Remote Hardware-in-the-Loop Approach for Microgrid Controller Evaluation

Preprint

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Remote Hardware-in-the-Loop Approach for Microgrid Controller Evaluation

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***Abstract*—Utilities have been installing microgrids because of the increased resilience and reliability advantages they may provide to the distribution system. A microgrid controller is a critical component in microgrids. It is of great benefit to derisk the installation of microgrid controllers before field deployment. Hardware-in-the-loop (HIL) testing is used by controller developers and utilities to evaluate the controllers under stressful conditions. In this work, a microgrid control function developed by the Synchrophasor Grid Monitoring and Automation (SyGMA) laboratory at the University of California, San Diego is tested in a remote HIL (RHIL) setup. The digital real-time simulation of the detailed microgrid system was operated at the National Renewable Energy Laboratory's Energy Systems Integration Facility. Under such RHIL setup, successful controller operation is contingent on understanding and characterizing the communications channel and in particular network latencies. The novelty of this paper is the proposed use of a RHIL setup that leverages existing power system communications protocols to evaluate the controller in conjunction with the simulation capabilities of a remote facility. The work presented here will provide the complete setup of the HIL evaluation platform, the details of the communications protocols used by the setup for data transfer between the two organizations, test cases developed to evaluate the controller, and the results from the experiments.**

***Index Terms*—microgrids, microgrid controller, hardware-in-the-loop, controller hardware-in-the-loop, remote hardware-in-the-loop, IEEE 2030.7, IEEE 2030.8.**

I. Introduction

Microgrids are gaining increasing adoption by utilities because of the advantages they may provide to the utility as well as the microgrid user [1]. Microgrids improve the resilience of the system because of their capability to isolate themselves from the grid and run in islanded mode of operation. Microgrid controllers are energy management systems that enable smooth operation of microgrids under various operating conditions, including different levels of load and distributed energy resource (DER) availability [2]. Hence, such controllers are pivotal to reliable and economic microgrid operation [3]. Evaluating microgrid controllers in a controlled laboratory environment is crucial to derisking the installation of such controllers in the field, and standards have been developed to aid their evaluation [4]. Hardware-in-the-loop (HIL) testing is an effective approach to evaluating controllers prior to field deployment [5]. This approach has been used in various applications to evaluate controllers [6], [7], protection schemes, and distribution management systems.

One challenge faced by controller developers is the costly and intensive nature of the microgrid controller HIL testing process. Digital real-time simulators (DRTS) and models of microgrids that need to be developed in them are often resource-intensive and costly. To address this, remote power HIL (RHIL) approaches have been proposed in the literature. In [8], [9], power HIL experiments were conducted between two facilities located geographically apart. The effect of delays in RHIL was studied in [10]. The importance and use of RHIL facilities distributed geographically were shown in [11] along with cosimulation test cases.

This paper proposes an RHIL architecture to evaluate a microgrid control function developed and located at a remote facility and that communicates with the simulator over the Internet. This architecture leverages the capability of the digital real-time simulator (DRTS) and existing Internet Protocol- (IP-) based power system communications protocols for the evaluation. The setup uses IEEE C37.118 [12] to send the state of the microgrid from the DRTS to the microgrid control function and uses Modbus to send control set points to the DERs and the point of interconnection (POI) circuit breaker. This is a crucial difference from other architectures that use custom communications protocols to enable feedback between simulators in multiple locations.

In the proposed Internet-based communications HIL setup, communications delays could become a defining factor because of the closed-loop nature of the control system. In such systems, delays are inevitable, and therefore it is imperative to characterize the existing delays to guarantee the stability and

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performance of the controller under delayed communications. Once delays are characterized, a controller is designed to achieve the objective of following the requested power flow set points at the POI by coordinated dispatch of the available DERs. We present a control architecture designed for this purpose. The team evaluated the microgrid control function using the proposed setup from two locations that are geographically apart.

The rest of this paper is organized as follows. Section II presents an overview of the experimental setup, including the microgrid model used in the DRTS, operational limits of the DERs, and the feeder circuitry programmed in the system. Section III presents the details of the communications and the delay characterization of the RHIL setup. Section IV presents the microgrid control objectives. Section V presents the details and results of the evaluated test cases. Finally, Section VI concludes the paper.

II. Experimental Setup

The experimental setup has three main elements, as shown in Fig. 1. The DRTS is located at the National Renewable Energy Laboratory's (NREL's) Energy Systems Integration Facility (ESIF) in Colorado. First, the DRTS simulates the microgrid model in real time. This model contains the DER, models—including two diesel generators (DGs), two battery energy storage systems (BESS), and one photovoltaic (PV) plant—as well as distribution lines, substation transformers, and existing measurement devices. Second, the microgrid control function regulates and coordinates the operation of the DERs and, finally, the communications channel through which the DRTS facility communicates with the microgrid control hosting facility. The microgrid control functions developed by the University of California, San Diego (UCSD) Synchrophasor Grid Monitoring and Automation (SyGMA) laboratory are implemented in a MATLAB® Simulink® environment located at the SyGMA laboratory in San Diego.

