A resilience event can also affect communication capabilities. To support quick recovery requires the controls to be adaptive to such disruptions in all architectures (central, distributed, hybrid). An example is a fallback option for a master-slave architecture in supervisory control. Other advanced topics are candidates for research and development under the MBB approach.

5. Related Enabling Technologies

MBB concepts leverage many different technologies, from those related to the underlying power electronics to simulation and optimization software to deploy and operate MBB-based designs. This section will provide a high-level discussion of technologies associated with MBB, facilitating the identification of mutually beneficial research and development needs.

Technologies related to power electronics will clearly play a key role in MBB deployment and utilization. As the different building-block components are added or removed from a microgrid, the electrical interconnections and overall energy capabilities will be major considerations for how blocks are reconfigured. Such devices must be able to interface through some common, preferably vendor-agnostic, connection or framework to provide their individual capabilities to the larger microgrid. Technologies that provide electrical protection during these reconfigurations will also enable the MBB concept. Determination on the smallest reasonable "build block unit" is also key here, allowing the building block concept to extend into individual DERs and devices, not just at an interconnection bus level. Concepts such as PEBB and SPSS frameworks explore many of these aspects and will be heavily leveraged.

While the connection of the power electronic and underlying power devices is a key component of MBBs, the communication and control of the building blocks and their aggregate are equally important. Mesh-based and ad-hoc network connection technologies will enable easier integration of various building blocks, especially through a common communication interface. Existing technologies, such as WiFi, WiMAX, and cellular networks, will be key to enabling the exchange of information on the interconnected microgrid building blocks.

With the underlying power electronic capabilities and communications to exchange data, various forms of control will be needed to properly coordinate and operate the building blocks for the microgrid. Underlying technology concepts, such as swarm or flock control approaches, may be needed for MBB components to properly interact and provide a larger capability in the individual microgrid. On a higher level, microgrid controls and hierarchical control technologies and schemes will be needed to coordinate the various devices. Controls that adjust to new capabilities being added will need to be expanded or developed, especially for operational control.

The design and operation of building block-based microgrid systems will require simulation and modeling packages. Coordination and evaluation between different model fidelities of the building blocks (e.g., electromagnetic vs. electromechanical time scales) will leverage co-simulation

technologies, which are covered in detail in the Topic Area #2 white paper. For real-time operations, technology to execute the analysis within operational time constraints will be needed, which may include parallel and cloud computing approaches.
In the past several years, optimization and control technologies for microgrids to operate in a resiliency mode without support from the utility sources have been developed, e.g., [18-19]. These methods are used to optimize the utilization of available generation resources to sustain service to critical load during an extended outage of the utility system. Methods for control and dynamics are also available to steer the microgrid back to nominal values following frequency and voltage deviations due to small or large disturbances [20].

6. Summary and Conclusion – R&D Recommendations for the Next 5 to 10 Years

Commercialization of the proposed MBB is critical for the future of microgrids. At a proper stage of the MBB R&D and field testing, manufacturers and/or spin-offs will be invited to participate in the implementation and technology transfer.

Based on the proposed vision and roadmap, the following recommendations for the future R&D are made:

R1: MBB Implementation and Field Test with Integration of Conversion, Communication, and Control

Priority: High

Short Term: 1-3 years

Task: Based on the results of conceptual studies that have been conducted, the next stage of MBB development should include the practical design, implementation, and field test at a realistic industry environment. A representative case is a microgrid with PCC to a distribution system with, say, 12.47 kV feeders. The microgrid can be small but it should be at a MW level size. MBB should include major capabilities as shown in Figures 1 and 2, e.g., integration of power processing, communication, and control as well as interfaces with at least one renewable generation with storage and one load node.

Impact: Demonstration of the MBB technology in an industry environment facilitates future deployment of the MBB-based microgrids. Successful implementation and field test with participation from manufacturers will provide a good market assessment for future commercialization of the MBB technology.

R2: Development of MBB Low Voltage at-Scale Validation Platform

Priority: High

Short Term: 1-3 years

Task: A low voltage test setup for demonstrating MBB use cases is envisaged using connectivity between various HIL, at-scale CHIL devices to demonstrate the dynamic and transient interaction in the microgrids.

Impact: The MBB concept results in standardization of MG architecture, thereby reducing cost and engineering efforts. To demonstrate and validate MBB features (maintainability, modularity, flexibility, and resilience), a high-fidelity evaluation environment is necessary.

R3: MBB Design and Validation to Demonstrate MBB Features in Emulated Real-World Environment

Priority: High

Medium Term: 3-5 years

Task: At-scale validation environment developed will be leveraged to design advanced controls for MBBs and validate features, such as maintainability and modularity, using tightly interconnected control nodes, in conjunction with stackable MBBs.

