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Model Quality and Measurement Density Impact on Volt/Volt Ampere Reactive Optimization Performance

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Abstract: The operation of the utility grid is being reshaped by the continuous addition of distributed energy resources and advanced metering infrastructure, which challenge existing grid control strategies. Some utilities deploy advanced distribution management systems (ADMS) to assist with the consolidation of various applications and to augment situational awareness in response to the new power delivery dynamics. An ADMS is an integrated software platform that provides utilities with a way to enhance their reliability, control, and optimization with advanced applications, such as volt/VAR optimization (VVO). A VVO application could serve as a vehicle to deliver cost savings by providing the utility with a method to reduce rates by controlling the voltage and decreasing the energy usage in their service territory. Some utilities are reluctant to integrate an ADMS, because it is a significant investment that requires approval from the public regulatory commission and/or their customers. This paper evaluates the impact on VVO performance when using a lower-quality network model supplemented with additional measurements, which could provide an implementation for cost savings. The results show that a better model quality would provide the highest energy savings; however, some level of telemetry is necessary in all scenarios to prevent voltage exceedances.

Keywords: advanced distribution management system (ADMS); volt/VAR optimization (VVO); conservation voltage reduction (CVR); and hardware-in-the-loop (HIL)

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1. Introduction

The idea of a smart grid presents many opportunities as well as challenges for distribution system operators. Utilities will need to adapt to more sophisticated monitoring and control systems to keep up with the new dynamics of power delivery and protection. The increase in the integration of distributed energy resources—such as photovoltaics, battery energy storage, and electric vehicles—has played a substantial role in the need for utilities to enhance their control capabilities for reliability and security. Many utility control rooms are equipped with aging, siloed applications for outage management and supervisory control and data acquisition (SCADA) that make the interoperability and integration process for new technologies difficult tasks [1].

An advanced distribution management system (ADMS) is a software platform with enhanced capabilities for utilities to leverage a data-rich environment and bridge the gap between multiple applications to increase situational awareness and provide faster control and service restoration to assist the industry in achieving its reliability and operational objectives [2]. With distribution applications such as fault location, isolation, service restoration (FLISR), distributed energy resource management systems, and volt/volt ampere reactive (VAR) optimization (VVO), an ADMS could support system operators in achieving increased reliability, energy savings, and security. The advanced applications assist in reducing the duration and impact of outages; however, the cost of deploying an ADMS has been a major inhibitor, preventing rapid adoption for many utilities. The utility would need to validate the equipment, system topology, and tempo-spacial to provide an accurate load forecast and state estimation to aid in the improvement of the system's

performance and reliability [3]. Every utility has a unique architecture requiring a level of surveying and customization of their existing network model, which increases the overall cost of the deployment process. For regulated utilities in the United States to secure funding for system upgrades, a rate case must be approved by the regulating commission outlining the costs and benefits justifying the rate increase for their customers. Some utilities have considered the implementation of VVO as a means to support the cost–benefit of an ADMS implementation by showing that it can reduce energy consumption by reducing voltages, which could translate to reduced energy bills [4].

Voltage regulation is a proven method to lower the energy consumption up to 3% by orchestrating the voltage reduction within the approved voltage limits, but it is hindered by traditional methods and lack of load forecasting tools [5]. Research has identified that a key variable in the effectiveness of an ADMS model-based VVO application to reduce power demand is the utility's model accuracy [5–7]. Improving the model's exactness and upkeep requires the utility to invest in surveying its service territory to verify the distribution power equipment status, configuration, line phasing, and ratings [3]. An effort of this magnitude could account for approximately 25% of the ADMS integration budget [8]. Utilities view this as a barrier of implementation, since an inaccurate model could impact the VVO application. The lack of awareness of the current state of the feeder could prevent the application from achieving the optimal performance, or contribute to voltage excursions that could adversely impact end-user equipment operations. Real-time situational awareness could mitigate the voltage excursion; however, it would require an additional investment to deploy and integrate more sensors. While the utility industry is considering the deployment of ADMS solutions for grid control, they are looking to understand the associated benefits to make investments decisions. The lack of studies that capture the impact of model quality and sensor measurement data availability in ADMS performance continues to be a key research gap. Recent works in this space that evaluate the performance of a commercial ADMS VVO in accomplishing energy savings through conservation voltage reduction (CVR) [9], ADMS's coordination with a distributed energy resource management system's (DERMS) in achieving peak demand reduction and voltage regulation [10], and associated hardware-in-the-loop (HIL) evaluations [11] did not consider the impact of network model quality and different measurement data levels on the ADMS performance.

To address this research gap, this paper evaluates the impact of the performance of an ADMS VVO application on an actual utility feeder under various model accuracy levels, and the potential to make up for the model inaccuracies with additional telemetry. The impact was quantified by evaluating the performance of a commercial ADMS VVO application with combinations of different levels of model quality and measurement density, to identify if there is a potential trade-off between the cost of field verification with additional sensors. This evaluation was guided by the initial simulation study of the performance impact on the VVO application under varying measurement density and model quality. The study captures the results of the energy reduction impact on six urban and rural feeders from Xcel Energy with the Schneider Electric (SE) EcoStruxure version 3.7 ADMS, as described in [8]. For a more comprehensive evaluation, we selected one of the feeder to asses the initial results. The simulation would provide the fidelity to evaluate quantifiable energy savings under varying conditions, such as model quality, measurement density, varying both, or none.

The key contributions of this paper are:

1. We evaluate the performance of a commercial ADMS VVO application with different levels of model quality and measurement density. To perform realistic evaluation, we used a real-world distribution feeder model and measurement sensor placement scenarios developed using the field data provided by a utility.
2. We analyze and quantify the benefits of improving the network model quality and the increasing network visibility by sensor measurements. Our study results show that improved model quality leads to increase in energy savings due to better estimation of system state. Additionally, the low network visibility due to lack of sensor

measurements results in a poor voltage profile, with voltage exceedances and more equipment wear and tear.

3. We provide the utilities the insights into the trade-offs between the implementation of varying levels of model quality with augmented telemetry that could offset an ADMS deployment cost. By considering these trade-offs, utilities can make more informed decisions about the cost of deploying an ADMS system.

