Performance Evaluation of Hierarchical Controls for Advanced Distribution Management System-Centered Grid Operations

Preprint

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Performance Evaluation of Hierarchical Control for Advanced Distribution Management System-Centered Grid Operations

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***Abstract*—This paper presents a hardware-in-the-loop (HIL) simulation to evaluate the performance of voltage regulation using an advanced distribution management system (ADMS) for grid operations to control legacy and grid-edge devices and coordinate with distributed energy management systems (DERMS) to manage high penetrations of photovoltaics (PV) on a utility distribution system. The HIL platform provides realistic laboratory testing, including accurate modeling (legacy devices, grid-edge devices, and PV) of the real-world distribution system from a utility partner, a real controller (ADMS), software controller DERMS, hardware grid-edge devices, and standard communications protocols. The test results demonstrate functionalities of the integrated platform and the performance of voltage regulation of the coordinated control systems. Based on laboratory testing, the utility can set up the same grid-automation system to manage DERs, legacy devices, and grid-edge devices to achieve their system-level control and operation objectives (e.g., voltage regulation), thus de-risking potential issues such as instability for field deployment.**

***Index Terms*—Advanced distribution management system (ADMS), distributed energy resource management system (DERMS), hardware-in-the-loop (HIL), voltage regulation.**

I. INTRODUCTION

Power systems today are experiencing massive changes, particularly at the distribution level, with increasing integrations of distributed energy resources (DERs), grid-edge devices, and controllable loads etc. This requires distribution management systems (DMS) to be updated to maintain effective management of electric power distribution systems [1]. DMS manages the distribution system legacy utility equipment—such as the load tap changer (LTC), capacitor banks, and voltage regulators—and it needs to modify current operational settings to accommodate the changes in the distribution systems (e.g., integration of DERs). A distribution energy resource management system (DERMS) is usually adopted as a DER aggregator to respond to grid services requested by DMS and to control DERs collectively to achieve system-level objectives (e.g., voltage regulation) [2]. In this regard, a DMS that smoothly manages legacy and newly integrated devices is referred to as an advanced distribution management system (ADMS), and it will enable the efficient and reliable operation of future distribution systems with high penetrations of photovoltaics (PV) [3].

Testing such an integrated system prior to field commissioning is crucial for utilities to have confidence in guaranteeing that all pieces in the distribution grid automation function correctly and work together, the distribution system is stable, and system voltages are within operating limits. An ADMS test bed is described in [4] that validates the stability, operation, and control of grid automation systems of large-scale electric grids to provide realistic testing results for system operators to understand how an ADMS controls and operates assets to meet control objectives in a realistic emulated environment and use them as references for real-world applications. The ADMS test bed provides a realistic laboratory testing environment, including real-time co-simulation of a distribution system, controller-hardware-in-the-loop (CHIL) and power-hardware-in-the-loop (PHIL), and industry standard communications protocols. The test bed is used in this work to evaluate coordinated control among ADMS, other utility management systems (e.g., a microgrid controller and DERMS), DERs, and legacy utility equipment controllers (e.g., a capacitor bank and voltage regulator controllers). The test bed was developed at the National Renewable Energy Laboratory (NREL) with funding from the Advanced Grid Research and Development program of the U.S. Department (DOE) 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 penetrations of PV; integrate a real controller (ADMS), a software controller DERMS, and power hardware (grid-edge devices); and evaluate the performance of voltage regulation coordinated among the ADMS, DERMS, DERs, legacy, and grid-edge devices for this power system. This advanced HIL platform helps utility partners understand the benefits of adopting hierarchical controls for ADMS-centered operation to collectively manage fast-response PV inverters and slow-response legacy devices to maintain grid voltages within safe operating limits in high PV penetration scenarios.

