21, rue d'Artois, F-75008 PARIS
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A Utility Experience: Accurate CVR Energy Savings Estimation Considering Additional Cleaning Based on the Real CVR Deployment Events and Data

W. FAN, A. HAQUE, M. PROCACCIO, S. RAJIB, L. WORKMAN, P. PABST
Commonwealth Edison Company
USA

A. KHODAEI
PLUC LLC
USA

SUMMARY

Electric utilities deploy Conservation Voltage Reduction (CVR) on the distribution feeders to enable energy savings and reduce peak demand without adversely impacting customer devices. One of the challenges for accurate CVR assessment is anomalous voltage or power data. Previously, there were some studies on anomalous data detection and cleaning. However, no researcher or utility has reported anomalous data cleaning for real-world events such as feeder baseline change due to the Covid-19 Pandemic lockdown. Data cleaning for irregular voltage and power data caused by CVR equipment or operational issues also remains to be explored. This paper aims to provide additional cleaning approaches for such events to assess the true CVR energy savings. Case studies are carried out based on CVR-enabled feeders from a major utility in the U.S. Midwest region. Extensive discussions are provided from the utility perspective as well.

KEYWORDS
Conservation voltage reduction, SCADA measurements, energy savings

Wen.Fan@ComEd.com

1. INTRODUCTION

Conservation Voltage Reduction (CVR) operates the distribution feeders in the lower voltage band (i.e., 114 to 120 V) to achieve energy savings and reduce peak demand [1,2], without adverse impact on customer devices. This is because many customer devices consume less energy when voltage is low due to load-to-voltage sensitivity [3]. A study from the Pacific Northwest National Lab reported that deployment of CVR throughout the feeders in the U.S. can yield energy savings of 3.04% annually [4]. Many electric utilities have deployed CVR in their service territories through pilot projects or large-scale programs. A paper [5] surveyed 37 utilities across the U.S. about their CVR programs. In general, utilities operate CVR by lowering the substation transformer Load Tap Changer (LTC) and coordinating with the Line Voltage Regulators (LVR) and Capacitor (CAP) banks installed along the distribution feeders. The coordination decisions, such as LTC tap position change and CAP bank open/close, are determined by Volt-Var Optimization (VVO) analysis in the CVR central control platform in real time. In practice, these equipment could have mechanical issues preventing CVR from operating as intended and resulting in irregular voltage or power profile [6]. For example, the substation transformer LTC can get locked at the bottom tap position, making LTC unable to participate in CVR operation and resulting in irregular CVR-off voltage.

Reference [5] also surveyed the popular CVR energy savings assessment methods (i.e., comparison-based, regression-based, and simulation-based). Authors in [7] present a methodology to quantify energy savings through Support Vector Regression (SVR). Due to the typical availability of historized power and voltage data, utilities tend to prefer utilizing comparison-based and regression-based methods. Since it takes additional resources to identify the control group for each CVR-deployed feeder, and in some cases, the control group may not even exist for comparison-based analysis, the regression-based method is more common among utilities. The energy impacts of CVR can be measured by the CVR Factor (CVRf), which refers to the ratio of the rate of change in power consumption to the rate of change in voltage during CVR-ON and CVR-OFF [2,3]. Therefore, despite the estimation methods, anomalous power and voltage measurements (e.g., interpolated measurements due to communication loss) can dilute the relationship between power and voltage during CVR-ON and CVR-OFF, impacting the accuracy of estimated savings. Furthermore, the inaccurate estimation results not only create a negative risk to the undergoing CVR pilot/program but also to the potential for future CVR deployments. Therefore, excluding anomalous measurements is of great importance for accurate CVR Measurement and Verification (M&V).

Cleaning anomalous data such as outliers, repetitive, and interpolation have been widely adopted by utilities for accurate CVR M&V analysis [8]. This is because such data must be excluded from the analysis due to data quality issues. However, not all anomalous data are contaminated by data quality concerns. Real-world scenarios such as pandemic lockdown, equipment upgrades and settings reconfiguration, CVR deployment testing, and load shifting can also result in anomalous data scenarios. On top of that, these scenarios have not been widely considered for CVR M&V, yet evidence shows that they should be. For example, during the Covid-19 lockdown, some feeders had abnormally lower power consumption. Feeding this data into the M&V savings estimation would affect the calculation of power consumption difference. Another example is load shifting between feeders, which can also disturb the power profile. Equipment reconfiguration due to CVR deployment can also distort the voltage profile and thus shall be considered for additional cleaning.

