Test Bed to Evaluate Advanced Distribution Management Systems for Modern Power Systems

Preprint

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A Test Bed to Evaluate Advanced Distribution Management Systems for Modern Power Systems

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***Abstract*—This paper presents a test bed that utilities, vendors, and researchers can use to evaluate the performance of existing and emerging advanced distribution management systems (ADMS) or specific applications of such systems. The test bed provides a realistic laboratory test setting, including detailed modeling of the power system, controller and/or power hardware, and industry-standard communication protocols. The test bed can further represent the current state of a specific utility's distribution system or the anticipated state with increased penetrations of distributed energy resources, such as rooftop photovoltaic systems, residential battery energy storage systems, electric vehicles, and loads with smart controls. The paper describes the design and implementation of the test bed. We present two use cases of the test bed and preliminary results for these two use cases. We also discuss upcoming and potential future use cases. Results from test bed experiments are intended to accelerate industry deployment of ADMS technologies and advance development of ADMS capabilities.**

Keywords—distribution power system, distribution management system, hardware-in-the-loop, cosimulation, power system simulation

I. INTRODUCTION

As the penetration level of distributed energy resources (DERs) increases—especially intermittent sources such as photovoltaics (PV)—distribution management system capabilities need to be updated to attain effective management of the electric power distribution system.

Some DERs are colocated in microgrids and managed locally by a microgrid controller [1]. DERs on distribution feeders are typically not controlled or they have only local controls (such as power factor control). As the penetration of DERs increases, a coordinated control strategy might be more appropriate, leading to the need for a distributed energy resource management system (DERMS). Both of these controller types need to be integrated with distribution management systems (DMS) when used by utilities. It is also possible to interface DERs directly with a DMS, but this is more common for a small number of utility-scale DERs. Many DMS vendors now offer products that integrate multiple functions, such as an outage management system (OMS), a geographic information system (GIS), and a supervisory control and data acquisition (SCADA) system. These integrated platforms are commonly referred to as advanced distribution management systems (ADMS). These platforms also offer advanced functions, such as Volt/VAR optimization (VVO); fault location, isolation and system restoration (FLISR); and dynamic voltage regulation (DVR).

Yet, despite the potential of an ADMS deployment to increase reliability and power quality, improve resilience and security, reduce costs, and enhance customer participation, adoption rates of ADMS remain low. Part of the reason for this is that ADMS deployment requires a significant investment of time and funds by utilities, which in turn requires the benefits to be well understood and quantified to build a strong business case for such an investment. This is especially critical for utilities that operate under the oversight of public utility commissions or similar oversight bodies; however, it can be hard to determine the impact of new management systems on a specific utility's distribution system ahead of time.

The Advanced Grid Research and Development Program of the U.S. Department of Energy Office of Electricity (DOE-OE) has invested in the development of a vendor-neutral ADMS test bed as part of the Grid Modernization Initiative to address this challenge [2]. The test bed provides utilities and vendors the opportunity to understand the benefits of specific applications for a specific distribution system under a wide range of conditions that can be simulated and emulated in a laboratory environment. Additionally, evaluation in a laboratory can be done at a much lower cost than a field pilot.

In addition, as power systems with high penetrations of DERs become increasingly common, ADMS applications need to function effectively. This requires at a minimum visibility of the DERs and ideally some level (direct or indirect) of controllability. The ADMS test bed can be used to evaluate the effectiveness of ADMS applications on a futuristic model of a utility feeder. For example, a feeder that currently has low PV penetration can be modeled with the level of PV penetration that is forecasted in 5, 10, or 20 years. Similarly, increased penetrations of electric vehicles or more efficient and flexible heating and cooling systems can be modeled.

This paper first describes the process used to determine a use case to simulate on the test bed, then it proceeds to provide an overview of the ADMS test bed. The test bed is configured

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based on the needs of individual use cases. We also discuss two use cases in more detail as examples of how the test bed is being used, with representative results. We conclude with a discussion on potential future use cases that can support the power industry in managing systems with high penetrations of DERs.

II. ADMS TEST BED USE CASE DEVELOPMENT

An ADMS offers many functions to distribution utilities, so there is a wide range of possible use cases [3] that utilities would like to verify prior to deployment. The initial use cases were selected for their potential in accelerating the adoption of ADMS. Future use cases might be more customer-driven, i.e., catering to the specific interests of utilities or vendors.

