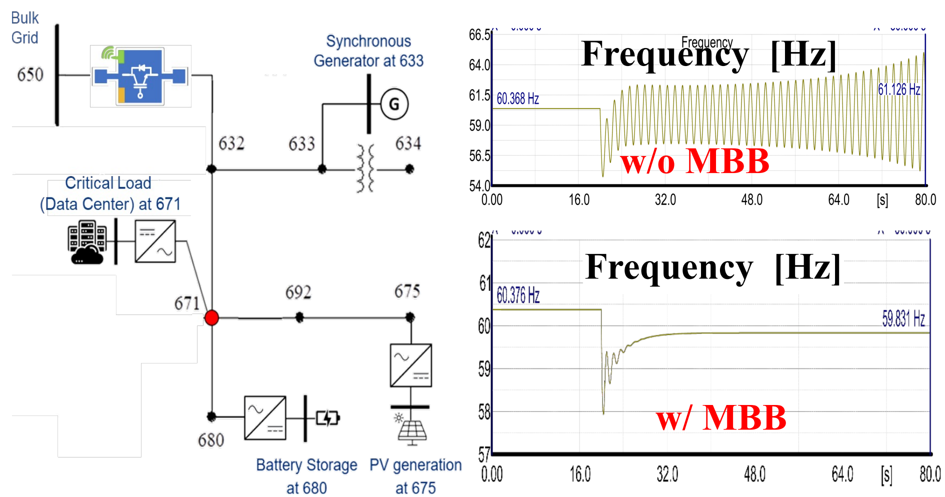
Enabling a Decarbonized, Equitable Grid with Microgrid Building Blocks (MBB)

Objectives & Outcomes

(1) Modular/standard design of MBB to reduce cost and time of microgrid deployment, (2) Development of a scalable MBB prototype for a wide range of microgrids, (3) Modular and standard interfaces between MBB and utility systems as well as generation, load, and controls, (4) Low-cost standard approach to affordability for widespread equitable deployment of microgrids.

MBB Stabilizing Microgrid with High Penetration PV



Technical Scope

- MBB Design and Prototype Development
- Modeling and Simulation of MBB, Performance Requirements and Evaluation
- MBB Modularization, Standardization, Validation and Testing
- MBB Demonstration
- Planning of Technology Transfer and Commercialization

Funding Summary ($3.4 M)

FY22 authorized	FY23 requested	FY24 requested
$1.15 M	$1.15 M	$1.1 M

Project Duration Mar 31, 2022 - Mar 31, 2025
Lead: Virginia Tech (VT)
Partners: PNNL, ORNL, NREL
Advisor: ABB

2022 DoE Microgrid Program R&D Peer Review

Enabling a Decarbonized, Equitable Grid with Microgrid Building Blocks

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Kevin Schneider, PNNL (Co-Lead)
Madhu Chinthavali, ORNL (Co-Lead)
Rob Hovsapian, NREL (Co-Lead)

Team Members

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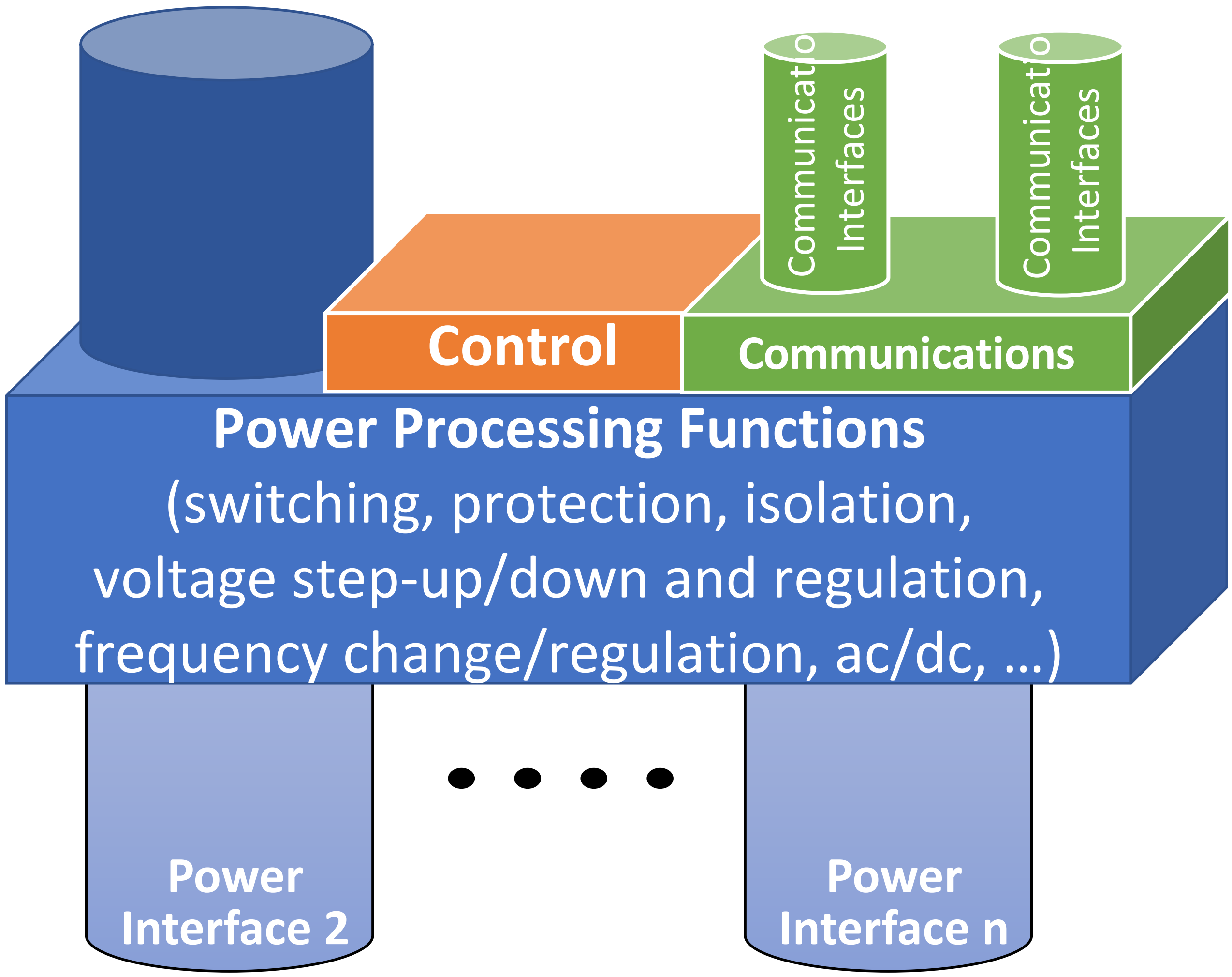
- **ORNL:** Misael Martinez Montejano, Joao Pereira Pinto
- **NREL:** Sayonsom Chanda, Manish Mohanpurkar

Microgrid Building Block (MBB): Concept

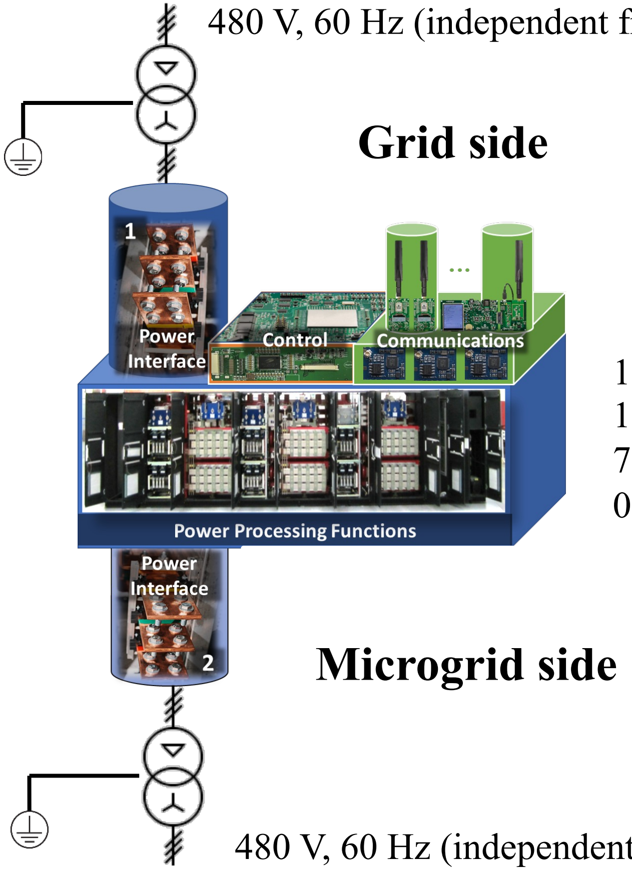


Power Conversion Module of MBB

Functional Requirements:

- Design for Multi-MW MBB (by simulation)
- Scaled-down 100 kW prototype development
- Bidirectional power flow
- Decoupled input-output side/control

480 V, 60 Hz (independent from the microgrid side)



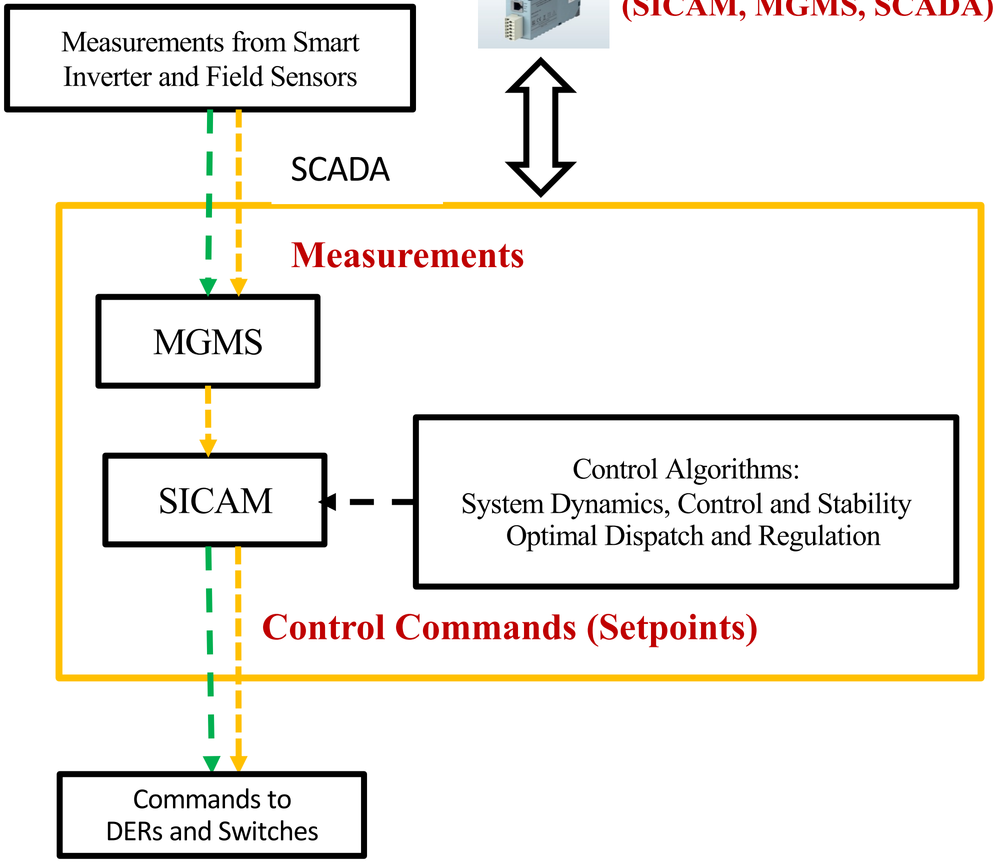
120 kVA
100 kW
75 kVAr (cosϕ = 0.8)

480 V, 60 Hz (independent from the grid side)

Control Module of MBB

- **Functional Requirements:**
  - Dynamics and control related with DER synchronization, load restoration and system stability
  - Optimal dispatch to manage load generation balance and minimize curtailment
  - Restoration planning using system topology and situational awareness to pick up critical loads and maximize restoration duration
  - Regulation and dispatch as a MGC – serves critical load as a priority
  - Faults and other disturbances – For example, 3-phase fault at generator busbar

Controller: CP-8050 (SICAM, MGMS, SCADA)



Communication Module of MBB

- **Functional Requirements:**
  - Data/measurements acquired from field devices (DERs, Loads, switches, etc.) must be transmitted securely to the microgrid controller, and control commands should be delivered securely to field devices
  - Low communication latency to maintain microgrid stability
  - Communication protocol to be decided based on discussions with PNNL, ORNL, and NREL
  - Data acquisition and remote control