II. DESCRIPTION OF THE HIL SETUP

This integrated HIL platform simulates four utility distribution feeders in Colorado (part of the Xcel Energy system) in a co-simulation platform using OpenDSS (a distribution power flow software) and OPAL-RT (a digital real-time simulator). In this experiment, Schneider Electric provided the ADMS, and the DERMS prototype was developed at NREL based on a real-time

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optimal power flow (RT-OPF) algorithm to manage behind-the-meter DERs [5] ARPA-E NODES program. Three Varentec grid-edge devices—Edge of Network Grid Optimizers (ENGOs)—are the physical hardware devices for voltage regulation to be tested, and they are controlled by the ADMS via a gateway grid-edge management system (GEMS) provided by Varentec. The overall HIL setup is shown in Fig. 1. The setup includes the main elements of the test bed [6]: multi-time scale co-simulation, controller HIL (ADMS, RT-OPF DERMS, GEMS), and power HIL (three grid-edge devices). The following sections explain each main element in detail and the data exchanges among them.

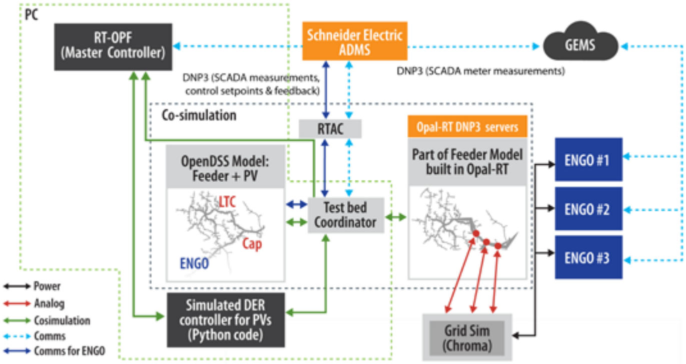

Fig. 1. Overall diagram of the HIL platform.

A. Co-simulation

Co-simulation is used to simulate most of the utility feeders in a large-scale electric grid by using a quasi-steady-state time-series (QSTS) simulation in OpenDSS, and a small portion of the distribution feeder in an electromagnetic transient (EMT) real-time simulation in OPAL-RT.

A set of four distribution feeders supplied by a 30-MVA, 110-kV/13.2-kV substation transformer is modelled in OpenDSS based on the data received from Xcel Energy. The feeders serve approximately 6,000 customers and have more than 13,000 buses in total. The topology of the system is shown in Fig. 2. In this system, the substation transformer is equipped with an LTC. Additionally, there are 13 switched capacitor banks for voltage regulation and reactive power management. Line voltage regulators are not available in this system. In addition to the legacy voltage regulation assets on the primary feeder, there are more than 3,000 residential PV systems and 144 ENGO devices are available at the grid edge to perform voltage regulation. The ENGO devices act as low-voltage dynamic VAR controllers to regulate the voltage at their terminals [6]. The peak demand at the substation on a low-load day of 15 MW is selected for this study. To represent extremely high penetration of DER for control evaluation purposes, a solar peak generation of 25 MW is simulated on the network.

Fig. 2. Schematic diagram of the Xcel Energy distribution feeders.

In OPAL-RT, a subtree of Feeder 1685 (one of the four feeders) with 30 nodes (encircled in red in Fig. 2) is modelled using an EMT simulator, eMEGASIM, with a time step of 100 μs. The head of the subtree is modelled as a Thevenin circuit with a voltage source and a grid impedance. Reference [7] gives details on how to derive the equivalent circuit of the large distribution system and close the co-simulation loop between OpenDSS and OPAL-RT. The PV local controllers (part of DERMS) are simulated in OPAL-RT to receive optimization parameters from the RT-OPF DERMS via User Datagram Protocol and output the optimal power setpoints for the simulated PV. Three physical grid-edge device ENGOs are tested via PHIL and interfaced with the OPAL-RT via analog IO to replicate the real dynamics of the hardware devices in OPAL-RT.

A co-simulation platform—referred to as the ADMS test bed coordinator—is developed in the Python programming language to coordinate the data exchange among the ADMS, OpenDSS, and Opal-RT processes. This platform uses the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) [8], an open-source cyber-physical-energy co-simulation framework for electric power systems developed through the Grid Modernization Initiative of DOE as the core co-simulation engine. The test bed coordinator is responsible for streaming the required measurements from OpenDSS to ADMS (as simulated supervisory control and data acquisition system (SCADA) measurements) and Opal-RT (to synchronize the co-simulation), receiving the optimal setpoints/commands from the ADMS to control LTC, capacitor banks and ENGOs simulated in the OpenDSS, and applying the P and Q setpoints computed by the RT-OPF to the simulated PV smart inverters during the co-simulation process. Note that an industrial gateway (a real-time automation controller [RTAC]) is used to carry out the required protocol conversion for the data exchange between OpenDSS and the ADMS because the OpenDSS software does not support communications protocols.