We use a collaborative approach involving multiple stakeholders, including utility and vendor partners, to determine use cases, as shown in Fig. 1. The use case could be defined by an operational challenge experienced or anticipated by a utility or by a value proposition, such as a new or enhanced application, proposed by a vendor. It could also be a combination of the two, i.e., a utility might be interested in evaluating whether a proposed vendor solution will address their operational challenge.

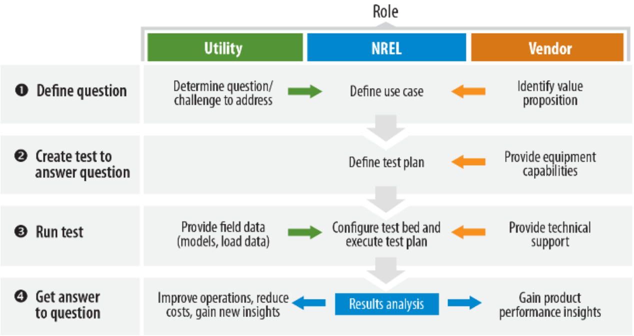

Fig. 1. Use case selection process.

Once the use case is defined, we define a test plan and configure the test bed for the specific use case with inputs from the utility and vendor. For a vendor-driven use case with the intent of showing the value of a new application, for example, we might choose to use synthetic feeders, i.e., anonymized, realistic feeders, such as those made available through the Advanced Research Projects Agency-Energy GRID DATA program [4] or representative feeders provided by the Electric Power Research Institute (EPRI).

Upon execution of the test plan, we analyze the results and disseminate them to our partners and, to the extent possible, with proper anonymization in place, with the broader utility industry and academic power research community.

III. OVERVIEW OF THE ADMS TEST BED

The ADMS test bed is an evaluation platform consisting of software and hardware elements that realistically represent a power distribution system to a commercial or precommercial ADMS. The test bed is hosted at the National Renewable Energy Laboratory's (NREL's) Energy Systems Integration Facility (ESIF). The ADMS is interfaced to the test bed using industry standard communication protocols so that it can be deployed as it would be in a utility environment. An overview diagram of the test bed is shown in Fig. 2. The main elements of the test bed are the multi-timescale simulation, controller- and power hardware-in-the-loop (CHIL and PHIL), remote hardware-in-the-loop, and other utility management systems.

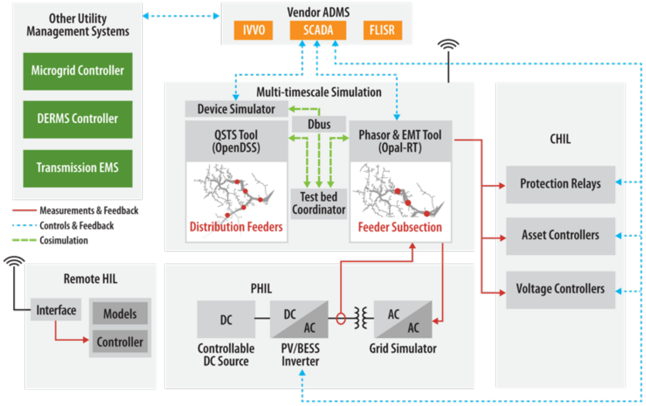

Fig. 2. Overview diagram of the ADMS test bed.

A. *Multi-Timescale Simulation*

The multi-timescale simulation of the power distribution system includes both an open-source, quasi-steady-state time-series power system simulator, OpenDSS, with a typical time step of 1 minute; and a faster power system simulator executed on an OPAL-RT digital real-time simulator. On the OPAL-RT, either a transient stability simulator (using a phasor-domain solver), ePHASORSIM, with a typical time step of 10 milliseconds, or an electromagnetic transient (EMT) simulator, eMEGASIM, with a typical time step of 100 microseconds, can be used to simulate the power system. We anticipate that other power system simulation tools, including other digital real-time simulators, will be integrated with the test bed in the future.