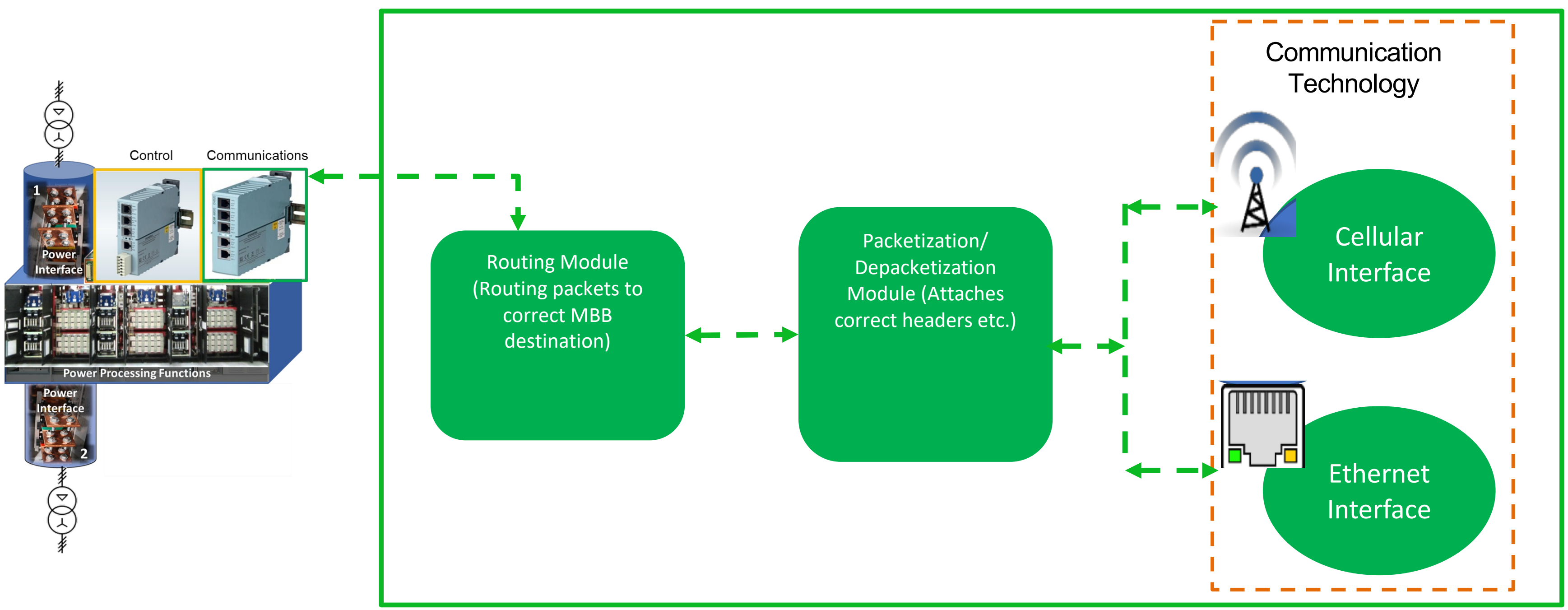
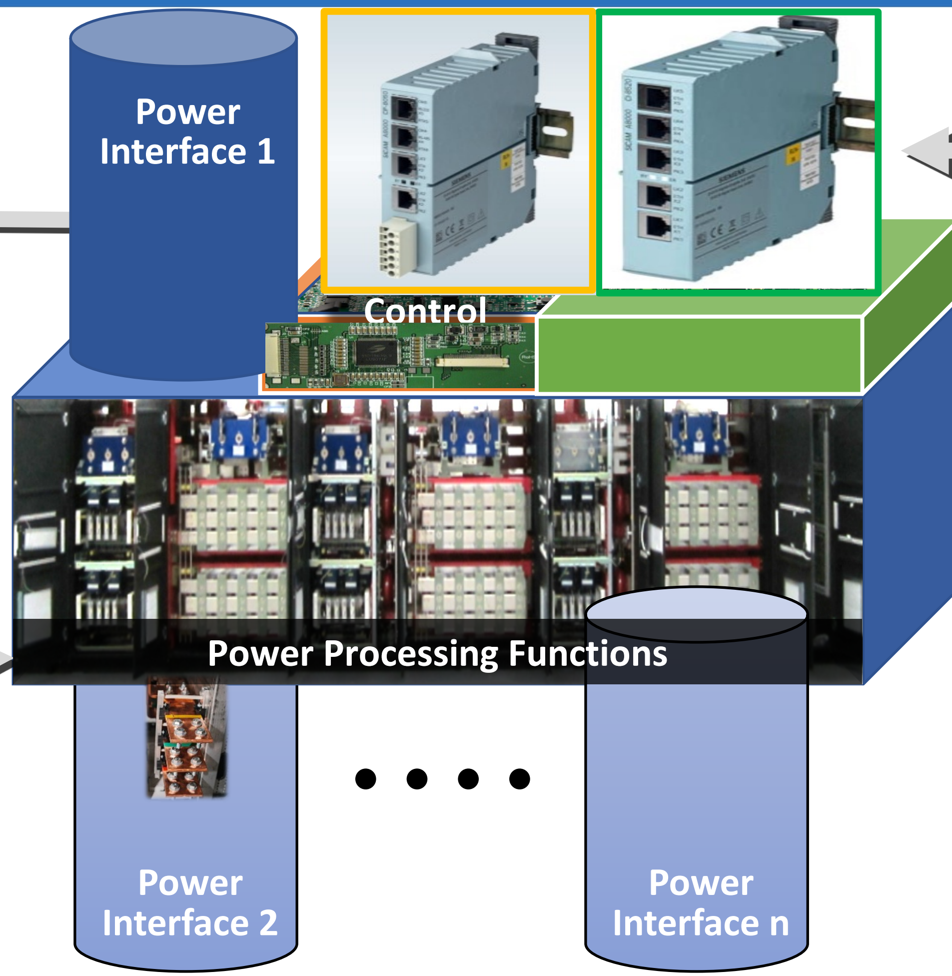


Illustration of MBB Prototype

Digital controllers (hierarchical control)

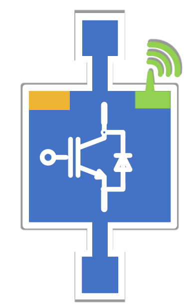
- **High-level control** (Microgrid controller)
- **Mid-level control** (Control of terminal waveforms in Power Processing Functions)
- **Low-level control** (High-frequency semiconductor device switching control)

Customized commercial power stage



Communication boards

→



Simplified representation

Goals for MBBs

- (G1) In the environment with high penetration of renewables and storage, a common scenario is that generation and load resources are widely available. MBBs provide integrated microgrid capabilities, including power conversion, communication, and control, to facilitate widespread deployment of microgrids and enhance resilience.
- (G2) MBB is to facilitate standard/modular design of microgrids and be able to address different levels of capability microgrids will need to perform. The proposed MBB will be customer-focused, i.e., MBBs will be designed to handle a wide range of needs ranging from simple microgrids that are just solar and energy storage to fully capable microgrids with the ability to manage different levels of DERs.
- (G3) MBB will enable the deployment of modular microgrids that can be tailored for specific communities and operational needs. This includes enabling the deployment of zero emission microgrids as well as microgrids that address the specific needs of rural communities.
- (G4) MBB is a critical technology to meet the goals of DOE Microgrid program, including (1) Microgrids act as a point of aggregation for DERs, and (2) Decrease microgrid capital costs while reducing project development, construction, and commissioning times.

MBB Features

The MBB goals lead to these features:

(A1) MBBs integrate microgrid capabilities, power conversion, control, and communications, as a systemwide controller with advanced control and operation capabilities.
(A2) MBB is an enabler for microgrids to serve as an aggregation point for DERs with microgrid system operator functionalities.
(A3) Based on the building block concept, MBB has the modularity to meet the needs of microgrids with different levels of capabilities.
(A4) MBB has the flexibility to meet different levels of affordability, including the specific needs for rural communities.
(A5) MBB reduces the cost of development and deployment of microgrids; an essential feature of modularized design of the MBB is to avoid costly customized engineering for each new microgrid.
(A6) MBB has the dynamic decoupling capability between the microgrid with the utility grid.

Use Cases and Demonstrations

(UC1) Grid connected mode: MBB controls the power flow and participate in electric energy trading and ancillary service activities (e.g., voltage control in a distribution system) through the hosting distribution system (A1, A2, A6), (A5: MBB helps generate new revenues)

(UC2) Resiliency (islanded) mode: MBB with high level DERs sustains critical load and maintains system stability under extreme conditions. MBB coordinates grid forming capabilities for the entire microgrid. (A1-A2)

(UC3) Supporting system restoration: MBB provides blackstart power from the microgrid to the bulk system. (A1-A2) (A5, blackstart as an ancillary service – a new source of revenue)

Commonly Available Functions

Following functions were commonly available in the MGCs surveyed*

- Economic dispatch for grid-connected and islanded modes (9),
- Peak shaving (10),
- Loss minimization (8),
- Reserve management (9),
- Two-way communication (8),
- Emergency load shedding (10),
- Islanding (9),
- Resynchronization (8),
- Uninterruptible power supply (UPS) function for critical load (9), and
- Provision of requested support (9).

All of these functions rely on an efficient two-way communication system.

*Guodong Liu, Michael R. Starke, Drew Herron, "Microgrid Controller and Advanced Distribution Management System Survey Report." US DOE, Oak Ridge National Laboratory, 2016.

Less Common Functions

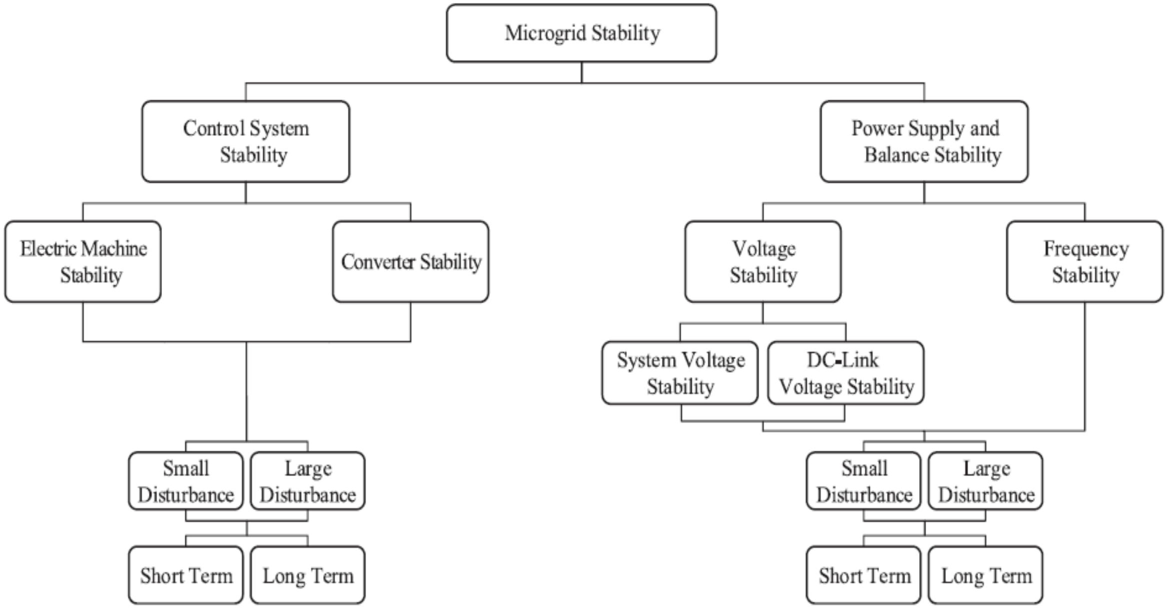
The following functions were not commonly available in the MGCs surveyed*

- Conservation voltage reduction (3),
- State estimation (5),
- Contingency analysis (6),
- Electrical vehicle management (4),
- Transient device-level control (4),
- Low-frequency ride-through (3),
- Low-voltage ride-through (3),
- Severe weather forecast (3), and
- Transmission and distribution congestion management (3).

Issue: Communication latency impact on control of DERs?

*Guodong Liu, Michael R. Starke, Drew Herron, "Microgrid Controller and Advanced Distribution Management System Survey Report." US DOE, Oak Ridge National Laboratory, 2016.

Stability Definitions for Microgrids



Category	Control System Stability		Power Supply and Balance Stability	
Subcategory	Electric Machine Stability	Converter Stability	Voltage Stability	Frequency Stability
Root Cause	Poor controller tuning.	Poor controller tuning, PLL bandwidth, PLL synchronization failure, harmonic instability.	DERs power limits, inadequate reactive power supply, poor reactive power sharing, load voltage sensitivities, dc-link capacitor.	DERs active power limits, inadequate active power supply, poor active power sharing.
Manifestation	Undamped oscillations, aperiodic voltage and/or frequency increase/decrease.	Undamped oscillations, low steady-state voltages, high-frequency oscillations.	Low steady-state voltages, large power swings, high dc-link voltage ripples.	High rate of change of frequency, low steady-state frequency, large power and frequency swings.

*M. Farrokhabadi *et al.*, "Microgrid Stability Definitions, Analysis, and Examples," *IEEE Transactions on Power Systems*, vol. 35, no. 1, pp. 13-29, Jan. 2020.

