Site-Specific Evaluation of Microgrid Controller Using Controller and Power-Hardware-in-the-Loop

Preprint

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Presented at the 2019 IEEE 45th Annual Conference of the Industrial Electronics Society (IECON)
Lisbon, Portugal
October 14–17, 2019

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Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5D00-72770
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Suggested Citation
Prabakar, Kumaraguru, Annabelle Pratt, John Fossum, Jing Wang, Brian Miller, Martha Symko-Davies, Muhammad Usama Usman, and Thomas Bialek. 2019. *Site-Specific Evaluation of Microgrid Controller Using Controller and Power-Hardware-in-the-Loop: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5D00-72770. https://www.nrel.gov/docs/fy20osti/72770.pdf.

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303-275-3000 • www.nrel.gov

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Site-Specific Evaluation of Microgrid Controller Using Controller and Power-Hardware-in-the-Loop

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***Abstract*—Microgrid assets are built by utilities to improve the resilience and reliability of segments of the distribution system. Controllers with advanced capabilities will operate and control these microgrids with diverse energy technologies, which vary from inverter-based photovoltaics and energy storage systems to conventional diesel generators. There are multiple challenges to building a microgrid controller for a site because of the unique requirements presented by the controllable and uncontrollable elements in a specific microgrid. There are also challenges to testing the performance of the microgrid controller for such unique microgrids. This paper presents the controller and power-hardware-in-the-loop evaluation platform built to enable site-specific evaluation for a microgrid as well as the test cases used to evaluate the operation of a microgrid controller for a specific site. Finally, this paper presents the results from a subset of the experiments performed to evaluate the microgrid controller.**

Keywords*—*Controller-hardware-in-the-loop, IEEE 2030.8, microgrids, microgrid controller, power-hardware-in-the-loop.

I. Introduction

Critical facilities have long used microgrids to achieve resilience for their operations, and more recently utilities have invested in microgrids as an option to improve the reliability and resilience of segments of their distribution systems [1], [2]. These microgrids use diverse generation technologies, including conventional diesel generators, inverter-based photovoltaics (PV), and energy storage systems. Improvements to renewable energy generation and storage devices—such as inverters that are capable of performing advanced grid support functions that were conventionally performed by rotating machines—have made it more viable to use renewable energy resources within microgrids [3].

These microgrids require specialized controllers to operate the microgrid assets and to dispatch the required generation sources. These controllers have the capability to control power flow across the point of interconnection (POI) based on specific objectives, operate the microgrid in islanded mode, safely island/resynchronize the microgrid from/to the utility grid, and operate appropriately during abnormal conditions. The microgrid controller needs to be configured for each specific site according to that site's mix of resources and specific control objectives. It is critical to evaluate the performance of a microgrid controller prior to field deployment [4]. This evaluation should be performed using the configuration of the controller that is specific to the microgrid site for which it is being evaluated, and it requires an environment that is capable of representing the conditions that the controller would encounter in the field.

In a laboratory setting, tests can be conducted under many different operating conditions, including abnormal operating conditions, without impacting the grid and microgrid customers. The performance evaluation used should be informed by standard specifications. The IEEE 2030.7 Standard for the Specification of Microgrid Controllers [5] describes the functions that a microgrid controller is expected to perform. The IEEE 2030.8 Standard for the Testing of Microgrid Controllers [6] describes how the functions prescribed in IEEE 2030.7 should be evaluated. The microgrid controller should also be evaluated with respect to site-specific requirements to address whether the controller can manage the specific mix of microgrid assets at the site and meet the specific utility interconnection and customer requirements.

Several options are available to evaluate a microgrid controller in a laboratory setting, including pure simulation, controller-hardware-in-the-loop (CHIL) simulation, controller and power-hardware-in-the-loop (PHIL) simulation, and hardware only, as described in [7]. The use of CHIL and PHIL simulation allows for the use of real hardware components, which can be either the exact hardware used at the microgrid site or representative hardware with similar characteristics. This reduces modeling inaccuracies, especially for proprietary controls embedded within the power hardware [7], [8].

This paper describes the evaluation of the microgrid controller used at the Borrego Springs, California, community microgrid using CHIL and PHIL experiments.