Fig. 1 shows the microgrid model simulated in the DRTS. The microgrid consists of a large 26-MWac PV system, two 1.825-MW diesel generators, one 1-MW substation BESS (3 MWh), and another substation 0.5-MW BESS (1.5 MWh). There are three feeder circuits in the microgrid. The peak load of the microgrid is approximately 12 MW. All three feeders and the substation have capacitor banks, and their local controls are programmed in the DRTS model [7]. Finally, the loads and the solar irradiance are programmable through the scripting capability of the DRTS. The programmed load profile and the PV profile are shown in Section V. The microgrid under study is operated and owned by San Diego Gas & Electric Company [13]. More details on this microgrid can be found in [7]. Fig. 1 shows the location of the seven phasor measurement unit (PMU) devices that send information to the microgrid control function implementation through C37.118 protocol. PMU 1 and PMU 2 send positive-sequence voltage and current phasors on both sides (utility side and microgrid side) of the breaker, frequency measured on both sides, phase angle difference, and, finally, the breaker status. PMU 3 and

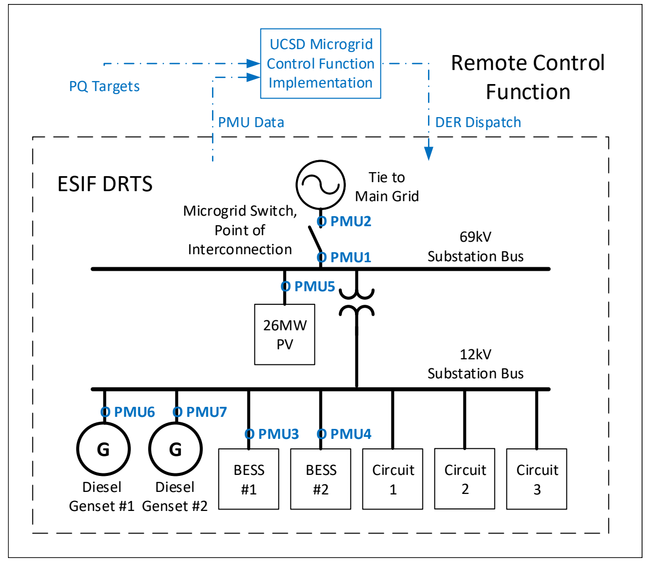

Fig. 1. RHIL setup for microgrid evaluation

PMU 4 send positive-sequence voltage and current phasors at the terminals of the BESS connection along with the state of charge and real and reactive power measurements. PMU 5 is used at the terminals of the PV inverter and sends positive-sequence voltage and current phasors, real, reactive power injection, and the solar irradiance at the inverter location. PMU 6 and PMU 7 send positive-sequence voltage and current phasors at the terminals of the diesel generators along with the real, reactive power injection and the measured power factor. All the PMU signals are sent at 60 samples per second from NREL to UCSD over Internet communications. Use of the already existing protocols helps eliminate the need to develop new protocols to communicate the information needed by the microgrid controller.

Since the information communicated by the 7 PMUs are not redundant, the loss of communication with any PMUs could potentially lead to the controller failing to meet the objectives. However, if there is a need to reduce the amount of high update rate communication with the PMUs due to bandwidth considerations, the PMUs associated with diesel generators (PMUs 6 and 7) could be programmed at a lower data communication rate. This can be made possible due to the slower dynamics of diesel generator assets that a lower update rate control loop could provide equally good performance for those assets.

III. Internet Communications and Delay Characterization

A. Internet Communications Protocols Implementation

The communications between the DRTS and the microgrid control function are performed over the Internet (Transmission Control Protocol [TCP]/IP) through a Virtual Private Network using the two communications protocols of Modbus and C37.118. This is shown in Fig. 2. The communications protocols are implemented in Simulink by creating standard

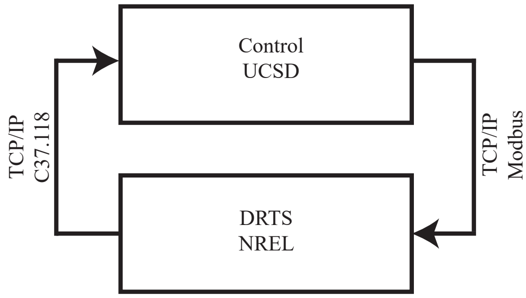

Fig. 2. Communication schematic for the HIL test bench

TCP/IP clients and performing the standard packing/unpacking for each protocol. To satisfy the desired control performance, it is imperative to run the control functions in real time because the modeled microgrid in DRTS runs in real time. This is accomplished by using the Simulink real-time environment. The C37.118 protocol is used for synchrophasor data communications from the PMUs to the microgrid control function. The use of synchronized data is particularly important in this project because of possibly different DER locations and the need for synchronized data in advanced control functions. PMUs are installed at different, possibly distant, points within the microgrid, including at each DER connection and at the POI of the microgrid. These PMUs use a common time source for synchronization provided by GPS, thereby providing synchronized real-time measurements of voltage and current phasors across the microgrid. Such synchronized measurements can be used by the microgrid control function even at the update rate required for precise power flow control. Synchrophasor data are transferred to the microgrid control function and used for active and reactive power control as well as frequency control. The microgrid control function receives PMU data packets in the Simulink environment and then performs the rest of data extraction process. Modbus communications are used to send dispatch commands to the DERs simulated in the DRTS.