This paper presents a utility experience of the additional cleaning and reports the results based on real utility CVR deployment scenarios and field data. The proposed study steps are as follows: first, several real utility CVR scenarios that require additional cleaning are presented. Power and voltage profiles will be illustrated through plots generated by real data. Meanwhile, approaches and procedures for the additional cleaning will be elaborated. Then, numeric analysis on energy savings analysis based on the pre- and post-additional cleaning data and results comparison will be reported. To the best of the authors' knowledge, no existing study has considered the additional cleaning systematically on CVR energy savings analysis. The major contributions of this article are summarized as follows,

- Present a real utility experience on CVR energy savings estimation considering additional cleaning on data scenarios such as lower power consumption due to Covid lockdown;
- Report M&V energy savings based on the pre- and post-additional cleaning data and savings comparison;
- Provide an exemplary approach for other electric utilities that have or are planning large-scale CVR programs.

The rest of this paper is organized as follows. Section 2 presents the real CVR events that require additional cleaning, followed by the illustration and demonstration in Section 3 and discussions in Section 4. The paper is concluded in Section 5.

2. REAL-WORLD CVR EVENTS AND ADDITIONAL CLEANING APPROACHES

This section presents a few real-world CVR events that require additional cleaning on voltage and power data for accurate M&V. All graphs are generated based on real utility data. The developed additional cleaning approaches are also elaborated. In some cases, the abnormal voltage/power profile due to CVR equipment or operational issues is not easily detectable without extensive knowledge of the system [9]. Furthermore, simply conducting visual inspections may not be able to reveal the real issues. The field measurements (i.e., LTC tap positions) and control signals can be utilized as necessary to overcome these obstacles.

A. Feeder Baseline Decrease During Covid Lockdown

In response to the Covid-19 pandemic, lockdown was issued as a measure for public health and safety. In a state located in the Midwest of the U.S., records [10] show that the lockdown began on March 16 and ended on May 28, which covered the most extreme periods of the pandemic. It is understood that the feeder energy baseline could decrease due to temporary close, for example, shopping malls and factories. A case of baseline change on an affected feeder is presented in Fig.1., where the feeder load consumption in 2020 was obviously smaller than the consumption in 2019 during the lockdown period (i.e., March 16 to May 28). Someone may argue that the load consumption difference could result from temperature difference in these two years. However, there was no big difference in temperature during the lockdown period, as shown in Fig.2.

Since the lockdown is a temporary measure that occurred in 2020 only, the impacted energy baseline data during the lockdown period should be excluded from the CVR energy savings analysis. Otherwise, the verified energy savings would be smaller than the true values due to a decrease of baseline. Furthermore, this inaccurate energy savings would be carried over through the entire measurement life, which also impacts the benefit-cost ratio.

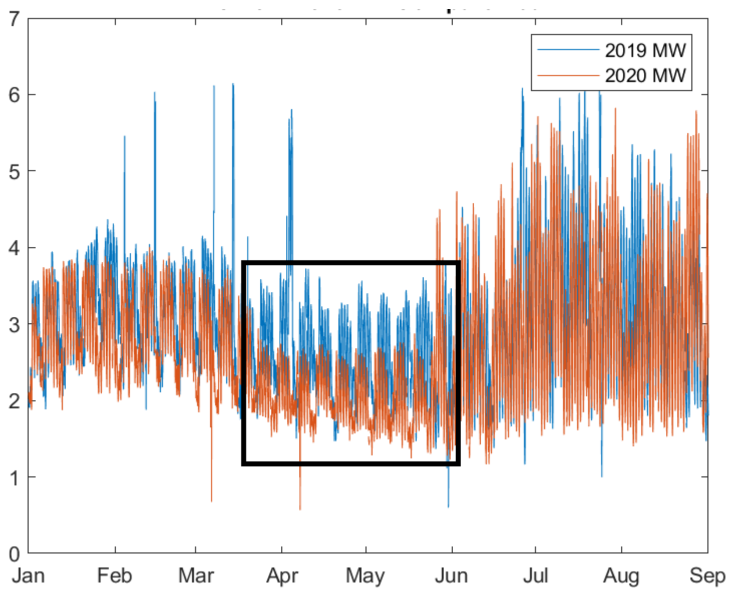

Fig. 1. Energy baseline comparison for a feeder based on its 2019 and 2020 power data