An HIL test bed was constructed that employs power and controller hardware to represent the microgrid's dispatchable energy resources—a large PV plant, substation battery energy storage system (BESS), and diesel generator controllers—and other circuit components are virtually represented in a model executing on digital real-time simulators (DRTSs). This test

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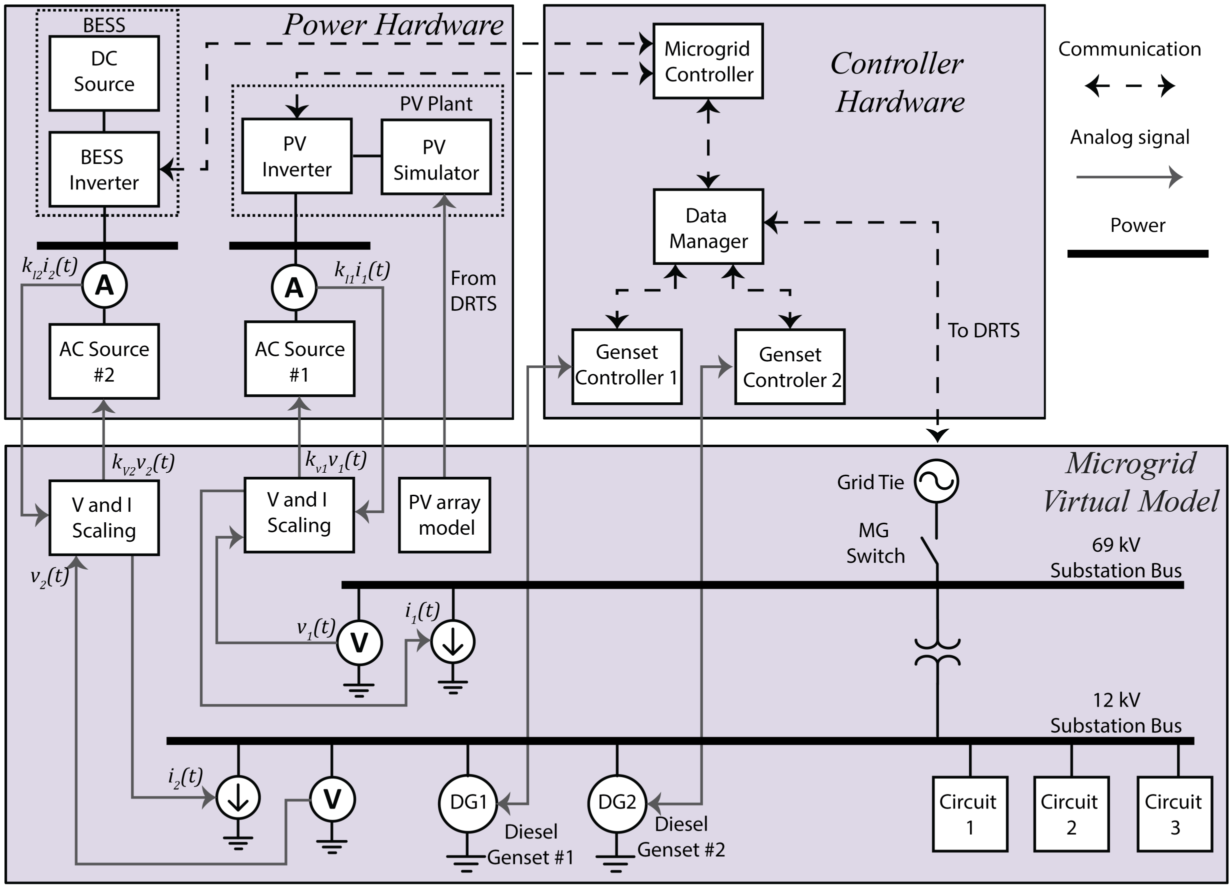

Fig. 1. HIL platform for site-specific microgrid controller evaluation

bed builds on prior development work [8] that implemented PHIL simulation for a BESS and extends it to PHIL simulations of both a BESS and a PV inverter. It also adds CHIL simulation of two diesel generator controllers. The microgrid controller used in the field is integrated with the test bed using CHIL simulation techniques. The microgrid controller actively monitors and controls the power and controller hardware and the virtual components modeled on the DRTSs. The goal of the HIL simulation is to evaluate the performance of the microgrid controller, particularly with regard to its management of disconnection and reconnection of the microgrid to the utility and its management of dispatch during grid-connected and islanded modes of operation.