In the remainder of this paper, Section 2 includes the VVO evaluation methodology details. Section 3 presents the experimental setup for the VVO performance evaluation. Section 4 describes the metrics used for the evaluation. Section 5 presents the simulation scenarios and results. Section 6 discusses these results. Finally, Section 7 provides the conclusions.

2. VVO Evaluation Methodology

The ADMS is a software platform with a collection of tools that assist utilities with their digital transformation to optimize and increase reliability of their power grid. VVO is an advanced application from the ADMS that aims to reduce the energy consumption by regulating the network voltage. To be effective, the VVO application relies on an accurate network configuration, load profiles, operational constrains, real-time information, and control of field devices. Utilities do not possess the capabilities to pilot a deployment of this magnitude in their service territory nor the ability to emulate a realistic environment. This presents an opportunity for utilities to partner with entities such as the National Renewable Energy Laboratory (NREL), which does have these capabilities. The NREL's ADMS Test Bed emulates a realistic environment for the evaluation of the performance of a commercial ADMS VVO application with two different ADMS model qualities and two different measurement densities, as shown in Figure 1. The ADMS Test Bed was developed with support from the U.S Department of Energy Office of Electricity, with the goal of establishing a realistic vendor-neutral laboratory environment to assist the industry in de-risking the adoption of ADMS technology and in understanding the performance of the system under future scenarios that a utility could face given the advancements in grid infrastructure and controls, as described in [12].

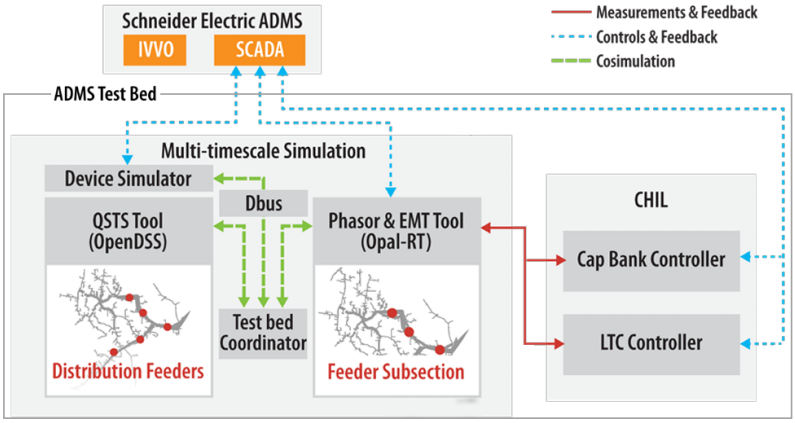


Figure 1. ADMS Test Bed setup for VVO performance evaluation.

2.1. ADMS and Emulation Environment Interface

The diagram in Figure 1 displays how the main elements of the Test Bed—the multi-timescale power network simulation, load tap changer (LTC), and capacitor bank controller-hardware-in-the-loop (CHIL)—are integrated with the commercial ADMS using industrial communication protocols. This configuration replicates the telemetry and situational awareness, similarly to a real field deployment. For the communication interface between the ADMS SCADA and the Test Bed, we use Distributed Network Protocol 3 (DNP3), a communication protocol widely used by electric utilities in the United States, to enable communications between the ADMS and the Test Bed.

The LTC controller, capacitor bank controllers, and Opal-RT are equipped to support DNP3 using their physical network interface. The Open Distribution System Simulator (OpenDSS) version 7.6 software was enhanced with the Distribution Automation Device Simulator [13] software developed by the Electric Power Research Institute (EPRI) to provide the DNP3 integration of the emulated grid devices and the ADMS. The SCADA in the SE ADMS handles the integration of the real-time communications to the simulated and real devices that provide situational awareness and control during the evaluation, as depicted by the blue dotted line in Figure 1.

2.2. Evaluation

The VVO application has been a mechanism for utilities to demonstrate an overall savings that will not require an enrollment program. A model-based VVO application can provide maximum impact when it has an accurate network model. In this paper, we assess the effectiveness of the VVO application trade-offs of utilizing a lower model fidelity with augmented telemetry to identify a potential offset for the implementation cost.

The software-only simulation work that preceded this project [8] identified the methodology to evaluate the possibility of offsetting the cost and need for model cleanup with additional field telemetry. The four levels of model quality consist of a direct extraction from the utility mapping with no verification for Model Quality 1 (Q1) to thorough field verification of connectivity, phasing, equipment status, and rating for Model Quality 4 (Q4). A similar approach was defined for the enhanced telemetry by defining only the feeder head measurements for Measurement Density 1 (D1), followed by the addition of 20 downstream tail-end voltage sensors for Measurement Density 4 (D4). For a detailed description of the different levels of model quality and measurement density, see [8].

To evaluate the performance of the ADMS VVO application, SE in collaboration with the utility developed four ADMS network schemas of different model qualities. The schemas were loaded into the ADMS to allow the manual selection and configuration of the desired model quality level under evaluation. The measurement density was configured trough the ADMS interface by enabling or disabling the field information that is used in the ADMS VVO control algorithm for each, according to each measurement density. During the laboratory evaluation, we used the lowest level of measurement density (D1) and the third level of measurement density (D3) including all primary measurements and 10 downstream meters in the feeder laterals. For the model quality, we used the lowest level (Q1), which contains the initial model migration from the utility, and the fourth level (Q4), which includes the highest level of network model accuracy.

In an effort to quantify the impact of the model quality on the VVO performance, we compared the percentage of energy savings between the baseline and the various configurations when VVO is enable. Additionally, we also capture the operation of field devices, such as capacitor banks or voltage regulators, during VVO enable to evaluate the sensitivity and long term network regulation of the application to mitigate any voltage excursions and prevent potential equipment failures. Finally, by having full visibility of the entire network, we are able to aggregated every minute a node experience a voltage excursion. This allowed the evaluation of the ADMS voltage stability when VVO is enabled.

