Performance Evaluation of Distributed Energy Resources Management System via Advanced Hardware-in-the-Loop Simulation

Preprint

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Performance Evaluation of Distributed Energy Resource Management via Advanced Hardware-in-the-Loop Simulation

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***Abstract*—This paper evaluates voltage regulation coordinated across advanced distribution management systems (ADMS), distributed energy resources (DERs), and distributed energy resource management systems (DERMS) using an advanced hardware-in-the-loop (HIL) platform. The HIL platform provides a realistic laboratory testing environment, enabling accurate dynamic modeling of a real-world distribution system from a utility partner, with real controller (ADMS and DERMS) and power hardware (DER) and standard communications protocols. The test results show proper performance of the voltage regulation by coordinated control systems and confirm correct functioning of the HIL platform. With this laboratory capability, utilities can test grid automation systems that can manage DERs to achieve system-level control and operation objectives (e.g., voltage regulation). This HIL testing capability will help mitigate risks of potential issues (e.g., instability) during field deployment.**

Index Terms--advanced distribution management system, distributed energy resource management system, hardware-in-the-loop, voltage regulation.

I. Introduction

Power systems are evolving toward massively distributed infrastructures with millions of controllable nodes [1]. Transformative changes are taking place particularly at the distribution level, where increasing numbers of renewable generation devices, energy storage devices, and flexible loads—collectively referred to as distributed energy resources (DERs)—are becoming prominent considerations. This requires operators and planners to modernize electric grids. The utility industry is exploring ways for leveraging DERs to enhance system operations, pave the way for distribution-level markets, and offer new services to customers [2].

Distributed energy resource management systems (DERMS) are emerging to aggregate, monitor, and control groups of DERs at the grid edge in a scalable way [3]. DERMS will interface with distribution management systems (DMS) in order to determine which distribution grid services are needed and DERMS provide the services as requested [4]. New integrated control strategies will be needed to coordinate DERMS with DMS in order to achieve system-level operation goals (e.g., voltage regulation, frequency regulation) through coordinated control and operation of DMS, DERMS, and DERs. Before deploying such an integrated system at a site, it is beneficial to perform laboratory hardware-in-the-loop (HIL) evaluation of the coordinated control to test the stability of the whole system, mitigate potential hazards or risk of hardware damage in the field, and increase confidence that the communications infrastructure works correctly and the desired control performance is achieved.

A test bed for evaluating coordinated control among ADMS, other utility management systems (e.g., DERMS), DERs, and legacy utility equipment controllers (e.g., capacitor bank and voltage regulator controllers) is described in [5]. This ADMS test bed provides a realistic laboratory testing environment, including real-time co-simulation of a distribution system, controller and power hardware, and industry standard communications protocols. The test bed was developed with funding from the Advanced Grid Research program of the U.S. Department of Energy Office of Electricity. We developed an advanced HIL platform by applying the capabilities of the ADMS test bed to simulate a utility power system with high penetration of photovoltaics (PV), integrate real controller (ADMS and DERMS) and power hardware (DERs), and to evaluate the performance of voltage regulation coordinated across the ADMS, DERMS, and DERs for this power system. This advanced HIL platform helps utility partners understand the benefits of adopting DERMS to manage large-scale DER integration and to mitigate risks of technology integration.

II. Overview of the HIL Setup

The advanced HIL platform simulates a utility distribution feeder in Colorado, part of the Holy Cross Energy (HCE) system. A co-simulation platform is used to simulate part of the feeder in OpenDSS and part of the feeder in OPAL-RT a digital real-time simulator. The DERMS includes a master controller and many distributed local controllers. The overall HIL setup is shown in Fig. 1.