B. Delay Characterization and Measurement

If delays in the system are not accounted properly, performance of any feedback control loop could deteriorate and push the system to unstable mode of operation. For network-based controls, delays are inevitable, and it is imperative to characterize the existing delays to guarantee the stability and performance of the microgrid control function even under the worst delay scenario. For the considered microgrid HIL testing, three sources of delay are considered:

- d_1: Internal delays within the digital simulator caused by DER input delays, measurement delays, and other device delays
- d_2: Protocol conversion delays for communications with the digital simulator
- d_3: Network communications delays caused by the remote communications between the digital simulator and microgrid control function over the Internet

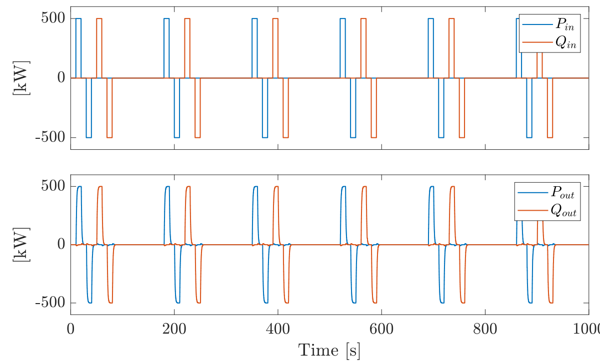

Fig. 3. Input real and reactive step signals sent by the microgrid control function (top) and the resulting inverter output power received by the microgrid control function(bottom)

d_1 could vary for different devices within the model, whereas d_2 could be dependent on the protocols used for each communication. The communications delay d_3 could also be dependent on network congestion and should be tested for worst-case consistency. We define the total system delay as the sum of these three contributions $d = d_1 + d_2 + d_3$ and try to characterize these delays by performing a number of experiments and measuring the round-trip delay between the moment the input is sent from the microgrid control function and the instant the measured response is received by the microgrid control function. To characterize this delay, we focus on the delays pertaining to the inverter-based DERs because the microgrid control function will demand the fastest response from those DERs and therefore communication between the microgrid control function and inverters could determine the overall closed-loop stability and performance.

Step response experiments: To characterize the delay and response of inverter-based DERs to input commands as received by the microgrid control function, a number of input excitation experiments are designed and implemented. The step input experiment is designed to measure the round-trip delay as well as real/reactive coupling of the inverters. In this experiment, successive positive and negative steps are sent to each inverter independently for real and reactive power. The input sequence is shown in Fig. 3 - top. The response received by the microgrid control function is shown in Fig. 3 - bottom and indicates the effects associated with the overall delay (d) as well as the dynamic response of the considered inverter system.

Fig. 4 further indicates the dynamic coupling between real and reactive power. Realization-based estimation algorithms are used to determine models for the measured inverter response that also capture the delay [14]. Fig. 5 shows the zoomed in input step excitation and the delay observed. Application of the realization method described in [14] to the measured input-output response would result in the following multiple-input and multiple-output (MIMO) transfer functions:

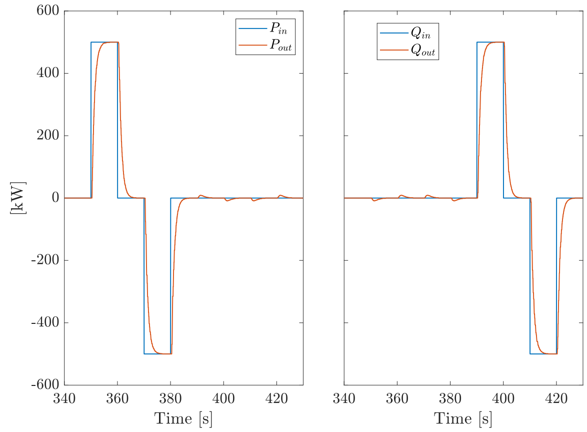

Fig. 4. The step experiment indicates the existing dynamic coupling between real and reactive power