Test bed coordinator software, implemented in the Python programming language, coordinates the ePHASORSIM, eMEGASIM, and OpenDSS simulators. The test bed coordinator uses the Hierarchical Engine for Large-scale Infrastructure Co-Simulation (HELICS) [5], an open-source cyber-physical-energy cosimulation framework for electric power systems developed through the Grid Modernization Initiative of DOE.

All the simulated devices that need to be interfaced with the ADMS's SCADA application must be able to communicate to the ADMS using an industry standard communication protocol. All devices—simulated and actual—use the DNP3 protocol in the current test bed setup. Simulated devices in ePHASORSIM or eMEGASIM can communicate through the DNP3 capability available on the OPAL-RT platform. The OpenDSS simulator does not support communication protocols, and we therefore developed software that can exchange data between the ADMS, which communicates using DNP3, and OpenDSS. The software consists of a device simulator software tool that emulates the characteristics of a device, such as a SCADA meter or a capacitor bank controller, and a custom data bus. This data bus (Dbus) is based on the Transmission Control Protocol (TCP) and features low latency, which makes it well suited to control applications.

The test bed coordinator software also coordinates the interactions of the power system simulations and the device simulators (through Dbus) and publishes data to a data management system and real-time visualization tool.

B. *Controller-Hardware-in-the-Loop*

CHIL is class of hardware-in-the-loop simulation that allow for the evaluation of hardware controllers through integration with software simulations. For the test bed, controllers of interest include protection relays; genset controllers; and controllers for capacitor banks, voltage regulators, and load tap changers (LTCs). Controller hardware are interfaced with the power system simulations through the digital-to-analog and analog-to-digital interfaces provided on the OPAL-RT platform [6]. The controllers receive low-voltage signals representing simulated voltages and currents from OPAL-RT and issue control set points that are extracted and fed back to the simulated equipment. The use of a real-time platform such as OPAL-RT enables this measurement-control feedback loop to be executed seamlessly; hence, the controller does not recognize that it is controlling software models and not actual hardware.

C. *Power-Hardware-in-the-Loop*

PHIL allows for the evaluation of actual power hardware, such as PV and energy storage inverters, through integration with software simulations. The power hardware is interfaced with the power system simulations through a grid simulator (a controllable AC power source). The grid simulator receives a low-voltage signal from the OPAL-RT representing the simulated voltage at the node in the power system simulation where the power hardware is connected, and it amplifies it to (nominally) the rated voltage of the power hardware [7]. The hardware-in-the-loop interface needs to be designed with the proper compensation to ensure stable and accurate hardware-in-the-loop simulation [8]. In addition, some power hardware, such as PV and battery inverters, require a DC power input, and this is supplied by a controllable DC source.

D. *Remote Hardware-in-the-Loop*

The test bed can be expanded through a connection to a remote site. This capability could be used when a remote site has hardware that is not available at the ESIF, where the test bed is hosted. It could also be used to address communication delays and networking issues that are encountered in actual ADMS field deployments.

E. *Other Utility Management Systems*

An ADMS needs to be interfaced upstream with a transmission energy management system (EMS) and might need to be interfaced with downstream management systems such as a DERMS, microgrid controller or building management system. These systems can be included in the ADMS test bed setup when required by a specific use case.

IV. USE CASE 1: ADMS MODEL QUALITY

A. *Model Quality Use Case*

The first ADMS test bed use case addresses the impact of ADMS model quality on ADMS performance. We will evaluate the performance improvements from more accurate models within the ADMS as well as the impact of additional telemetry. Specifically, we will evaluate the performance of a VVO application with different levels of model quality within the ADMS and different levels of measurement density on the distribution feeder, as described in more detail in [9].

B. *Test Bed Setup for Model Quality Use Case*

The ADMS test bed setup for the model quality use case is shown in Fig. 3. The test bed is interfaced with Schneider Electric's ADMS and simulates a feeder from Xcel Energy, an investor-owned utility that operates in four states in the United States. This feeder has 69 rooftop PV systems that operate in unity power factor mode. The PV system capacity is 539 kVA, which is 11% of the peak load. The upstream part of the feeder is modeled in OpenDSS, with a time step of 1 minute, and the downstream part of the feeder is modeled using ePHASORsim, with a time step of 5 milliseconds.