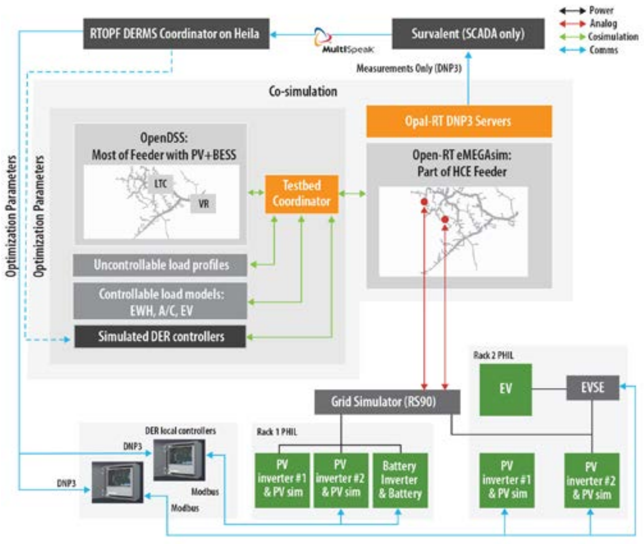

Fig. 1. Overall diagram of the HIL platform.

The main elements of the test bed are the co-simulation (OpenDSS, Test bed Coordinator, and OPAL-RT), controller HIL (Survalent ADMS, DERMS coordinator, and two DER local controllers), and power HIL (six DER inverters). The following sections explain each main element in detail along with the communications protocols and data exchanges between them.

A. Co-simulation

The co-simulation of the real-world distribution feeder includes both a quasi-steady-state time-series (QSTS) simulation in OpenDSS with a simulation time step of 1 s and an electromagnetic transient (EMT) real-time simulation in OPAL-RT with a simulation time step of 100 µs.

Most of the utility distribution feeder is modelled using OpenDSS. The feeder has a peak load of 11 MW and approximately 4,000 three-phase nodes. The feeder contains 163 customers who have all electric loads suitable for the control algorithm being evaluated here, i.e., these customers are assumed to have heating, ventilating, and air-conditioning (A/C) units, electric water heaters (EWH), as well as PV and battery storage units on their premises. The feeder model uses yearly load and PV shapes for spot loads and PV units taken from utility advanced metering infrastructure (AMI) measurements. Fig. 2 plots the feeder topology with markers showing the locations of the PV systems. Simulated PV penetration is increased for this feeder to help evaluate the efficacy of coordinated control especially the DERMS algorithms.

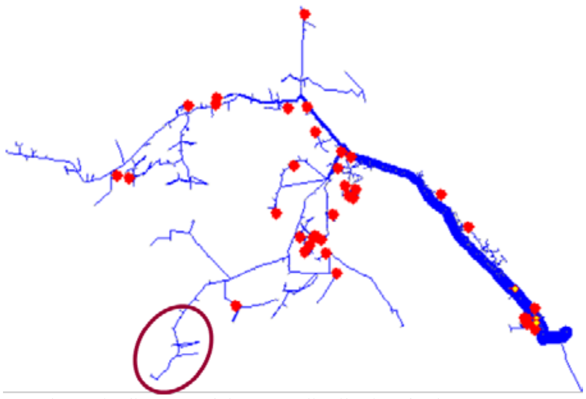

Fig. 2. Schematic diagram of the HCE distribution feeder.

In OPAL-RT, a subtree of the feeder with 72 nodes (encircled by the oval in Fig. 2) is modelled using an EMT simulator, eMEGASIM. The head of the subtree is modelled as a Thevenin circuit V_s and Z_s, where the magnitude and angle of V_s (frequency set to nominal) come from OpenDSS in real time, and Z_s is calculated offline based on the short-circuit impedance at the subtree point of common coupling (PCC). Apart from real-time simulation of the power system model, OPAL-RT communicates with the power hardware via analog inputs and outputs and communicates the power system model measurements to the ADMS using the standard industrial Distributed Network Protocol 3 (DNP3).

Test bed coordinator software developed for the ADMS test bed [5] is used to enable communications and synchronous data exchange between OpenDSS and OPAL-RT. The test bed coordinator is a set of Python scripts that uses the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) [6] as the core co-simulation engine. Note that the inputs of the DERMS algorithm are measurements from the simulated distribution feeder in OpenDSS and OPAL-RT, which are sent from OpenDSS to OPAL-RT, from OPAL-RT to the ADMS, and finally from the ADMS to the DERMS coordinator.

We also co-simulate 160 local controllers (one for each all-electric customer) that are not implemented in controller hardware. These simulated controllers receive the optimization parameters (e.g., the gradient) from the DERMS coordinator through an HTTP interface, receive measurements from OpenDSS through the test bed coordinator, and send the optimized power set points for the simulated DERs to OpenDSS.