Functions of the Proposed MBB

Transient Device-Level Control

- Enhancing MG *transient stability* (large disturbances including switching, faults, etc.)
- State- or output-feedback control
- Different time scales of SG and IBRs

Communication

- Communication delays to be less than the *critical latency* to maintain MGs transient stability

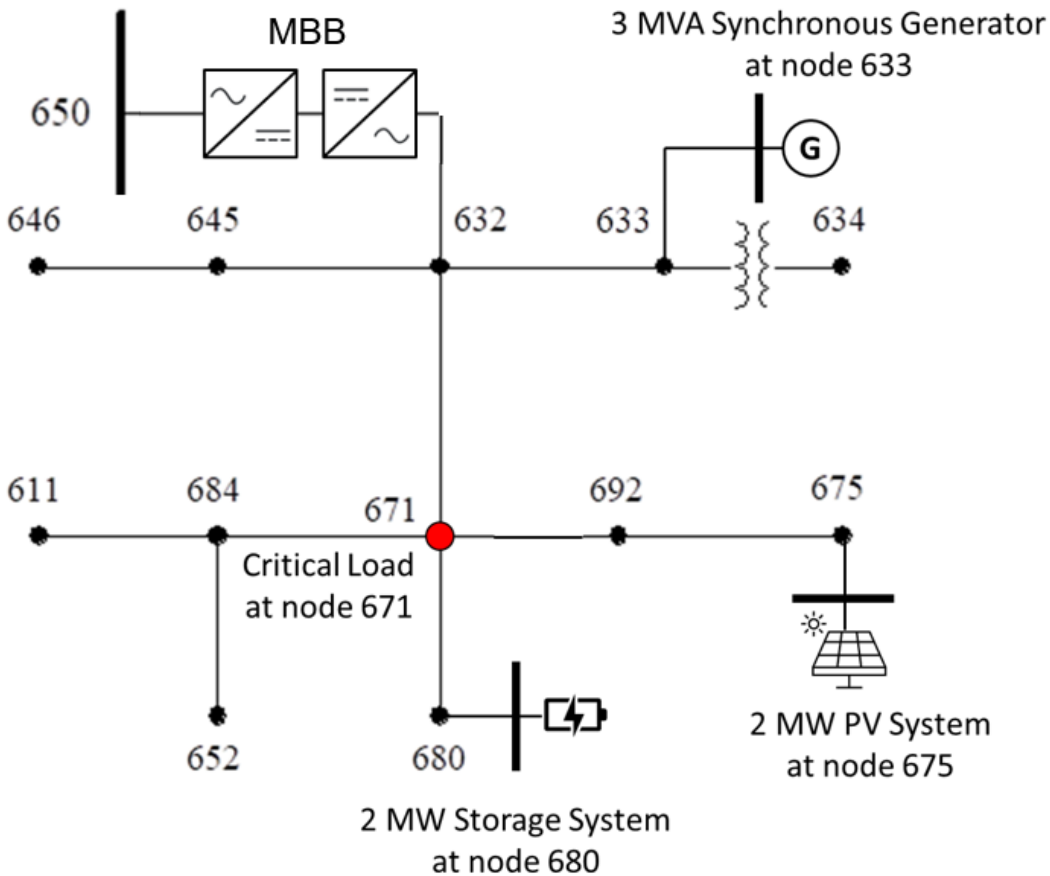
Situational Awareness

- Accurate demand and generation estimation such as with Net Metered Customers
- Voltage regulating equipment state estimation with limited measurements
- *Optimal microgrid-restoration* considering obtained estimates
- Supporting bulk grid blackstart

Optimal Power Flow

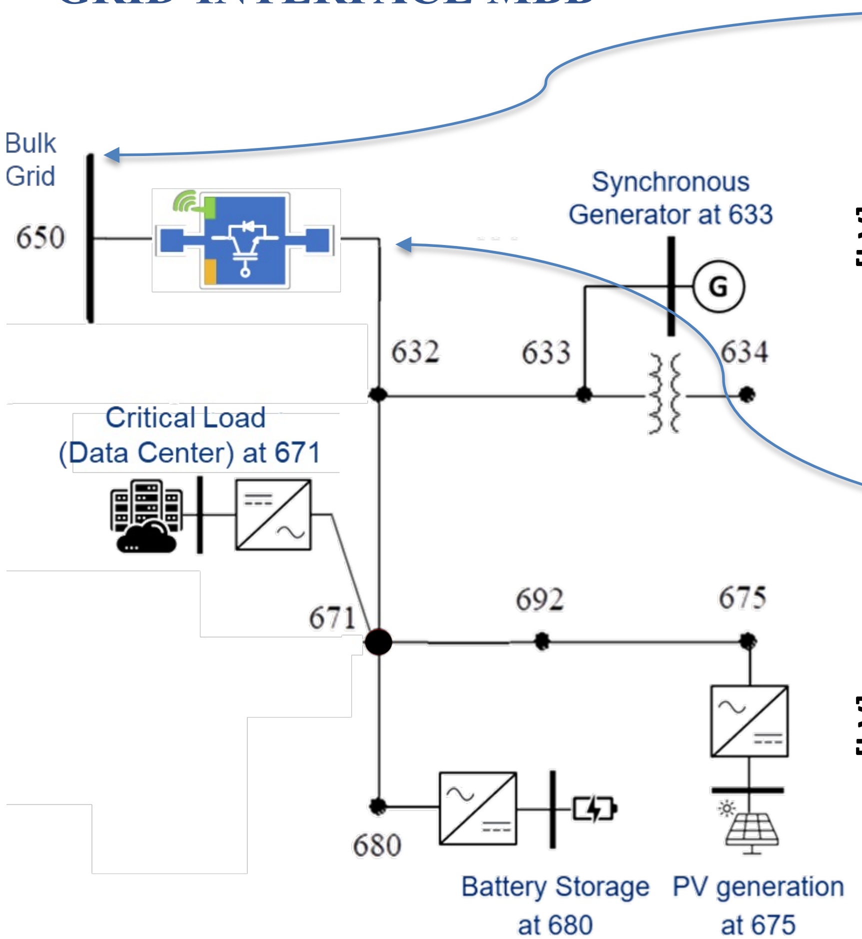
- 3-phase *unbalanced optimal power flow* considering DER intermittency
- Integrated P and Q dispatch for different types of DERs
- Optimal AVR and capacitor bank control

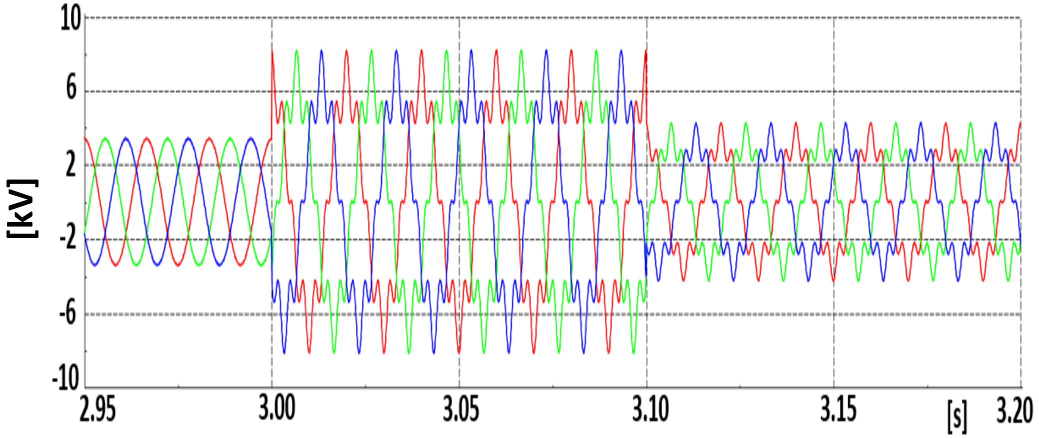
IEEE 13-Node Test System as a *Microgrid*

