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Comprehensive Hardware in the Loop Testing and Verification of Microgrid Controller Functionalities

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SUMMARY

Utilities are working to integrate higher renewable generation and improve the resiliency of the grid in response to increasing extreme weather events caused by climate change as well as cyber-security threats. Microgrid technology has evolved as one of the most effective options to ensure the grid of the future is more resilient, sustainable, and connected. ComEd, a utility serving more than 4 million customers in northern Illinois including the city of Chicago, is installing the first utility-operated microgrid cluster in the United States: the Bronzeville Community Microgrid (BCM), located on the south side of Chicago. The BCM is designed to power approximately 1,000 residences, small businesses, and institutions, including customers providing critical public services like the Chicago police headquarters.

A comprehensive test setup has been developed in the laboratory similar to the final field setup wherein a microgrid management system (MGMS) interacts with SCADA, DA devices and DER controllers. MGMS is responsible for coordinating the microgrid assets and ensure maximum reliability of the connected customers. MGMS functionalities include solar-storage coordination, islanding, black-start and restoration, grid-synchronization and reconnection, and clustering with neighboring microgrid. A test plan has been prepared to thoroughly test these functionalities using a hardware-in-the-loop (HIL) environment. HIL test setup allows testing MGMS in conjunction with other control devices in numerous scenarios in a safe and economic manner as ComEd prepares to deploy the controller into the microgrid. This paper shares the results and learning from this comprehensive laboratory testing of the microgrid controller.

KEYWORDS

Microgrid control, hardware-in-the-loop testing, solar photovoltaics, battery energy storage System

1. Introduction

Microgrids allow for the decentralization of electricity, incorporation of clean energy, and enhancement of power system reliability and resilience [1]. Microgrids host a variety of components including distributed energy resources such as solar photovoltaic (PV) and battery systems, master controllers, and smart inverters [2] which can be used in concert to simulate a flexible demand for the utility grid and disconnect from the utility grid during disturbances [3].

One of the primary goals of the Bronzeville Community Microgrid (BCM) launched by ComEd [4] is addressing the inherent fluctuation in power injections of solar PV systems by incorporating BESS and advanced control features of smart inverters. However, as mentioned above, one of the defining characteristics of microgrids is their ability to operate autonomously as an island during disturbances. The site for the Bronzeville Community Microgrid (BCM) includes two distribution feeders tied together allowing the project to host solar Photovoltaics, Battery Energy Storage System, and controllable generation to support the microgrid in islanded mode, see Figure 1. It will also have the capability to form a microgrid-cluster with another microgrid installed at the Illinois Institute of Technology (IIT). ComEd developed a microgrid master controller in partnership with the United States Department of Energy that enables monitoring and control of the microgrid under different conditions, coordination between solar photovoltaics and battery energy storage system, and providing uninterrupted power to customers by forming an island during grid outages. A solar storage coordination algorithm was developed to enable penetration of higher amounts of solar into the microgrid, called Microgrid Integrated Solar Storage Technology (MISST) [5], supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy.