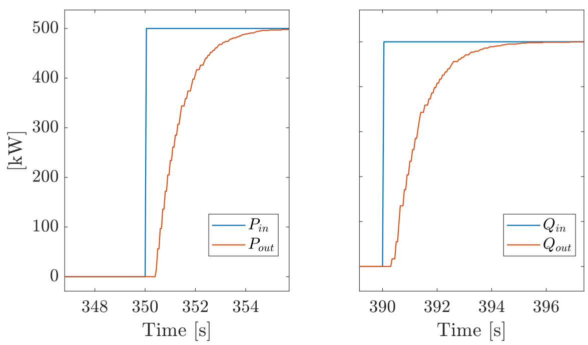

Fig. 5. Input step excitations designed to characterize total network and dispatch delay as observed by the microgrid control function

$$P_{out} = z^{-8}\left[\frac{0.05z^{-1} - 0.047z^{-2}}{1 - 1.9z^{-1} + 0.9z^{-2}}P_{in} + \frac{0.002z^{-1} - 0.002z^{-2}}{1 - 1.9z^{-1} + 0.9z^{-2}}Q_{in}\right]$$

$$Q_{out} = z^{-8}\left[\frac{-0.002z^{-1} + 0.002z^{-2}}{1 - 1.9z^{-1} + 0.9z^{-2}}P_{in} + \frac{0.05z^{-1} - 0.047z^{-2}}{1 - 1.9z^{-1} + 0.9z^{-2}}Q_{in}\right] \quad (1)$$

As shown in the MIMO transfer functions, the identified models captured eight steps of delay as well as some dynamic coupling between real and reactive power. Figure 6 demonstrates and compares the estimated model versus validation data for real and reactive power. The normalized root mean square errors (NRMSE) measure of the fit between simulated response using the MIMO model (estimated) and measurement data are 98.0% and 98.1% for real and reactive power respectively. Through several experiments, it is found that the round-trip communications can be achieved consistently with eight steps of delay, and therefore this number of steps should also be considered in the design of the microgrid control function.

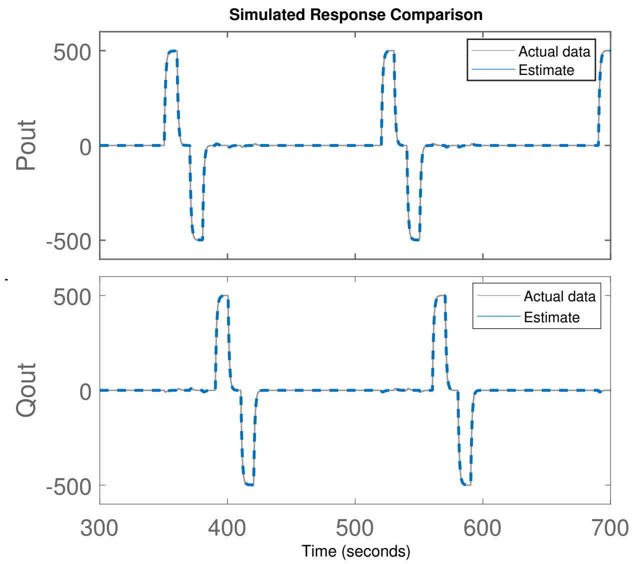

Fig. 6. Simulation of the estimated dynamic model between power set points and power measurements as observed by the microgrid control function. Comparison between the estimated model and actual test data verify eight steps of delay with an update rate of 20 Hz

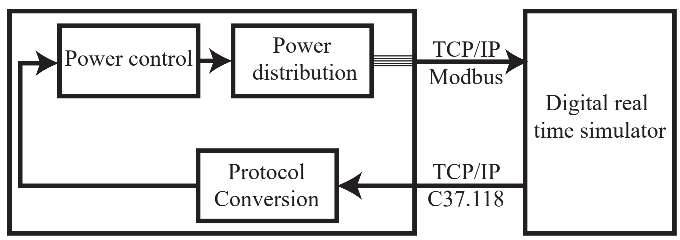

Fig. 7. Schematic of the microgrid control function and its communication with the DRTS over the Internet. The microgrid control function consists of two internal stages of power control and power distribution between the DERs.

Fig. 6 shows both actual test data and the identified model, and these two almost overlap. Also, the legend shows the NRMSE measure of the fit between the simulated response and measurement data.

The control objectives as explained in this paper are expressed in a rather qualitative manner as the specific controller design parameters are not discussed. The level of delay at which the control objectives are no longer achievable depends on the exact objectives defined and the weighting of the objectives in the cost function. For the experiments discussed in this paper, the objectives were reachable in the presence of the time delay that was normally observed in the connection. However, the maximum delay at which the controller will fail to reach the objectives was not investigated. For connections with large values of delay that may considerably deteriorate the performance of the control loop, using Smith predictor to design the control loop might provide better performance.