B. Controller Hardware-in-the-Loop

The DERMS algorithms were developed by the National Renewable Energy Laboratory team based on the real-time optimal power flow (RTOPF) algorithm from [7]. Both the DERMS coordinator and local DER control algorithms are embedded in commercial Heila EDGE controllers, referred to in this paper as the Heila DERMS coordinator and Heila local controllers, respectively. The Survalent ADMS, the Heila DERMS coordinator, and the Heila local controllers are the hardware controllers to be evaluated for the coordinated control of voltage regulation. The Survalent ADMS has two roles: (1) to enable/disable the DERMS algorithm and set voltage limits and power references for the distribution feeder and, (2) to work as a supervisory control and data acquisition (SCADA) system for visualization and as a gateway to pass all measurements to the Heila DERMS coordinator through the standard enterprise-level communications protocol MultiSpeak.

The DERMS optimization algorithms are embedded in the Heila platforms, which provide decentralized processing and simplify DER integration and deployment. The DERMS includes the coordinator and multiple distributed local controllers. The coordinator is the master controller, which computes optimization parameters for each local controller to achieve system-level objectives. The local controllers compute the optimal set points for each DER asset, and the DERs work together to achieve the system objective (voltage regulation). Details about the DERMS algorithms are not provided here because the focus of this paper is on the HIL evaluation of coordinated control.

As shown in Fig. 3, the Heila coordinator receives inputs from the ADMS through the MultiSpeak communication protocol every 3 s in the form of a set of vectors (P_{sp} feeder head active power setpoints, P_{pcc} feeder head active power, V_{meas} selected 163 voltage measurements, and V_{lim} voltage upper and lower limits). These data are forwarded to the Heila control functions, which manage in-and-out data for the coordination algorithm. These Heila control functions read data from the ADMS, send start/stop commands, and set real and reactive power set points. The DERMS coordination algorithm runs every 3 s to determine the optimization parameters (voltage and power gradients computed from dual variables λ, γ, and μ), which are then passed through the Heila control function, to the downstream communications module, and to the Heila local controllers through DNP3 every 1 s.

The Heila local controllers then forward their individual coordinator outputs along with local DER measurements from the DER inverters (e.g., active and reactive power, state of charge) through the Heila control functions to the local control algorithm. The local control algorithm computes the individual optimal power set points for each physical DER inverter in the PHIL system. Lastly, the Heila local controllers forward these set points to physical assets through Modbus, which runs every 2 s. The schematic of the implementation in the Heila local controller is shown in Fig. 4. Note that each local controller manages the computation of the set points for multiple DER inverters.

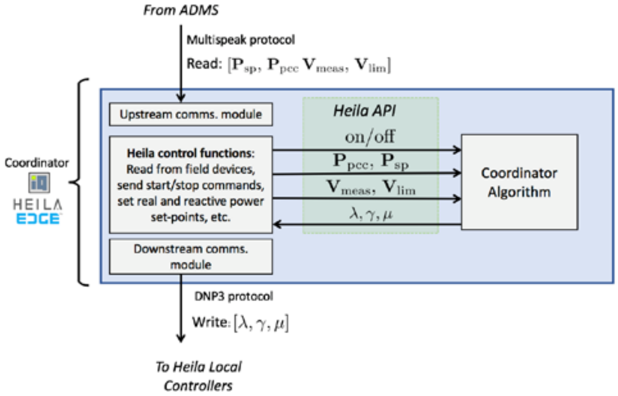

Fig. 3. Schematic of implementation in Heila DERMS coordinator.

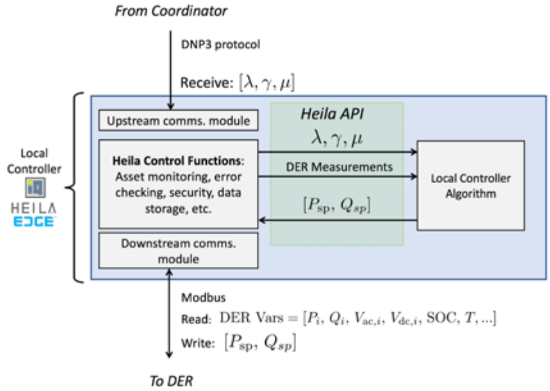

Fig. 4. Schematic of implementation in Heila local controller.