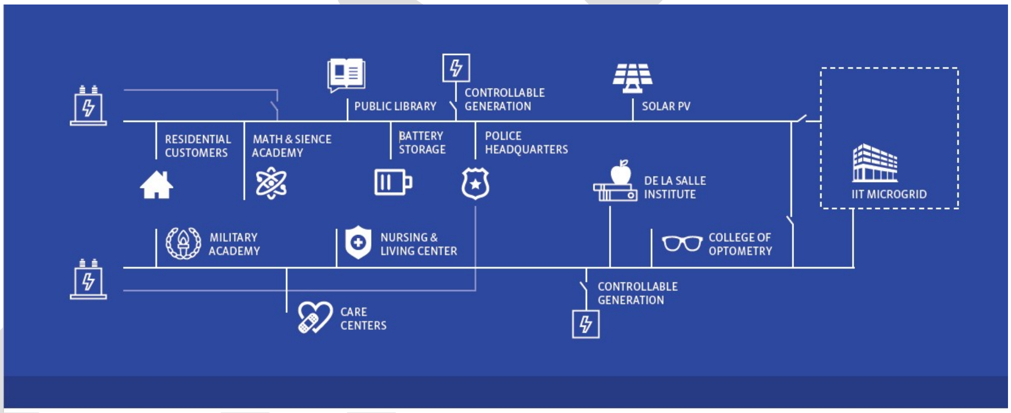

Figure 1. Schematic of Bronzeville Community Microgrid

The BCM's control system employs a multi-timescale, two-stage, robust unit commitment and an economic dispatch model to optimize microgrid operation [5]. The prototype MISST controller was successfully tested in ComEd's Grid Integration and Technology laboratory utilizing integrated power and control hardware-in-the-loop (HIL), built around a real time digital simulator (RTDS). The RTDS emulates the dynamics of the microgrid including the feeder network and Distributed Energy Resource (DER) generators and serves as the platform to interface and test the control hardware devices as well as the microgrid controller functionalities. The algorithm has now been refined and integrated with a microgrid management system (MGMS) that directly dispatches the DERs while also monitoring and controlling the distribution automation (DA) devices as per requirements specified in the controller's sequence of operation (SOO). This paper focuses on HIL testbed prepared for MGMS testing, which is a preparatory step before deploying the controller in the field.

2. Hardware-in-the-loop Testbed

2.1. Test Objectives

The RTDS HIL testbed for BCM aims to achieve a comprehensive testing of the functionalities of the MGMS before final installation in the field. The intention is to design RTDS test setup and perform tests in a manner that programming of MGMS functionalities and communication points list mapping stay almost the same from laboratory test setup to the field deployment.

The tests are designed to verify:

- MGMS interface with the field control devices, including DER controllers, protection and control (P&C) devices, Distribution Automation (DA) switches, circuit breakers, and capacitor controllers on the BCM feeder.
- Interface between MGMS and a representative of operating center control and monitoring (SCADA Emulator)
- Execution of the microgrid sequence of operation by MGMS.

2.2. Testbed

While the complete power circuit of the BCM is modeled in RTDS, a select number of physical Intelligent Electronic Devices (IED) are proposed to be integrated and used as part of the test setup in a HIL manner. This testing approach is referred to as Controller Hardware-in-Loop (CHIL) in the literature and standards. The remainder of the protection and control devices and distribution switchgears are simulated inside the RTDS model. Models of the BCM's DERs, along with pertinent load profiles and solar irradiation profiles are also included in the RTDS real-time simulation model.

Using the simplified single line diagram (SLD) of the BCM, Figure 2 shows the control and protection devices that are to be represented through hardware. The remaining P&C devices associated with circuit components (switches, capacitors, and IIT DER) in Figure 2 will be modelled in RTDS, using generic representation of key functionalities. In addition, IIT microgrid master controller will be interfaced in the RTDS environment.

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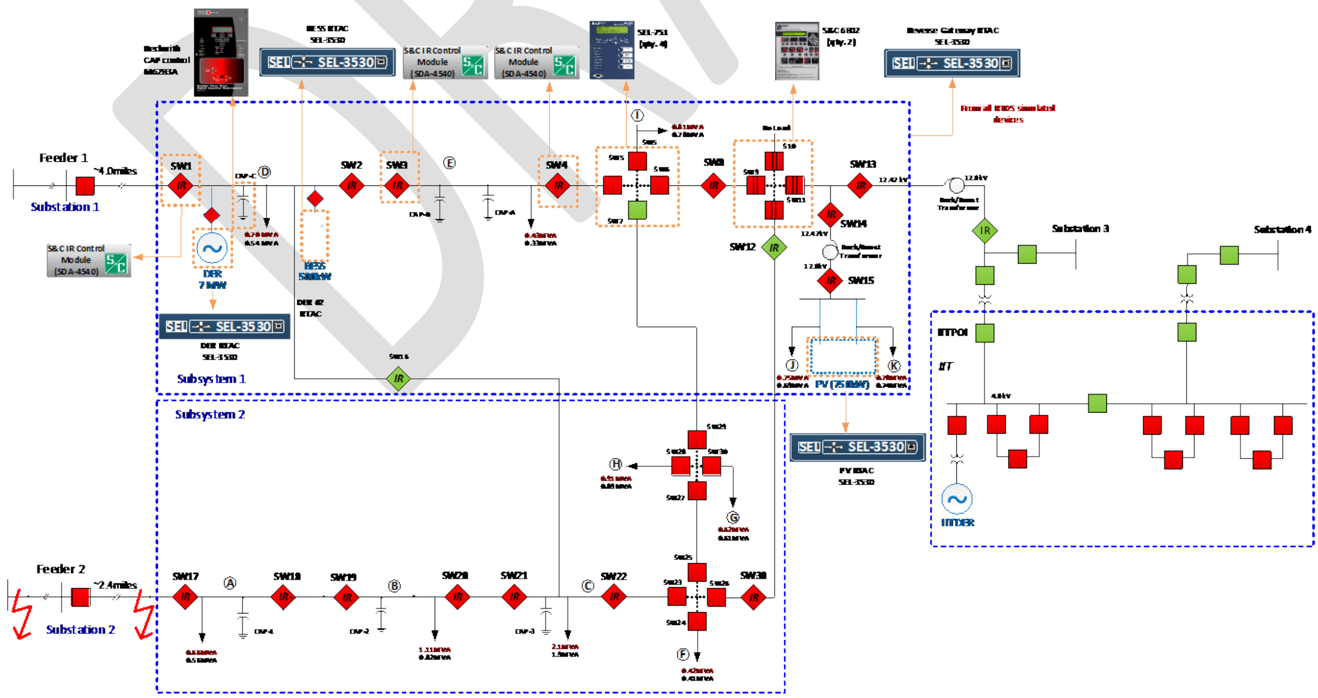