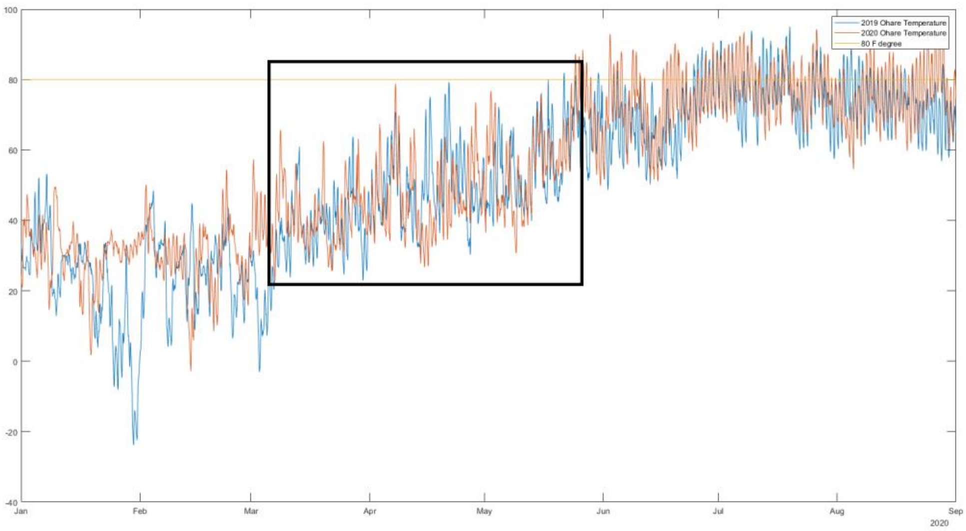

Fig. 2. Temperature comparison – year 2019 and 2020

In this case [10], to accurately calculate the CVR energy savings for feeders that had baseline impacted by lockdown, the electric utility, third-party evaluator, and state commissions have reached agreement that the power data (MW or AMP) affected by the lock down should be excluded from the analysis. Through visual comparison based on 2019 and 2020 data, approximately one-quarter of feeders were identified while voltage data was not affected [11].

B. Feeder Baseline Change due to Load Shift

Load shift can be temporary (e.g., N-1 contingency) or permanent (e.g., feeder load reconditioning), and either could reduce or increase feeder energy baseline and thus impact estimated energy savings accuracy. The impact on energy savings would be insignificant for the temporary load shift between two or more feeders attached to the same CVR-enabled substations. However, if the temporary load shift happens on feeders from different substations, whether CVR-enabled or not, the estimated energy savings will be impacted due to different voltage reduction levels at these substations. In this case, the power data during the load shift period should be excluded from the savings analysis. Such action should also be applied to permanent shift for accurate M&V analysis.

Fig.3. presents examples of temporary load shift (in red rectangle) and permanent load shift (in the yellow rectangle). It is obvious that a load shift is permanent if the load has been transferred to/from a feeder for more than one month. Additionally, M&V engineers can work with the utility planning department to identify if there is any load reconditioning or feeder topology change as necessary. To determine where the load has been transferred to/from for a temporary load shift, M&V engineers can utilize the PI historized OPEN-CLOSE status of substation transformer breakers, bus-tie and/or feeder tie breakers to identify the load transfer details.