Impact: An iterative mitigation of the risks through traditional analytical approaches will result in a slow and conservative path for innovation. Alternatively, a disruptive approach such as at-scale evaluation using HIL of MBB configurations based on real world data, and future pairing of technologies for MBB will accelerate innovation.

R4: MBB-Based Microgrid Implementation and Field Test

Priority: High

Medium Term: 3-5 years

Task: Based on the results of MBB demonstration and field test, this task will involve implementation and field testing of an MBB-based microgrid in the distribution system environment. The implementation and testing should demonstrate the power conversion, communication, and control capabilities in an operational environment under a utility-connected or a resiliency mode.

Impact: Successful implementation and testing of an MBB-based microgrid is an important milestone to demonstrate the operations and cost-benefits of the MBB-enabled modular design, implementation, and maintenance. It is expected that the demonstration will facilitate large-scale deployment of MBB-based microgrids by the industry, government, and communities.

R5: Development of Building Block Architectural Approaches

Priority: Medium

Short Term: 1-3 years

Task: Options of the MBB architectural design need to be developed and evaluated. They include centralized or decentralized (distributed) MBB with the associated power conversion, communication, and control capabilities. It is expected that the architecture will depend on the functional and reliability requirements, the application environment, and resources available.

Impact: The result of this R&D task is an enabler for solving microgrid architectural challenges. The MBB architecture is critical to enhance the modularity and reliability and reduce the cost. Well designed and tested architecture options facilitate the efficiency of microgrid development and reduce the cost and effort.

R6: Modular, Scalable Integrated Software Platform with Real-Time Control Capabilities

Priority: Medium

Short Term: 1-3 years

Task: To support the integrated power conversion, communication, and control and other real-time functions, the MBB needs a software platform for operation and control in a real-time environment. The capabilities to be provided include acquisition of data and measurements, delivery of control commands, as well as data sharing among nodes and MBB.

Impact: Modularity of the MBB design applies to the software design, enhancing the software reliability and ease of maintenance. Scalability enables the large-scale deployment of the MBB-based microgrids.

R7: Modular, Scalable Design and Implementation of MBB Communication and Control Systems

Priority: Medium

Short Term: 1-3 years

Task: Practical implementation of the MBB depends on reliable and cost-effective communication and control systems. The R&D work here is to consider realistic operating environments of microgrids and develop corresponding communication and control systems that meet the functional and performance requirements. Control systems ensure that the MBB-based microgrids maintain stability under a wide range of operating conditions. Communication systems meet the cyber security and privacy as well as real time performance requirements.

Impact: Well tested and cost-effective communication and control systems enhance the performance and reduce costs for MBB-based microgrids.

R8: Smart Reconfigurable System for Any Microgrid Systems

Priority: Medium

Long Term: 5-10 years

Task: The R&D work is to provide the reconfiguration capability for the MBB-based microgrids. A smart reconfigurable system can be adapted for various microgrid conditions and scenarios. The reconfiguration capabilities apply to power conversion, communication, and control systems for different scenarios of generation and load resources.

Impact: Smart reconfigurable systems rely on increased modularity and flexibility of the MBB design. As microgrid conditions change, the power conversion, communication, and control systems need to meet the performance required for a wider range of scenarios.

R9: Demonstration of Market Participation in a Distribution System Environment

Priority: Medium

Medium Term: 3-5 years

Task: The functions of MBB are expanded to support market functions in a wholesale or retail market environment. MBB needs to optimize the trading decision options for the microgrid as a supplier or demand for energy and ancillary services. The MBB needs to provide the control and communication capabilities for the market-related functions.

Impact: The market functions are revenue generating activities for the MBB-based microgrids. The MBB market function is to perform optimization of the transactive energy or bidding activities based on the available generation and load resources.

The high priority recommendations are *foundational* technologies upon which the medium priority items will be built. If the medium recommendations are not pursued, the MBB performance, design features and capabilities, and use cases may not be fully achieved or demonstrated.

In addition to the R&D recommendations above, several other subjects are of interest: Plug-and play features for reducing the balance of system costs, Automation of energy flow between multiple sources and loads with real-time optimization, Integration of AC-DC technologies, protection technologies into a microgrid application, Hardware agnostic control platform for bulk grid systems, Cohesive integration of virtual power plants, Virtual storage, and On-line load estimation and prediction for achieving system level goals within the framework of building blocks. Microgrid protection is an on-going R&D area where new concepts and technologies have been developed such as differential protection. Protection functions embedded in microgrid building blocks should be investigated; for example, how the communication capabilities can be used for protection functions.

The R&D recommendations in this paper are focused on areas where we believe DOE funding is critical and justified. MBB is a novel, foundational technology upon which commercial products and tools can be built. The potential impact on the future large-scale deployment of microgrids is high. Without leadership and initiatives from DOE, it is difficult for the industry or manufacturers to invest in the development of fundamental technologies.

