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Xcel Energy Information Request No. 1
Docket No.: E002/M-19-721, E002/M-20-812
Response To: Minnesota Public Utilities Commission
Requestor: Michelle Rosier
Date Received: January 6, 2021

Question:

In Docket No. E002/M-17-797, Xcel Energy’s November 8, 2017 Transmission Cost Recovery (TCR) Rider Petition estimated \$31 million in capital costs would be needed for Geospatial Information System (GIS) Data Collection efforts which includes field verification of the distribution system as part of implementing the Advanced Distribution Management System (ADMS) (pp.15-16; Att. 1A, p. 19).

In Docket No. E002/M-19-721, Xcel Energy’s November 15, 2019 TCR Rider Petition highlights GIS improvements and \$27.2 million in forecasted ADMS expenses in 2019 and 2020 for inclusion in the TCR. The \$27.2 million includes capital, operating, and maintenance costs for ADMS and GIS improvements and removes ADMS and GIS improvement costs included in the base rates for 2016-2019. (pp. 9; 15; 18; Att. 1A, p.10-12; Att. 4B) The filing also discusses \$12.8 million in GIS improvement costs between 2018-2024. (p. 15) The filing highlights the Company has completed “collecting data such as the size of wiring, the size and location of equipment such as transformers, switches, poles, phasing and connectivity, and device control settings” for 80 feeders as of 2019 and planned an additional 50 feeders in 2020 (130 feeders total). In addition, Xcel Energy notes the Company completed an ADMS “Testbed” review¹ noting “initial indications are encouraging, showing that we can expect adequate performance with lower data collection if coupled with additional sensors.” (Att. 1A, pp. 10-12)

In Docket No. E002/M-20-812, Xcel Energy’s November 2, 2020 Hosting Capacity Analysis (HCA) Report filing states a “conceptual cost” of \$40-48 million is needed for field verification of primary and secondary systems for monthly HCA updates or automated initial review screens. (p.20; Att. F) The 2020 HCA Report describes “... the collection of data such as the size of wiring, the size and location of equipment

¹ Xcel Energy, Petition (November 8, 2017), Docket No. E002/M-17-797, Att. 1A, App. A, pp. 1-8: Identification of Impedance Model Improvements Needed to Implement ADMS Applications in Xcel Energy Territory appears to outline the ADMS “Testbed” review scope and timeline.

such as transformers, switches, poles, phasing, and connectivity. Hence, this process validates and enhances the various data attributes contained in the corporate GIS system by increasing its specificity and quality such that it could be used in an automated fashion to support the DER interconnection Use Case.” The Company’s 2020 HCA Report filing notes that field verification will benefit ADMS and the Advanced Planning Tool; as well as, potential future advanced applications like FLISR and IVVO. (Att. F at pp. 9-12)

Staff notes the GIS data to be collected appears nearly identical between the 2019 TCR petition and the 2020 HCA Report except for inclusion of device control settings in the 2019 TCR list. It is not clear to staff whether the GIS improvements in the 2019 TCR petition include secondary system data and/or extends beyond the 130 primary feeders planned or completed. Staff does not have a full picture of what is involved in the Company’s GIS data improvements, field verification or validation, and how that differs from the standard, ongoing distribution asset management the Company currently does. For instance, the Company’s November 1, 2019 Integrated Distribution Plan (E002/M-19-666) has an O&M budget that “...is composed of labor costs associated with maintaining, inspecting, installing, and constructing distribution facilities such as poles, wires, transformers, and underground electric facilities.” (pp.19, 34)

The 2019 IDP also states: “The GIS data improvement needed to enable ADMS also furthers grid modernization efforts related to DER. Specifically, this effort will help DER adoption by improving the GIS model which is used for system planning and for hosting capacity analysis. The data collection and improvements will reduce the amount of time that planning engineers spend preparing each model for analysis. The verification and population of additional data attributes will also help our designers validate capacity necessary for EVs.” (Att. M2, p. 35)

- a. Please explain how the Company prioritized which 80-130 feeders would have field verification of data for the ADMS, and whether incremental data collection or validation is necessary for those feeders to achieve the primary and secondary system field data validations proposed in the 2020 HCA to enable more frequent HCA updates or automated Initial Review screens.
- b. Please explain if, and why, the secondary system field verification conceptually proposed in the 2020 HCA Report is necessary to increase the frequency from the newly proposed quarterly HCA updates to monthly.
- c. Please explain which, if any, benefits identified in the ADMS certification would not be fully realized without the additional GIS data improvements proposed in the 2020 HCA Report.

- d. Please explain why the GIS data collection proposed in the 2020 HCA Report is incremental and a conceptual cost; rather than already included in the Company's annual O&M budget, ADMS budget, or otherwise captured in the Company's existing revenue requirements in base rates or the Transmission Cost Recovery (TCR) Rider.
- e. Please provide a summary of results and any report created on what the Company refers to as the "ADMS "Testbed"" review which discusses the level of data collection required for more frequent HCA, automated Initial Review screens, or to achieve the benefits proposed when ADMS was certified.