B. Schneider ADMS

We evaluate voltage regulation, a critical application for distribution utilities facing with high PV penetrations to maintain the system voltage within ANSI operating limits. To achieve this, ADMS is configured to perform volt/volt-ampere reactive (VAR) optimization (VVO) to manage voltage and reactive power flow to optimize the state of the system. The objective functions (e.g., reduce energy loss) and operational constraints (e.g., consumer voltage upper and lower limit) are configured in VVO to allow the ADMS to automatically issue control setpoints to the LTC and capacitor banks at primary distribution circuits and grid-edge devices at secondary distribution circuits. At the same time, the ADMS coordinates with the RT-OPF DERMS by enabling/disabling the DERMS and sending the voltage setpoints to manage behind-the-meter DERs indirectly to contribute to voltage regulation. This avoids uncoordinated DER actions that might run counter to the objectives of the ADMS.

The effectiveness of the coordinated voltage regulation among the ADMS, legacy and grid-edge devices, and the RT-OPF DERMS and PV is of particular interest in this HIL test to see how the ADMS handles the hunting effects and harmonizes the controllable assets for the same control objective: voltage regulation.

C. RT-OPF DERMS

As shown in Fig. 1, the RT-OPF DERMS has two layers: one master controller (/coordinator) on the upper layer and various distributed local PV controllers on the lower layer. The coordinator receives all the measurements from the simulated distribution feeders in the co-simulation and runs the optimization algorithm to send the optimization parameters (gradients) to the distributed PV controllers. Each distributed PV controller receives the optimization parameters from the coordinator and local measurements from the PV and outputs the optimal active and reactive power setpoints to control the simulated PV in OpenDSS and OPAL-RT. The master and distributed local controllers collectively respond to the request from the ADMS for voltage regulation. The RT-OPF algorithms are implemented in a PC and tested as controller software-in-the-loop.

D. GEMS and Grid-Edge Device ENGOs

Grid-edge devices are used to increase the flexibility in controlling the voltage profile of the distribution feeders. The grid-edge devices use power electronics-based, fast-acting, decentralized, shunt-VAR technology for voltage regulation. Each device, which is connected to the secondary side of a service transformer, can inject 0 to 10 kVAR reactive power and can regulate the voltage tightly (±0.5 V band) at local scale.

In this test, three physical ENGO devices are connected at different locations in the subtree simulated in OPAL-RT. The simulated terminal voltage for each ENGO is sent out through analog output to the grid simulator (Chroma) to reconstruct the physical voltage 240 V. The three ENGOs are connected to phase A, B, and C of the grid simulator, respectively. The ADMS issues the voltage setpoints to ENGOs using standard communications protocol DNP3 via the gateway, GEMS, and the ENGOs track the voltage setpoints by injecting reactive power to regulate the voltage at the connection point to track the reference voltage. The output voltage and current of each ENGO device will be measured by a potential transducer and a current transducer and sent back to OPAL-RT via analog inputs to calculate the active and reactive power to control the current source and close the PHIL loop.

III. IMPLEMENTATION AND TESTING OF ADMS-CENTERED OPERATION AND CONTROL

We model the Xcel Energy distribution feeders in OpenDSS to perform QSTS simulation with a time step of 5 s and the subtree in OPAL-RT to carry out the simulation in real time with a time step of 100 μs. To 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 build the voltage source of the subtree in OPAL-RT, and two variables (subtree head active and reactive power) are sent back from OPAL-RT to OpenDSS to close the co-simulation loop, all through the test bed coordinator. Furthermore, solar irradiance and load profile information is sent from OpenDSS to OPAL-RT to keep the simulation in OpenDSS and OPAL-RT synchronized. The co-simulation is then validated by checking the active and reactive power at the subtree head in these two software types.