The contributions of this paper are as follows: The paper (i) describes the HIL test bed that accommodates multiple power hardware (two inverters at 0.5-MVA each, combined to reach 1-MVA power hardware capability) and controller hardware (diesel generator controller and microgrid controller); (ii) outlines the technical challenges and solutions for building the HIL test bed; (iii) explains the test cases that can be used to evaluate microgrid controllers for microgrids; and (iv) presents results from the evaluation of a microgrid controller's capability to operate the microgrid.

II. Experimental Setup

This section describes the HIL evaluation platform, which includes the model used for the real-time simulation, controller equipment connected in CHIL, and power equipment connected in PHIL. A functional block diagram of the HIL evaluation platform that is set up to represent the Borrego Springs microgrid site is shown in Fig. 1. It consists of DRTS racks that model the microgrid, the microgrid controller, diesel generator (genset) controllers, a PV inverter and a battery inverter, and the hardware/software interfaces among the DRTSs and the hardware.

A. Background on the Microgrid Under Study

The Borrego Springs community microgrid is the largest utility-owned microgrid. It is operated and owned by San Diego Gas & Electric Company [1], and it has a very high penetration of renewable generation. This community is located 90 miles northeast of San Diego, California, and it is served by a single transmission line that is subject to extreme wind, heat, and storms, leading to power outages. The microgrid delivers increased resilience to customers (approximately 2,500 residential and 300 commercial and industrial customers) within the community. The peak load is approximately 12 MW, which is served by two 12.5-MVA transformers that feed three 12-kV circuits. The substation also has one 6-MVAr capacitor bank connected at 12 kV for volt-ampere reactive control. In addition to this capacitor bank at the substation, all three feeders have capacitor banks distributed for voltage support. The microgrid includes multiple nondispatchable distributed energy resources (DERs), including a 6.5-MWac concentrating

TABLE I. HIL HARDWARE COMPONENTS

Functional component	Specification
Controllable AC sources/sinks (AC power amplifiers)	Two, 0.540-MVA each, bidirectional, 0–600 Vac
Controllable DC source/sink (DC power amplifier)	0.660-MW bidirectional 0–1000 V
BESS inverter (battery inverter)	0.540-MVA bidirectional, 300 Vac, 440–885 Vdc
Controllable DC source (PV array simulator)	1.500-MW, 0–1000 Vdc
PV inverter	0.550 MVA, 270 Vac, 430–820 Vdc
Diesel generator controllers	Control diesel generators in grid-connected and islanded operation
Data manager	Compatible with DNP3, Modbus, and IEC protocol
Microgrid controller	Dispatch in grid-connected & islanded mode, islanding and resynchronization

photovoltaic (CPV) system, rooftop PV systems (3 MWac total), and three distributed BESS (0.075 MW, 0.150 MWh total). When islanded, the microgrid controller will dispatch a large (26-MWac) PV system, two 1.825-MW diesel generators (DG1 and DG2), and a substation BESS (1 MW, 3 MWh total). Another BESS with a rating 0.5 MW with 1.5 MWh will be added later. In islanded mode of operation, the entire community load can be served during the daytime when there is abundant generation from PV, but at night, only critical loads can be served using the diesel generators and BESS. The details of the hardware components used in the setup is shown in Table I.

B. Microgrid Virtual Model

Fig. 1 shows a simplified diagram of the full microgrid model, which is run in the DRTS in real time. The microgrid model includes the diesel generator models, capacitor banks in the distribution system with capacitor bank controllers, POI circuit breaker with a synchronization check relay, distribution lines, and programmable software load models distributed across three circuits in the system. For the programmable loads, we used the net load measurement at the three circuits. This net load includes the load, rooftop PV, and CPV. The BESS and the large PV system are replaced with current injection models that represent the measured currents from the power hardware. The HIL evaluation platform can execute the microgrid model with a minimum time step on the order of a hundred microseconds, view system behavior in real time, and save the data for post-processing. Data are collected during the testing using software metering points inside the virtual microgrid system model. Data are accumulated from the real-time simulation as a time series, collected for the duration of the test and stored in a structured file (e.g., comma-separated values file).