3. Experimental Setup for VVO Performance Evaluation

The evaluation is crucial to increase confidence in the performance of the ADMS VVO application and to mitigate potential challenges. To provide representative behavior, a real-world distribution system and industrial protocols for communications are used for the evaluation. The ADMS Test Bed multitimescale and hardware-in-the-loop (HIL) capabilities provide the venue to evaluate the performance of the VVO application. This section describes the details of the SE ADMS integration into the ADMS Test Bed.

3.1. Distribution Feeder Modeling

The feeder used for this evaluation is from Xcel Energy, an investor-owned electrical utility serving Colorado, Michigan, Minnesota, New Mexico, North Dakota, South Dakota, Texas, and Wisconsin. This feeder was used in a previous software simulation-only evaluation of the SE ADMS VVO application performance on six urban and rural Xcel Energy feeders with various model qualities and measurement densities, as described in [8]. The results of the simulation assisted in downselecting a feeder for a more in-depth evaluation using NREL's ADMS Test Bed cosimulation and HIL capabilities. SE assisted in the deployment of an instance of their ADMS platform with the selected urban feeder for the evaluation depicted in Figure 2 and outlined in [8]. The Test Bed provides a realistic laboratory environment representing the power system through multitimescale simulation and controller hardware to support the assessment of the impact on the SE ADMS VVO application's power consumption reduction with different model qualities and measurement densities.

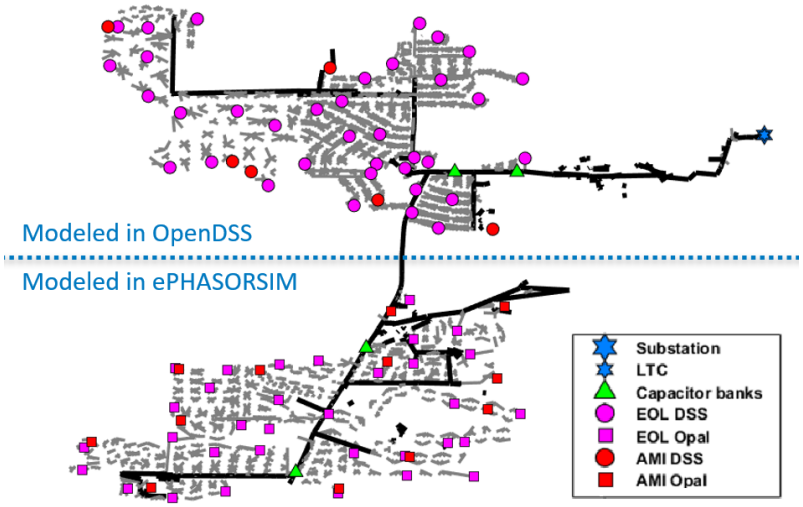


Figure 2. Xcel Energy distribution feeder used for evaluation.

The selected feeder is representative of an urban feeder within the utility's service territory. The feeder model was provided by the utility in a Common Information Model (CIM) format that was converted and validated in EPRI's OpenDSS. A subsection of the OpenDSS model was converted to OPAL-RT's electromechanical power system real-time simulator ePHASORSIM and cosimulated in the ADMS Test Bed, as described in [12]. The feeder operating voltage is 13.2 kV, and it has a length of 100 km and a mix of approximately 3000 residential and commercial customers. Approximately 70% of the feeder consists of underground service lines. The feeder has an LTC at the feeder head and four pole-mounted controllable capacitor banks downstream from the feeder, as identified in Figure 2. A heavy load day was selected for the simulation, which provides higher potential energy savings. Preliminary results for a light load day were reported in [12]. From the historical data provided by Xcel Energy, 26 June 2018 was selected for the evaluation, because it exhibited the highest energy peak demand for the test feeder of approximately 12 MW between the hours of 17:00 h and 21:00 h, as seen in Figure 3. This date was employed during the evaluation.

An additional characteristic of the feeder that has an impact on the potential energy savings performance of the VVO application is the conservation voltage reduction factor (CVR_f) [14]. The CVR_f represents the feeder energy savings sensitivity to voltage reduction. The CVR_f is the relationship ratio of the energy savings to voltage reduction. A CVR_f of 1 implies that 1% energy savings are expected from 1% voltage reduction. The energy savings through CVR can vary among the feeders, depending on the load composition and characteristics. In pilot project studies, CVR_f values between 0.7 and 1.0 are commonly observed

in distribution feeders [15,16]. The CVR_f can be derived from the constant impedance, constant current, and constant power (ZIP) load modeling commonly used in the industry for various network studies. The utility partner provides ZIP parameters of [0.24, 0.36, 0.4] from previous system studies, resulting in a CVR_f of $(2p_z + p_i) = 0.84$ from [17], with p_z and p_i denoting the impedance and the current ZIP parameters, respectively.

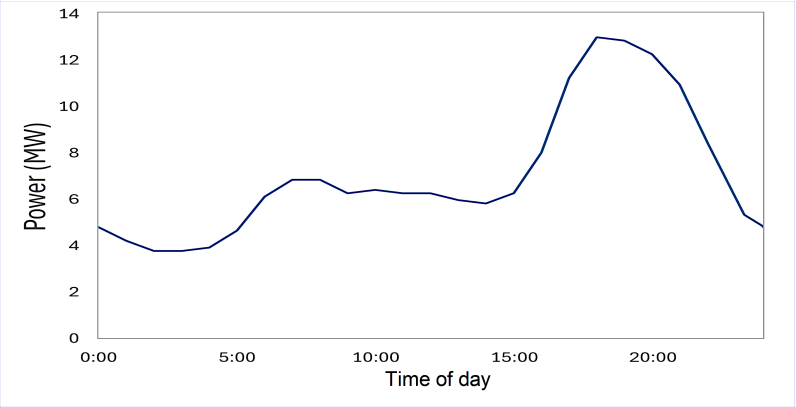


Figure 3. Load profile used in the Test Bed simulation and the ADMS.

To better assess the performance of the feeder voltage control during the VVO operation, data from an additional 146 end-of-line (EOL) secondary monitoring points are gathered during the simulation, as shown in Figure 2. These additional meters are not in the purview of the ADMS, because the objective is to assist in the evaluation of the VVO application's ability to reduce the voltage without experiencing any voltage excursions.