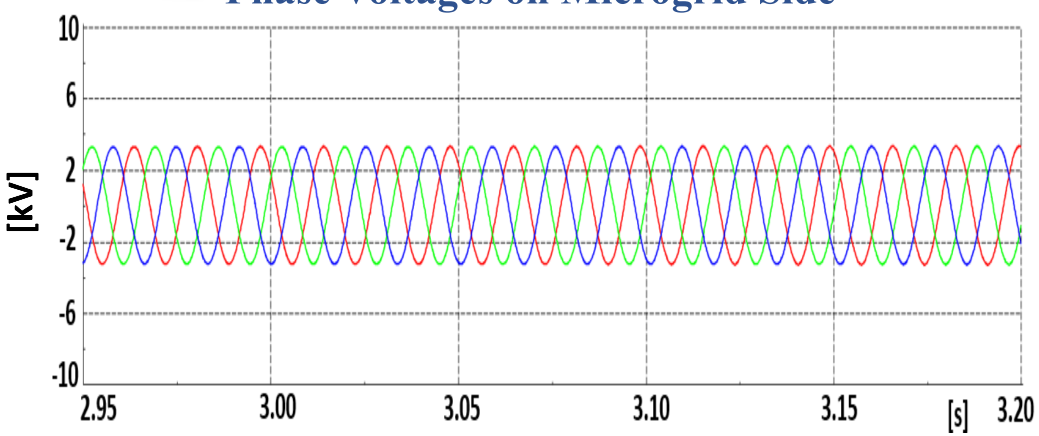


Feasibility Study: Dynamic Decoupling

GRID-INTERFACE MBB

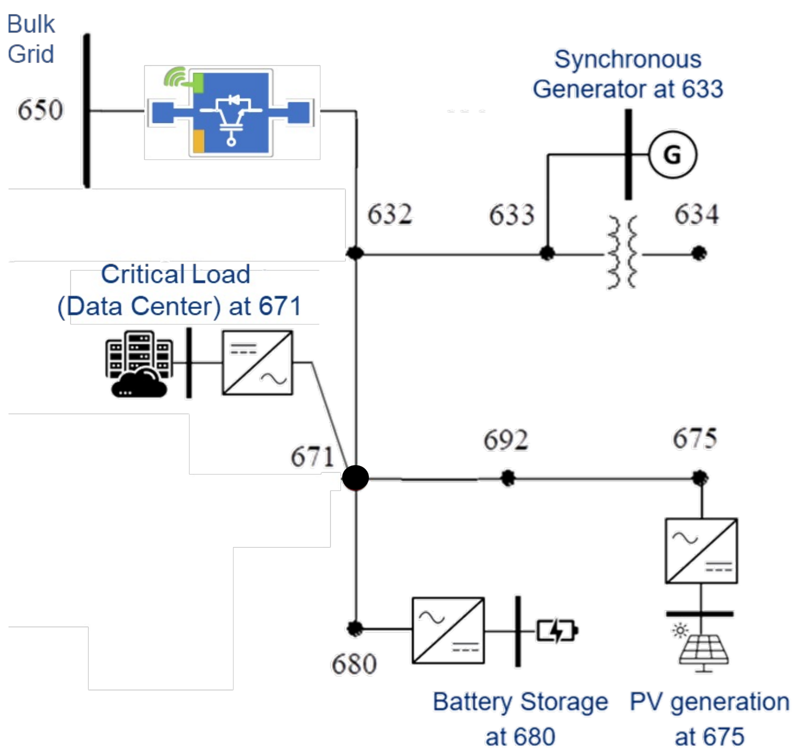


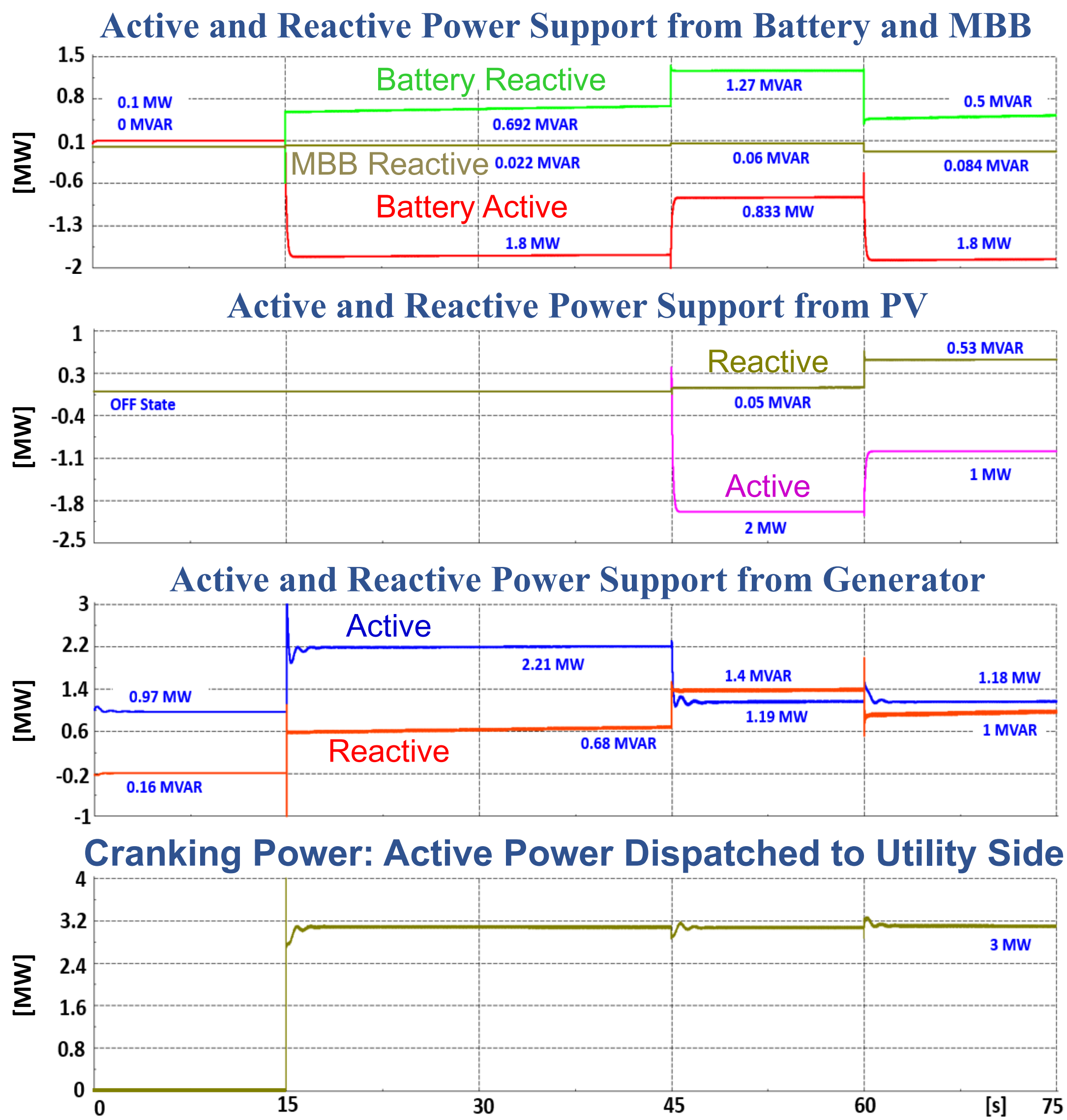




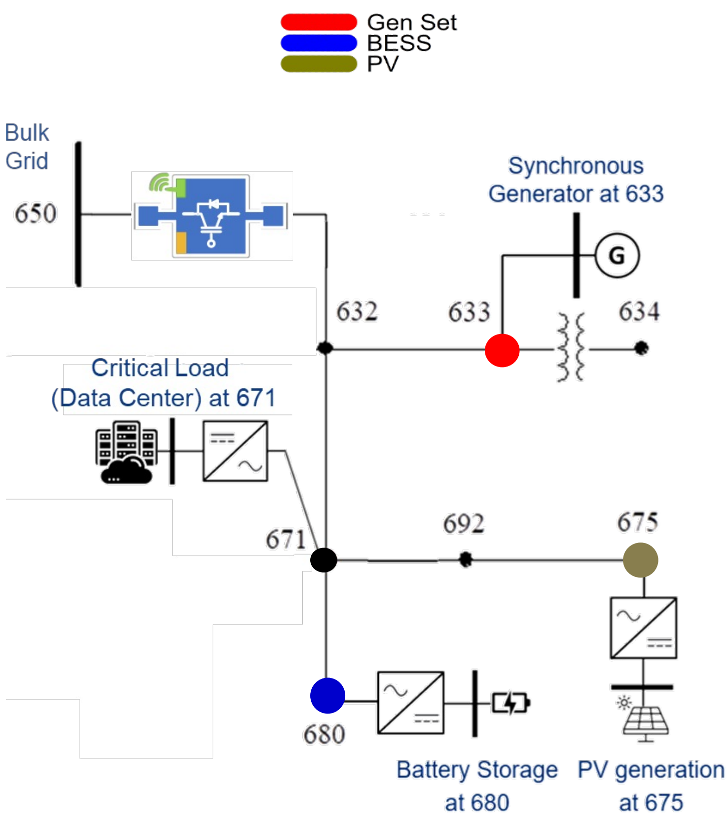
Feasibility Study: Providing Cranking Power to the Bulk Grid Using MBB Optimal Dispatch Functions

At 15 s utility requests 3 MW to be dispatched from the microgrid.

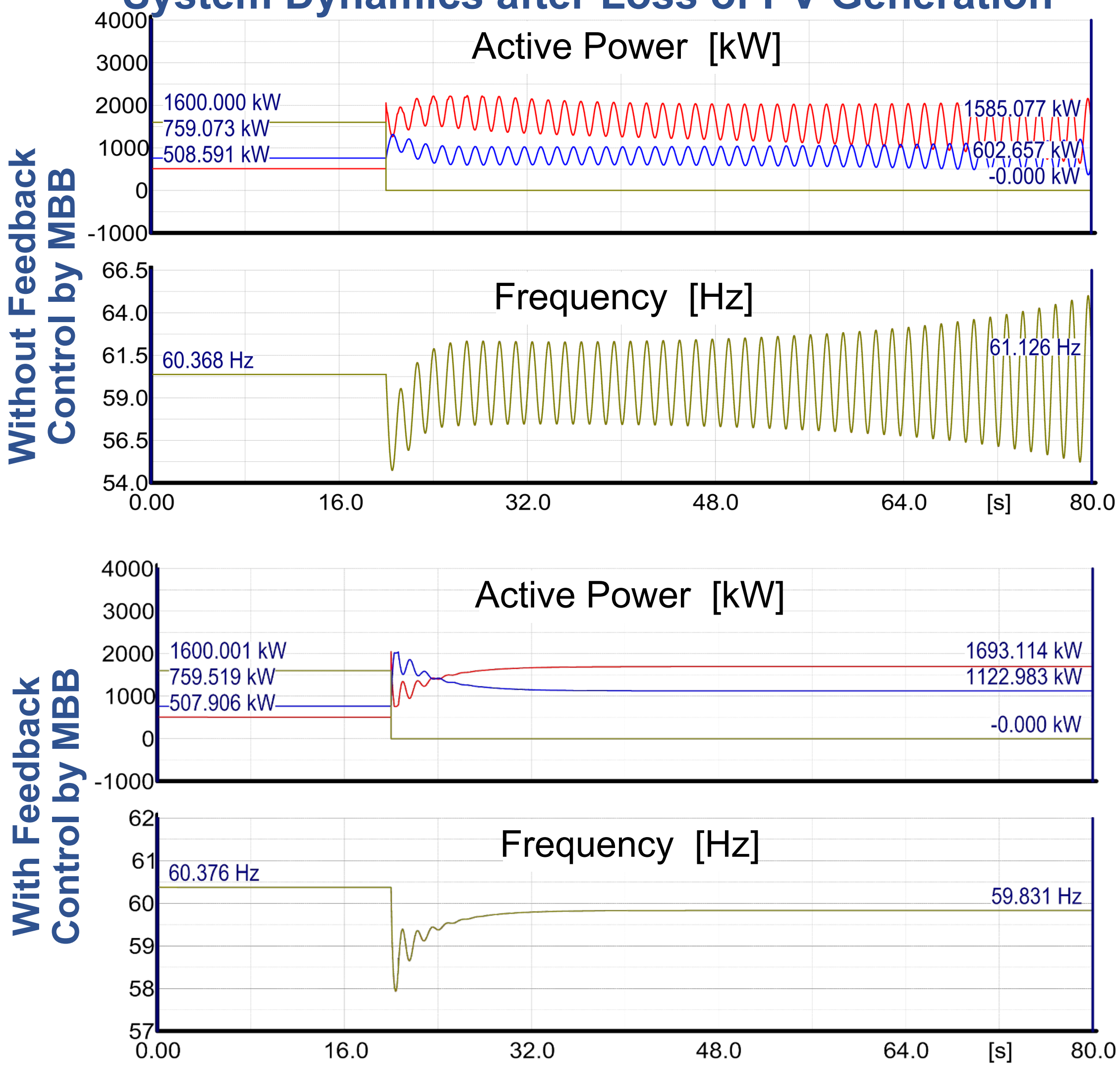




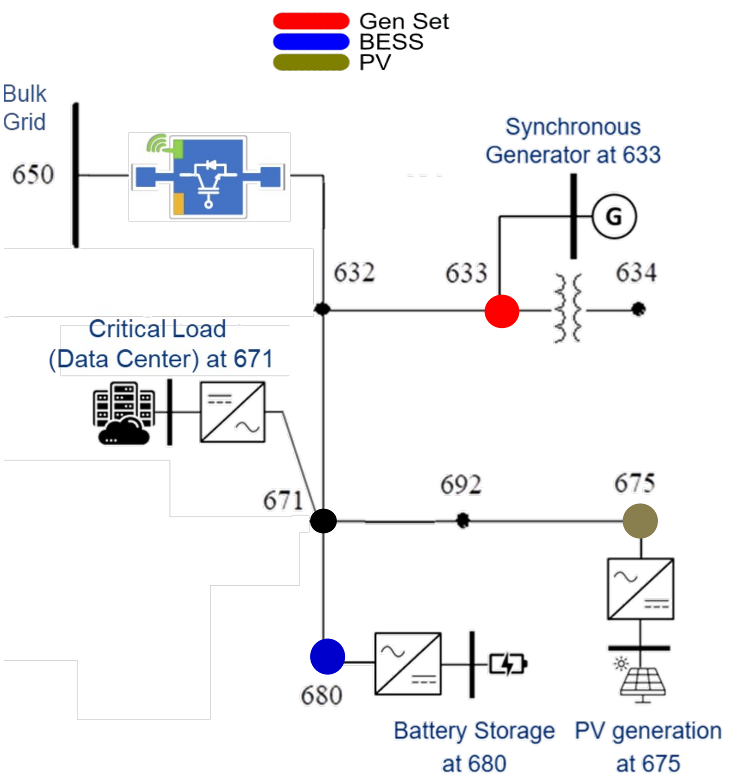
Feasibility Study: Stabilizing the Microgrid under High Penetration of PV Using MBB Control



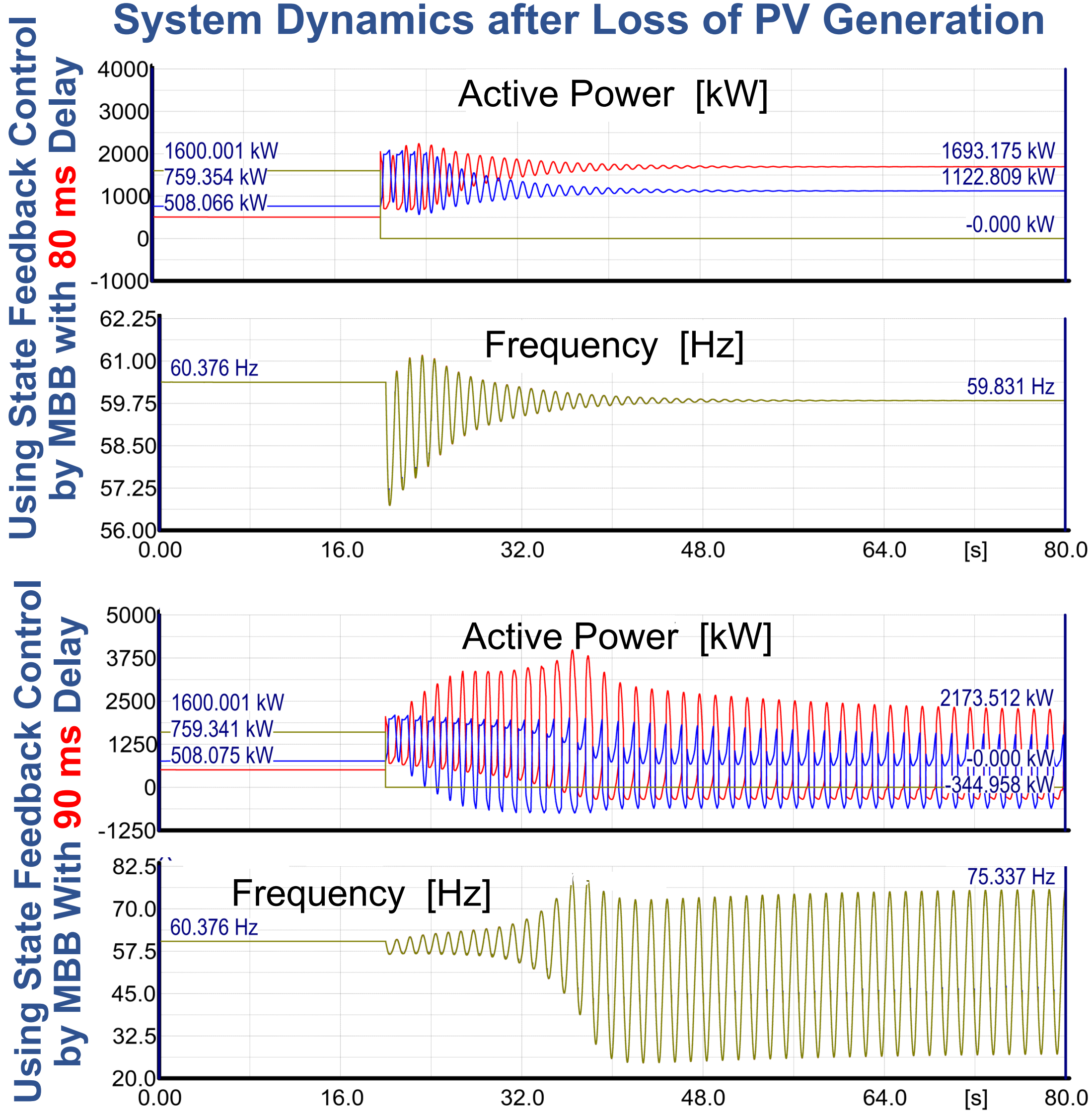
System Dynamics after Loss of PV Generation