For practical deployment of MBB technologies, partnership with industry, national laboratories, and academic institutions are important to take advantage of the best talents and available resources. Future commercialization of the MBB-based technologies will require field testing and validation from power grids, especially distribution utility systems.

References

[1] T. Ericsen and A. Tucker, “Power Electronics Building Blocks and Potential Power Modulator Applications” IEEE 23rd International Power Modulator Symp., New York, 1998, pp. 12-15.

[2] IEEE Power Engineering Society, *Power Electronics Building Block (PEBB) Concepts*, IEEE Publication 04TP170, 2004.

[3] "IEEE Guide for Control Architecture for High Power Electronics (1 MW and Greater) Used in Electric Power Transmission and Distribution Systems," *IEEE Std 1676-2010*, vol., no., pp.1-47, 11 Feb. 2011.

[4] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The Future Renewable Electric Energy Delivery and Management (FREEDM) System: The Energy Internet," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133-148, 2011.

[5] J. E. Huber and J. W. Kolar, “Applicability of Solid-State Transformers in Today’s and Future Distribution Grids,” *IEEE Trans. on Smart Grid*, 10(1), 317–326, 2019.

[6] *Solid State Power Substation Technology Roadmap*, U.S. DOE Office of Electricity Transformer Resilience and Advanced Components (TRAC) Program, June 2020.

[7] D. Boroyevich, I. Cvetkovic, R. Burgos, and D. Dong, “Intergrid: A Future Electronic Energy Network?,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 1, no. 3, pp. 127-138, 2013.

[8] K. Bunker, S. Doig, K. Hawley, and J. Morris, *Renewable Microgrids: Profiles from Islands and Remote Communities Across the Globe*; Technical Report; Rocky Mountain Institute and Carbon War Room: Basalt, CO, USA, 2015.

[9] J. Wild, V. Boutin, P. Barton, and L. Haines, *Microgrid Benefits and Example Projects*, White Paper, Schneider Electric, 2016.

[10] A. Pratt and T. Bialek, *Borrego Springs Community Microgrid*, 2019. Available online: https://www.nrel.gov/docs/fy19osti/74477.pdf (accessed on Feb. 2, 2021).

[11] C. Marnay, H. Aki, K. Hirose, A. Kwasinski, S. Ogura, and T. Shinji, “Japan’s Pivot to Resilience: How Two Microgrids Fared after the 2011 Earthquake,” *IEEE Power Energy Mag*. 2015, 13, 44–57.

[12] J. Hamilton, M. Negnevitsky, X. Wang, and S. Lyden, “High Penetration Renewable Generation within Australian Isolated and Remote Power Systems,” *Energy 2019*, 168, 684–692.

[13] R. Allen, D. Brutkoski, D. Farnsworth, and P. Larsen, *Sustainable Energy Solutions for Rural Alaska*, Technical Report, Lawrence Berkeley National Laboratory, Washington, DC, USA, 2016.

[14] G. Holdmann, R. Wies, and J. Vandermeer, “Renewable Energy Integration in Alaska’s Remote Islanded Microgrids: Economic Drivers, Technical Strategies, Technological Niche Development, and Policy Implications,” *Proceedings of the IEEE*, 2019, 107, 1820–1837.

[15] M. Farrokhabadi, C. A. Cañizares, J. W. Simpson-Porco, E. Nasr, L. Fan, P. A. Mendoza-Araya, R. Tonkoski, U. Tamrakar, N. Hatziargyriou, and D. Lagos, et al., “Microgrid Stability Definitions, Analysis, and Examples,” *IEEE Trans. Power Syst*., 2020, 35, 13–29.

[16] S. Hoffman and C. Carmichael, *Nine Lessons Learned from Successful Community Microgrids*, Technical Report; Hoffman Power Consulting: Palo Alto, CA, USA, 2020.

[17] National Renewable Energy Laboratory, *Phase I Microgrid Cost Study: Data Collection and Analysis of Microgrid Costs in the United States*, NREL Technical Report 5D00-67821, Oct. 2018.

[18] H. Gao, Y. Chen, Y. Xu, and C. C. Liu, "Resiliency-Oriented Critical Load Restoration Using Microgrids in Distribution Systems," *IEEE Trans. Smart Grid*, Nov. 2016, pp. 2837 - 2848.

[19] Y. Xu, C. C. Liu, K. Schneider, F. Tuffner, and D. Ton, "Microgrids for Service Restoration to Critical Load in a Resilient Distribution System," *IEEE Trans. Smart Grid*, Jan 2018, pp. 426-437.

[20] L. A. Lee, C. C. Liu, Y. Xu, K. Schneider, F. Tuffner, K. Mo, and D. Ton, "Dynamics and Control of Microgrids as a Resiliency Source," *Int. Trans. Electrical Energy Systems,* Sept. 2020. https://doi.org/10.1002/2050-7038.12610