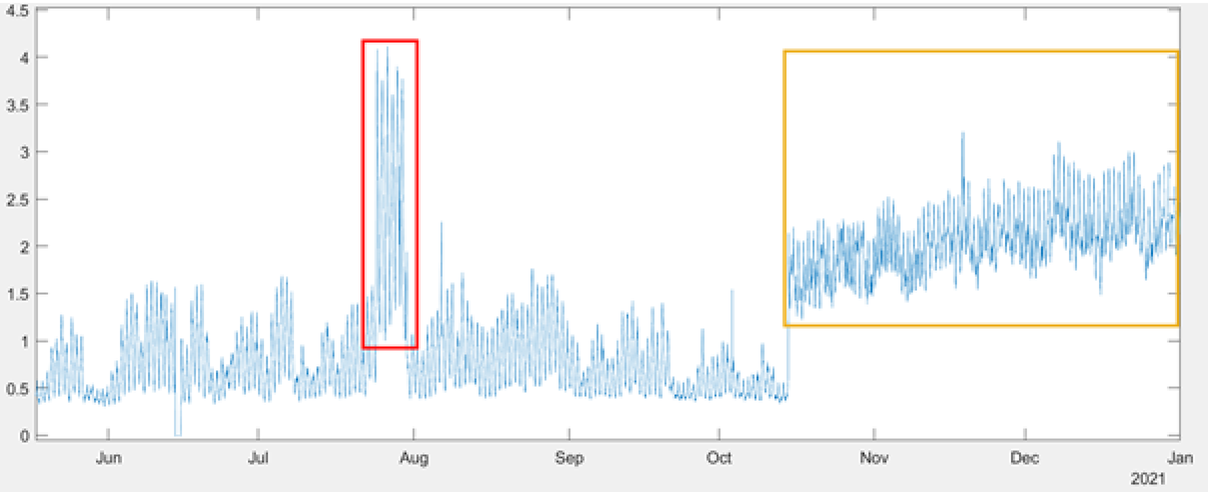

Fig. 3. Load consumption of a feeder through the year of 2021

A special scenario that requires additional cleaning is load ramping on a new feeder. For example, when a new feeder is installed as part of a new business project to accommodate a new customer's load addition, there are uncertainties regarding when the projected target loads will materialize [12]. The CVR savings for a newly commissioned feeder cannot be claimed while there is no load on the feeder. However, the savings can be claimed when a pre-defined threshold of the feeders' projected load is reached. The threshold (e.g., 70%) can be determined by utilities, evaluators, and commissions. An example is presented in Fig.4., where the load ramped up around mid-April on a newly commissioned feeder. Since the pre-defined threshold has been met, the CVR energy savings can be claimed with the load consumption data before mid-April be excluded from the analysis for accurate M&V.