The next step is to configure VVO in the ADMS. VVO is implemented based on solar and load forecasting, state estimation, and load flow. The VVO function receives voltage measurements from the co-simulation via RTAC through DNP3 protocol and executes every 15 minutes in real time to determine a new optimum setpoint for the LTC, capacitor banks, and grid-edge devices. The objective function of the VVO is to improve consumer voltage, and the constrains defined for consumer voltage are between 0.95 and 1.04 p.u., medium voltage between 0.975 and 1.05 p.u., and primary voltage between 0.95 and 1.04 p.u. from low voltage readings. The functionality of the ADMS gives priority to the LTC setpoint to achieve voltage reduction before changing the capacitor bank status. In addition, the LTC setpoint is replicated and sent to the simulated ENGOs in OpenDSS and cloud server GEMS to the hardware ENGO devices via the industrial protocol DNP3.

For coordinated voltage regulation, the ADMS enables/disables the RT-OPF algorithms based on the needs and sends the voltage limits to the RT-OPF coordinator if the RT-OPF is enabled. Control parameters, such as gradient update step sizes, and associated weights for active power curtailment and reactive power generation in the objective function, affect the performance of the RT-OPF. After tuning these control parameters, the RT-OPF algorithms converge well, and individual PV inverter outputs active and reactive power as expected: curtail a small amount of active power and absorb reactive power to maintain voltage below the upper limit under high solar irradiance. The converged RT-OPF coordinator runs every 10 s, and the distributed local controller runs every 5 s.

After developing co-simulation, ADMS, and RTOPF, the implementation of the ADMS-centered HIL platform includes another three integrated steps:

1) ADMS control of slow-response legacy voltage control devices. Communication is set up between the ADMS and simulated legacy devices in OpenDSS through the RTAC and test bed coordinator. The ADMS receives measurements and the status of legacy devices and sends the control commands and voltage setpoints to the legacy devices. Likewise, the simulated legacy devices in OpenDSS apply the control commands and setpoints and send the measurements and status back to the ADMS. Closed-loop simulation is tested with the co-simulation, test bed coordinator, RTAC, and ADMS to check if the feedback control and communications work correctly together to regulate the voltage of the distribution feeders.

2) ADMS control of fast-response grid-edge voltage control devices. This is implemented and tested the same way as the LTC because the setpoint for the LTC is replicated and sent to the simulated ENGOs in OpenDSS and GEMS to the hardware ENGOs. For the hardware ENGOs, we test the PHIL configuration beforehand with only the grid simulator, ENGOs, and OPAL-RT in the loop to check if the reference voltage of each ENGO is correctly reconstructed by the grid simulator and the feedback current and voltage from the analog inputs are correctly rescaled to represent the physical values of hardware ENGOs.

3) ADMS coordination with the RT-OPF DERMS to manage fast-response PV inverters for voltage regulation. This is implemented manually based on the observation of the voltage profiles. With overvoltage, the RT-OPF is enabled by the ADMS, and voltage setpoints are issued to the RT-OPF coordinator. To make the RT-OPF work more efficiently for voltage regulation, the voltage setpoints are usually tighter than the distribution system operation limits (0.95 -1.05 p.u.).

Once the ADMS control of all the elements is enabled, tuning is needed again in the RT-OPF to ensure that the master and local control algorithms converge and that the PV inverters work as expected to regulate voltage without countering the effects of other voltage regulation devices. The ADMS uses an LTC as the dominant source for voltage regulation and the rest of the voltage regulation devices as fine-tuning sources. This helps avoid the hunting effect by having all regulation devices collectively work in one direction. A preliminary evaluation of the ADMS-centered operation for voltage regulation using the HIL platform shown in Fig. 1 is tested with a selected load profile and the voltage measurements are checked to see if the measured voltages are maintained within the operating limits (0.95-1.05 p.u.).

IV. EXPERIMENTAL RESULTS

The demand at the substation for the year 2018 from the historical SCADA data records is received from Xcel Energy. From these data, a minimum load of 11.48 MW was observed on May 13, 2018. The loads in each of the four feeders are assumed to follow the load demand shape observed at the feeder head of that feeder on the low-load day. A moderately intermittent PV profile, shown in Fig. 3, from the solar insolation data recorded at the NREL Flatirons Campus [9] is used for this study. The insolation data, available at a 1-minute resolution, are normalized, and all the PV systems in the OpenDSS model are assumed to follow the same insolation profile. The section of the PV profile from hour 10 to hour 14 used for the HIL experiment is highlighted in red in Fig. 3.