The DRTSs also output signals to and receive inputs from the microgrid controller, the genset controllers, and the PV and battery inverters in real time, providing for a closed-loop HIL simulation of these hardware and the microgrid power system. The microgrid controller interacts with both the hardware and virtual components of the microgrid model. A data manager is used to exchange information between the virtual microgrid model within the DRTS and the microgrid controller and the diesel generator controller, as shown in Fig. 1. The data manager is an off-the-shelf, commercial device that has the capability to communicate using multiple protocols with multiple devices.

C. Controller Hardware in the Setup

A microgrid controller and two diesel generator controllers are included in the HIL evaluation platform.

1) Diesel Generator Controller: Commercial, off-the-shelf diesel generator controllers are used to control the diesel generators simulated in the model. The controllers are the same model as the diesel generator controllers in the field. The controllers can operate the diesel generators in grid-connected PQ mode and also in droop-based voltage and frequency master mode. The CHIL setup for the diesel generator controllers is described in [13].

2) Microgrid Controller: The final piece in the CHIL setup is the microgrid controller under evaluation. It is a mature, commercially-available microgrid controller that was configured to interface with the virtual and hardware components of the HIL evaluation platform. The microgrid controller under evaluation can island, resynchronize, and dispatch under grid-connected and islanded modes of operation. Its control algorithms can perform cost-optimized dispatch to meet load. It can manage peak demand and shift load based on time-of-use pricing using on-premise generation—conventional and renewable—and storage. It further dispatches resources to maintain frequency and voltage of the system while maintaining adequate spinning reserves to account for load and generation fluctuations. It also offers functionality to black-start a microgrid in the event of an outage.

D. Power Hardware Setup

In addition to the controller hardware in the HIL setup, two units of power hardware were used in the HIL setup. The power hardware replicated the capabilities of the power hardware in the field. The first is a PV inverter with a rating of 0.500 MVA. The second is a battery inverter with a rating of 0.540 MVA. The measurements from the experimental setup were scaled up to represent the 26-MW PV inverter and the 1-MW BESS inverters in the field.

1) PV Inverter: The PV inverter used in the experiment is an SMA inverter with a rating of 0.5 MVA that represents the large 26-MW PV system. The inverter used in the HIL setup is the same model with the same firmware and ride-through settings as the inverters in the field. The DC side of the PV inverter is connected to a controllable DC source. The operating DC voltage and current set points are sent through analog channels from a PV panel model in the DRTS. The grid-side voltage is controlled from the voltage measurement at the POI for the PV inverter. The real power set point from the microgrid controller is sent to the PV inverter through a DNP3-Modbus connection with the microgrid controller via the data manager.

2) Battery Inverter: The battery inverter is representative of but not identical to the inverters in the field. For the battery inverter, the DC-side voltage is controlled by a bidirectional DC source. The AC-side voltage is controlled by the measured voltage at the POI for the battery inverter. The real and reactive power set points from the microgrid controller are sent to the

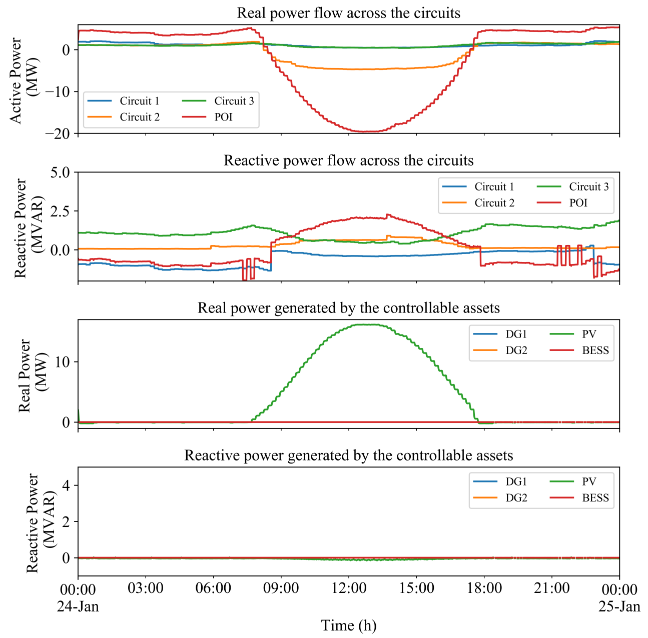

Fig. 2. Results for baseline test case with programmed load profile and solar profile in the HIL platform