Figure 2. Circuit diagram of Bronzeville Community Microgrid with hardware devices for CHIL testing

The selected hardware devices:

- Receive secondary voltages and currents from the RTDS, and
- Communicate with the MGMS and SCADA emulator over the hardwired Ethernet network.

The DER site controllers for the BESS, PV and Generator are represented by SEL RTAC devices. The RTACs communicate with the RTDS which holds the power model of the various DERs.

Figure 3 shows the connection details for the CHIL test setup where various hardware devices representing BCM system components are interfaced with the RTDS and the MGMS.

The SCADA Emulator and Reverse Gateway RTAC device fulfills two separate functions:

- **SCADA Emulator –** simulates the interface that an operator at the OCC would have with BCM and MGMS. The Emulator also acts as a third source of test results (MGMS and PI being the other two). A data logger is connected to the SCADA Emulator to record all pertinent data observed by the Emulator

- **Reverse Gateway** – solves a RTDS restriction that prevents all the simulated IEDs that exist in the BCM from being externalized via DNP interfaces. The Reverse Gateway extracts data from the RTDS and parses it such that the MGMS sees it as it is coming from individual IEDs. The same feature is available in reverse for controls and setpoints – MGMS issues these to what it sees as individual IEDs; the Reverse Gateway consolidates and re-issues these to the RTDS. This approach minimizes configuration rework on the MGMS and makes the interface more representative of what MGMS will encounter in the real system.

Figure 4 also shows screenshots of the MGMS display and SCADA emulator's user interface that are utilized for monitoring and control of different microgrid functions and components.

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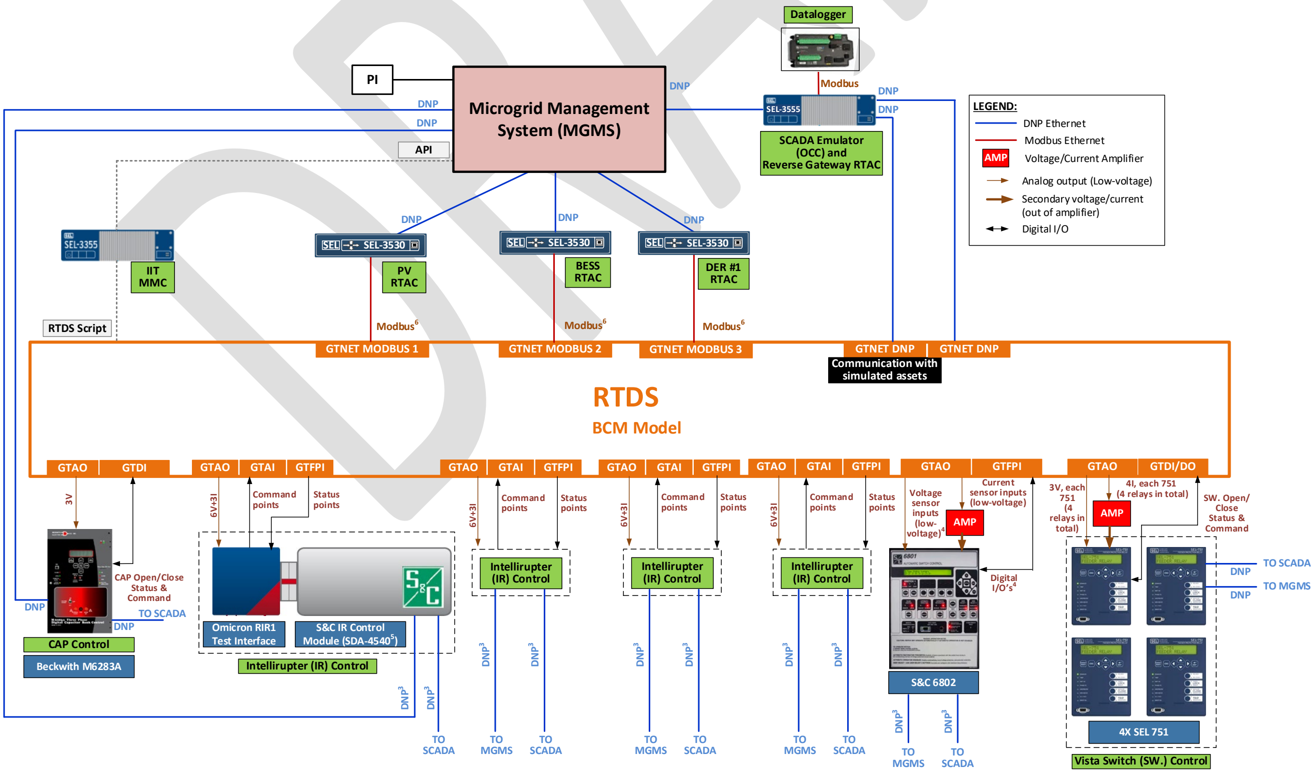