3.2. Multitimescale Simulation

To provide a realistic representation of the dynamic behavior of the distribution network, a multitimescale simulation strategy is implemented for the VVO evaluation with a portion of the feeder simulated in a quasi-static time series and the rest in the phasor domain, openDSS, and OPAL-RT's ePHASORsim, respectively. Industrial communication protocols facilitated the integration between the simulation and the SE ADMS. The hardware controllers were integrated into the simulation using OPAL-RT's eMEGASIM electromagnetic transient tool, as described in Section 3.4. The Test Bed coordinator enables data exchange between the ePHASORSIM, eMEGASIM, and OpenDSS simulators using the Hierarchical Engine for Large-Scale Infrastructure Co-Simulation (HELICS) [18]. User Datagram Protocol (UDP) is used for the data exchange between the Test Bed coordinator and the OPAL-RT system. OpenDSS is an electric power distribution simulator software [19], and OPAL-RT is a digital real-time simulator platform. As shown in Figure 1, part of the utility distribution feeder is simulated in OpenDSS, and a subtree is simulated in OPAL-RT's ePHASORSIM [20] phasor domain simulator. The time step resolution of the OpenDSS simulation is 20 s, and that of the ePHASORSIM platform is 10 ms. The hourly historical field data provided by Xcel Energy were linearly interpolated to a 1 min time step, so the loads and photovoltaic generation are updated every 1 min. All photovoltaic system irradiance profiles are configured with a single clear-sky day from 26 June 2017, from data extracted from the National Solar Radiation Database (NSRDB) [21]. Each platform solves its portion of the network power flow, and exchanges data as time advances at the common time step defined by the OpenDSS platform, as described in [12].

The network model was divided into two sections, with one section of the feeder model in OpenDSS and the other portion in ePHASORSIM, as shown in Figure 2. To link the simulations, both OpenDSS and ePHASORSIM need to exchange power flow information. For OpenDSS, the simulation provides the voltage magnitude and phase angle at the model merging point to define the base voltage for the ePHASORSIM subtree network model simulation. The ePHASORSIM simulation supplies the aggregated active and reactive

power demand at the subtree source to OpenDSS, which is used to sum the total load demand of the entire network model.

3.3. ADMS and VVO Configuration

The SE ADMS instance with the appropriate utility network schemas was installed and configured at NREL's Energy Systems Integration Facility to aid in the evaluation of the performance of the VVO application under different levels of model quality and measurement density. The SE ADMS is a commercially available model-based solution system that combines the distribution management system, SCADA, and outage management system, along with advanced applications, such as VVO and FLISR, into a single platform [22]. The SE ADMS has the flexibility to leverage the utility legacy control equipment—such as the LTC, voltage regulators, and capacitor bank controllers—as resources for the VVO application, to reduce the voltage along the feeder and to increase energy savings without any voltage violations. The ADMS enhanced situational awareness and data-rich environment provide the VVO application with the necessary resources to dynamically reduce the voltage across the feeder while maintaining the voltage within the operating limits. In this feeder, the VVO application employs control of the LTC at the feeder head to regulate the feeder voltage and four capacitor banks to inject reactive power along the evaluation feeder to boost the voltage if the voltage drops below the operating limits. An additional 20 bellwether meters provide real-time SCADA visibility of the feeder and assist the ADMS system in mitigating and preventing any voltage excursions during the operation of the VVO application. The locations of all these devices are shown in Figure 2.

The ADMS VVO application is configured similarly to the Xcel Energy field deployment with a 15 min cadence to achieve an energy savings objective. During this interval, the SCADA system is arranged to poll the integrated field devices every 30 s. The SCADA information is ingested by the ADMS system, and performs a state estimation and power flow analysis every 13th and 14th min, respectively, to determine the current state of the network. The VVO application uses this information to calculate an optimal solution that can be implemented by the devices under the ADMS remote control to reach the desired objective. The ADMS VVO application is equipped with a variety of predefined objective functions, such as power consumption reduction, active power loss reduction, and consumer voltage improvements, to list a few. For our evaluation, we configured the ADMS for power consumption reduction—the same objective used by Xcel Energy in the field—and measured the percentage of energy savings. To assist the VVO application in preventing feeder voltage exceedances, the ADMS is configured with voltage limits on the primary and secondary voltage to regulate the network voltage within the acceptable industry voltage range defined by the American National Standard Institute (ANSI). The allowable voltage tolerance defined by ANSI ranges from 114 V–126 V (±5%). Table 1 lists the VVO voltage constraints programmed inside the VVO application for the model-derived consumer voltage, advanced metering infrastructure (AMI) voltage, and primary medium-voltage measurement to provide prudence over the feeder voltage during our evaluation.

Table 1. ADMS VVO voltage constraints.

	Lower Limit	Upper Limit	Deadband
Consumer voltage	114	126	0
AMI voltage	114	126	0
Medium voltage	117	126	0

The ADMS is equipped with the flexibility to change the operating model quality schema from its interface, allowing us to configure the desired model quality before each evaluation. For the measurement density, SE configured all the telemetry devices and their corresponding measurement points in the SCADA system database with distinct names for each measurement density. The remote point names in the ADMS had an L1, L2, L3, or L4 at the end corresponding to each measurement density level to facilitate the identification.

To change the measurement density levels for the VVO application, the ADMS needed to be configured to exclude a group of points by modifying the trust factor for each point, allowing the optimization process to omit that signal during the evaluation window.

3.4. Controller-Hardware-in-the-Loop

To evaluate the realistic operation conditions and emulate the field setup, hardware controllers for some of the legacy devices—an LTC and two capacitor banks—are integrated with the ADMS Test Bed. The LTC and two capacitor bank controllers are interfaced with the OPAL-RT via CHIL techniques. To achieve the analog output signal fidelity for the controllers to perform as if they are connected to the field, a submodel was developed in OPAL-RT's eMEGASIM platform with a 50-µs time step and incorporated with the cosimulation. The Beckwith Electric LTC controller's analog voltage input was modified by the manufacturer to accept a ±10-V signal generated by the OPAL-RT system constructed from the feeder head voltage information provided by the OpenDSS simulation. The LTC controller responds to a set point command issued from the ADMS system either manually or during the VVO operation. The LTC voltage correction actions of tapping up or down to reach the desired set point are digitized by Opal-RT and sent to the OpenDSS simulation to adjust the electrical network emulation voltage accordingly. The adjusted OpenDSS voltage is fed back to the controller to stop the voltage regulation, confirming it has reached the desired voltage level. A similar configuration is implemented for the capacitor bank controllers, with the only modification in the open/close command feedback to the ePHASORSIM simulation.