C. Power Hardware-in-the-Loop

PHIL is used to integrate actual DER inverter power hardware to receive optimal power set points from the Heila local controller and output the desired amount of power. As shown in Fig. 1, there are six DER inverter hardware under test (HUT), which are installed in two DER racks. Each rack represents a PCC. A high-level description of each rack is presented in Table 1.

Table 1. List of DERs

Rack Components	Description
Rack 1: • 3-kW SMA PV inverter • 5-kW Fronius PV inverter • 8-kW SolarEdge battery inverter	Both PV inverters produce active and reactive power, and the battery inverter produces only active power. The PCC voltage and current are fed back to OPAL-RT. The DC side of the PV inverters is powered by PV emulators, and the battery inverter is powered by a LG battery.
Rack 2: • 3-kW SMA PV inverter • 5-kW Fronius PV inverter • 6.6-kW/22-kWh Nissan Leaf EV	Rack 2 has the same PV units as Rack 1. The electric vehicle (EV) is connected through an EVSE and can only draw active power from 0 to rated power, i.e., it cannot discharge or provide reactive power.

Each DER rack is interfaced with the distribution feeder simulated in OPAL-RT through a grid simulator (a controllable AC power source to reconstruct the simulated voltage in OPAL-RT where the DERs are connected). Rack 1 and 2 share the same grid simulator (RS90 manufactured by California Instruments) and connect at Phase A and Phase B, respectively. Note that each phase of the grid simulator RS45 connects with a single-phase isolation transformer (15 kVA) for protection purposes. That means that the maximum power for these two racks cannot be more than 15 kVA. Fig. 5 shows a schematic diagram of the interface algorithm in OPAL-RT that represents the physical DER inverter dynamics in the real-time simulation through a closed PHIL loop. This interface algorithm calculates the actual power output of the DER racks based on current and voltage measurements from a current transformer (CT) and potential transformer (PT) respectively. It feeds the controlled-current source in OPAL-RT with current synchronized with the simulated voltage, which ensures satisfactory stability and accuracy.

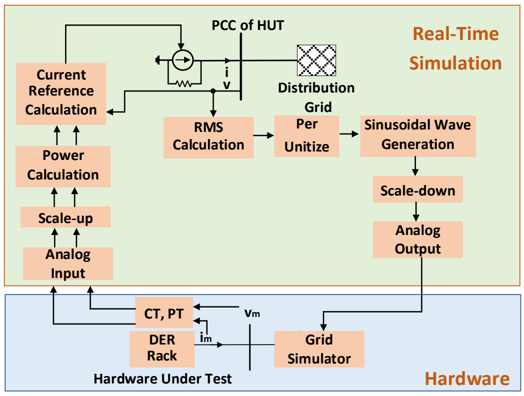

Fig. 5. PHIL interface algorithm in OPAL-RT.

III. Implementation of the HIL Platform

The HIL platform is implemented through a step-by-step approach. The Internet Protocol (IP) network is set up first to enable communications among devices. In this setup, all the devices except the ADMS are assigned to the same subnet, and an Internet exception is implemented in the ADMS for the communications to go through. Then, each device is configured to make sure the correct settings (IP address, port number, address, and master/slave relationship) are mapped. Next, extensive preliminary communications testing is performed to ensure that the communications between devices are working correctly, including co-simulation between OpenDSS and OPAL-RT, between OPAL-RT and ADMS, between ADMS and the Heila coordinator, between the Heila coordinator and Heila local controllers, and between the Heila local controllers and DER inverters. Once communications across the whole platform works correctly, each element is deployed.