Figure 3. MGMS RTDS test system components and connections

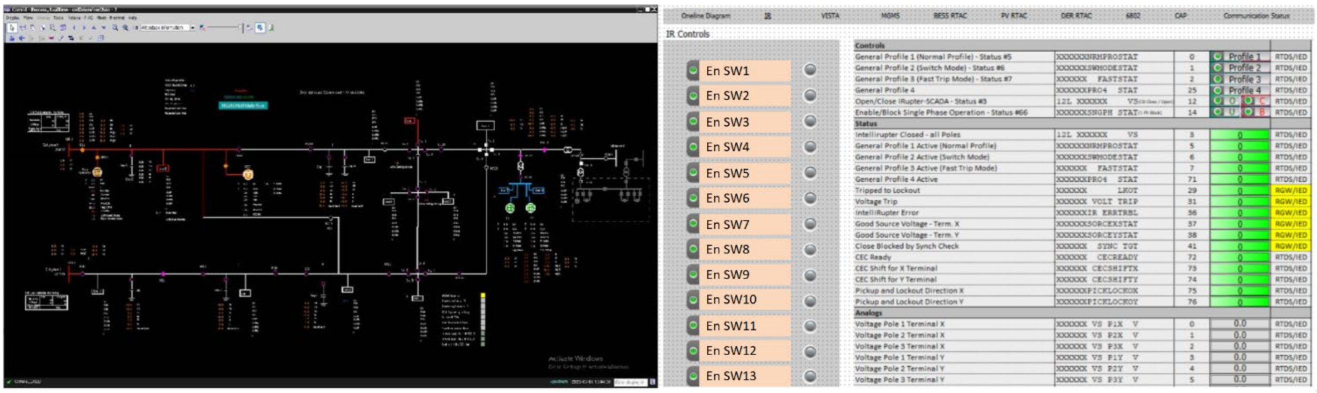

Figure 4. Screenshots of MGMS display (left) and SCADA emulator's user interface (right)

3. Test Cases

The BCM will be operated by the MGMS as prescribed in the microgrid's sequence of operations (SOO). The BCM SOO details the checks and actions to be performed as the system transits from grid-connected to islanded mode of operation and vice versa. Figure 5 shows a simplified overview of the MGMS sequence of operations.