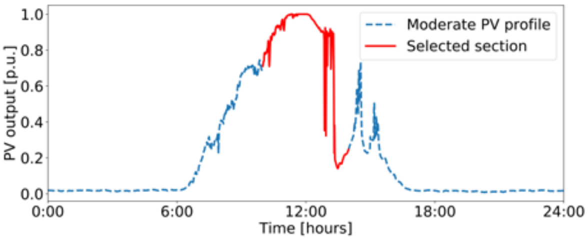

Fig. 3. PV profile and selected time slot for HIL test.

A photograph of the experimental setup is shown in Fig. 4, which includes all the elements presented in Fig. 1. During the experiment, the distribution feeder model in OpenDSS and the subtree in OPAL-RT run first, and the co-simulation loop is closed when the observed RMS values of the voltage and current for the subtree head in OPAL-RT are close to the measured RMS values in OpenDSS. Then, the grid simulator and hardware ENGOs are powered and switched on. Finally, we enable the VVO function in the ADMS. Note that the RTAC and GEMS are gateway and running all the time. Representative results reflecting the performance of the voltage regulation of the ADMS-centered operation are selected and presented in this section.

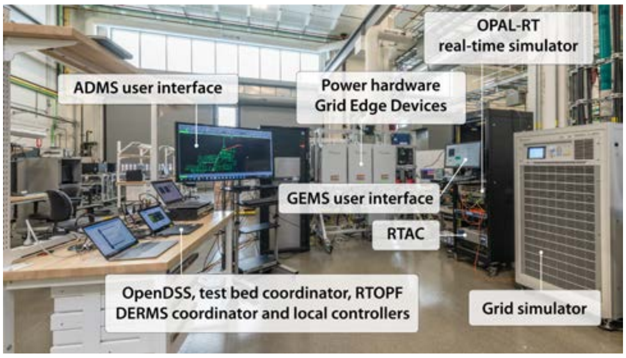

Fig. 4. Photograph of the experimental setup of the HIL platform. *Photo by Joshua Bauer, NRE*

Fig. 5 shows the measured voltages of the distribution feeder with the baseline in pure simulation and with the ADMS-centered control in the HIL test. In the baseline, there is no ADMS control and the operations of the controllable assets are as follows: legacy devices with local control mode, ENGOs disabled, and PV inverters with unit power factor control. As shown in Fig. 5, a large number of overvoltage exceedances above 1.05 p.u. are observed under the baseline scenario because of a lack of control and coordination from the ADMS, and the maximum voltage is as high as 1.08 p.u. With the ADMS control, all the measured voltages are kept within the operating limits (0.95–1.05 p.u.), and the highest voltage is always less than 1.05 p.u. The results shown in Fig. 5 demonstrate the effectiveness and performance of the ADMS-centered operation to regulate the system voltage within the operating limits under high PV generation.

The results of PV total power in the baseline and ADMS control are shown in Fig. 6 to highlight the performance of the RT-OPF and PV inverters. As observed from the results, since the PV inverter is not oversized, the total PV active power with RT-OPF control is curtailed to allow reactive power absorption to regulate the voltage within operating limits. The calculated total curtailment over a day is 16% of the total generation MWh in the baseline scenario. The results show that the ADMS, RT-OPF, and PV inverters work coordinately to maintain system voltages within limits.

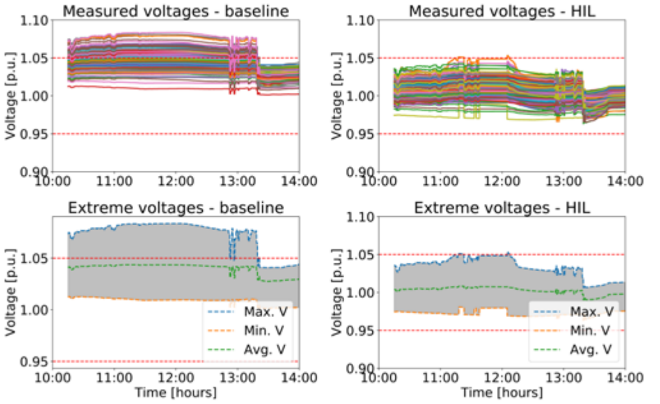

Fig. 5. Measured voltages of distributiuon feeder: baseline in pure simulation (left) and with ADMS-centered control in HIL test (right).