Response:

- a. **Please explain how the Company prioritized which 80-130 feeders would have field verification of data for the ADMS, and whether incremental data collection or validation is necessary for those feeders to achieve the primary and secondary system field data validations proposed in the 2020 HCA to enable more frequent HCA updates or automated Initial Review screens.**

The feeders selected for field verification as part of the initial go-live phase of the ADMS initiative were chosen based on the requirements necessary to ensure the ADMS functionality is fully tested and functional on a representative set of feeders. This includes aspects such as Supervisory Control and Data Acquisition (SCADA) capabilities, automated field devices, and potential for benefits from advanced applications enabled by ADMS. This field validation process is fully focused solely on the primary portion of the Minnesota system. Because Minnesota maintains multiple control centers, which equates to control of different geographic areas, the Minnesota implementation of ADMS was initially focused on one control center – specifically the Metro West Control Center. Further data validation to support the ADMS was informed by a study performed by National Renewable Energy Laboratory (and discussed in more detail in part e below), and will complete a streamlined data validation process for the remaining two Minnesota control centers – Outstate and Metro East.

Finally, as discussed in the ADMS Compliance filing submitted today in Docket Nos. E002/M-19-666, E002/M-19-721, and E002/M-20-680, the ADMS project contemplates performing data collection on additional feeders on which we have not performed these activities previously, and that are necessary to support the additional advanced functionality of ADMS, such as FLISR and IVVO. We are however, evaluating our future data collection strategy for this phase of the ADMS project, in light of the Commission's decision to not certify FLISR or IVVO as part of our 2019 Integrated Distribution Plan. We anticipate we will develop and solidify our plans for

our data collection strategy as it relates to potential advanced applications over the next year.

All that said, the primary system aspect of the conceptual field data verification initiative outlined in the HCA filing is directly comparable to the data verification being performed for ADMS. However, the project we outlined for the HCA would result in additional verification than what we are planning to support ADMS. We note however, the ADMS would benefit from improved data accuracy and the additional data validation process. So, should the Commission determine it is in the public interest for the Company to advance and mature the HCA to be conducted more frequently and/or to integrate with the interconnection process – or provide more specific direction with regard to the HCA potential futures analysis we outlined – we would work to refine the relevant project cost and timing estimates, which today are conceptual. Part of this would be evaluating in more detail any overlap with the remaining ADMS data validation and bringing that information back to the Commission.

We clarify that the secondary system field data verification we outlined in the HCA filing is wholly separate from work necessary for the ADMS, so is fully incremental to work being completed to support ADMS.

b. Please explain if, and why, the secondary system field verification conceptually proposed in the 2020 HCA Report is necessary to increase the frequency from the newly proposed quarterly HCA updates to monthly.

Field verification of secondary assets is not necessary to increase the frequency of the HCA to monthly in its current primary system-focused, Early Indicator for the Interconnection Process Use Case. As discussed in the HCA filing starting at page 11 of Attachment F, primary system verification will benefit the usefulness of the HCA and enable its potential use within the MN DIP Supplemental Review Screens, with additional benefits to the MN DIP System Impact Study Process; it would also provide more general benefits to ADMS and our overall planning for the system. Verification of the secondary portions of our system is needed to fully automate the MN DIP Initial Review Screens, but would not have any impact on the HCA in its current primary-focused form.

c. Please explain which, if any, benefits identified in the ADMS certification would not be fully realized without the additional GIS data improvements proposed in the 2020 HCA Report.

The benefits described in the ADMS certification and cost recovery proceedings are solely dependent on completion of the GIS data verification as described in those

proceedings. As noted in response part (a), we anticipate the data collection requirements for ADMS and HCA to have some overlap (for the primary portion of the system), which may require some adjustments to the HCA conceptual estimates in the future.

d. Please explain why the GIS data collection proposed in the 2020 HCA Report is incremental and a conceptual cost; rather than already included in the Company's annual O&M budget, ADMS budget, or otherwise captured in the Company's existing revenue requirements in base rates or the Transmission Cost Recovery (TCR) Rider.

As we have discussed in conjunction with our ADMS effort, our grid modernization strategy envisions a fully integrated advanced electric distribution grid. Our existing electric distribution model and analysis tools available to our planners and operators were not built to support advanced grid applications such as ADMS. Additionally, while we have maintained good asset records over time, we have not tracked all of our field assets to the level of detail necessary to support a tool such as ADMS or to accommodate increasing penetrations of DER. Increased and more detailed asset records are necessary to support our planning and operations in a new environment of more complex interactions.

That said, we need more detailed information to adequately support implementation and use of ADMS – thus a specific initiative to gather and update a fundamental portion of our overall primary system data. That effort also aids other internal processes and systems, as the data is updated in the primary system of record – our GIS, which shares data with more systems than just ADMS. For example, GIS also feeds our Synergi system, which supports our distribution system planning and HCA processes today. We have also updated our work practices to ensure that we are proactively collecting the higher level of data necessary to support the advanced grid for any new projects or as we reconstruct portions of our system over time.

Our approach to this substantial effort has been to do it incrementally, and consistent with where we believe customers will get the greatest benefit. To a large extent, that has been our approach with our first major advanced grid investment – ADMS – and changing our work practices to ensure that we are now collecting what we believe will be essential going forward. We believe a next logical step may be expanding the data validation process to prepare for advanced ADMS applications, such as FLISR and/or IVVO – however, where those applications may glean the greatest benefits, rather than take a system-wide approach. Similarly, if the Commission determines full automation of the HCA or portions of the interconnection process are in the public interest, that would necessitate a further, and likely comprehensive, data validation process that would have benefits beyond just HCA and MN DIP. That would mean

that all of our Minnesota system data would be fully updated to the current standard and available to all applications – which would overall increase our readiness to further leverage existing systems such as ADMS.