For the second step, we model the HCE feeder in OpenDSS and the subtree in OPAL-RT and set up the co-simulation between them. Two variables (subtree head voltage root mean square (RMS) and angle) are sent from OpenDSS to OPAL-RT to set up the voltage source of the subtree in OPAL-RT and two variables (active and reactive power) are sent back from OPAL-RT to OpenDSS to close the co-simulation loop. Some variables (current RMS, active and reactive power) are exchanged between OpenDSS and OPAL-RT to compare the power flow. In addition, 166 variables (160 voltage RMS values and feeder-head three-phase active and reactive power) are sent from OpenDSS to OPAL-RT. These measurements (plus 3 additional voltage measurements from OPAL-RT subtree) are then sent from OPAL-RT to ADMS using the DNP3 protocol every 2 s, which emulates the field deployment wherein the ADMS collects measurements from meters via DNP3 protocol at a fixed time interval. Those data points are then passed to Heila coordinate using MultiSpeak protocol. Next, the DERMS algorithms are integrated into the Heila coordinator and the Heila local controllers. The Heila coordinator pulls the voltage measurements from the ADMS using the MultiSpeak protocol every 3 s and runs the RTOPF optimization algorithm. The Heila local controllers receive the control parameters from the coordinator every 1 s and run the local optimization algorithm every 2 s. The DER inverters receive the power set points every 2 s. The multiple timescales of the HIL platform are illustrated in Fig. 6. Note these various time steps were arrived at through a tuning process to ensure that the DERMS optimization algorithms converge. Future work is warranted to determine the time steps that are required for optimal performance and to understand the impact of time delays.

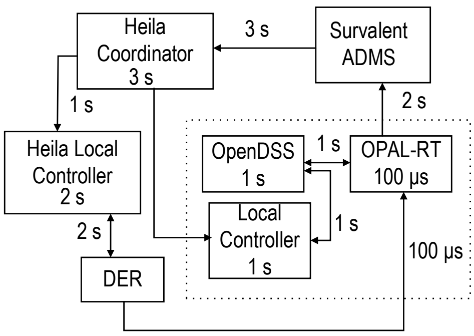

Fig. 6. Multiple time steps in the integrated HIL simulation.

Preliminary evaluation of the DERMS algorithm in the HIL platform is performed to check if the Heila coordinator and Heila local controllers work correctly by comparing their outputs to pure simulation results of the DERMS algorithms. An integration test is also performed to evaluate whether the whole HIL platform works stably for the final tests.

IV. Experimental Results

This section presents experiments that are designed to evaluate the performance of the DERMS algorithms. Local control for PV comprises volt-ampere reactive (VAR) control and generation curtailment. For storage, optimal charging and discharging signals are solved. Local controllers can also control the PV/storage inverter set points based on tariff inputs when provided. Local DER controllers receive additional control signals that reflect the gradient values between system voltages and/or feeder-head power and nodal power injections from the Heila coordinator to achieve system-level benefits.

For this evaluation, a 1-h simulation window is selected when voltage issues are usually found (11 a.m.–12 p.m.) because of low load levels and comparatively higher outputs from PV. This pushes the voltages of the distribution system significantly beyond safe operation limits: 1.038 p.u., as shown in Fig. 8. Input data for these tests contain load and PV profile data that are originally AMI measurements but extrapolated to 1-min resolution to mimic near real-time operation of the DERs.

A photograph of the experimental setup is shown in Fig. 7, which includes most of the elements presented in Fig. 1. Note that the ADMS server is in a different location and we access it through its user interface software. Representative results reflecting the HIL platform work collectively, and the DERMS control algorithms function correctly, and demonstrate coordinated control across the ADMS, DERMS, and DERs with the co-simulation accurately simulating the utility feeder.

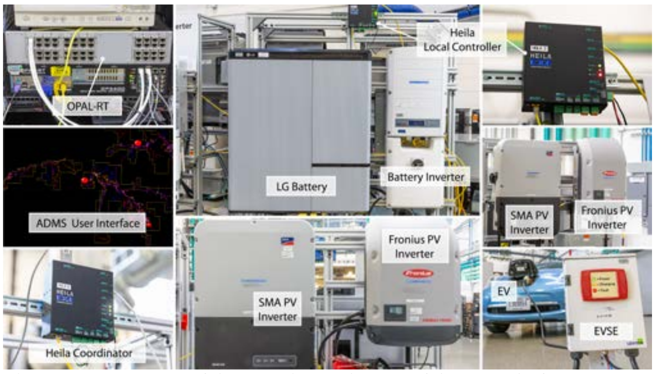

Fig. 7. Components of the experimental setup of the HIL platform.