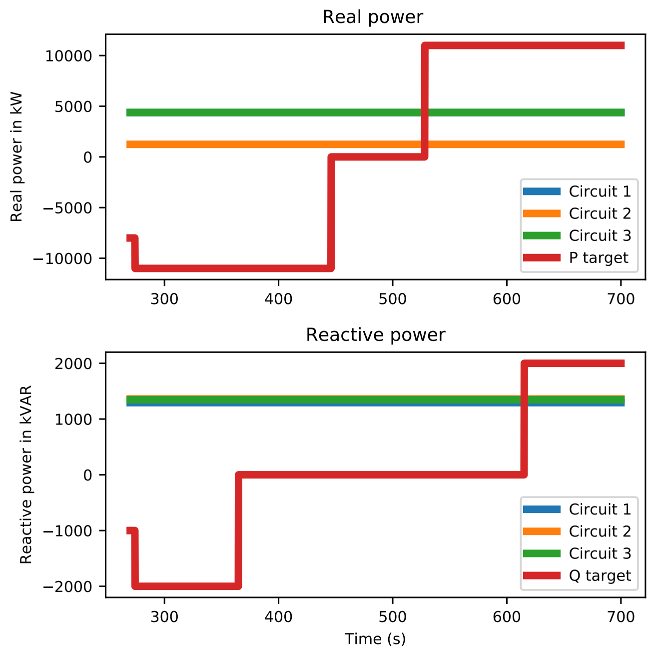

Fig. 8. Load set points and POI power flow set points for Test Case 1

IV. Overview of Control Objective and Architecture

A microgrid control system should be designed to satisfy requested performance criteria under a variety of different test cases. This section presents an overview of the control objectives and the controller architecture. Further details on the control design and implementation will be provided in a follow-up manuscript. The control objectives comprise satisfying the reference power flow at the POI of the microgrid subject to the operational limits of the DERs and within tolerable voltage and frequency bounds. The microgrid control function should meet these objective by dispatch of the available DERs, i.e., PV, diesel generators, and energy storage. The microgrid control function is divided into two separate subsystems of power control and DER power distribution. At the first stage, the total dispatch required by all DERs to meet the reference POI power is computed. In the next stage, this computed set point is distributed between the DERs while considering the operational limits of each DER. This is shown in Fig. 7. The following rules concern the microgrid control function decision-making at the stage of power distribution:

- PV power should be prioritized for supplying the load demand and meeting the POI power set point. PV use should be maximized unless more PV leads to a violation of the POI power set point. In this case, PV curtailment is allowed.
- In mitigating disturbances or meeting abrupt set point changes, the high ramp rate of inverter-based DERs should be used to mitigate POI power deviations from the set point.
- The state of charge of the energy storage systems should be maintained within certain limits to ensure a sufficient power margin for the controller to react to sudden power fluctuations.
- Under grid-connected operation, diesel generators are dispatched only to provide additional power to meet the POI power set point when all other DERs cannot provide the requested power.

To implement these conditions, a quadratic program is formulated with linear constraints. This quadratic program is solved in real time with an update rate of 10 Hz, and the result is then communicated to each DER controller over the Internet. The uncertainties in solar generation is compensated by allowing the controller to use non-renewable asset (diesel generator) whenever needed as well as by allowing energy storage to deviate from nominal SoC profile. The details of the controller are not discussed in this paper as the focus of this work has been to demonstrate the internet-based HIL and successful feedback communication over the Internet. Future work will discuss the details of the controller.

V. Selected Test Cases and Results

Multiple test cases are developed to evaluate the microgrid control function in the RHIL setup. In the test cases, the team used the scripting capability of the DRTS to program the load values (real and reactive power), solar irradiance, and, finally, real and reactive power flow set points for the microgrid control function to control at the POI. The set points were changed approximately every 2 to 3 seconds. Each test case was run for almost 300 seconds. In the test cases presented here, the microgrid was operating while connected to the utility. The test cases presented here were designed to demonstrate the microgrid control functions' capability to track the real and reactive power flow across the microgrid POI. In this paper, three test cases among the multiple test cases run are presented along with the results. These include:

- Test Case 1: Real and Reactive Power Tracking with High Load and High PV Generation
- Test Case 2: Real and Reactive Power Tracking with High Load and Low PV Generation
- Test Case 3: Real and Reactive Power Disturbance Mitigation with Low Load Variability and High PV Generation

A. *Test Case 1*

The load profiles and target power flows across the POI are shown in Fig. 8. A constant solar irradiance of 900 W/m^2 was used. In this test case, the real and reactive power starts with an export to the grid. Then there is a step change to make the POI power flow zero and then another step change to start importing power into the microgrid. The results from the experiments are shown in Fig. 9. The results indicate the set points and the actual values of the simulated power flow across the POI (P,Q) and the error between the PR,QR and the P,Q. They also show the set points and simulated power of the two distributed generators, the battery, and the PV. The