EPRI's Distribution Automation Device Simulator allows for the direct integration of the two simulated capacitor bank controllers and seven EOL meters with the OpenDSS portion of the simulation. The tool serves as a gateway between the ADMS and the simulation by emulating an outstation that allows for a seamless integration with the SE ADMS SCADA system to be controlled remotely, or provides real-time telemetry as the real controllers (see Figure 4).

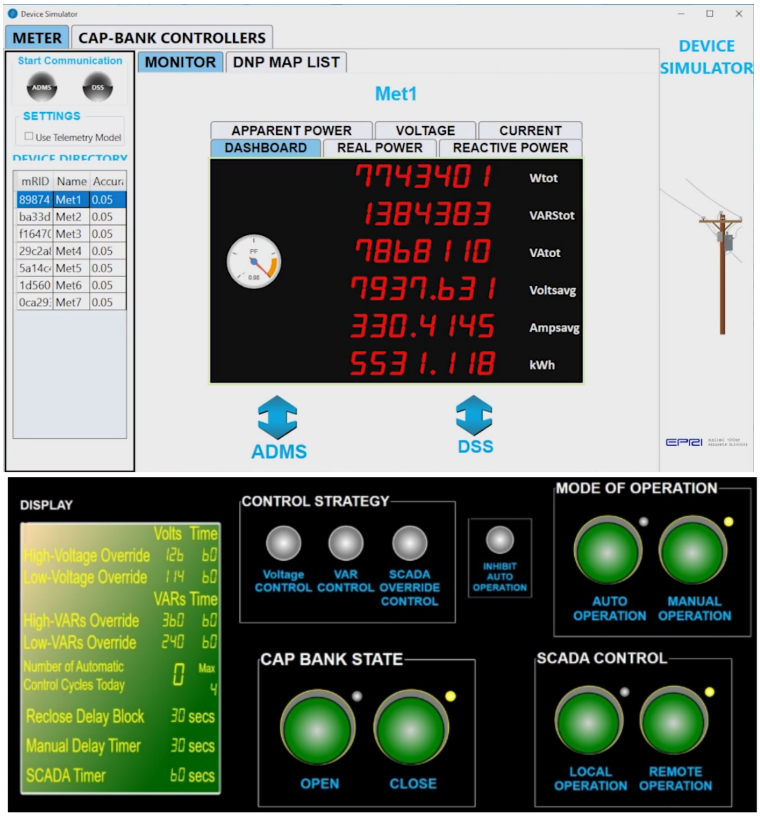


Figure 4. EPRI's distribution automation device simulator.

To replicate the field response for both the real and simulated controllers, we program the devices with the same configuration the utility uses. Tables 2 and 3 list the legacy devices' initial status, set point, and limits we use in the evaluation. Additionally, the same DNP3 communication interface that is used in the field was used to communicate between the controllers and the ADMS.

Table 2. Load tap changer set point and status.

	Center Band (V)	Bandwidth (V)	Intertap Delay (s)
LTC	124.3	3.0	25

Table 3. Capacitor bank set point and status.

	Initial Status	Size (kVAR)	Overvoltage Limit (V)
Capacitor Bank	Close	1200	126

4. Evaluation Metrics

The performance of the ADMS VVO application under varying model qualities and measurement densities is evaluated by using the following four criteria:

Percentage of energy savings: this is the percentage of energy savings calculated using the difference in the total energy delivered during different scenarios with VVO in the loop and in the baseline operation when VVO is not enabled.

LTC and capacitor bank operations (N_l/N_c): This is the number of times the LTC and capacitor bank changed tap positions/statuses during the simulation period. The number of equipment operations indicates the responsiveness of the VVO application to achieve the desired objective. A higher number of equipment operations can introduce wear and tear on the field equipment.

ANSI limit voltage exceedances (V_{ex}): this is computed by monitoring the additional 146 m distributed throughout the model and summing all the instances where the voltage magnitude is outside the ANSI voltage range of 0.95 p.u.–1.05 p.u. for a period of 1 min during the whole duration of the test.

5. Results

The evaluation of the efficacy of the ADMS to implement the desired objective when enabling the VVO application for power consumption reduction is analyzed with five different scenarios. The scenarios focus on enabling the VVO application over a period of 4 h, from 17:00 h to 21:00 h, when the residential feeder experiences its peak load demand. The simulation starts at 15:30 h to provide real-time data to the ADMS of the current environment. This allow the ADMS to purge any outdated data that could impact the VVO algorithm decision making. During all the scenarios, we configured all real and emulated legacy devices to operate in automatic mode, confirming to the configuration shown in Tables 2 and 3. In automatic mode, the legacy devices are expected to change state only when the equipment measurements exceeded the predefined limits or the ADMS issues a command.

For the baseline scenario results, the setup was configured to capture the ADMS operation during the observed period with the VVO application disabled. For the remaining evaluation scenarios, the VVO application is enabled at 16:30 h, with the combinations of different model qualities and measurement densities as follows:

Q1D1: the lowest model quality (Q1) and the lowest measurement density (D1) are configured in the ADMS.

Q1D3: The lowest model quality (Q1) and a moderate measurement density (D3) are configured. Measurement density 3 (D3) consists of 10 bellwether meters, in addition to the feeder head measurements and other utility assets that provide feeder visibility back to the ADMS.

Q4D1: the ADMS is configured with the highest model quality (Q4) and the lowest measurement density (D1).

Q4D3: the ADMS is configured with the highest model quality (Q4) and moderate measurement density (D3).