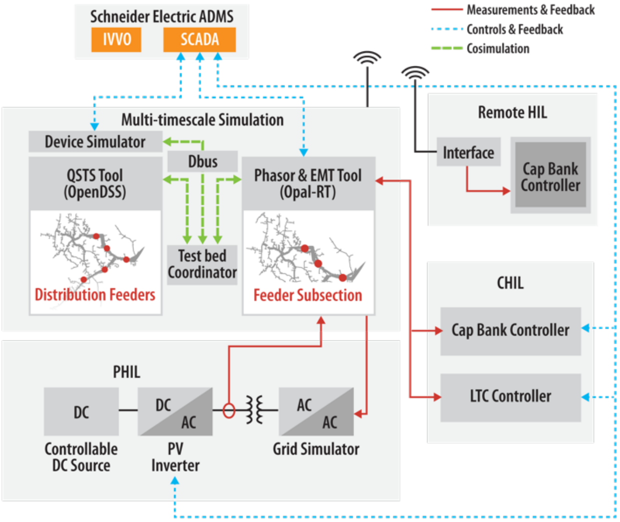

Fig. 3. ADMS test bed setup for the model quality use case.

The feeder has an LTC at the feeder head, and it is therefore simulated in OpenDSS and interfaced with LTC controller hardware. The feeder also has four controllable capacitor banks, two of which are simulated in OpenDSS and controlled using capacitor bank controller device simulators. The other two capacitor banks are simulated in ePHASORSIM and are interfaced to capacitor bank controller hardware. One capacitor bank is set up to use either local—i.e., colocated with the test bed at the ESIF—controller hardware or remote controller hardware located at the Pacific Northwest National Laboratory (PNNL), approximately 840 miles from the ESIF. When the remote controller hardware is used, voltage and current measurements from the multi-timescale simulation are relayed using the IEEE C37.118 standard to the capacitor bank controller at PNNL, and the control decisions from the controller are relayed back using the DNP3 protocol to the ADMS located at NREL.

We also use SCADA meter device simulators to provide data to the ADMS from the SCADA points within the part of the feeder that is simulated in OpenDSS.

We use a three-phase12-kVA PV inverter as power hardware to represent a 10-kVA PV inverter on the feeder by scaling down the current measurements. The measured power output from the hardware is scaled up to match the actual power rating of the PV system that is represented in the hardware. The DC source is programmed using an irradiance profile from historical data for the feeder location [10].

Fig. 4 shows a photograph of the ADMS test bed setup for the model quality use case in NREL's ESIF.

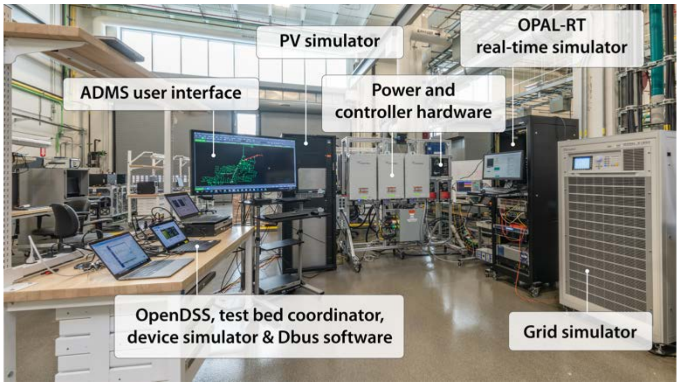

Fig. 4. Photograph of the ADMS test bed setup for the model quality use case. *Photo by Joshua Bauer, NREL*

C. *Preliminary Results from Model Quality Use Case*

This use case will evaluate the performance of the ADMS's VVO application through simulation of several test scenarios that use different levels of model quality within the ADMS and different measurement densities on the feeder. The test scenarios were selected based on results from simulations for this feeder using the training simulator of the ADMS as a proxy for the feeder in the field. Four levels of data quality and four levels of measurement density were simulated using the ADMS training simulator. Details on this simulation setup and the data quality and measurement density levels are available in [9].

The ADMS VVO application was tuned to perform conservation voltage reduction with the objective to reduce the energy consumption. The ADMS aims to achieve this by flattening the voltage profile and reducing the voltage across the feeder while avoiding voltage violations, i.e., consumer voltages are set as constraints on the optimization. The energy consumption was calculated using feeder head power values from the ADMS training simulator.