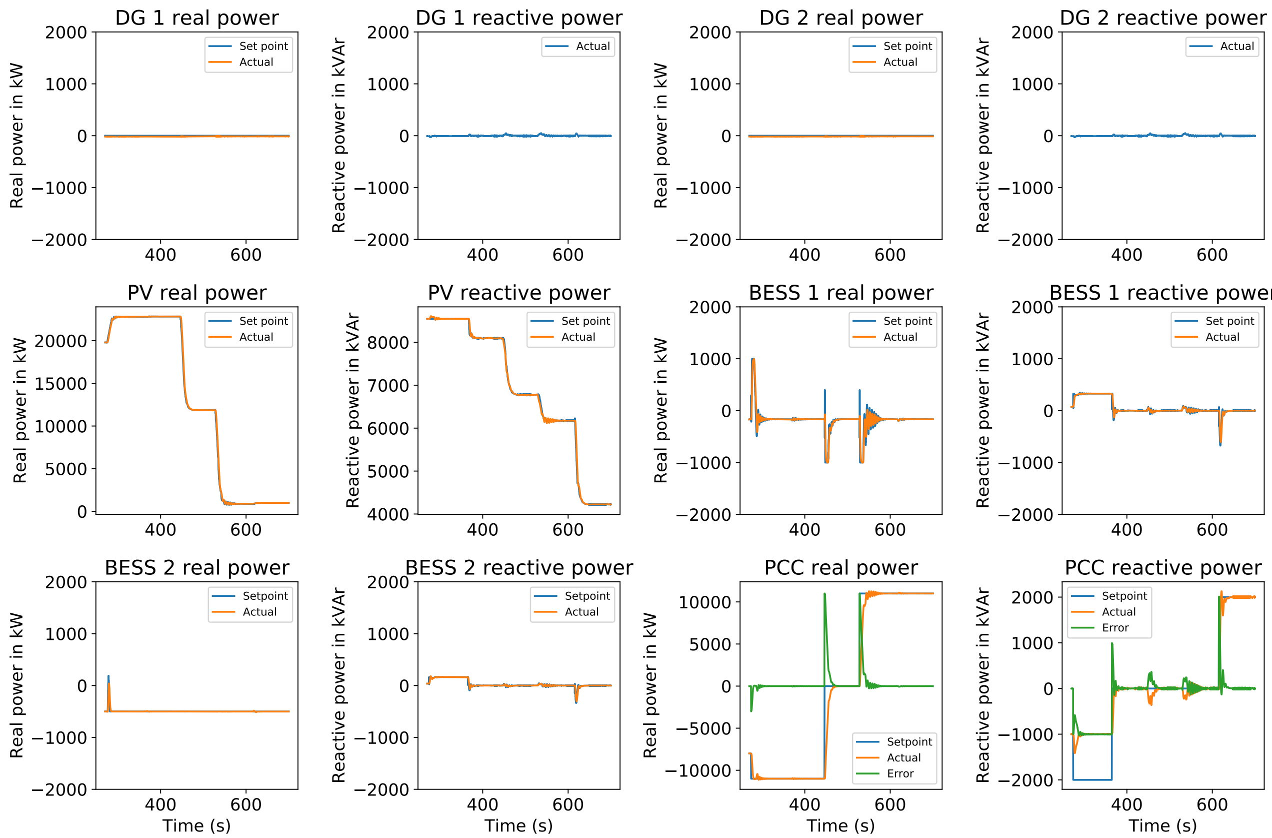

Fig. 9. RHIL results for Test Case 1

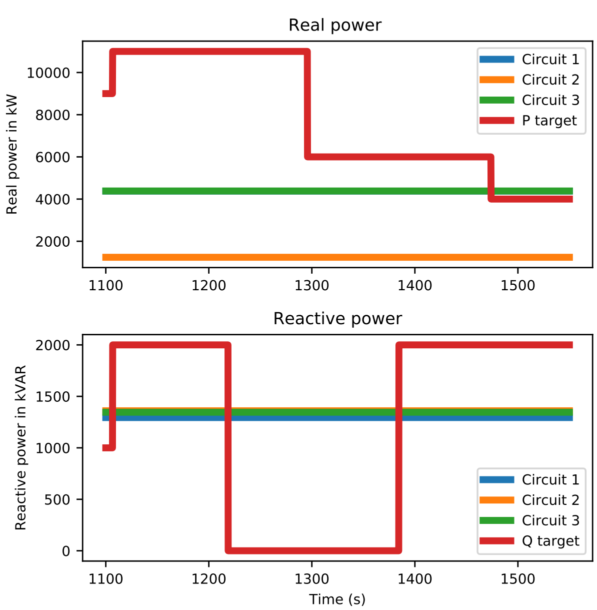

Fig. 10. Load set points and POI power flow set points for Test Case 2

microgrid control function was able to meet the real power set points throughout the experiment. The reactive power set point from 270 to 370 seconds was not met. It can be observed that the microgrid control function was dispatching all the assets to its max; however, the distributed generators were not able to provide any reactive power support because they were not dispatched to provide any real power. But once the set point was changed, the DERs were able to provide enough reactive power support to meet the set point. The instantaneous errors were up to 11 MW and 2 MVAR, respectively, and the root mean square errors (RMSEs) over the duration of the experiment were 1.583 MW and 0.484 MVAR, respectively.