- e. Please provide a summary of results and any report created on what the Company refers to as the “ADMS ‘Testbed’” review which discusses the level of data collection required for more frequent HCA, automated Initial Review screens, or to achieve the benefits proposed when ADMS was certified.**

We clarify that this report and study was specific to the data necessary to support ADMS. In order to confirm the benefits proposed when ADMS was certified, the Company partnered with the National Renewable Energy Laboratory (NREL) and the ADMS product developer, Schneider Electric to perform analysis regarding the evaluation of ADMS performance for different levels of model quality. We first discussed and provided a report on this in our November 8, 2017 filing in the TCR Rider filing in Docket No. E002/M-17-797.

The project team evaluated the performance of the ADMS Volt/VAr Optimization (VVO) application in regulating the feeder voltage and performing conservation voltage reduction (CVR) for different levels of model quality and different levels of field device measurement density. It is this effort that is referred to as the “ADMS Testbed.” As part of this effort, we analyzed whether the Company’s initial primary feeder field verification strategy would capture sufficient information to support various levels of model quality. As a result of this work, we determined that the volume of data initially targeted for capture to stand-up ADMS could be reduced. We are applying the result of this study to the ADMS data validation processes that will support its implementation in the Outstate and Metro East Control Centers, as well as any further ADMS data validation to support use of its advanced applications.

We provide an updated version of the NREL report as Attachment A to this Response.

Preparer: Chris Punt
Title: Manager, Distributed Energy
Resource Integration
Department: Distribution Electric Engineering
Telephone: 651-229-2549
Date: January 25, 2021

Evaluating the Impact of Model Quality and Measurement Density on ADMS Performance

Santosh Veda, Shibani Ghosh*, Murali M. Baggu, Jal Desai, National Renewable Energy Laboratory, Golden, CO US
Pete Gomez, Jessica A. Augdahl, Brian D. Amundson, Xcel Energy, Denver, CO US

*Email: Shibani.Ghosh@nrel.gov

Abstract—This report presents the methodology and results from evaluating the performance of advanced distribution management systems (ADMS) for different levels of model quality and measurement density. The project team evaluated the performance of the ADMS Volt/VAr optimization (VVO) applications in regulating the feeder voltage and performing conservation voltage reduction (CVR) for different levels of model quality and measurement density. The results show that the benefits of field verification strongly depend on the feeder characteristics. Some general observations include - i) VVO settings, for example, consumer voltage constraints—need to be tuned based on feeder characteristics to maximize the benefits. The settings can be tuned for reduction in energy consumption, power factor improvement or voltage profile improvement; ii) The analysis showed that Level 3 model quality (Q3) greatly improves the performance of ADMS VVO deployment. Further improvements in model quality to Level 4, do not significantly improve performance; ii) The inclusion of at least one advanced metering infrastructure sensor in Level 2 measurement density (D2) provides good visibility into feeder voltage performance. Level 4 (D4) measurement density ensures that all the laterals, large customers, and critical points are observable by the ADMS; iv) Urban feeders traditionally experience more growth (new customers, upgrades, rebuilds, etc.), and because of this activity, the current field verifications might not significantly improve the model quality. This observation was corroborated through Xcel Energy’s internal analysis on data enrichment from field verification. Urban feeders showed a low level of enrichment (30%) – field verification did not result in significant changes in the feeder impedance model; v) Rural feeders traditionally do not experience fluctuations as a result of minimal growth and related system modifications; hence, a pronounced impact on energy consumption was observed during different levels of model improvement analysis. This observation was corroborated through Xcel Energy’s internal analysis on data enrichment. Rural feeders show a high level of enrichment (70%) – field verification resulted in significant changes in the feeder impedance model; and vii) For very long feeders, the minimum voltages and maximum voltages observed in the feeder may span the entire allowable voltage limits. Thereby, such feeders may not be optimal for implementing CVR due to lack of sufficient room for reducing voltage, unless zone-wise voltage reduction can be achieved (such as, with voltage regulators). Otherwise, undervoltage conditions can be observed at the feeder end.

I. INTRODUCTION

When utilities deploy an advanced distribution management system (ADMS), they typically migrate network data from existing systems, such as supervisory control and data acquisition (SCADA) systems, outage management systems (OMS), customer information systems, (CIS) and the utility’s geographic information system (GIS). The GIS data provide information on the location of customers and utility assets

in addition to their connectivity and some asset information, such as cable sizing. Usually, these data need some remediation, or enhancement, before they can be used by advanced ADMS applications, such as Volt/VAr optimization (VVO). Remediation refers to the process of checking data for completeness, conformity, consistency, duplicates, integrity, and accuracy. Depending on the size of the utility network and quality of available GIS data, the remediation effort can add significant costs to an ADMS deployment. Data collection and model-tuning costs can be reduced using model-tuning tools available in ADMS without performing a field test. A field test is performed only for feeders marked for the additional check. The following questions are important to address when preparing for an ADMS deployment:

- What level of data remediation does the utility need for a successful deployment?
- How many and which type(s) of sensors need to be installed for optimal ADMS performance?
- What is the impact of the lower data remediation level on the performance of ADMS and its applications?
- How much will additional remediation improve the ADMS performance?