Results were taken from a baseline test without any DERMS control and from a controlled test with the HIL setup shown in Fig. 8. The 163 controlled voltages are shown in Figure 9. The upper and lower limits for the voltage set points are 0.96 p.u. and 1.038 p.u. The baseline voltages without controls exceed the maximum voltage of 1.038 p.u. The DERMS coordinator induces VAR control, which significantly reduces the voltage to less than the maximum limit, and all voltages settle within the limits in less than 10 minutes. Overall, this test shows that the coordinated control across the ADMS, DERMS, and DERs can regulate the voltage of the distribution feeder within the desired limits.

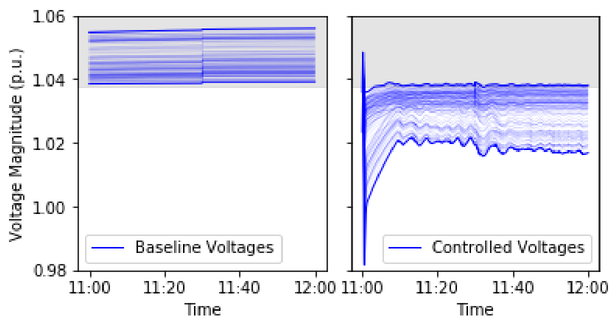

Fig. 8. Voltage measurements of the utility distribution feeder with baseline (without control) and with DERMS control evaluated in the HIL.

The gradient values are sent from the DERMS coordinator to the local controllers to compute optimal set points. Fig. 9 shows the gradient values related to the overvoltage violations, V_{upper} gradient, for both active power (P) and reactive power (Q) for two selected local controllers. The gradient values are only nonzero when at least one controlled voltage of the feeder exceeds the voltage limits. The magnitude of the gradients depends on the number of devices exceeding the limits, the magnitude of the excess voltage, and the proximity of the controller to the selected nodes with overvoltage. Note that the observed convergence time for the Heila coordinator is approximately 1 min.

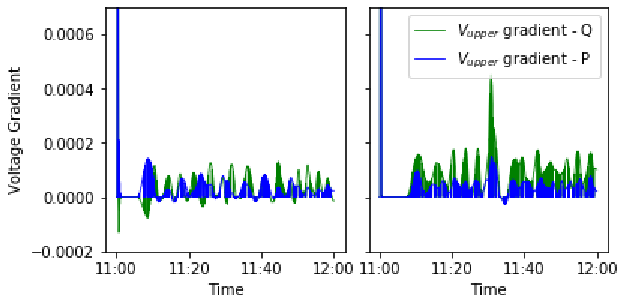

Fig. 9. Selected outputs of Heila DERMS coordinator.

The optimal power set points, $P_{setpoint}$ and $Q_{setpoint}$, that are outputs of each of the two Heila local controllers and the measured power outputs, $P_{measured}$ and $Q_{measured}$, of the individual DERs for each rack are shown in Fig. 10. Note that the observed convergence time for the Heila local controller is approximately 1–3 min. The results show that each DER inverter tracks the power references sent by the local controller. In addition, the Heila local controllers optimize the DER set points as expected. Some PV systems are curtailed and controlled to sink reactive power to maintain low voltages. The battery and EV are both dispatched to charge to further reduce voltages with optimized set points.