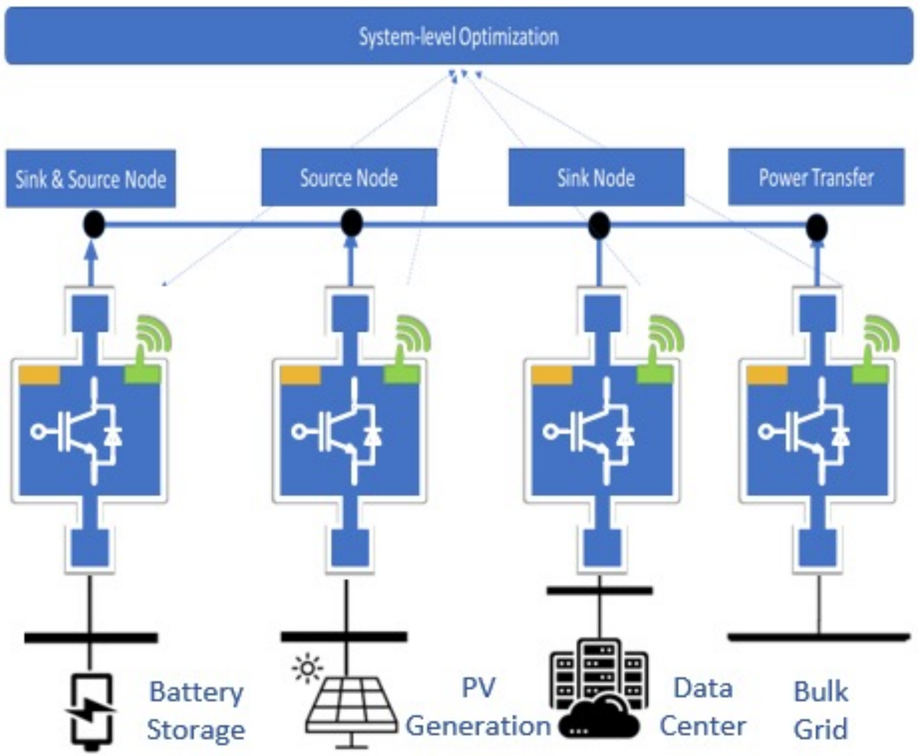
Feasibility Study: Communication Latency and Instability



System Dynamics after Loss of PV Generation



System Architecture with MBB

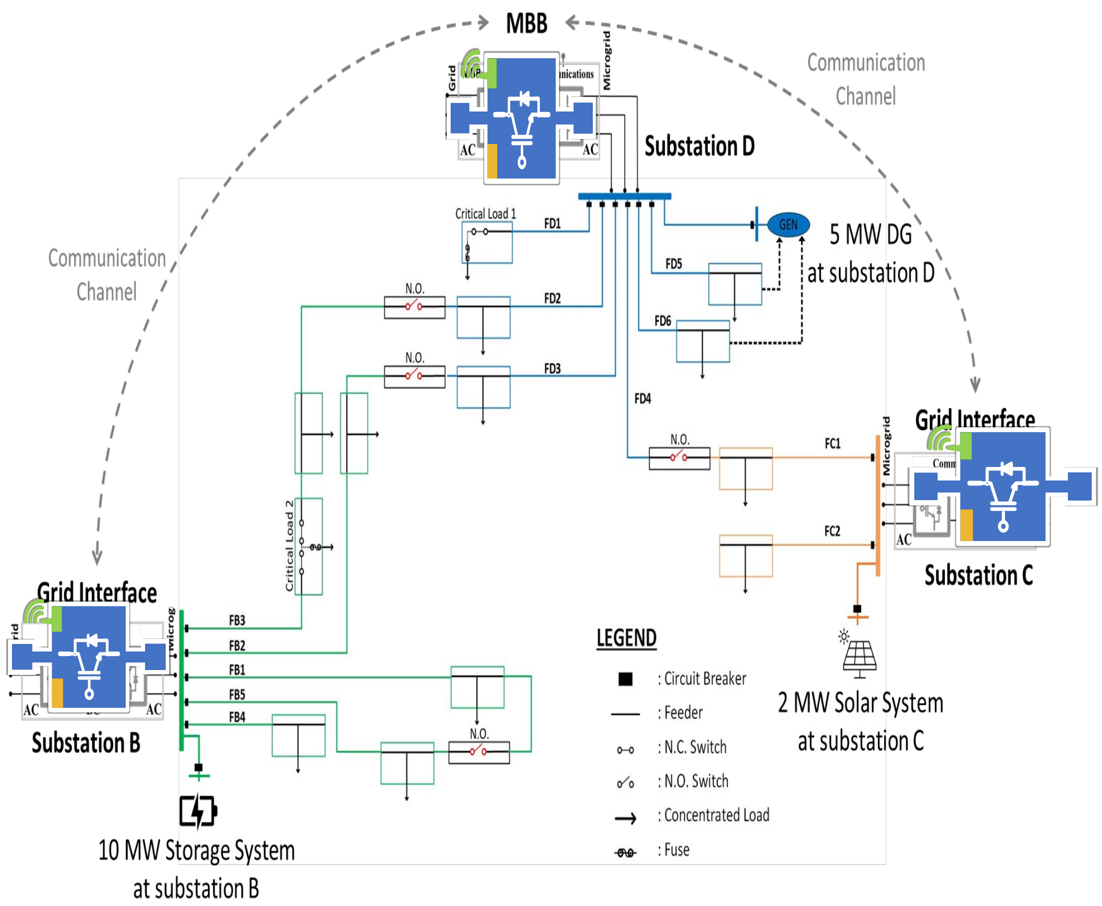


To obtain a simple system architecture using MBB:

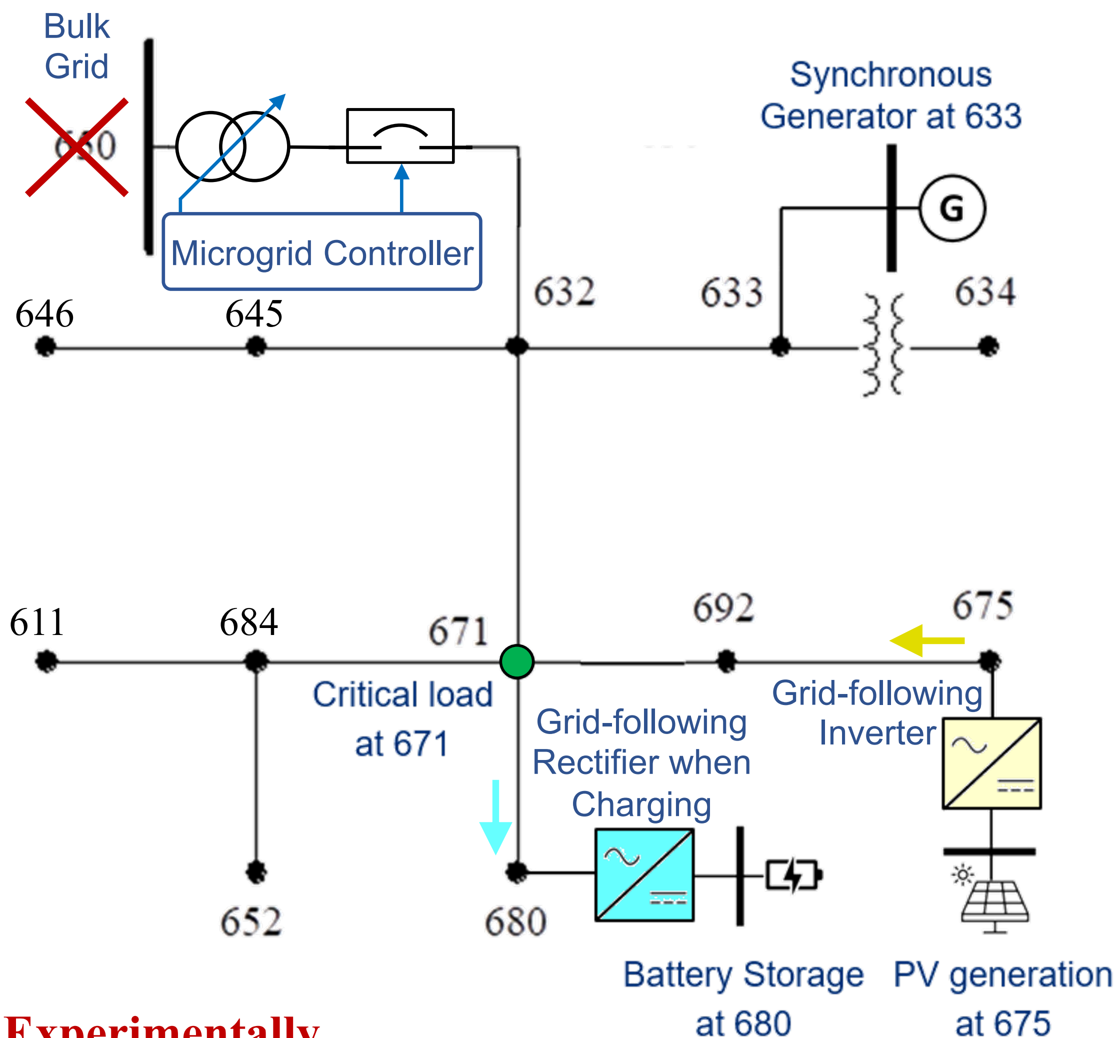
- Providing cohesive interfaces with source nodes, sink nodes, as well as the bulk grid
- Add DERs and load to the relevant nodes
- Simplify the MBB representation

Microgrid with Multiple MBB Grid Interfaces

Based on the operating conditions, one of the MBBs will assume "lead" role and will be responsible for microgrid controller functionalities



Example: Instability after Islanding with State-of-the-Art Microgrid



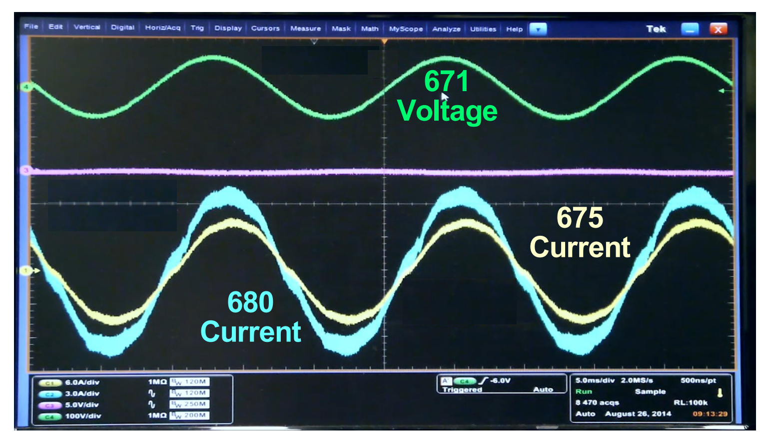
Experimentally recorded inverter↔rectifier instability with weak grid:

Grid-connected mode

- Synchronous Generator and all Inverters and Rectifiers follow the "stiff" bulk grid.

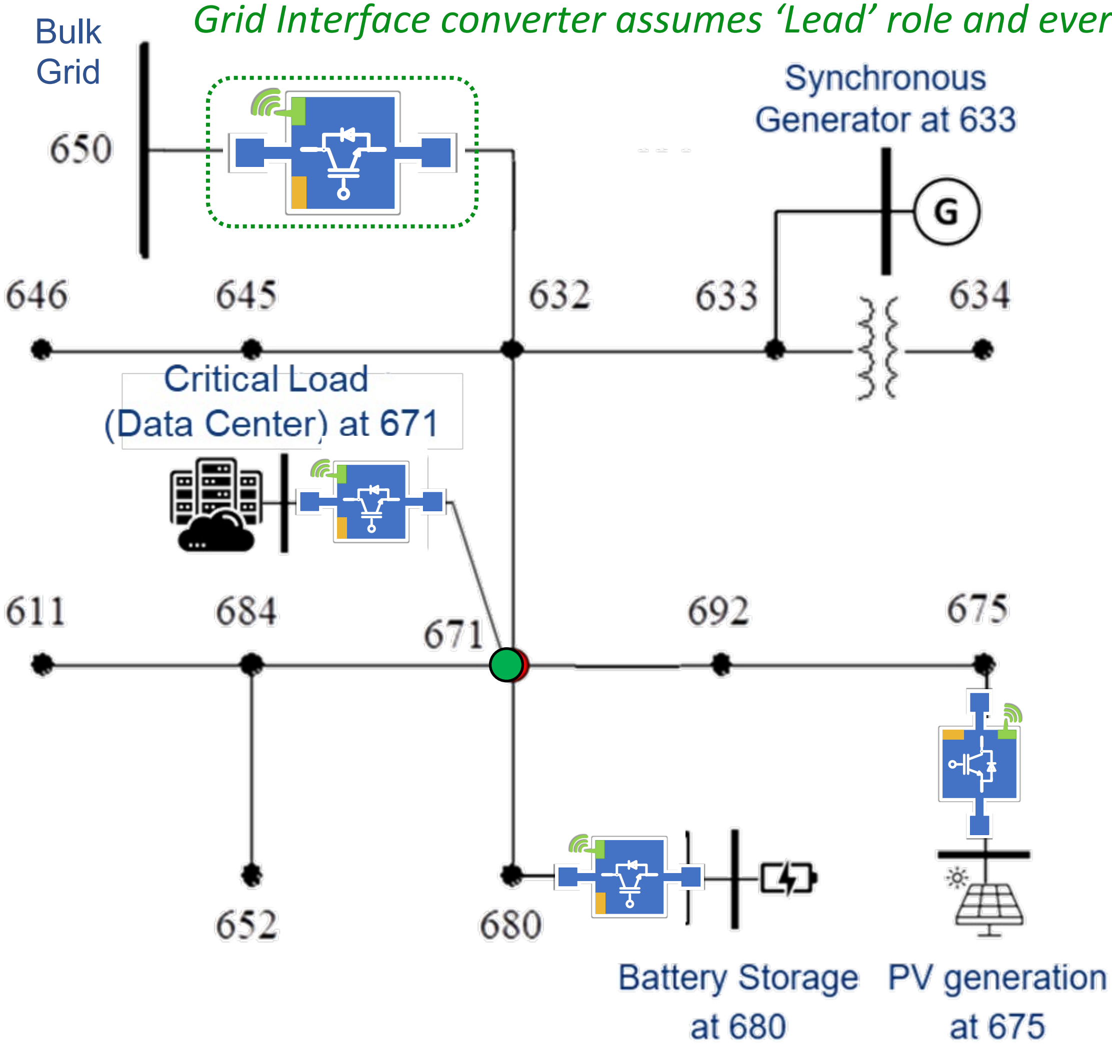
Islanded mode

- Synchronous Generator becomes a "weak grid."
- Inverters and Rectifiers synchronize with each other (and themselves!), which can lead to instability:



MBB Architecture Applied to IEEE 13 Node System

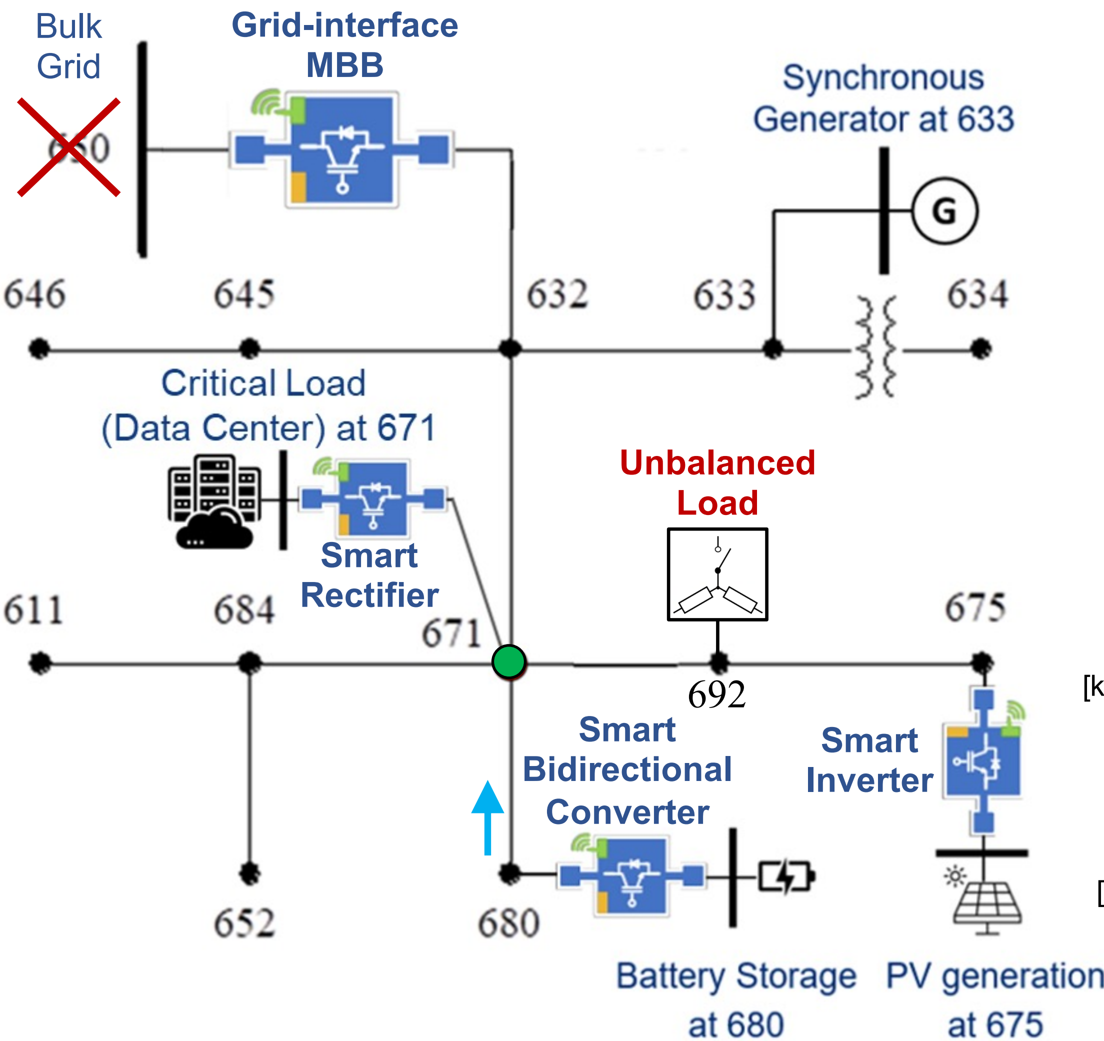
Grid Interface converter assumes 'Lead' role and everyone in the Microgrid follows it.



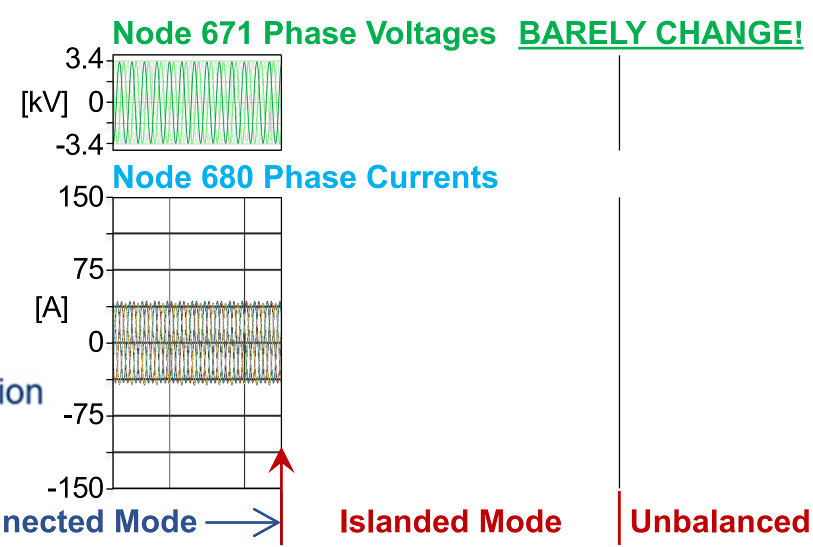
The following nodes have MBB interfaces:

- Grid Interface Converter
- Smart Inverters
- Smart Loads

Example: System Voltage and Frequency Integrity with the Future MBB-based Microgrid



- Grid-interface MBB becomes "Microgrid System Operator," even in islanded mode.
- MBB has the capability of microgrid-forming and coordinates system integrity.



Simulation results:

Technical Approach

THRUST 1 - MBB DESIGN AND PROTOTYPE DEVELOPMENT (LEAD: VT)

THRUST 2 - MODELING AND SIMULATION OF MBB, PERFORMANCE REQUIREMENTS AND EVALUATION (LEAD: PNNL)

THRUST 3 - MBB MODULARIZATION/STANDARDIZATION, VALIDATION AND TESTING (LEAD: ORNL)

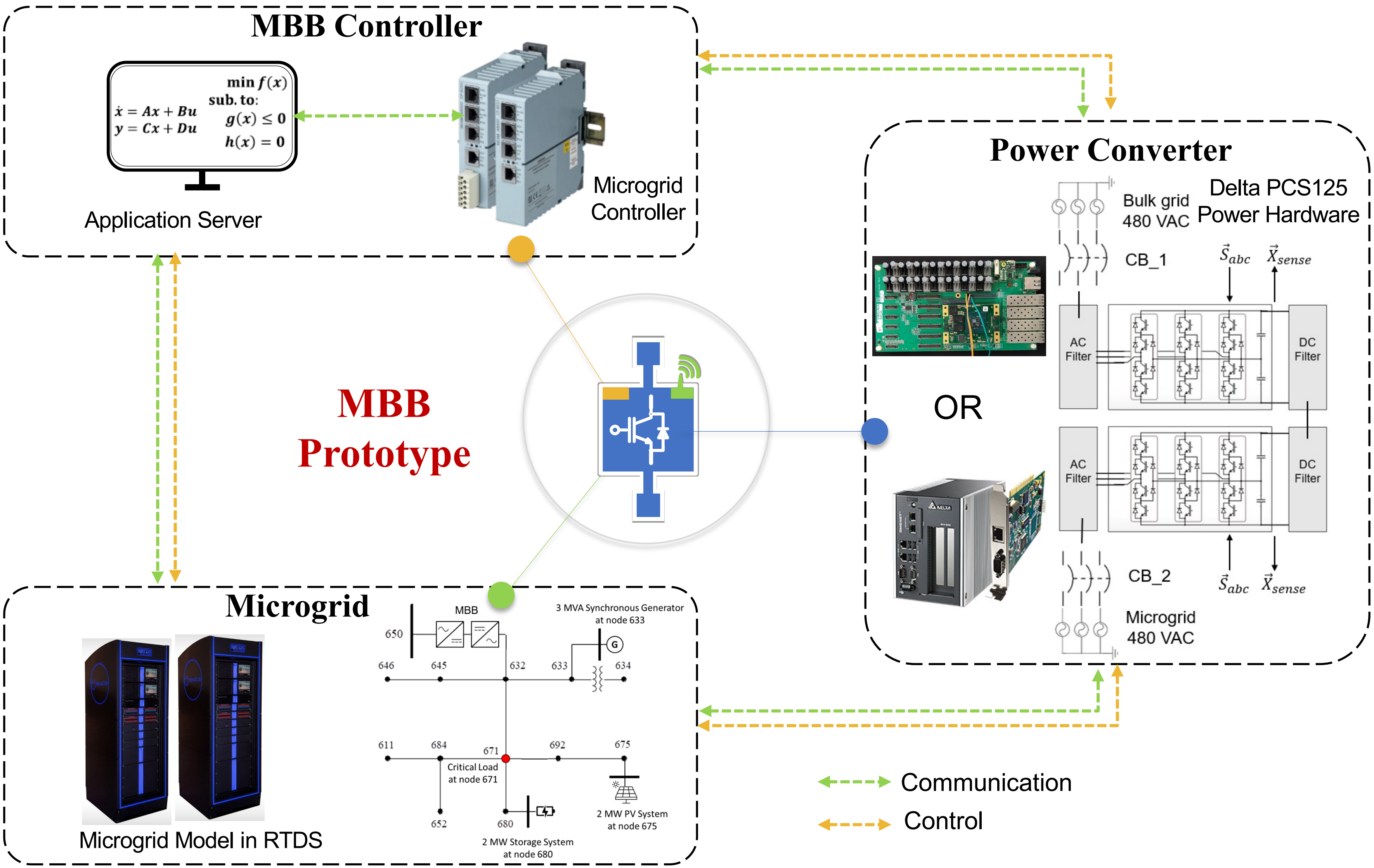
THRUST 4 - MBB DEMONSTRATION (LEAD: NREL)

Preparations for Prototype Development

Technical Approach

- Select a microgrid-to-grid-interface substation for MBB technology development and demonstration.
- Leverage power electronics building block (PEBB) concepts, research and technology development experience at VT (ONR).
- Leverage medium-voltage modular solid-state-substation research and technology development experience at VT (ARPA-E).
- Leverage VT industry consortia with over 80 companies for advice and technical information on state-of-the-art and roadmaps for microgrid development that enable a decarbonized future.
- Survey state-of-the-art research and commercial solutions for microgrid controllers, grid-interface converters, battery-energy-storage bidirectional converters, and smart inverters/rectifiers.

Preliminary Specifications for Scaled-Down Grid-Interface MBB Prototype



MGC Vendors

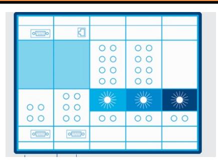
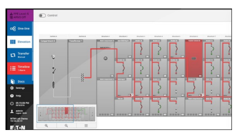
Literature review of existing MGC vendor surveys and reports was completed

- ABB
- Advanced Control Systems
- Alstom Grid
- Blue Pillar
- Eaton
- Encorp
- Enphase Energy
- ETAP
- General Electric
- Green Energy Corp
- Intelligent Power & Energy Research Corporation
- Opus One Solutions
- Power Analytics
- Schneider Electric
- Siemens
- Spirae
- Sustainable Power Systems
- Toshiba
- Viridity Energy

*Guodong Liu, Michael R. Starke, Drew Herron, "Microgrid Controller and Advanced Distribution Management System Survey Report." US DOE, Oak Ridge National Laboratory, 2016.

MGC Selection

- Literature review was helpful in identifying the common MGC functions
- However, MGCs were programmed by the vendors and information about ease of programming, support for commonly used programming languages etc. was not available.