The selected use case will address some of these questions. For this use case, the project team will evaluate the performance of the ADMS VVO application on regulating the feeder voltage and performing conservation voltage reduction (CVR) for different levels of data remediation and different levels of measurement density. The goal is to estimate the optimal level of data quality and measurement density to have enough information to perform model-based VVO/CVR. There might be an opportunity to reduce the amount of data remediation (and hence the cost of deployment) by deploying additional sensors, i.e., by increasing the measurement density. The project team will therefore investigate the trade-off between data remediation and measurement density

II. FEEDERS SELECTED

The feeders in Fig. 1 were identified by Xcel Energy for testing. They were selected to represent the variety of characteristics of the feeders across Xcel Energy’s service territory. The peak loads mark the highest load recorded in the year from time-series feeder-head load data provided by Xcel Energy for the individual feeders.

III. EVALUATION STRATEGY

The evaluation strategy consists of a differential test procedure wherein the results are compared for different

Feeder	Type	Circuit Miles (apprx.)	Customers (#)	Underground (UG %) / Overhead (OH %)	Peak Load (MW, apprx.)
Feeder 1	Rural	80	1571	54/46	1.07
Feeder 2	Rural	125	2143	70/30	7.13
Feeder 3	Semi-urban	47	2799	87/13	6.73
Feeder 4	Urban	22	477	13/87	12.34
Feeder 5	Urban	14	351	25/75	11.3
Feeder 6	Urban	61	2880	73/27	12.46

Fig. 1. Overview about selected feeders

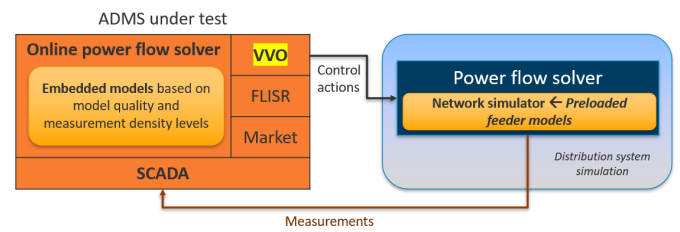


Fig. 2. Illustration of test setup

combinations of measurement density levels (D1, D2, D3, D4) and model quality levels (Q1, Q2, Q3, Q4).

A. Model Quality Levels

Schneider Electric's ADMS under test has a database with four sets of selected feeder data; each set represents a certain level of data remediation model quality improvement. Xcel Energy will have undertaken remediation field verification efforts for the selected set of feeders and provided the data for each level. Following are short descriptions of the levels of data remediation model quality provided:

- Level 1 (Q1): These are base-level data extracted from the Xcel Energy GIS adjusted just enough to provide power flow convergence.
- Level 2 (Q2): In addition to Level 1 remediation, field verification will occur at select locations to obtain wire size and material (where unknown), capacitor, regulator, recloser, and step transformer attributes. These asset locations will be noncontiguous.
- Level 3 (Q3) : In addition to Level 2 remediation, phasing information will be collected through field verification at select locations.
- Level 4 (Q4): In addition to Level 3, field confirmation will be performed for each primary circuit to obtain distribution transformer attributes, identifying new assets not shown in the GIS data and identifying assets that no longer exist in the field.

The feeder data was extracted from Xcel Energy's GIS as CIM extracts. The CIM files for each level of model quality was then imported by the Schneider team into their ADMS database. Further tuning was performed by Schneider team to make sure that the imported data was accurate and that it met all the sanity checks (like customers are energized, there are no loops in the network, switch positions are accurate, etc.).

B. Measurement Density Levels

The levels of measurement density will be achieved by adjusting the number and location of telemetry points in the simulated distribution system. Following are the levels of measurement density:

- Level 1 (D1): Feeder head and tail-end measurements
- Level 2 (D2): Measurements from D1 along with measurements at capacitor banks as well as reclosers and one tail-end advanced metering infrastructure (AMI) sensor
- Level 3 (D3): Measurements from D2 and a total of 10 AMI sensors per feeder

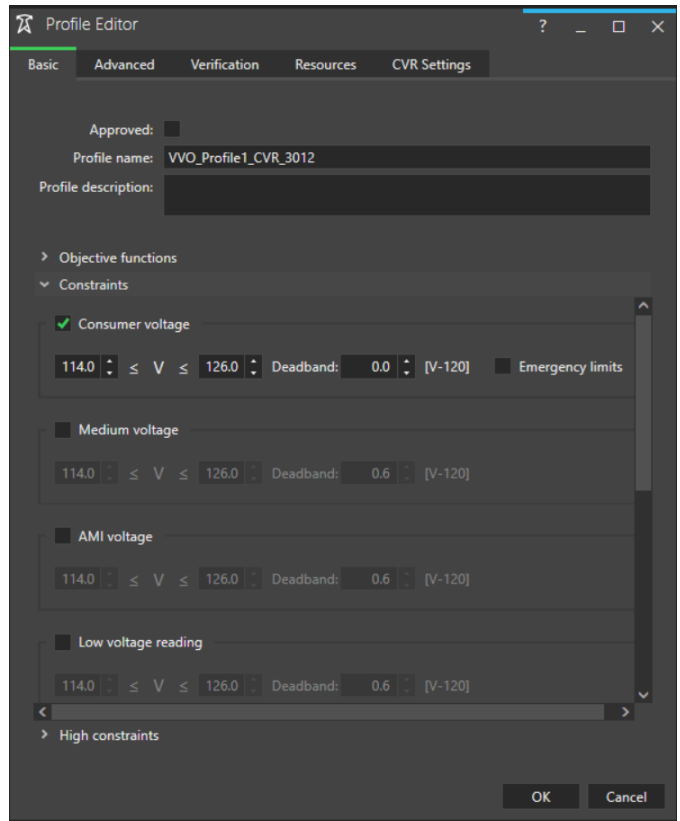


Fig. 3. VVO profile configuration screenshot from the ADMS real-time profile

- Level 4 (D34): Measurements from D2 and a total of 20 AMI sensors per feeder.