B. Test Case 2

The load profiles and target power flows across the POI are shown in Fig. 10. A constant solar irradiance of 100 W/m^2 was used. The microgrid control function is able to track the reference signal, as shown in Fig. 11, with peak instantaneous errors of 5 MW and 2 MVAR, respectively, and RMSEs of 0.697 MW and 0.255 MVAR, respectively. The ramp rate of the distributed generators, which is accounted for in the microgrid control function, was a significant contributor to the active power error.

C. Test Case 3

The load profiles and target power flows across the POI are shown in Fig. 12. These load profiles have low variability. A constant solar irradiance of 900 W/m^2 was used so that the PV generation could be high, and therefore the PV was

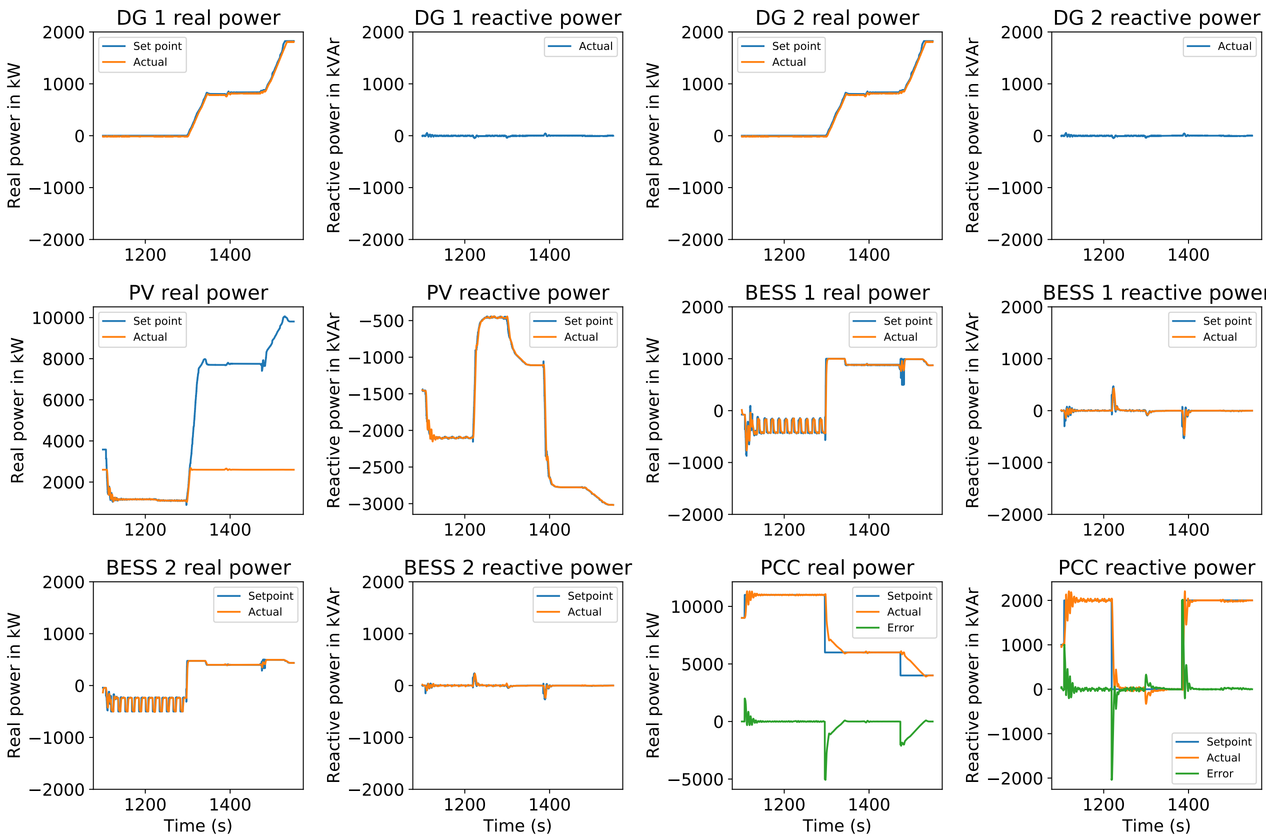

Fig. 11. RHIL results for Test Case 2

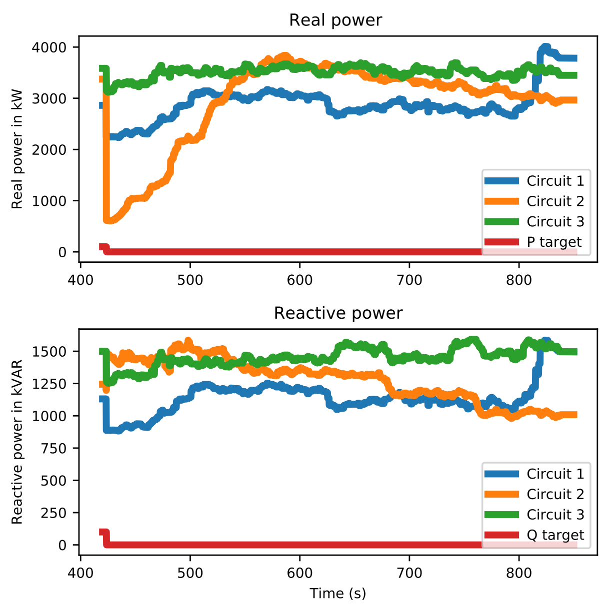

Fig. 12. Load set points and POI power flow set points for Test Case 3

primarily used to support the load. The microgrid control function was able to mitigate the load variability, as shown in Fig. 13 with peak instantaneous errors of 4 MW and 1 MVAR, respectively, and RMSEs over the test duration of 0.286 MW and 0.172 kVAR, respectively.