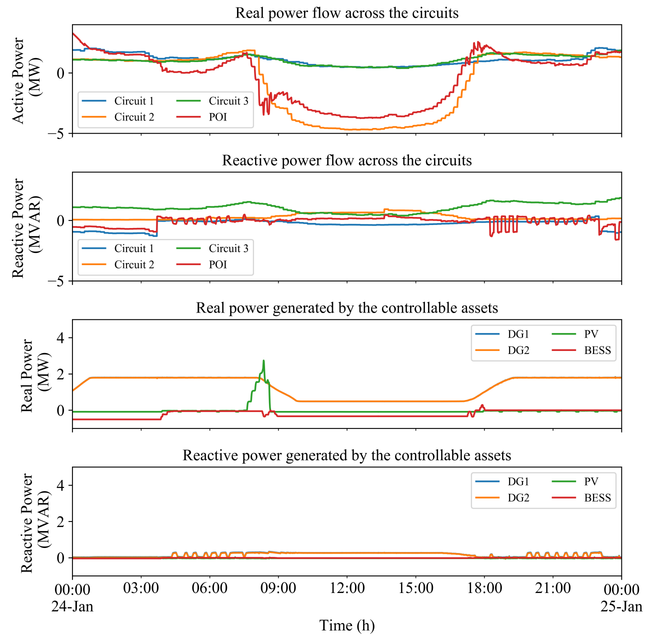

Fig. 3. Results for grid-connected dispatch test case evaluated in the HIL platform

battery inverter through a DNP3-Modbus connection with the microgrid controller via the data manager, as described in [8]. With two units of power hardware included in the evaluation platform, proper design of the PHIL interfaces is critical to ensure stable operation. Compensators based on the design described in [9] are used for the power inverter interfaces and stable operation is achieved over the entire operating range of the battery inverter; however, the PV inverter becomes unstable at about one-third of its power rating, and this was found to be because of the high scaling factor—from 500 kW to 26 MW (52 times)—which results in significant amplification of the harmonics from the real inverter. This is addressed by using the calculated power based on the voltage and current measurements from the inverter to control the current source in the simulation instead of directly using the current measurement.

III. Test Cases and Results

Multiple test cases are performed as part of the site-specific evaluation, and results from all test cases are provided in [11]. The test cases include and expand on those described in [8], [10]. The test cases were developed prior to the publication of IEEE 2030.8 [6], so we did not have the benefit of following industry standards during development. Our test cases are designed to evaluate the functionality of the microgrid controller under a grid-connected scenario and an islanded scenario and the transitions between them. This paper presents the results from the four test cases to demonstrate the capabilities of the HIL evaluation platform. All the test cases are run in the HIL platform with the 1-MVA power hardware and the controller hardware. The following four test cases are discussed:

- Normal grid-connected operation with nondispatchable generation (baseline case)
- Dispatch in grid-connected mode of operation
- Dispatch in islanded mode of operation
- Resynchronization from islanded mode to grid-connected mode

A. Normal Grid-Connected Operation with Nondispatchable Generation

This is the baseline scenario. In this test case, the load profile and the solar profile are programmed in the virtual microgrid model. The microgrid controller is kept idle. The dispatchable generators and BESS are also kept idle, and the 26-MW PV plant is modeled as a nondispathcable asset, along with the distributed rooftop PV plants and the 6.5-MW CPV plant. Fig. 2 shows the results from the baseline experiment. The genset controllers are not activated in this test case to understand the performance of the system in the absence of dispatchable assets. In this test case, the HIL component is the PV inverter emulating the 26-MW plant. The solar insolation profile programmed as an input to the PV panel model in the DRTS is based on the profile from January 24, 2016, at the microgrid site. There are no clouds present on this day, and the peak power output is around 65% of the rated power output. The real power flow to Circuit 2 indicates that the distributed PV and the CPV system are generating real power that is fed back into the grid. The reactive power flow to Circuit 1 indicates that the capacitors on this circuit are connected and providing reactive power to the rest of the system. At noon, because of the significant real power flowing from Circuit 2, the voltage becomes higher, and the capacitor banks on Circuit 1 turn off. Because controllable assets DG1, DG2, and BESS are turned off, there is no power generation from them.