The location and number of telemetry points were determined through Xcel Energy's internal analysis. The AMI sensors were selected based on factors such as end of a lateral, primary-metered customer, and large customer loads. The selected AMI sensors are bellwether meters that report voltage information at higher rates than non-bellwether (regular) AMI sensors. The following data are polled every 5 minutes: 5-min average power (kW), 5-min average reactive power (kVar) and 5-min average per phase voltage (V). The SE ADMS was configured to select between these different levels of measurement density.

C. Loading Levels

... high vs normal loading levels

IV. TEST SETUP

As shown in Fig. 4, the test set-up consisted bed will consist of Schneider Electric's ADMS along with VVO and

SCADA applications that are under test. The ADMS will contain the models of the selected feeders (four metropolitan and two rural). The distribution power flow block will perform the computations required to simulate the behavior of the distribution network through the power flow solver. The solver will be loaded with the real ADMS distribution feeder models consisting of detailed representations of power system assets such as cables and transformers and relevant secondary assets such as protection relays and voltage control devices.

A. VVO Configuration

In the ADMS, the VVO algorithm can be configured to optimize between the following different objective functions (or a combination of these):

- Power consumption reduction
- Active power losses reduction
- Consumer voltages improvement
- Medium voltages improvement
- Power factor improvement
- Cost of manipulation minimization
- VAR control
- Emergency voltage reduction
- Voltage reduction

The technical objectives of the above functions are self-evident. VVO profiles can be created for different combinations of these objective functions, depending on the utility objectives. Thus, a VVO profile for a certain feeder can be configured for a combination of power factor improvement and power reduction while another feeder can be configured for, say for improving medium voltages. The ADMS VVO optimizes set points for the voltage control devices (like LTCs and Cap banks) for these VVO profiles under a given set of constraints. These constraints and high constraints can include parameters like ranges of consumer voltages, medium voltage, low-voltages, AMI voltage, power factor measurements, and voltage unbalance metrics. These constraints are also determined by utility objectives. The project team used the same VVO profiles that are used by the Xcel Energy team. The test results presented in the following sections follow the VVO profile given in the snapshot in 3. The objective is to implement CVR or reduce power consumption. As shown, the constraints are set to keep the consumer voltages within the range from 114–126 V. High constraints are not used in this analysis and are set to none; however, they would take priority over constraints. The resources tab includes which control devices are to be included in this optimization problem. All the tap changers and capacitor banks available at the substation and feeder level are included as resources in this profile.

B. Post Processing

... Texts about how the data outputs from the test platform were post-processed... ..

V. IMPACT OF FIELD VERIFICATION ON MODEL QUALITY

Given the base-level model quality of each feeder, it is necessary to assess the impact of the field verification on the actual feeder data quality. This assessment is performed

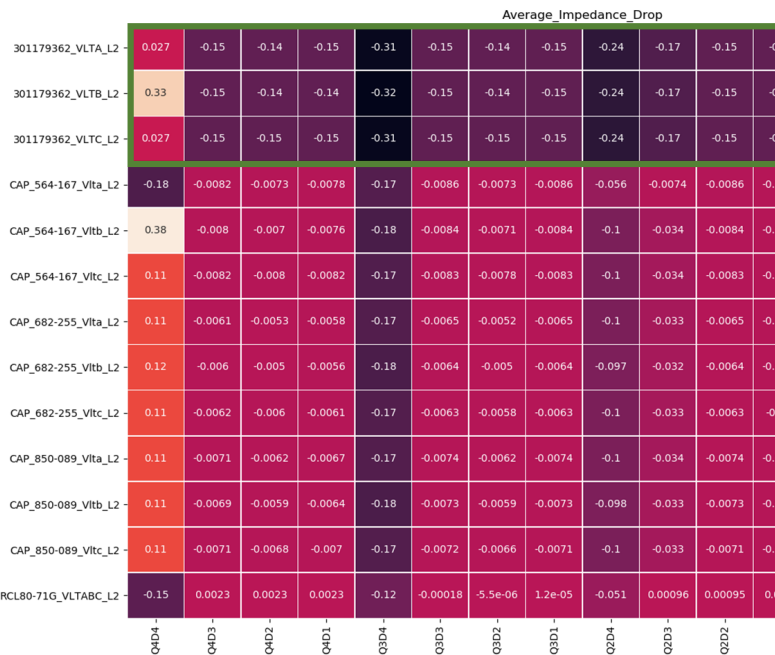


Fig. 4. Voltage drop between the substation and the different measurement locations for Feeder 5