The simulation results using the ADMS training simulator show that, for this feeder, there is not a significant difference in energy consumption between different model quality levels nor between different measurement density levels. We selected to simulate two scenarios (Q1/D2 and Q4/D2) on the test bed. First, a baseline simulation was performed where the ADMS is not running VVO. Then the ADMS was programmed with the Q4 model and D2 measurements, and then with the Q1 model and D2 measurements, and VVO was activated.

Fig. 5 shows preliminary simulation results, including an end-of-line voltage (top) and feeder head active power (bottom). Both the voltage and the power are lower when VVO is activated. This is a result of the ADMS VVO application disconnecting one of the four capacitor banks from the feeder.

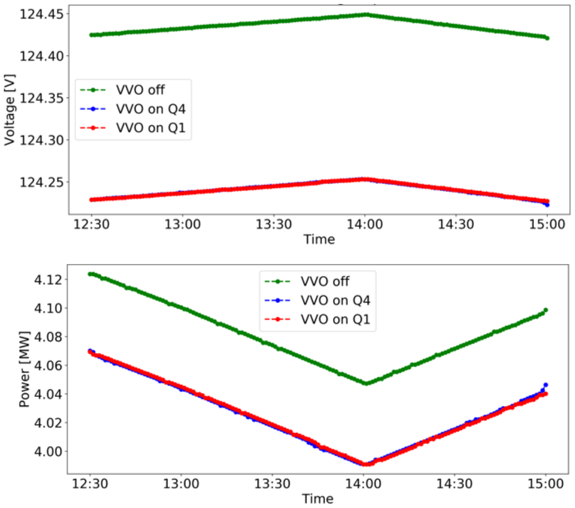

Fig. 5. Preliminary ADMS test bed simulation results for the model quality use case. End-of-line voltage (top) and feeder head active power (bottom).

Other Xcel Energy feeders that were evaluated using the ADMS training simulator showed more pronounced differences in energy consumption for different model quality and measurement density levels. Future work is warranted to simulate those feeders on the ADMS testbed to further assess the impact of model quality on VVO performance for feeders with different properties. All the test metrics that we will calculate using the simulation results are discussed in [9].

V. USE CASE EXAMPLE 2: DERMS INTEGRATION

A. *DERMS Integration Use Case*

This use case addresses the impact of higher penetrations of residential rooftop PV systems—some with battery energy storage systems (BESS)—along with flexible residential load, specifically water heaters and air conditioners controlled by smart thermostats and electric vehicles (EVs).

We evaluate peak load management (PLM), a critical application for utilities that enables distribution utilities to avoid high peak demand costs by reducing demand when system peak is anticipated. This is typically achieved by reducing the voltages across the distribution network by changing LTC, voltage regulator, and capacitor bank settings. These changes can be made automatically by an ADMS. With increased DER penetrations, distribution system operators have the opportunity to leverage these DERs to reduce load directly. The DERs can be controlled at an aggregate level by a DERMS. This enables the ADMS to use the DER assets without having to exert direct control, thereby simplifying DER integration challenges. It is critical to coordinate the actions taken by the ADMS and the DERMS because uncoordinated DER actions might run counter to the objectives of the ADMS, thereby reducing its effectiveness.

We will evaluate the performance of PLM coordinated between the ADMS and the DERMS, specifically the effectiveness of DERMS in complementing ADMS operations. We will quantify the increase in load reduction and the contribution of different DERs.

B. *Test Bed Setup for DERMS Integration Use Case*

The ADMS test bed setup for use case 2 is shown in Fig. 6. The ADMS is Survalent Technology's SurvalentOne, and we specifically use their SCADA and DVR applications.

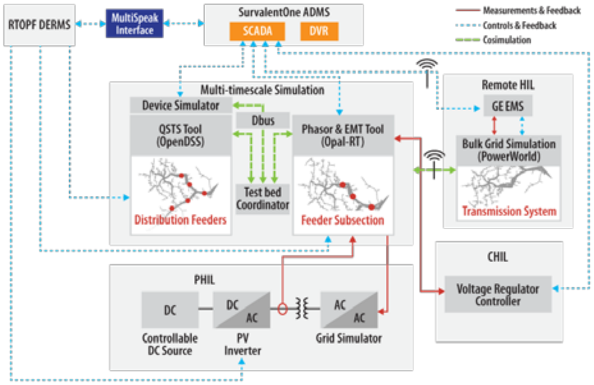

Fig. 6. ADMS test bed setup for the DERMS integration use case.