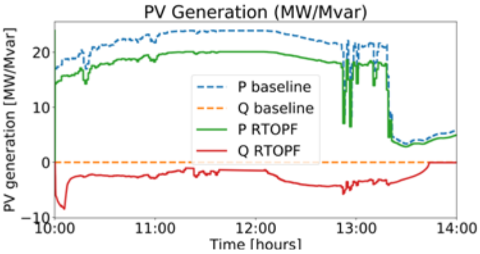

Fig. 6. Total PV generation: baseline amd with ADMS control.

Fig. 7 shows the HIL test results of the voltage regulation devices controlled by the ADMS, including the LTC, two selected capacitor banks, and two selected simulated ENGOs. because of the high voltage, the tap position of the LTC is lowered up to -5 by the ADMS to reduce the system voltage. The results show that the ADMS gives priority to the LTC to regulate the system voltage before changing the commands for the capacitor banks. This is in line with the control configuration of the VVO function in the ADMS. For the ENGOs, because the voltage setpoint is less than the measured voltage and the ENGOs are capacitor-based VAR injection sources, the ENGOs inject zero reactive power to the grid. The results show that all these assets follow the commands/setpoints from ADMS correctly to collectively regulate the system voltage.

The outputs of the RT-OPF DERMS coordinator are gradient values sent to each PV local controller to compute the optimal power setpoints. Fig. 8 shows the outputs of the RT-OPF DERMS coordinator for two selected PV local controllers. Each PV local controller receives six gradient values, including $V_{mag\_upper\_P}$, $V_{mag\_upper\_Q}$, $V_{mag\_lower\_P}$, $V_{mag\_lower\_Q}$, P_{sub_P} and P_{sub_Q}. As the names indicate, $V_{mag\_upper\_P}$ and $V_{mag\_lower\_Q}$ relate to an overvoltage violation , $V_{mag\_lower\_P}$ and $V_{mag\_upper\_Q}$ relate to an undervoltage violation, and P_{sub_P} and P_{sub_Q} relate to active power tracking of the feeder head. The results show that the overvoltage violation-related gradient values are nonzero from hour 10:00–13:30 and become zero after hour 13:30. This works as expected because the PV generation reduces after hour 13:30 due to the reduced solar irradiance and overvoltage is eliminated. The other four gradient values are almost always zero during the test because there is seldomly undervoltage violation and no active power tracking is enabled. The results shown in Fig. 8 indicate that the RT-OPF algorithm inside the coordinator converges and works correctly to regulate the system voltages.

Fig. 9 shows the HIL test results of two example PV local controllers, including the available power from solar irradiance and active and reactive power setpoints. The local PV inverter controllers respond collectively to high voltages to have a small amount of curtailment in the active power and absorb reactive power. Therefore, the results in Fig. 9 show that the RT-OPF distributed PV inverters work together with the RT-OPF coordinator to regulate the system voltages.

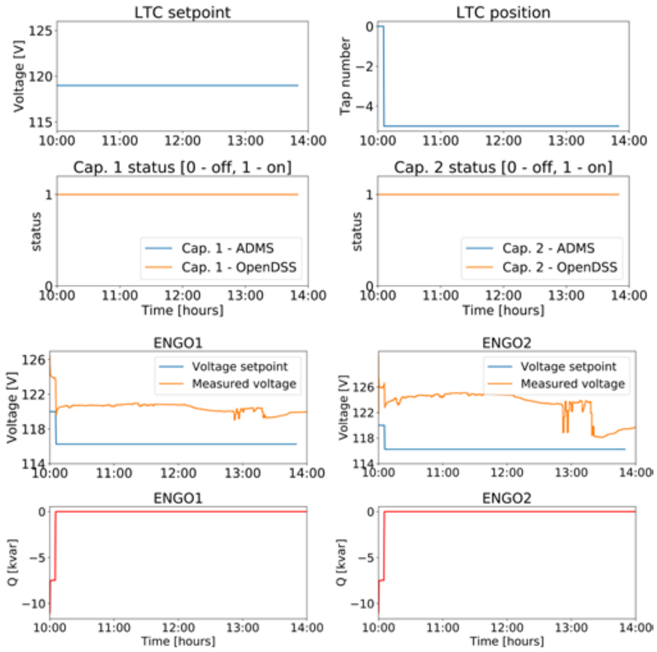

Fig. 7. HIL test results: LTC setpoint from ADMS and measured tap position (top); two selected capacitor banks: commands from ADMS and meaured status (middle); and two selected ENGOs: setpoint from ADMS and measured voltage, and output reactive power (bottom).