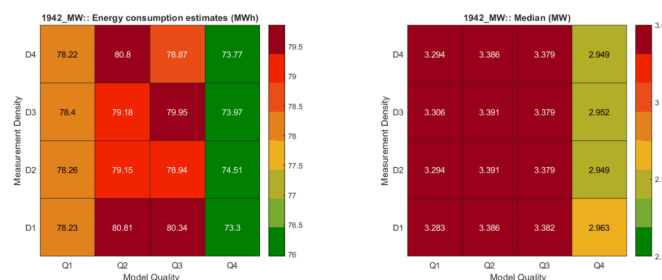


Fig. 5. Energy consumption (MWh) and median power (MW) for Feeder 1

by calculating the impedance (estimated as voltage drop) between the substation and the end-of-line point for each feeder within each level of model quality. This enables the ability to quantify the impact of the field verification on the actual impedance model.

REDO figs and RE-SUMMARIZE the findings

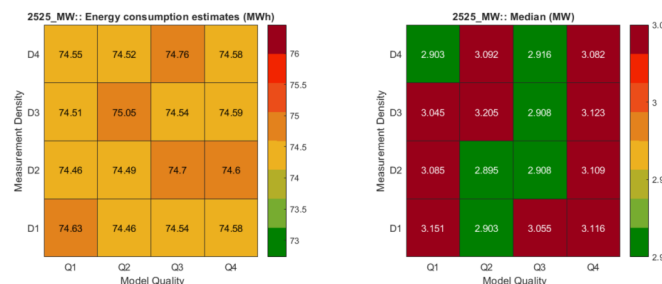


Fig. 6. Energy consumption (MWh) and median power (MW) for Feeder 2

VI. IMPACT ON ENERGY SAVINGS

The ADMS VVO can optimize the asset operations based on the objective function selected by the user—e.g., power consumption reduction, medium-voltage improvement, power factor improvement, VAR control. The case studies presented in this report are targeted to perform CVR—i.e., the objective function is to minimize power consumption within the predefined voltage constraints. This function aims to reduce energy consumption by flattening the voltage profile and reducing the voltage across the feeder while avoiding voltage violations.

This VVO function is triggered to optimize and update control actions on a minute interval, whereas the real-time day-long load profiles are simulated within an hour. The changes in energy consumption was calculated for each feeder from the measured power values at the feeder head for the day in question. For the feeders, two sets of heat maps are provided: energy consumption estimated during the day (in MWh) and median power level (in MW). The energy consumption heat maps are arranged so that the color map(s) for individual feeders are spread across a 5% range of the average energy consumption. This average consumption represents the mean MWh for all 16 cells in the heat maps (Q1D1–Q4D4). Median MW heat maps are colored to show the same step size across all the feeders—i.e., the minimums of all 16 cells are presented in green, and step color changes are considered within a range of 0.15 MW. If the power level for an individual cell is more than that of the upper level, that cell is shown in dark red.

For example, in Fig. 5 for Feeder 1, Q1 power (leftmost column on the right heatmap) is dark red because all these values are more than the highest value in the equivalent bar (3.05 MW). Feeder 1 being one of the shorter feeders, has reduced energy consumption with better model quality but for Feeder 2 the reduction is less pronounced as the energy consumption and net demand vary within a close range in the heatmaps. Like Feeder 6, Feeder 2 also has higher percentage of UG lines

VII. IMPACT ON VOLTAGE REDUCTION

Given the long length of Feeder 2 (a rural feeder and the longest, with 120 circuit miles), the voltage drop between the feeder head and the end-of-line locations is high enough that the CVR does not have enough flexibility to reduce the voltages any further. This effect is evident in Fig. 7, which plots the daily voltages for different measurement locations for the Q4D4 test case. Even though this case reflects the highest level of model quality and measurement density, all the voltages remain within the upper end of the voltage range. This implies that the VVO function cannot perform CVR for this feeder. The energy consumption levels also showcase similar values for all model qualities for this feeder (Fig. 6).

Similar figures for other locations in Feeder 1 are provided in Fig. 8 and Fig. 9. These figures provide a basis of comparison for changes seen in voltage profiles as the model quality/measurement density changes. The analysis of the voltages that were measured at all the selected measurement locations shows that for the same CVR setting, certain feeders are closer to the 0.95 p.u. voltage limit, whereas