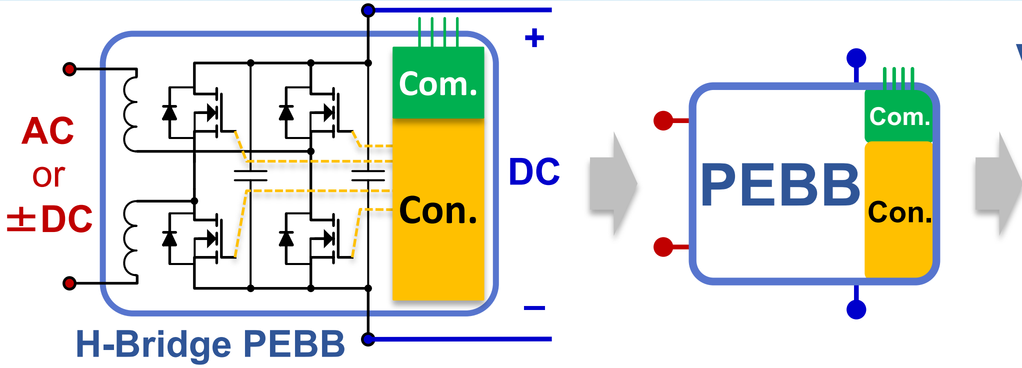
ABB MGC 600 Platform	Eaton Power Xpert	GE Grid IQ	Schneider Electric EcoStruxure Platform	SEL RTAC+PowerMax	Siemens SICAM+CP8050
					
Modbus, CAN-Bus …	Modbus TCP BACnet IP…	DNP3 Modbus Modbus RTU Modbus TCP IEC 61850…	Modbus, IEC60870-5, IEC 61850…	DNP3 Modbus Modbus RTU Modbus TCP IEC 61850…	DNP3 Modbus Modbus RTU Modbus TCP IEC 61850…

…

- Most surveyed MGCs support the Modbus protocol, among others.
- Proposed back-to-back converter also supports the Modbus protocol.
- Siemens MGC was chosen as VT has prior experience in using this MGC and supports the Modbus protocol.
- However, all other MGC's can also be used to implement the control algorithms.

Power Electronics Building Block (PEBB)

Office of Naval Research (ONR) 30-year research program for standardization and scalability of power conversion

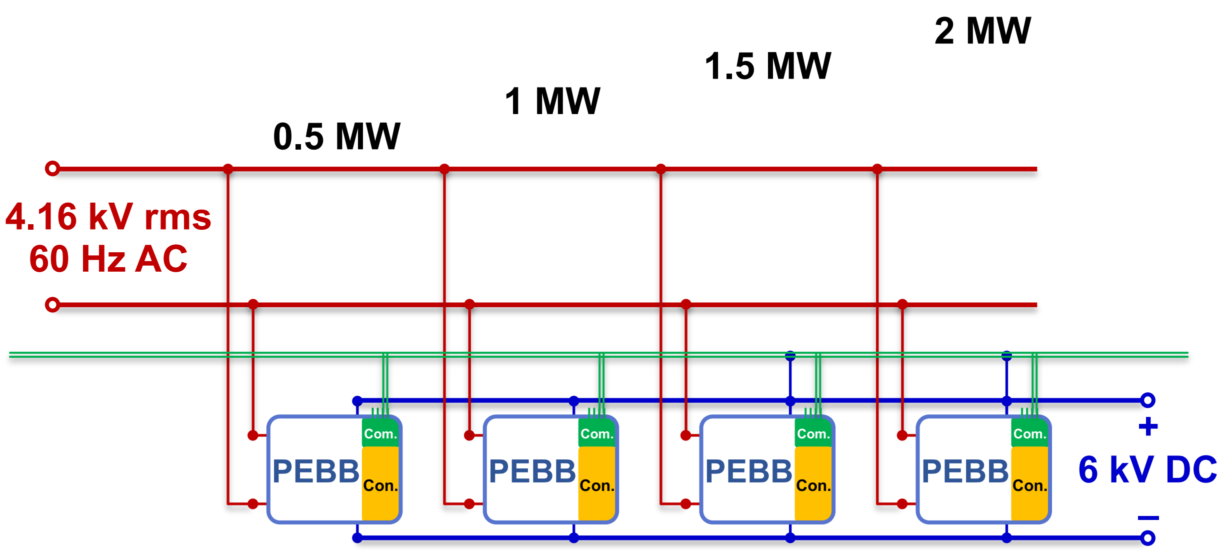


VT prototype sponsored by ONR & ARPA-E

PEBB-6000
6 kV, 85 A
half-bridge

with 10 kV SiC MOSFETs switching at 10 kHz

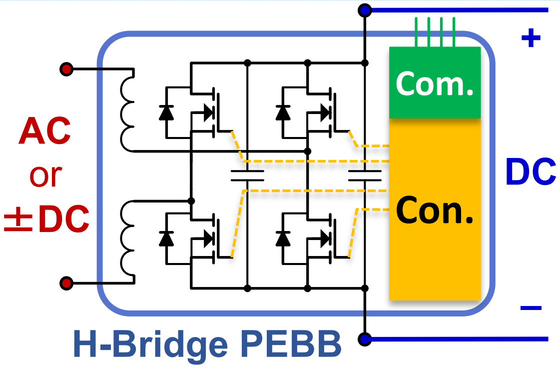
Example: Increasing current (power) rating by PEBB paralleling

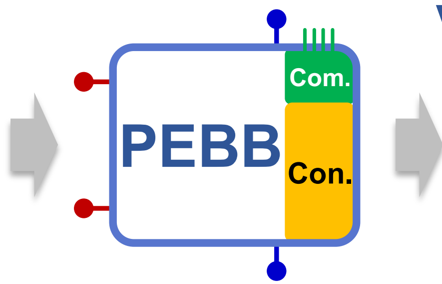


Standardized Serial Communications
and
Hierarchical Distributed Control
enable
Plug & Play
and
Power Architecture Self-configuration

Power Electronics Building Block (PEBB)

MV Solid-State Substation SiC Converter by ARPA-E (2019-22) demonstrates voltage-scaling with different converter topologies





VT prototype sponsored by ONR & ARPA-E

PEBB-6000
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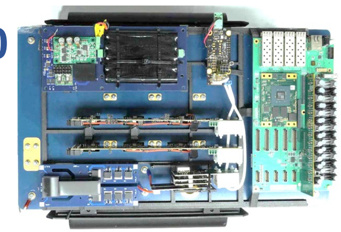
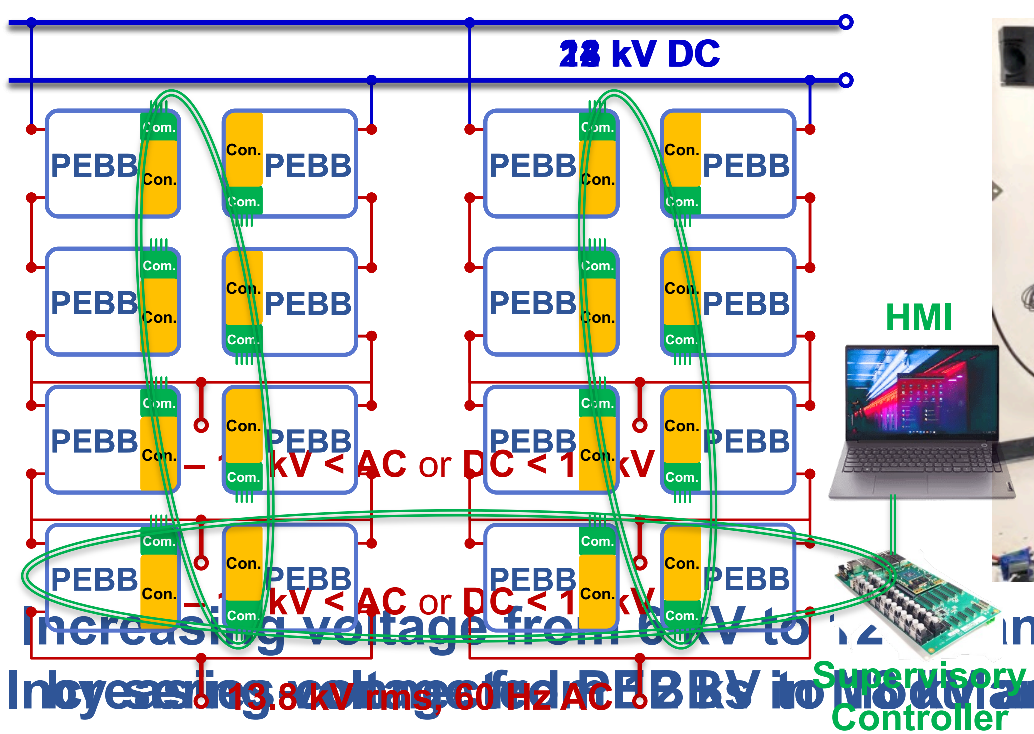
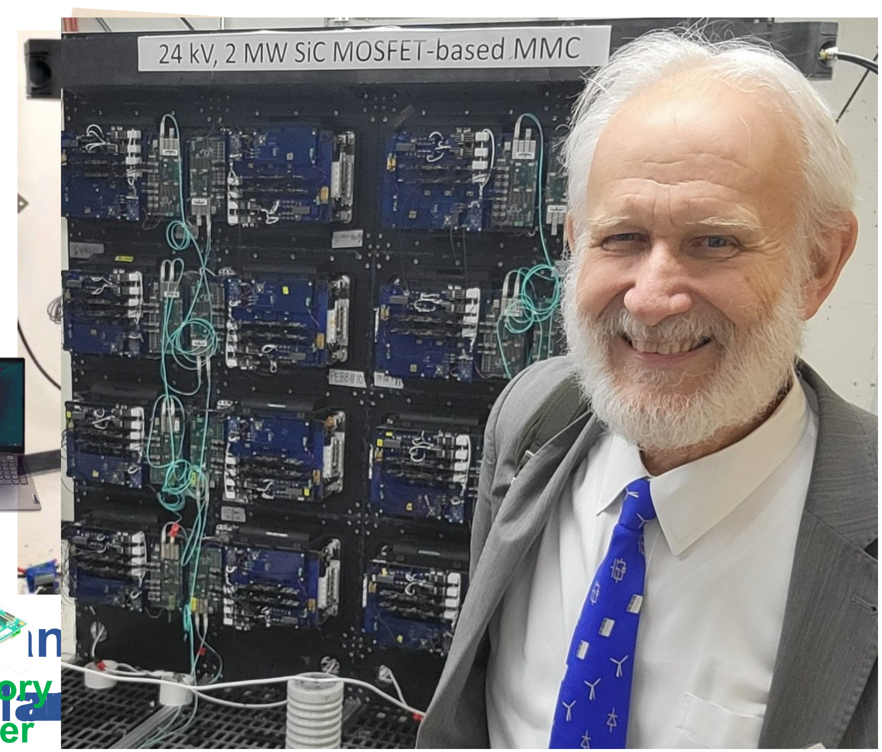


with 10 kV
SiC MOSFETs
switching
at 10 kHz





PNNL Modeling and Simulation

MBB Object Modeling in GridLAB-D

Basic AC-DC-AC Back-to-Back converter model with individual power electronics control dynamics

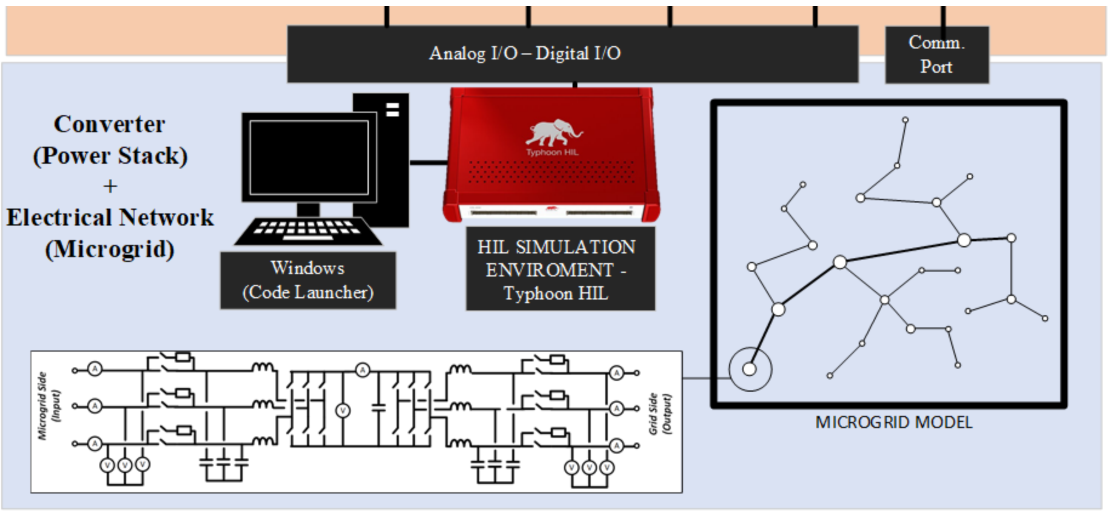
Translate the average response using RMS values to phasor domain dynamic equations to be implemented in GridLAB-D