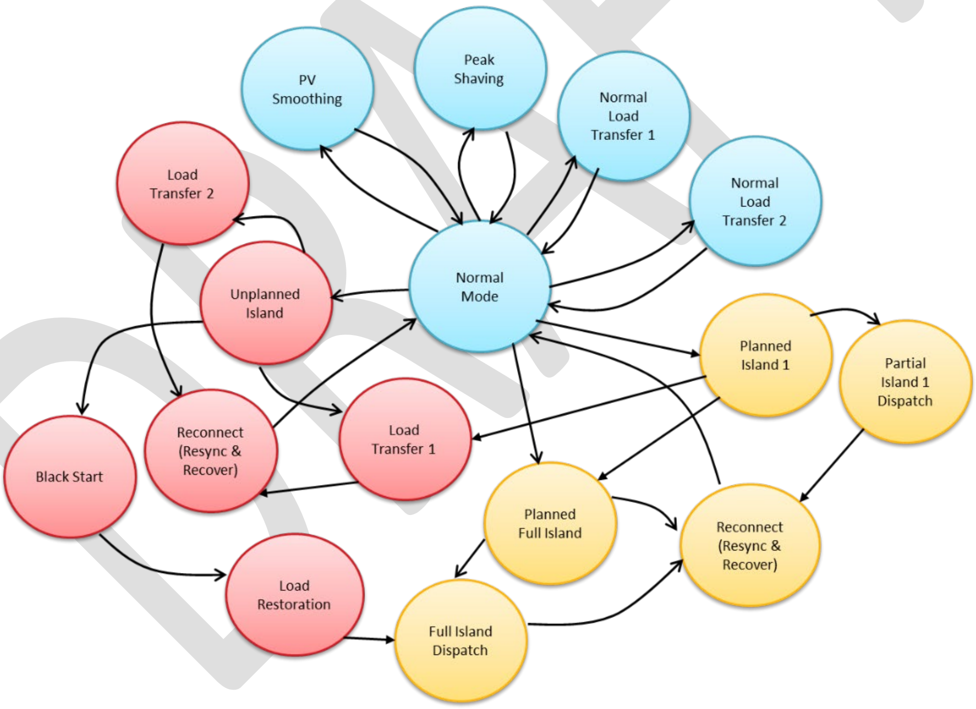

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Figure 5. Overview of MGMS Sequence of Operations

Based on the sequence of operations and functionalities of the MGMS, the following major test categories are proposed to be performed in this RTDS lab testing:

a. MGMS communication tests with the P&C hardware devices and SCADA emulator, including: Automatic (MGMS in charge) & manual (OCC in charge) control of devices and switch over

2. Normal, grid-connected test

a. Peak shaving

   b. Renewable smoothing
   c. Load transfer
3. Planned partial islanding test
4. Load transfer test
5. Planned full islanding test
6. Unplanned islanding test
7. Black start and load restoration test
8. Partial and full re-connection test
9. Clustering test and de-clustering test
   a. Generation dispatch during islanded mode, under various load profiles and resource conditions
10. Re-synchronization
11. System protection test (internal and external faults or equipment failure)

4. Performance Indicators

To evaluate each test discussed in the test plan, various key operation parameters (KOP) and key performance indicators (KPI) are defined and used. The KOPs and KPIs are either directly measured or calculated from a set of BCM measured parameters and are to be updated at a resolution of 2 s. Below is a general list of proposed parameters and indicators that will be monitored:

- Power flow at various points across BCM
- Power flow for IIT system
- Voltage and current at various points in the BCM
- Digital and analog measurements from IntelliRupters and Vista switches
- Trends for PV production, battery SOC and load consumption
- Alarms
- Calculated indices, such as:
    - Rate of change of frequency
    - Voltage deviation
    - Voltage and current unbalance
    - Duration of the island
    - Reserve capacity level
    - Response time, or recovery time
    - Load served

To confirm system stability during each test procedure of the test plan, the following indicators are recommended to be monitored:

- Stability in voltage and frequency at main switches,
- Stability in voltage and frequency at points of connections of BESS, controllable DER and PV,
- During clustering and de-clustering, stability in voltage and frequency at BCM-IIT point of interconnection (POI),
- Power flow targets at BCM POIs and point of connection of DERs are within 5% of light load.

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5. Laboratory Testing

5.1. I/O and Communication Tests with Hardware Devices

The I/O and communication tests are mainly intended to ensure integration of the I/O devices and control hardware devices to the RTDS and the MGMS and the data exchange among the controllers and the MGMS display as well as SCADA emulator. Therefore, the focus of test would be on verifying communication interfaces, including data mapping and data quality.

In addition, RTDS communications and preparation tests are recommended to:

- Verify I/O and control hardware communications with the RTDS,
- Ensure accuracy of all controller measurements and statuses as shown on the user interface and reported in RTDS,
- Change MGMS operation modes (normal, partial island, load transfer, etc.) and,
- Establish 'Normal Mode of Operation' for MGMS (default control mode and setpoints),
- Verify the interlocking and control inhibition between Auto (MGMS controls) and Manual (OCC operator controls).