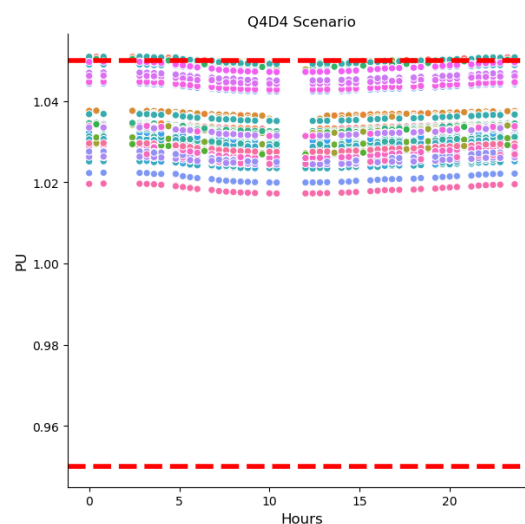


Fig. 7. Feeder 2 (rural, even mix of UG and OH assets) - Q4D4 voltages

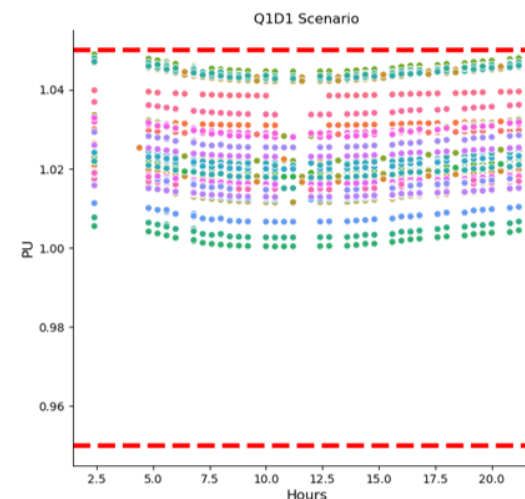


Fig. 8. Feeder 1 (rural, even mix of UG and OH assets) - Q1D1 voltages

others have substantial room for further voltage reduction. A key outcome of this study is that CVR settings should be tuned for specific feeder types to enable greater benefit from these applications. Having only one CVR setting might prevent us from maximizing the benefits from CVR.

... Add section on critical voltage reduction explaining Fig. 10...

VIII. SUMMARY OF FINDINGS

This section presents the summary of findings from the studies.

A. Impact of Feeder Characteristics

The feeder characteristics greatly influence the impact of different model quality levels:

- Urban vs. Rural:
The urban feeders (ENGL and GREE) are relatively new and have been field-verified in recent years. The impact of model quality is much less pronounced compared to the rural feeders (BERG). The rural feeders

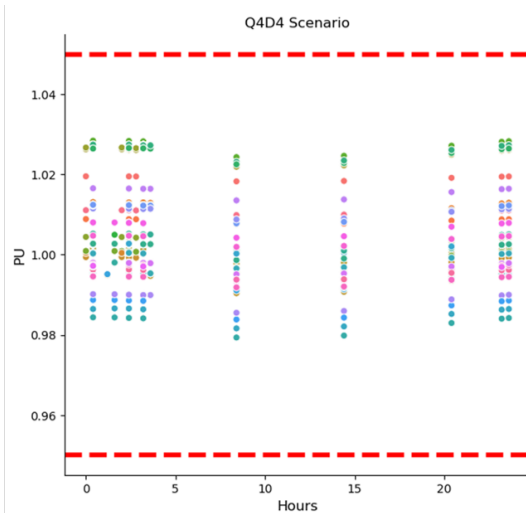


Fig. 9. Feeder 1 (rural, even mix of UG and OH assets) - Q4D4 voltages

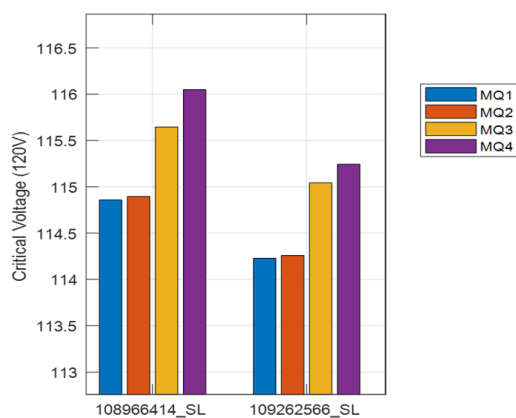


Fig. 10. Feeder 1 (rural, even mix of UG and OH assets) - reduction in critical voltages in selected feeder nodes

(BERG) have not been subject to field verifications and hence show a more pronounced impact. The urban feeders are also much shorter; hence, the voltage profiles are much tighter.

- **Underground vs. Overhead:**

The costs for the field verification for the overhead and underground structures vary widely, as presented in Figure 4. Feeders that have a significant portion of underground structures (Feeder 3, which has 87% underground network assets) have much fewer attributes that are field-verified compared to other feeders that have a higher proportion of overhead structures. It is important to recognize that Level 4 field verification for the underground feeders will yield significantly less information than the Level 4 verification for the overhead feeders.

B. Impact of Model Quality

The level of data remediation depends on the size of the utility network and the quality of available GIS data. The quality of the existing GIS data for the selected feeders is good. Q3 model quality is required for successful model-based VVO deployment on selected feeders, as observed

from the results presented in the previous sections. The results show that after performing selected field tests for the Q3 model quality, further improvements in model quality do not significantly improve calculated voltage drops, and thus Q4 verification might stand redundant. The feeder characteristics are critical when considering the impact of model quality. Q4 for an urban feeder might not represent the same level of model improvement as that for a rural feeder. Similarly, feeders that have more underground structures than overhead structures have significantly lower levels of information collected from field verification (and lower costs as well). Given these considerations, the following observations were made:

- When the system is stressed by increasing the feeder loading, Q4 model quality reduces the number of occurrences related to undervoltage violations for all feeder types.
- For urban feeders, the field verification might not significantly improve the model quality. For example, Feeder 5 and Feeder 6 show similar levels of energy consumption for all scenarios of different model quality and measurement density.
- Rural feeders such as Feeder 1 show a very pronounced impact on energy consumption for different levels of model improvement. Q4 improves the energy savings more than Q3 or Q2, and field-level asset verification seems to play an important role for feeders such as Feeder 1 (as depicted in Section 4).