System Level Analysis with MBB GridLAB-D Object

- Development of dynamic system simulations that include all MBB functionality in GridLAB-D
- Perform system-level analysis in GridLAB-D on largescale models for the various use cases
  - Bulk-grid connected microgrid
  - Networked microgrids
- Example of a large system is IEEE 9500 node system:
  - 3 Substations
  - 3 Circuits
  - 9,500 Nodes
  - DERs
    - 4 Diesel Generators
    - 1 Steam Generator
    - 4 Micro Turbines
    - 3 Wind Turbine Generators
    - 178 Solar PV Units
    - 2 Bess
  - Equipment
    - 1287 Transformers
    - 18 Voltage Regulators (6 Full Per Phase Units)
    - 10 Shunt Capacitors (Mix Of Single And 3 Phase

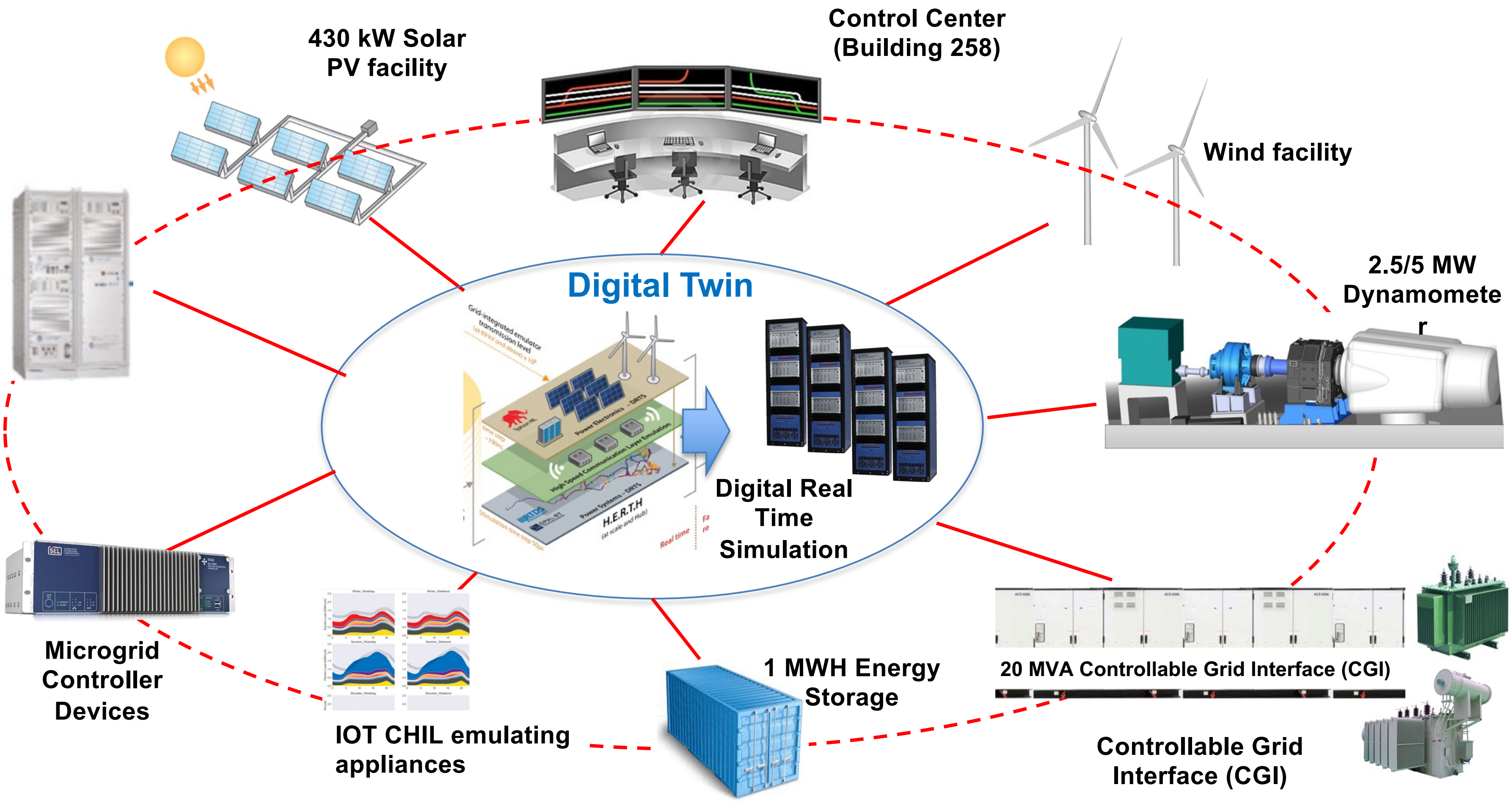
Illustration of the IEEE 9500 Node System

ORNL Validation Testing



- ORNL will utilize the CHIL platform developed at ORNL with MBB controller hardware prototype developed at VT.
- The software interface which includes communication and controls along with the microgrid controller will also be integrated with the MBB topology simulated in real time platform with closed looped operations.
- The MBB CHIL platform will be used to simulate and validate the use cases.
- The use case profiles will be used to validate the MBB hardware prototype at NREL.

NREL Field Demonstration
NREL-ARIES HIL/CHIL Interconnected Devices



NREL - MBB DRTS HIL/CHIL Testbed

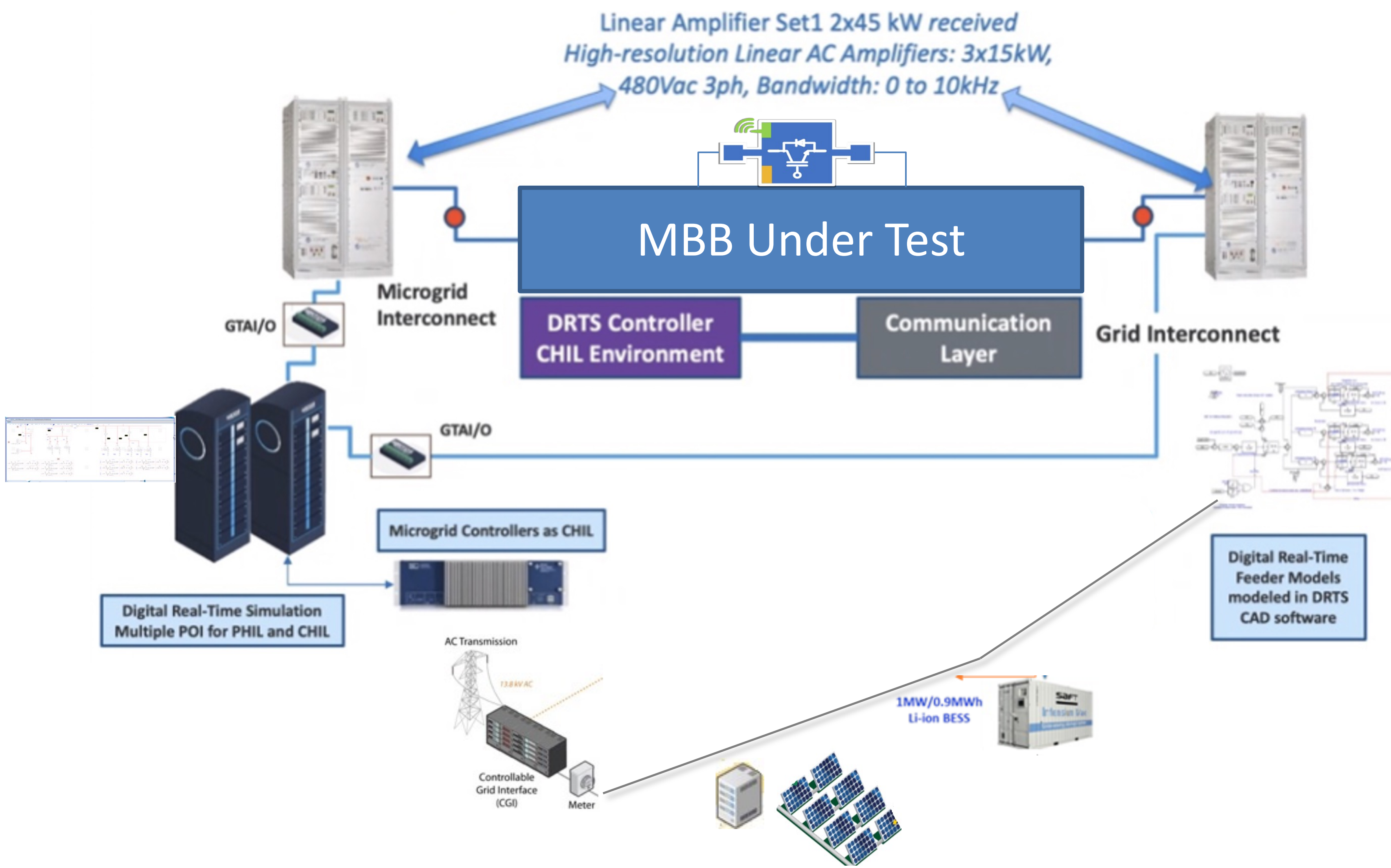
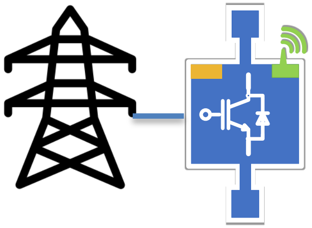


ABB Tech Transfer

Related ABB products:

- UPS (PCS120, PCS100, etc),
- Grid connected interface converters



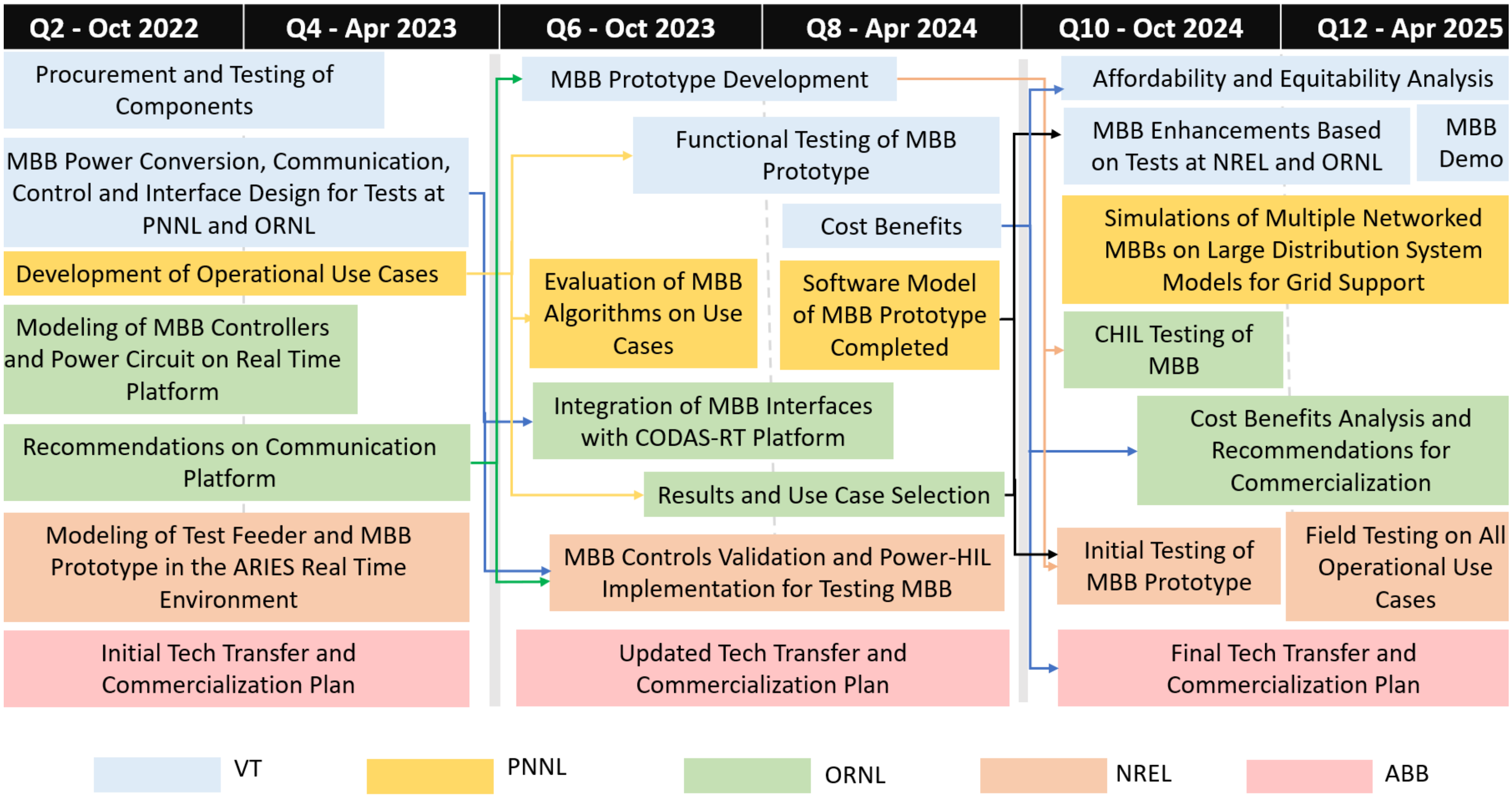
Tech transfer plan

- Bi-weekly MBB team meetings
- Technology transfer meetings
- Technology demonstrations
- Technical reports and programs

Commercialization plan

- Identification of challenges and gaps in commercialization

MBB Project Timeline



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