The following sections describe the observed impact and effectiveness of the VVO optimization application with different model quality and measurement density combinations on each test metric.

5.1. Active Power Demand

The purpose of the ADMS VVO application is to meet its operational objective of energy consumption reduction by decreasing the power at the feeder head. To evaluate this, NREL's ADMS Test Bed was configured to emulate the electrical demand based on historical load information from a local utility. The ADMS acquires insight into the current state of the electrical network's power consumption by analyzing the real-time measurements from the real and emulated devices. The information allows the ADMS to estimate future consumption by performing a power flow that is validated with the current field telemetry. The performance of the VVO application depends on the accuracy of the power flow which, in turn, depends on the difference between the projected and actual load. To assist the ADMS with the power flow calculations, historical seasonal consumption profiles are uploaded into the system to identify demand trends and forecast more precise demand. SE developed various average load profiles based on historical data from Xcel Energy that the system could reference during normal operations. This profiles represent the different average demand for each seasons or holidays. However, since our aim is to evaluate the impact of model quality and telemetry on the VVO performance, we updated the ADMS system reference load profile to be consistent with what we use in the Test Bed simulation, as shown in Figure 3. This assures the active power demand from the simulations is the same for all scenarios.

The feeder head power demand is logged for each scenario to be able to asses the energy savings between the baseline and all scenarios previously described. The ADMS VVO application analyses the real-time feeder head power measurement to forecast the state of the network and calculate the optimal voltage set point to try to achieve its energy consumption reduction objective. Figure 5 shows the power demand curves for all scenarios. The top blue line represents the power demand during the baseline simulation with VVO disabled. The simulation reaches a demand close to 13.01 MW near 18:00 h, which starts to taper off as the evening progresses. The remaining curves show the power demand with VVO enabled for the other four scenarios with different model qualities and measurement densities. The curves with VVO enabled did reach the power demand levels seen in the baseline. During the lowest model quality condition, there was only marginal energy reduction compared to the baseline. The scenarios with higher model quality experienced a significant energy reduction. The SE ADMS is a model-based system that analyzes the internal power flow and state of the system to predict the system voltage across the entire feeder, indicating that model errors have an impact on the energy savings. The accuracy of the model could impact the optimization by estimating inaccurate voltage levels that prevent the ADMS from achieving maximum power consumption reduction, or by impacting the system's reliability.

The largest power consumption reduction coincides with the scenarios that have the highest model quality levels, allowing the ADMS to calculate a lower voltage regulation set point to optimize the energy savings. This is in contrast to the lower quality results that estimate the network near its limit forcing the LTC to remain at a higher set point during the VVO optimization. Table 4 lists the percentage energy savings for each scenario.

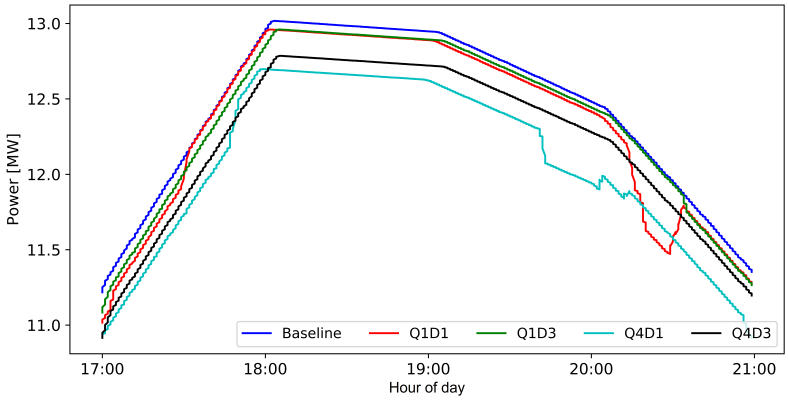


Figure 5. Feeder head power: (blue) baseline, (red) Q1D1, (green) Q1D3, (aqua) Q4D1, (black) Q4D3.

Table 4. Summary of experimental metrics.

	Number of Capacitor Operations	Number of LTC Tap Operations	Energy Savings (%)	Number of Voltage Exceedances
Baseline	0	0	N/A	0
Q1D1	0	11	0.81	90
Q1D3	0	1	0.51	0
Q4D1	0	7	2.9	1014
Q4D3	0	0	1.8	0

5.2. Field Equipment Operations

We observe the legacy devices' operations as an added metric in the implementation of VVO that could have a financial impact on the utility from added equipment maintenance costs. The additional operation of the hardware adds wear and tear that could potentially cause premature failure and stress to the equipment, which could impact the utility both operationally and financially. During our evaluation, each individual device state change was tracked to evaluate whether there was an impact on the operation of each device due to the different model quality or measurement density levels.

The ADMS VVO is configured to prioritize the use of LTC to manage the system voltage directly from the substation. Some utilities complement the VVO operation by implementing reactive power control from capacitor banks or distributed generation managed by the ADMS downstream from the feeder to flatten the network voltage profile and improve voltage regulation. The reactive power injection from these devices boosts the voltage at predefined sections of the feeder, allowing the LTC to further reduce the system voltage and increase the energy savings potential. For our configuration, the LTC and capacitor banks are the only controllable resources available for the VVO algorithm to implement a combined control strategy to achieve its objective.

The legacy hardware controllers monitor the primary feeder voltage from the network in the emulation through an analog input. This observation allows the controller to evaluate the current state and perform any corrective action based on the predefined set point or status configuration. The LTC controller set point governs the voltage level by triggering a raise or lower tap command to bring the voltage level to within the allowable bandwidth. The LTC controllers have a waiting period of 25 seconds between taps to allow the voltage in the simulation to settle and prevent hunting. The capacitor bank controller has similar operations that allow it to automatically operate if the analog voltage input is outside its voltage limits. The capacitor bank controller has a discharge interlock of 10 min operation intervals, to allow for complete discharge and prevent equipment damage.