B. Grid-Connected Dispatch

In this scenario, the microgrid switch is kept closed, and the community microgrid is connected to the external utility,

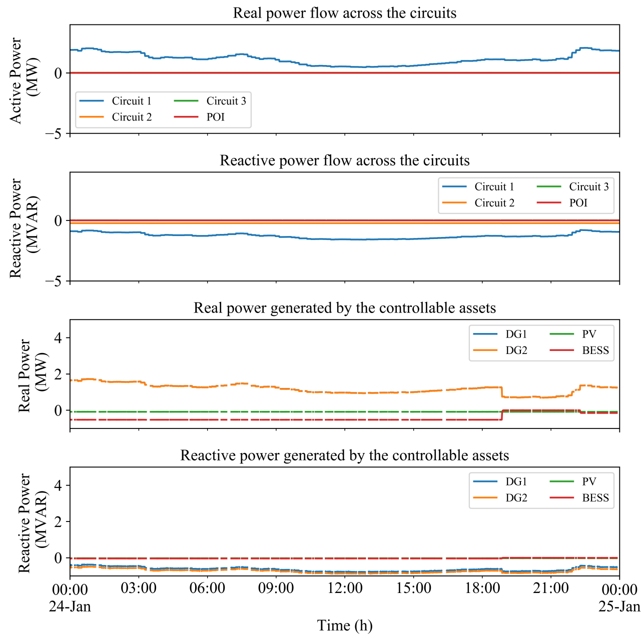

Fig. 4. Results for islanded dispatch test case evaluated in the HIL platform

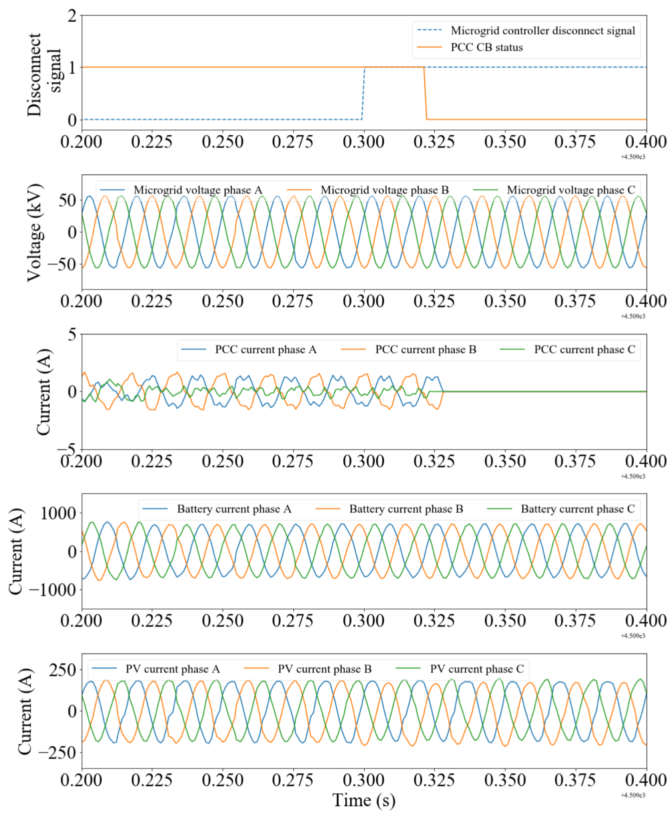

Fig. 5. Results from successful islanding of the microgrid evaluated in the HIL platform

which effectively controls both voltage and frequency in the microgrid. The microgrid controller is set to regulate the power flow across the POI to zero. Fig. 3 shows the grid-connected dispatch results. The same load and solar insolation profiles