The following communication and I/O wiring verifications has been performed for the MGMS-RTDS electrical test setup:

- Finalize the point list for RTDS communications and simulated devices
- Prepare RTDS model of the BCM and IIT with simulated devices, simulated controls, and simulated simplified protection schemes, as well as communication interfaces (DNP and Modbus),
- SCADA emulator (RTAC) programing and setup with DNP3 points lists for MGMS and RTDS
- Reverse gateway (RTAC) programing and setup with DNP3 points lists for MGMS and RTDS
- PV system SEL-3530 RTAC setup with DNP3 points list (for MGMS and SCADA) and MODBUS points list (for RTDS),
- BESS SEL-3530 RTAC setup with DNP3 points list (for MGMS and SCADA) and MODBUS points list (for RTDS)
- DER SEL-3530 RTAC setup with DNP3 points list (for MGMS and SCADA) and MODBUS points list (for RTDS).
- Beckwith M6283A capacitor control (incl. amplifiers) analog/digital I/O setup and DNP3 points list
- S&C IR modules analog/digital I/O setup and DNP3 points list
- S&C 6802 controllers' analog/digital I/O setup and DNP3 points list
- SEL-751 Vista switch control (incl. amplifiers) analog/digital I/O setup and DNP3 points list
- MGMS HMI/SCADA setup and DNP3 lists from all hardware device
- RTDS setup and configuration with RSCAD model
- Wiring of all analog and digital I/Os from hardware to RTDS

5.2. Normal Operation

The BCM is defined to be in normal, grid-connected mode of operation when both subsystems are connected to the utility grid, which translates to SW1 and SW17 to be closed and connected to their respective feeders. In cross-coordination between OCC and the MGMS, the grid-connected BCM should be operated in a similar manner as any part of the distribution systems for applications such as

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load transfer during normal conditions and dispatch of DERs for peak shaving and PV smoothing applications governed by the Solar PV – BESS Coordination function.

The test cases for the normal mode of operation aim to perform a base case test, load transfer during normal conditions and to validate dispatch strategies for peak shaving and PV smoothing under the Solar PV-BESS Coordination function. Note that MGMS does not deal directly with Controllable DER and load fluctuations during normal operation. Therefore, changing loads (min/max/etc.), or creating scenarios such as DER tripping, or Capacitor switching will not have any effect on MGMS during normal operation. Fault and voltage/frequency disturbances are tested in Protection test section.

If there is a need for load transfer from one BCM feeder to another feeder, OCC can request the MGMS to perform a load transfer of subsystem 1 to subsystem 2 (Load Transfer 1) or perform a load transfer of subsystem 2 to subsystem 1 (Load Transfer 2).

5.2.1. Peak Shaving

MGMS should follow the instructions provided by the microgrid operator to reduce peak load of each subsystem by a given target by using only the BESS and PV. The schedule should be communicated to MGMS well in advance. For the purpose of the peak shaving test, a sample schedule and reduction target should be created where the time that the peak shaving is to be performed will coincide with the time of the test. The schedule should expire within the time of the test or such that state of charge (SOC) will be less than 30% before the end of the test. Note that after performing peak shaving, the BESS will charge at a time automatically decided by the MGMS optimization function.

5.2.2. Renewable Firming

The renewable firming test will verify the firming algorithm under the Solar PV – BESS Coordination function. The algorithm will be tested in real-time under dynamically changing PV outputs for high and low battery SOC conditions. The purpose of the renewable firming test is to validate the ability of the BESS to compensate for PV flicker such that the combined output of the BESS and PV are fixed over 15-minute intervals. PV profile has better than 10 second resolution. Load profile has 1-minute resolution.

5.3. Planned Islanding

An execution of a planned island is dependent on factors such as system loading, PV output, battery SOC and DER availability. Therefore, the testing for planned islanding should involve several iterations of test cases to assess if the MGMS can complete a planned islanding under varying system conditions.

5.4. Unplanned Islanding

The unplanned islanding process is initiated when the MGMS detects that POI switch SW1 is open. The MGMS will then island the subsystem from the faulted or disconnected feeder and then perform a load transfer; provided that the second feeder is healthy and connected to the BCM power system.