Figure 6 displays the LTC tap position for the different scenarios. The baseline was defined as the initial tap position of 0. The LTC tap position remains constant throughout the evaluation. During the evaluation, it was observed that the measurement density had

an impact on the number of LTC operations. During the scenarios with lower measurement densities, the LTC presented higher activity in attempting to regulate the feeder voltage compared to the ones with higher measurement densities, occasionally reaching a tap position of −6, as shown in Figure 6. The higher measurement densities provided improved visibility of the feeder voltage, which allowed the ADMS to improve its state estimation analysis and reduce equipment activity. The capacitor bank controllers remained in their initial closed states for all the evaluations, i.e., they did not receive any state change control command from the ADMS VVO application. This is a result of the prioritization of the LTC in the ADMS VVO configuration and the ability of the ADMS to achieve its objective by using only the LTC. A summary of the equipment activity is listed in Table 4.

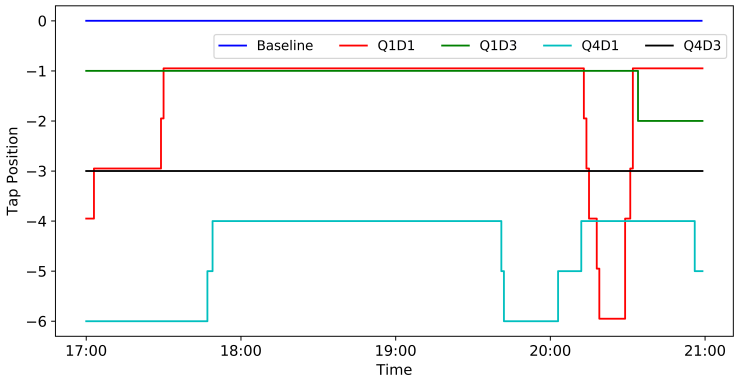


Figure 6. LTC tap position: (blue) baseline, (red) Q1D1, (green) Q1D3, (aqua) Q4D1, (black) Q4D3.

5.3. Voltage Excursion Management

The third criteria that is used to evaluate the VVO application's effectiveness is the ability of the ADMS to prevent voltage excursions that could potentially impact the network stability and reliability. The feeder simulation was equipped with 146 additional secondary monitoring points across the feeder outside of the purview of the ADMS, as shown in Figure 2. These data allow for the observation of the ADMS voltage management ability across the entire network while implementing the VVO objective to reduce the energy demand under the various scenarios. It is a significant responsibility of the utility to keep the customer voltages within the ANSI Standard C84 voltage limit range during the VVO operations to avoid equipment damage or increased losses. To help compute the voltage excursions during the evaluation of the different model qualities and measurement densities, the data from the EOL meters were collected and averaged over a 1 min period. The results for each scenario are represented in a shadow plot in Figure 7 to illustrate the voltage span across the feeder from the various monitored EOL voltages. The lines in each shadow plot represent the maximum, minimum, and average voltage observed during that scenario.

The baseline simulation is evaluated with no VVO optimization to assess the feeder response with a fixed LTC set point of 124.3 V (1.035 p.u.). During the entire run, the feeder voltages are observed to remain high, obeying the LTC set point, to maintain the system voltage within the approved operating limits, as represented by the horizontal lines in Figure 7a. The standard indicates that voltages exceeding 1.05 p.u and 0.95 p.u. are considered voltage exceedances. It can also be observed in the baseline plot that there is available capacity on this feeder to have the VVO application reduce the network voltage without exceeding the lower limit. In the scenarios with lower measurement density, it can be observed that the ADMS calculates a lower set point for the LTC that drives the voltage outside of the operating limit. Because there is no real-time EOL feedback during this scenarios, the VVO is unable to rectify the lower set point and quantified by adding every minute there is a voltage exceedance during the evaluation period, as shown in Figure 7b,d. The addition of telemetry illustrated in Figure 7c allow the ADMS to increase its situational awareness to be able to mitigate any voltage excursions that were present in the lower

measurement density scenarios. Figure 7e reveals that, with the highest measurement density and model quality, you could achieve a substantial level of energy savings without any voltage excursions and excessive equipment operation. A summary of the voltage excursion for each scenario is provided in Table 4.