We model a feeder from Holy Cross Energy (HCE), a cooperative electric utility in Colorado. The feeder has four voltage regulators that is used by the DVR application of the ADMS to reduce voltage during a PLM event. Similar to use case 1, most of the HCE feeder is modeled in OpenDSS, with a time step of 1 second, and the part of the feeder that is interfaced to hardware is modeled in OPAL-RT's EMT simulator eMEGASIM, with a time step of 100 microseconds. We integrate the voltage regulator controller hardware used in the field, and we use one phase of a 12-kVA three-phase PV inverter to represent a 5-kW rooftop PV system in the field.

This feeder has a utility-scale 200-kW PV system and 38 residential rooftop PV systems with a combined capacity of 230 kW for a total PV capacity of 430 kW, which is 9% of the peak load. These systems all operate in unity power factor mode. The utility expects further growth of rooftop PV systems, and therefore we model the feeder with an additional 164 rooftop PV systems with a combined capacity of 982 kW for a total installed capacity of 1,412 kW, which is 30% of peak feeder load. We further assume that the 164 additional rooftop PV systems are controllable, i.e., that their active power can be curtailed and that their reactive power can be dispatched.

We created a DERMS prototype by modifying the real-time optimal power flow algorithm developed at NREL [11] to manage behind-the-meter DERs. Control decisions for inverter-based DERs—PV, BESS, and EVs—are updated on a faster timescale, every 10 to 15 seconds, and decisions for thermostatically controlled loads—water heaters and air conditioners—are updated on a slower timescale, every 15 minutes.

The integration of the ADMS and the DERMS will be achieved by using the National Rural Electric Cooperative Association's MultiSpeak-based standardized interface. We will expand upon the existing MultiSpeak specification and develop a reference implementation for interoperability between ADMS and DERMS.

Similar to use case 1, communication between the ADMS and all devices—simulated and actual—will use the DNP3 protocol. Communication from the DERMS prototype to the PV inverter hardware will be MODBUS TCP.

In addition, we will remotely link to a simulation of a transmission system at PNNL, managed by a commercial EMS by GE. The EMS will initiate the PLM event by sending a message to the ADMS located at NREL using the Inter-Control Center Communications Protocol (ICCP). The voltage and current measurements are exchanged between the multi-timescale distribution system simulation at NREL and the transmission system simulation at PNNL using the IEEE C37.118 standard.

C. *Preliminary Results from DERMS Integration Use Case*

The modified DERMS algorithms are being evaluated using only the OpenDSS simulation of the HCE feeder, and Fig. 7 and Fig. 8 show preliminary simulation results using the DERMS to control 356 PV inverters to mitigate overvoltages caused by high PV penetration. A full day was simulated and the results shown are for 12 p.m., when the PV generation is high and many overvoltages occur. Fig. 7 shows that there are many points on the feeder with voltage violations with no DERMS and that all voltage violations are eliminated by the DERMS. Fig. 8 shows that the voltage issue is mainly mitigated by dispatching reactive power and that only a small amount of active power is curtailed to reduce the voltages.

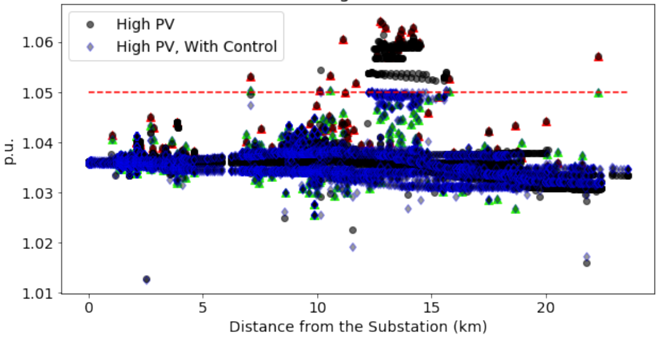

Fig. 7. Comparison of voltage profiles between no DERMS (black circles) and with DERMS (blue diamonds). The voltages at the nodes with PV are highlighted using red triangles (no DERMS) and green triangles (with DERMS).