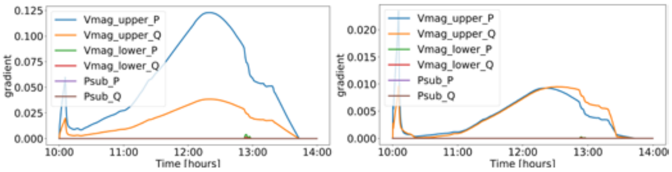

Fig. 8. HIL test results: selected outputs of RT-OPF DERMS coordinator.

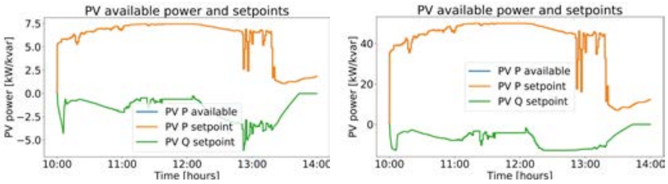

Fig. 9. HIL test results: selected outputs of RT-OPF PV local controllers.

Fig. 10 shows the real-time measurements of three hardware ENGOs in GEMS, which include ENGOs' voltage setpoints from the ADMS, measured voltage, and output reactive power. Note that while the ENGOs operate at 240 V voltage base, and we scale the voltage setpoints and measurements to a base of 120 V to be consistent with the simulated ENGOs. The results show that each ENGO injects reactive power only when the voltage setpoint is higher than its measured voltage. This is expected because the ENGO is a capacitor-based device and only injects reactive power. The results show that the hardware ENGOs work as expected to follow the setpoints from the ADMS.

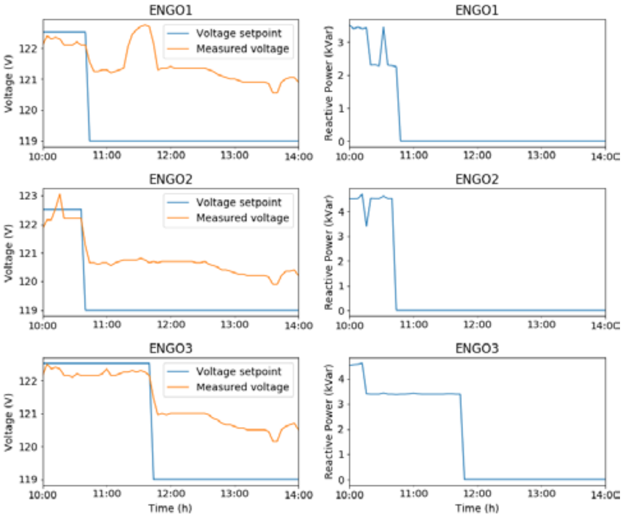

Fig. 10. HIL test results of three hardware ENGOs: voltage setpoint from ADMS, measured voltage and output reactive power of ENGO1 (top), ENGO2 (middle), and ENGO3 (bottom).

V. CONCLUSIONS

This paper presents a performance evaluation of voltage regulation of ADMS-centered operation using an advanced HIL platform. In this HIL platform, a utility distribution feeder is simulated in co-simulation between OpenDSS and OPAL-RT, the ADMS is tested as hardware CHIL, the RT-OPF DERMS is tested as software CHIL, and the grid-edge devices are power HIL. The ADMS controls simulated legacy, grid-edge devices, and hardware grid-edge devices and coordinates with the RT-OPF DERMS to regulate the system voltages within limits. The HIL platform development, implementation, and testing are described. The experimental results demonstrate the effectiveness and performance of the voltage regulation using the ADMS-centered operation to coordinately manage the slow-response legacy devices, fast-response grid-edge devices, and PV inverters.

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