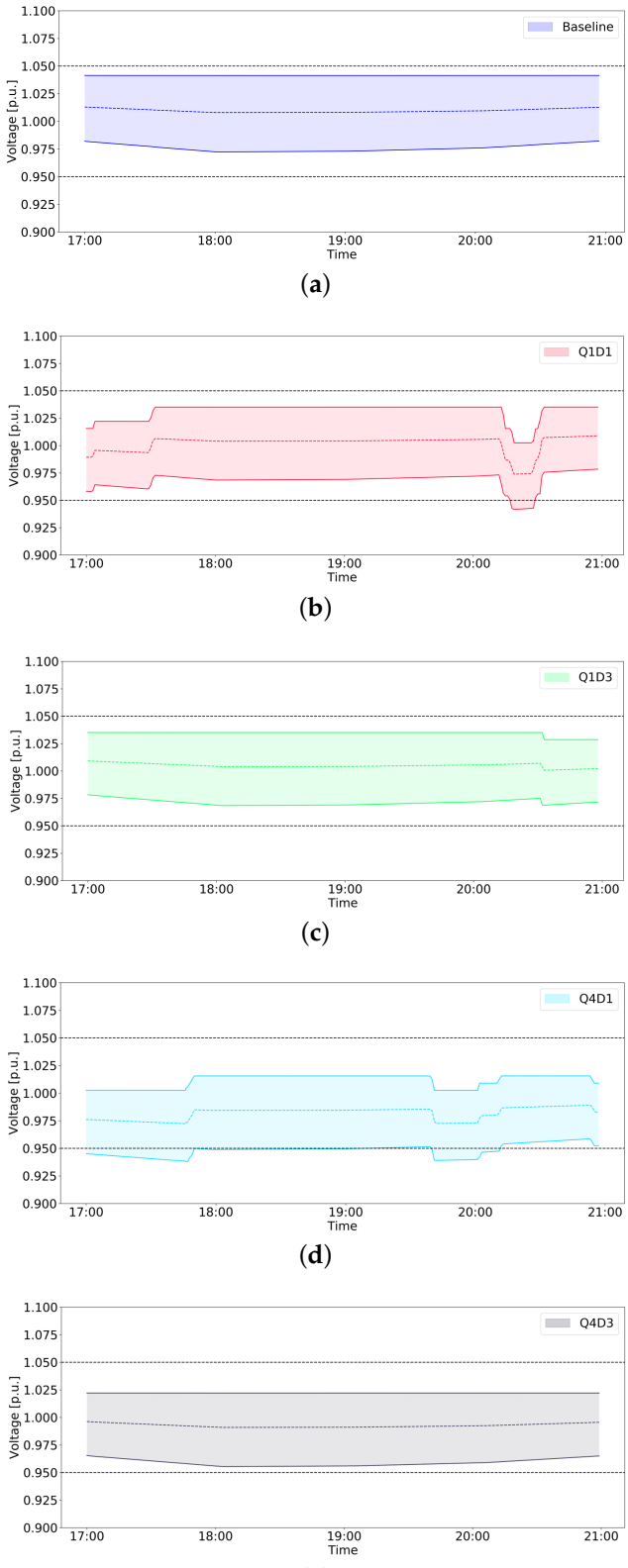


Figure 7. Feeder voltage statistics: (**a**) baseline, (**b**) Q1D1, (**c**) Q1D3, (**d**) Q4D1, (**e**) Q4D3.

6. Discussion

The integration of an advanced application such as VVO can increase the performance and optimization of the electric grid. In order to achieve wider adaptation, utilities and vendors need to find ways to reduce the cost of implementation or identify avenues to offset the initial cost with ongoing operational savings. This paper analyzed the trade-offs of deferring the initial capital cost for model verification by augmenting the situational awareness with additional telemetry. A summary of the observed experimental metrics is shown in Table 4. To asses the performance of the VVO application under two different model quality and measurement density scenarios, we monitor the capacitor bank operations, tap changer operations, energy savings, and number of voltage exceedances. The ADMS VVO application prioritizes the use of the LTC over the capacitor banks to regulate the voltage. The capacitor banks did not have a state change, and remained in their closed state for all the evaluations, reducing any unnecessary wear and tear to the equipment. The LTC tap position remains unchanged for the baseline and Q4D3. A voltage adjustment was observed in the Q4D1, Q1D1, and Q1D3 configurations. The Q1D1 and Q4D1 scenarios with the lowest telemetries observe the highest LTC activity, with 11 and 9, respectively. The highest model quality (Q4) results in the highest energy savings compared to the lowest model quality (Q1). Q4D1 observes the highest energy savings, 2.9%, because the VVO reduces the voltage the most, as shown in Figure 7d; however, there were more than 1000 voltage excursions below the ANSI lower limit. Q1D3 has the lowest energy savings compared to all the other VVO scenarios, along with zero voltage exceedances, at 0.51%. Q1D1 had an energy savings of 0.81%, with 90 voltages outside the limits, as shown in Figure 7b. Q4D3 had a calculated energy savings of 1.8%, with a combination of the highest data remediation and extended situational awareness, which averted any voltage excursions.

Considering the results, the higher model quality provides a substantial energy savings from the VVO application. This could increase the return on investment by providing higher operational savings. However, additional telemetry is still required to mitigate any potential voltage exceedances and maintain voltage stability. A utility looking at implementing an ADMS with a phase approach could distribute cost by starting with the lowest model quality and the highest measurement density. This would provide marginal energy savings and ensure voltage stability. The combination would provide the utility with a starting point to increase their reliability, flexibility, and resiliency.

Additionally, the evaluation illustrates that model quality provides an increase in energy savings upwards of 2%. The energy reduction can also be quantified with the potential greenhouse gas emission avoidance. One MWh of energy savings is equivalent to 700 kg of carbon dioxide emission avoidance, with an average of 800 kg of CO_2 for the improved model quality scenarios [23]. The extent of model quality could determine the impact on energy savings. Additional telemetry provided the ADMS system with a method to improve voltage stability with negligible impact on the energy consumption reduction objective of the VVO application.

Utilities can play a major role in reducing carbon emissions by delivering power more efficiently. This project's results can help formulate their power delivery strategies. Specifically, they can deploy ADMS that leverage utility assets and DERMS solutions that leverage grid edge device flexibility. Our previous work [9] showed 3% to 5% energy savings by utilizing BTM DERs. With a ADMS + DERMS, utilities can achieve higher carbon-free power delivery. Since many ADMS solutions are model-based, utilities can invest in keeping the models accurate.

7. Conclusions

Electric utilities continue to move forward with the digital transformation to help maintain affordable rates while increasing reliability and efficiency. The utilities need to develop a strategy to mitigate the risks they face when taking the leap to implement an ADMS solution in their control rooms. Often, their hesitation is due to the high initial cost, demanding system migration, and interoperability verification of legacy devices. This

paper investigates the performance of a VVO application in a laboratory environment to inform utilities on the impact of reducing the initial effort (and associated cost) of data remediation and of adding supplemental telemetry. VVO performance is measured through energy savings, the number of equipment operations, and the level of voltage exceedances. In conclusion, the laboratory evaluation results illustrated that situational awareness is a key factor for the overall system performance and voltage stability when implementing VVO. The additional telemetry allow the ADMS to instantaneously rectify any voltage excursions in the network, in case the VVO issues a low voltage set point. To obtain the highest possible energy savings, a higher model quality is required. Future studies should focus on investigating the integration and control of distributed energy resources (DERs) and the control of reactive power for capacity constraint relief, to enhance the robustness and applicability of VVO. Given the increased grid interconnection of DERs such as PV, battery energy storage systems, and electric vehicles, utilities should also consider deploying distributed energy resource management system (DERMS) to leverage the flexibility offered by these resources to provide grid services. Our previous work [9,10] evaluated and quantified the benefits of DERMS solutions, both as a standalone solution as well as working in coordination with an existing ADMS solution. The DERMS would provide additional controllability to the utilities by providing visibility and control of the behind-the-meter (BTM) DERs connected at the grid edge, facilitating more robust performance of the VVO application in varying grid conditions.

This paper highlights the capabilities of NREL's ADMS Test Bed to provide a realistic laboratory environment and evaluate the performance of ADMS applications.

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