VI. Conclusion

In this paper, a remote HIL setup was implemented to evaluate a microgrid control function developed by the SyGMA laboratory at UCSD. The remote HIL setup consists of a DRTS running a simulation of the microgrid at NREL in Colorado, an implementation of the microgrid control function at UCSD in California, and an internet-based connection between these two location. The novelty of the approach is the use of power system communications protocols (C37.118) to exchange information between two different locations. By characterizing the effects of networked communications on the closed-loop feedback controller, a control system is designed that sends DER power commands to each simulated DER over the Internet and successfully achieves the objective of following the power set points. The remote controller-simulator setup is tested with three test cases, demonstrating successful power control at the POI of the microgrid.

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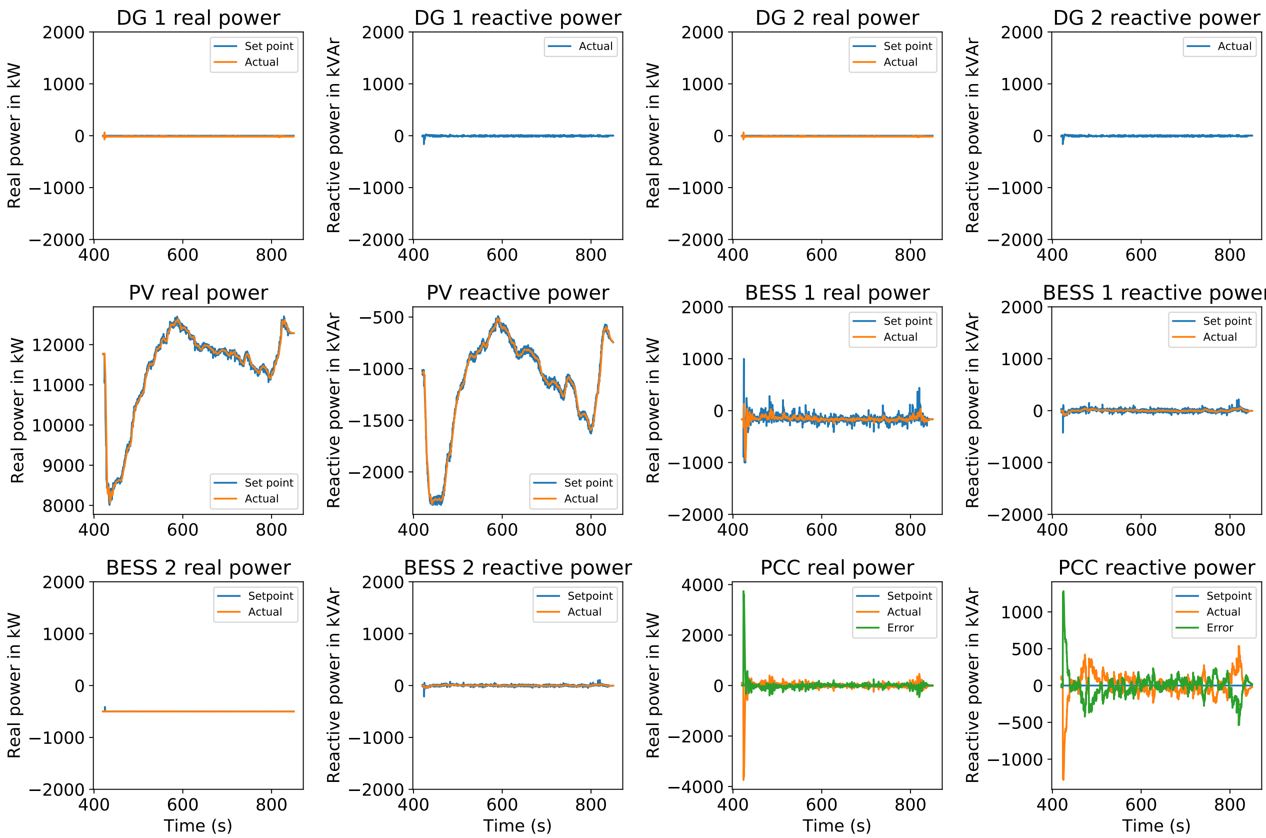

Fig. 13. RHIL results for Test Case 3

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