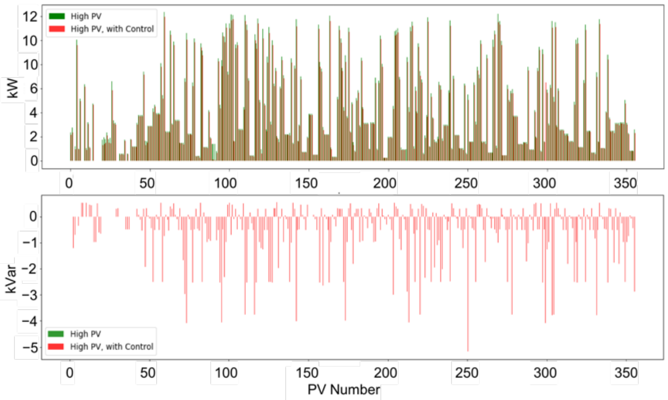

Fig. 8. Active power (top) and reactive power (bottom) output from each PV inverter.

VI. FUTURE ADMS TEST BED USE CASES

The ADMS test bed could be an invaluable tool for the power industry to evaluate the performance of existing and emerging management systems, or specific applications of such systems, as the characteristics of power distribution systems change. These power system changes include increased PV penetration, increased penetration of distributed BESS and EVs, and more flexible loads, e.g., smart thermostats allowing control of air-conditioner and electric water heater loads.

Several other research projects at NREL will be using the ADMS test bed and can be considered additional use cases of the test bed. One of these projects will use the test bed to evaluate a control architecture proposed for distribution grids with very high DER penetrations. The proposed controls feature ADMS-centered centralized control and operations supported by grid-edge controls consisting of static compensators and fast regulation of PV inverters. In addition to controlling legacy voltage control devices, such as capacitor banks and LTCs, the ADMS uses its solar and load forecasting, state estimation, load flow, and SCADA capabilities to coordinate with two other enterprise systems: a grid-edge management system provided by a vendor and a DERMS prototype similar to the one developed for use case 2. The grid-edge management system uses its fleet of fast-response static var compensator equipment, whereas the DERMS controls PV systems to achieve optimal voltage profiles at the grid edge. The test bed provides a realistic evaluation of the effectiveness of the proposed controls to reliably operate distribution feeders with high PV penetrations and of the interoperability of the constituent components of the proposed control architecture.

Another project will use the test bed to evaluate a proposed proprietary wireless communication system for utilities. And a project that is developing a distributed FLISR application with communications based on the Open Field Message Bus (OpenFMB) interoperability framework will also use test bed capabilities.

Some potential future use cases include evaluation of VVO applications for feeders with very high PV penetration and determining the optimal FLISR configuration for a feeder on which the load consistently exceeds 50% of line capacity or that has a very high PV penetration. More generally, we expect to use the test bed to quantify the operational benefits of deploying a wider range of advanced applications for specific utilities.

VII. CONCLUSIONS

Distribution power systems are changing as a result of increased penetration levels of DERs, such as inverter-based rooftop PV systems, residential BESS, and EVs. Power system loads are also changing with more loads exhibiting smart controls, such as air conditioners and electric water heaters, which make them more flexible and potentially able to provide grid services. As a result, distribution power management systems, including ADMS, need to adapt so that they can continue to effectively manage the power system.

This paper presents an ADMS test bed that has been developed for utilities, vendors, and researchers to use for evaluating the performance and quantifying the benefits of existing and emerging management systems or specific applications of such systems. The results from experiments using the test bed can therefore serve to accelerate industry deployment of ADMS technologies and advance development of ADMS capabilities.

The paper describes the general design and implementation of the test bed as well as the specific setup for two current use cases. Preliminary results are presented for these two use cases. We also discuss upcoming use cases as well as examples of what future use cases might be.

The test bed enables evaluation of existing and future ADMS applications in a realistic laboratory test setting (including other utility management systems and field equipment). Results from these laboratory experiments can inform field deployment decisions to ensure continued reliable operation of modern distribution systems.

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