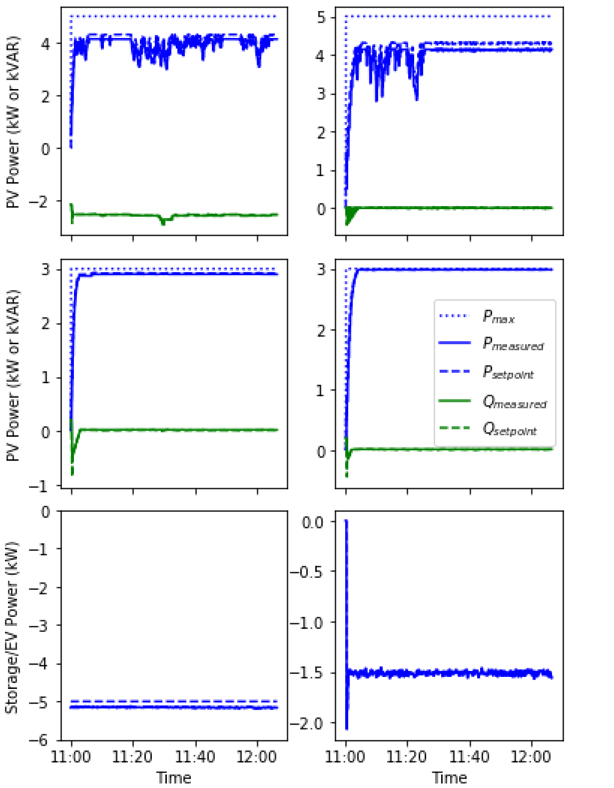

Fig. 10. Optimal power set point outputs from the two Heila local controllers and measured power outputs of all DER inverters for Rack 1 (left) and Rack 2 (right).

Outputs of two selected simulated local controllers and corresponding simulated PV inverters in OpenDSS are shown in Fig. 11 to demonstrate that the DERMS algorithm works correctly in the simulation as well. The results show the slightly different performance in power references and output power compared to the hardware local controllers. The simulated local controllers control PV inverters to sink reactive power to maintain low voltages. Thus, the simulated local controllers work as expected.

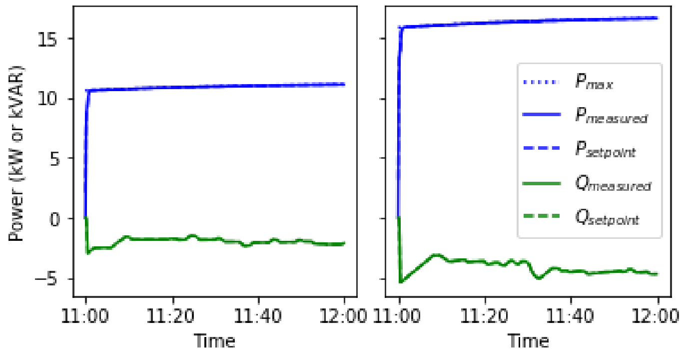

Fig. 11. Optimal power set point outputs of two selected simulated local controllers and output power of simulated PV inverters in OpenDSS.

V. Conclusions

This paper evaluates the performance of voltage regulation algorithms coordinated across ADMS, DERMS, and DERs using an advanced HIL platform with a simulated real-world utility feeder. The HIL platform includes a co-simulation of the distribution system model, real controller (ADMS and DERMS) and power hardware (DER) and standard communications protocols. The structure and implementation of the HIL platform is described with details on each component's hardware, integration, and communication. An experimental test with large PV penetration is performed and the test results demonstrate the effectiveness of the voltage regulation algorithm. The results show the benefits of using this advanced HIL platform to evaluate coordinated control systems prior to site commissioning to mitigate risks of technology integration.

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References

[1] J. Cook, et al., "Expanding PV Value: Lessons Learned from Utility-led Distributed Energy Resource Aggregation in United States," Technical Report, Golden, CO: National Renewable Energy Laboratory, available: https://www.nrel.gov/docs/fy19osti/71984.pdf.

[2] Jan Vrins, Global Energy Practice Lead, Distributed Energy Resource, https://www.navigant.com//media/www/site/downloads/energy/2016/distributedenergyresourcesimpactsonstrategybusines.pdf.

[3] Microgrid Knowledge, What are Distributed Energy Management Systems? Available: https://microgridknowledge.com/derms-next-generation-grid/.

[4] B. Seal, A. Renjit, and B. Deaver, 2018, *Understanding DERMS*, CA: Electric Power Research Institute, https://www.epri.com/#/pages/product/000000003002013049/?lang=en.

[5] A. Pratt, M. Baggu, F. Ding, S. Veda, I. Mendoza, E. Lightner, "A Test Bed to Evaluate Adanced Distribution Management Systems for Modern Power Syystems," *IEEE Eurocon 2019*, Novi Sad, Serbia, July 1-4, 2019, available: http://eurocon2019.org/program.html?r.

[6] Denholm, P., Ela, E., Kirby, B., Milligan, M., "The Role of energy storage with renewable electricity generation", National Renewable Energy Laboratory, Golden, CO, Tech. Rep. NREL-TP-6A2-47187, 2010.

[7] E. Dall'Anese and A. Simonetto, "Optimal power flow pursuit," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 942-952, March 2018.