C. Impact of Measurement Density

For optimal ADMS performance, three-phase active and reactive power sensors at the feeder head are required. For unbalanced feeders, per-phase active and reactive power sensors need to be installed on feeder heads, reclosers, and capacitor banks. The optimal trade-off between cost and benefit is to use model-based VVO, which is configured to address the constraints of reliably estimated voltages on the primary side of the feeder (medium-voltage constraints) and ignore the unreliable voltages on the low-voltage side of the feeder (customer voltage constraints). With a Q3 level, the accuracy of the distribution transformers and consumer data is not confirmed; hence, the voltages on consumers are not reliably estimated, but the power flow on the primary side of the feeder is accurate.

The cost/benefit ratio is too high to invest in having a Q4 level. If AMI integration is already available, having one critical bellwether meter available for monitoring can replace the efforts needed to raise the confidence of voltages on the low-voltage side of the feeder. More CVR savings can then be achieved by setting less conservative voltage constraints and configuring the VVO to monitor the AMI readings.

- Model quality has a more pronounced impact than different levels of measurement density—i.e., changing model quality results in higher voltage drops (or energy reduction) when measurement density is kept constant compared to changing measurement density for the same model quality.
- The number of voltage violations observed for the D1 level either increased or remained the same compared to the results for the D2 — D4 levels. This implies that

with D1 the system visibility results are not as granular as those of higher levels to reduce the number of occurrences of voltage violations; hence, the inclusion of at least one AMI sensor in D2 and higher would support complete visibility into the feeder. D4 ensures that all the laterals, large customers, and critical points are observable.

- Even though the one AMI sensor in D2 is considered the end-of-line location (i.e., lowest voltage), lower voltages were recorded elsewhere. This could be attributed to the configuration and customer profiles along the feeders. Thus, the case for using several groupings of AMI measurements to deal with the uncertainty of end-of-line location(s) is supported.

D. Impact of High-Loading and Low-Loading Conditions

Under high-loading conditions, as discussed in Section 5, the loading gradually increases on the feeder to capture the performance of the VVO. As a result of the higher loading, the voltages decrease, thus creating voltage violations; hence, it can be inferred that with the Q4 level, there is a significant reduction in the number of occurrences of violations and a moderate reduction in the duration of these violations.

Under low-loading conditions, as discussed in Section 4, no voltage violations are observed. Although some feeders (i.e., Feeder 3) are near 0.95 p.u., other feeders have significantly higher voltages. This shows that for the same VVO settings, the voltage profiles are significantly different. The selected VVO settings (such as voltage constraints and objective function) for long feeders such as BERG show more important would power factor and loss reduction, but for short urban feeders, voltage reduction can be optimal for some and might not be for others. VVO settings, such as objective function and voltage constraints, might need to be tuned using feeder characteristics to maximize energy-saving benefits from CVR while minimizing voltage violations.

E. Impacts of some additional features

- Impact of load profiles:
ADMS models depend on three forms of data: SCADA (number of measurements, sensor accuracy), model/impedance data, and load profiles. The impact of load profiles are not addressed in this effort. The impact of the accuracy of load profiles should be examined. Given the historical data from AMI, a data-driven approach to developing load profiles could be explored.
- Attribute-level impacts:
The field verification was grouped into four broad levels. Although this approach is important for a first-cut analysis, an important question is which attributes are the most impactful? A flexible test setup would be required to address this question, especially given the large number of attributes (382 in this study) associated with a complex exercise such as field verification.
- Impact of photovoltaic (PV) penetration:
A traditional feeder shows a steady decline in voltages as we move away from the substation. A feeder with PV penetration shows a distinctly different voltage profile, where the voltages near a location with PV sites could

show much higher voltage on the feeder. In this case, it might be necessary for the ADMS to observe voltages from the AMI in these locations to optimize control decisions.

- Impact of voltage regulators:
The feeders selected for this study did not include field voltage regulators. The presence of voltage regulators increases the actuators that the ADMS can control to achieve an optimal voltage profile and would increase the potential for CVR on certain feeders, especially long rural feeders. The benefits of CVR can be improved further if the feeder has additional voltage controls.

IX. CONCLUSION AND FUTURE WORK

The lower data remediation level gives less trust to the calculated voltages in the feeder. This can cause the utility to use more conservative medium-voltage constraints, keeping the voltages in the feeder on the safe side (higher) to avoid potentially supplying customers with low voltage. This results in less CVR savings. Having a bigger data remediation level gives more confidence in the calculated state and enables the utility to set less conservative voltage limits. Voltage is then reduced even further, greater CVR savings are achieved, and the customer voltages remain within prescribed bounds. A lower level of remediation might require the low primary limit to be set to 120 V, whereas a higher level of remediation allows for setting the low primary limit to 118 V. These additional 2 V could produce an additional 2% of CVR savings (using the CVR factor of 1%/%). In summary, the results presented in this report indicate that the impacts of model quality and/or measurement density on the overall performance of the VVO application in the ADMS require considering other parameters—for example, feeder characteristics, loading levels, and VVO configurations. As future work, sensitivity analyses could be conducted keeping these parameters constant to quantify the behavior of the VVO application on changes in model quality and measurement density.

Future direction? Pointers to SDGE work?

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REFERENCES

- [1] National Renewable Energy Laboratory and U.S. Department of Energy, "High Performance Computing Data Center," Fact Sheet, August 2014..