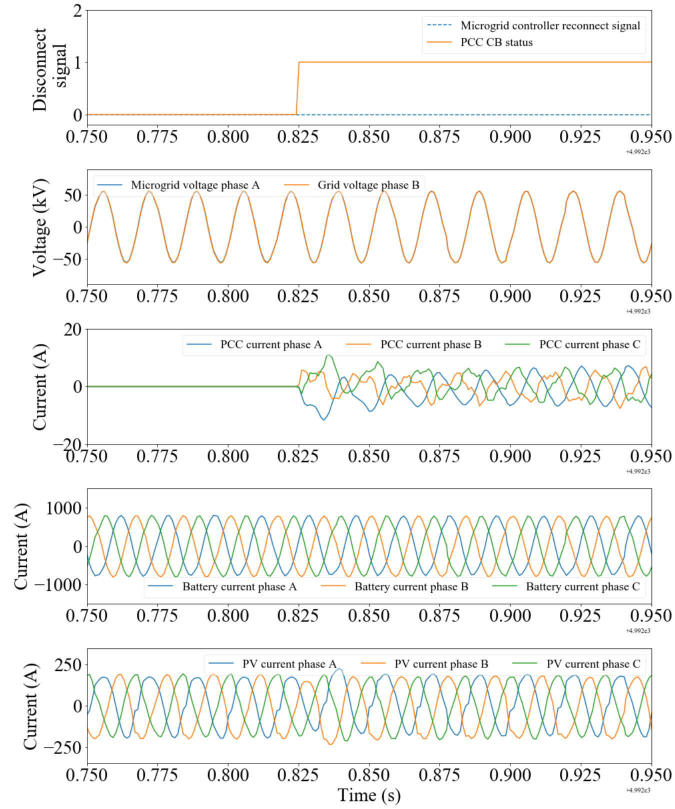

Fig. 6. Results from successful resynchronization of the microgrid evaluated in the HIL platform

used for the baseline case are used, and therefore the real and reactive power flow to the circuits look very similar to the results shown in Fig. 3. The reactive power support from the capacitor banks in Circuit 1 turns off earlier than shown in Fig. 2. This is caused by the reactive power support from the distributed generation as dispatched by the microgrid controller. Fig. 3 also shows that the microgrid controller stopped dispatching the large PV plant and relied on the real power injection from Circuit 2 during the middle of the day.

C. Islanded Dispatch

In this test case, the microgrid is operated in islanded mode. Operation of the HIL platform in islanded mode is achieved by starting in grid-connected mode and then islanding with the use of the microgrid controller. The same load and solar insolation profiles are used as in the baseline; however, the assets available during nighttime (DG1, DG2, and BESS) will not be able to support the load. Thus, Circuit 2 and Circuit 3 are removed from the microgrid, and only Circuit 1 is powered. DG1 and DG2 maintain the voltage and frequency of the microgrid, and the rest of the assets are dispatched by the microgrid controller to meet the real and reactive power load. The two diesel generator assets support most of the load in this case. The battery is charging for most of the time, and PV is not dispatched because the loads in Circuit 1 can be supported by the two diesel generators.

D. Planned Islanding

The goal of this experiment is to test the ability of the controller to successfully separate the target microgrid from the external utility as part of the planned operation. A static load is programmed while the microgrid controller is islanding the system. Although the DRTS model reflects the real microgrid, in the field there might be additional transients while the islanding or resynchronization happens. To achieve successful islanding, the microgrid controller would need to minimize the real and reactive power flow across the POI and then open the POI circuit breaker for minimum transients. The results shown in Fig. 5 indicate that the POI current is minimal just before islanding, and there is no impact on the PHIL current. During and after islanding the microgrid, there are minimal transients in the PHIL current and in the POI current.

E. Resynchronization

The goal of this experiment is to validate the ability of the microgrid controller to reconnect the (islanded) microgrid to the utility following the restoration of utility service. It must resynchronize the microgrid to the external utility and maintain conditions in the range specified during reconnection. Then, the controller should restore the microgrid to normal grid-connected operation following reconnection. In this test case, the island is resynchronized to the main grid using the evaluation platform. As shown in Fig. 6, in this experiment the transition occurrs seamlessly. There are very minimal transients in the PHIL current and minimal transients in the POI current. This can be observed in Fig. 6.

IV. Conclusion

An HIL test bed to evaluate the performance of a microgrid controller was built in the Energy Systems Integration Facility at the National Renewable Energy Laboratory. This work used site-specific models that determine the microgrid performance and thus the controller evaluation. The setup further used either the same or representative hardware compared to that deployed in the field as well as the same communications protocols as those used in the field. This paper presented an overall approach to the design of an HIL setup to perform site-specific evaluations of microgrid controller performance and referred the reader to previously published works on specific aspects of the HIL setup. The HIL setup could be used by a utility to run scenarios that can provide useful feedback. This paper also presented a subset of the test cases evaluated using the test bed and results for these test cases.

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