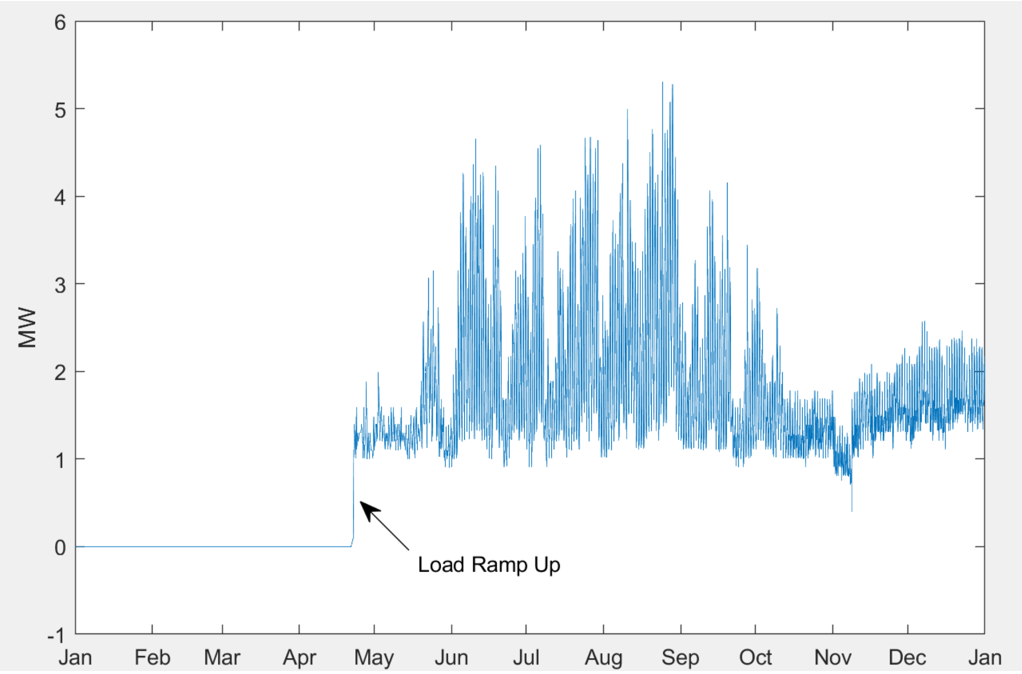

Fig. 4. Load consumption of a feeder throughout an entire year

C. Irregular Voltage Due to Locked Substation Transformer LTC

Besides feeder energy baseline change, the irregular voltage can also impact CVR assessment. Therefore, additional cleaning approaches to irregular voltage profiles are being developed. One of the cases is a locked substation transformer LTC. When an LTC gets locked at the bottom tap position, it prevents the LTC from regulating the feeder head voltage as part of the CVR operation.

To elaborate more, each tap position allows LTC to adjust the secondary voltage by 0.75 voltage on a 120 V base. CVR control platform sends setpoints to LTC to bring its tap to a lower tap position for CVR voltage reduction. Sometimes, the LTC must be brought to its bottom tap position to bring the voltage to the desired range. When CVR is deactivating, LTC raises its tap position to bring the voltage back to the CVR-off level. In practice, however, there is a chance that the LTC can get locked at the bottom position. This mechanical issue requires manual work to unlock the LTC tap.

Before the LTC is unlocked, CVR operation will be affected and the feeder head voltage will remain in the CVR-on voltage range or between the CVR-on and CVR-off (as illustrated in Fig.5), even if the CVR is scheduled to be turned off already. This scenario is especially disturbing when CVR is running ON/OFF testing. It dilutes the relationship of CVR-on and off voltage data and further impacts CVR results.

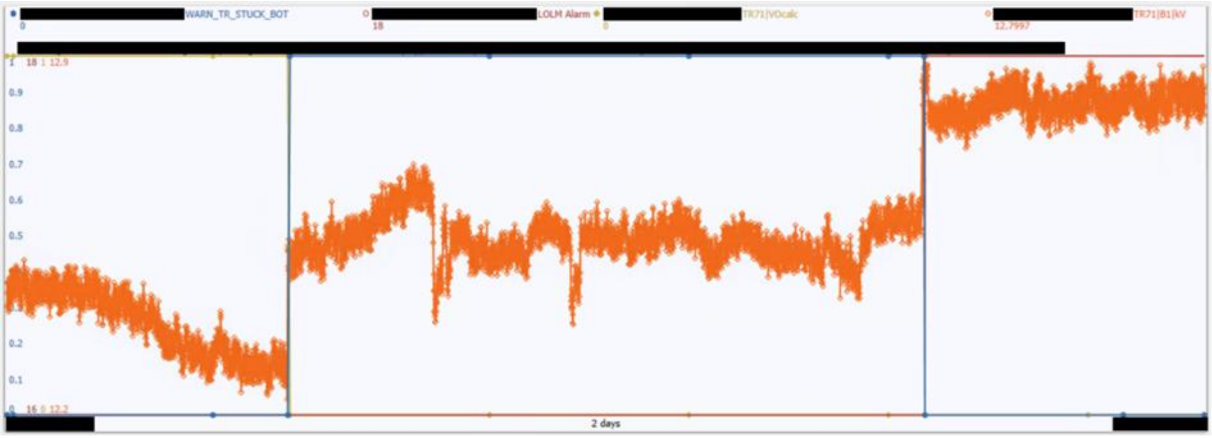

Fig. 5. Feeder-head voltage remains in between the range of CVR-on and CVR-off voltages [6]

In practice, LOLM_ALARM is used to detect such a scenario. It stands for low-limit alarm, which is a PI point in SCADA that historized the alarms captured from LTC. The alarms are transmitted in a digital set and displayed in string. The relationship of the commonly utilized strings is shown in Table 1.

Table 1. String expression of the digital set of LOLM_ALARM [6]

Digital set	String Expressions
16	ALAM-METER
17	INVALID!-METER
18	NORMAL-METER

When implementing this detection algorithm, the CVR on/off status needs to be considered. This is because an LTC can reach the bottom tap position to reduce voltage while CVR is ON, but it does not necessarily mean LTC is locked. When CVR is deactivated, the LTC can move away from the bottom tap if it is not locked. However, if an LTC remains at the bottom tap position, even when CVR is OFF, then the LTC is indeed locked.