5.5. Black Start and Load Restoration

The black start mode of operation is initiated when an island cannot be completed, and the alternative feeder is not healthy. This scenario translates into black out across BCM system. Restoring the system is through black starting DER in subsystem 1 and picking up loads step by step.

5.6. Clustering and De-Clustering

The clustering process aims to connect the IIT campus microgrid to the BCM. The microgrid clustering allows two microgrids to operate islanded from the main grid but connected to each other by enabling controlled energy exchange between them. The energy exchange respects the physical limits of each microgrid. In this test setup, the MGMS, the RTDS model of the BCM, the IIT microgrid master controller

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(MMC) and the RTDS model of the IIT campus microgrid will be utilized. The clustering can only occur when both microgrids are operating in island mode.

During cluster mode of operation, BCM DER will be grid-former and IIT microgrid's gas generator will be grid-follower. When the clustering signal is received by IIT MMC, if accepted, IIT microgrid will synchronize itself with BCM by adjusting voltage magnitude, frequency and phase angle difference. The process for this synchronization is based on sensing the difference between frequency, phase and voltage magnitude between the two microgrids and zeroing out the difference.

There is a breaker control component at the POI of IIT microgrid and BCM that will close the breaker automatically when the difference between voltage magnitude, phase and frequency are within a certain range. Currently, the breaker controller is set to close the circuit when the angle difference is less than 10 degree, the frequency difference is less than 0.1 Hz and the voltage magnitude is less than 3% of the nominal value.

The external interface between the two microgrids will be through web services API, as shown in Figure 6. Through the web service API, the two microgrids will communicate through three types of messages:

- Notify emergency (request assistance)
- Receive bid (offer of assistance)
- Notify award (accept the assistance)

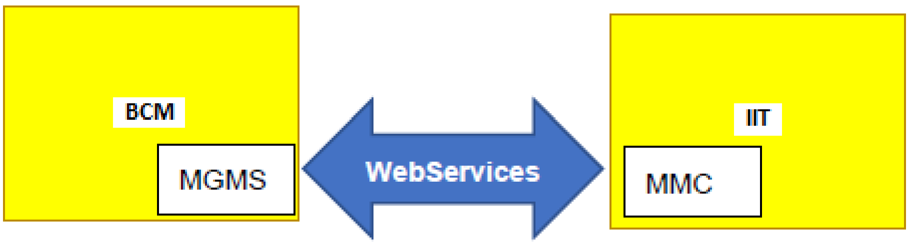

Figure 6. Microgrid clustering interface between the two microgrid controllers

5.7. Resynch and Reconnection

In the scenarios where the BCM wants to re-connect to the grid, the MGMS synchronizes the two systems using the measurements sent by the IRs. Synchronization is performed by MGMS via sending voltage and frequency reference signals to Controllable DER to match the main grid. The IRs can measure voltage magnitudes at both sides and delta angle and delta frequency between two sides. The data is communicated to the MGMS through a defined DNP points list. The MGMS adjusts the DER setpoints until the voltage magnitudes, delta frequency and angle gets to the specified range.

The partial and full re-connection mode of operation aims to re-connect both subsystems to their substations and opening the tie switch between the two subsystems, if necessary. The partial reconnection process is tested for the scenario where the alternative feeder is disconnected and for the scenario where the alternate feeder is connected. The full reconnection process is tested as a continuation of the partial re-connection test.

6. Conclusion

ComEd, a utility serving more than 4 million customers in northern Illinois including the city of Chicago, is installing the first utility-operated microgrid cluster in the United States: the Bronzeville Community Microgrid (BCM), located on the south side of Chicago. The BCM is designed to power approximately

1,000 residences, small businesses, and institutions, including customers providing critical public services like the Chicago police headquarters. The test setup developed in the laboratory to simulate a setup very close to the final field setup has been presented in this paper, wherein MGMS interacts with SCADA, DA devices and DER controllers. MGMS is responsible for coordinating the microgrid assets and ensure maximum reliability of the connected customers. MGMS functionalities include solar-storage coordination, islanding, black-start and restoration, grid-synchronization and reconnection, and clustering with neighboring microgrid. A test plan and test procedure has been presented to thoroughly test these functionalities using the HIL environment. HIL test setup allows testing MGMS in conjunction with other control devices in numerous scenarios in a safe and economic manner as ComEd prepares to deploy the controller into the microgrid.

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