D. LTC No Load Tap (NLT) position change

The substation operators can manually bring the LTC out of the bottom tap position, however, this does not prevent the LTC from being locked in the future. If an LTC gets locked too frequently, it will not only add a burden to the substation operators but also potentially damage the LTC itself. In addition, this kind of behavior can affect the CVR ON/OFF activation and testing, which further impacts the evaluation results.

Also, a frequently locked LTC indicates its No-Load Tap (NLT) setting may need an adjustment. The idea is that the LTC can reach the bottom tap position more often if its NLT is set to a relatively lower tap position. Since the customer load on distribution circuits changes from time to time, the NLT settings need to be reviewed and reconfigured if necessary.

The CVR-related station and feeder construction work provides utilities an opportunity to reconfigure the NLT settings. If the construction complete month falls within the evaluation year, the power and voltage data before construction completion should be excluded from the analysis. This is because adjustment of NLT position helps CVR operation to reach the full potential of voltage reduction on a station. Otherwise, the energy savings verified would be inaccurate.

E. Voltage shift

The operating voltage at a substation may not be at the intended voltage level (e.g., 1.04 p.u. of the nominal). In these cases, a voltage shift will be performed along with the CVR construction work by adjusting the existing 90 devices that is regulating the substation transformer. The new settings to the LTC controller or replacing the LTC controller would also do this. Area Maintenance Engineers (AMEs) should be consulted to identify any historical voltage issues they are aware of.

Fig.6. illustrates an example of voltage shift, where the voltage is being shifted from an average of 1.02 p.u. to 1.04 p.u in June. In this case, the voltage prior to the voltage shift should be excluded from the analysis for accurate M&V results. It is important to note that voltage can be shifted up or down depending on the previous operating voltage.

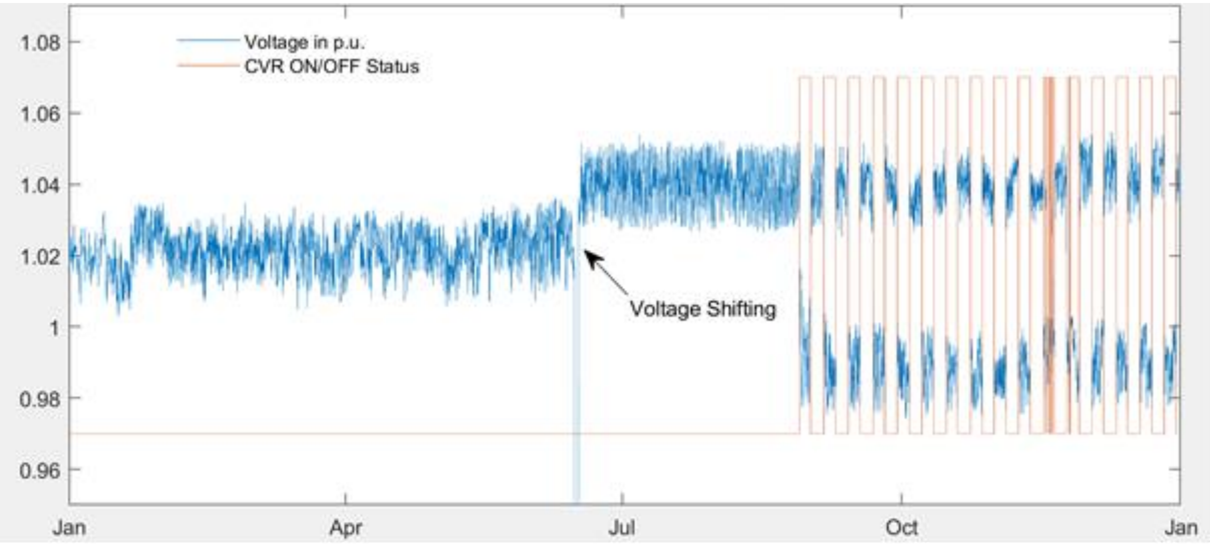

Fig. 6. The operating voltage at a substation transformer brought to the intended voltage level through voltage shift

The voltage shift should be completed sooner rather than later as it will help in the M&V analysis to show the CVR-off voltage for months prior to CVR activation. Otherwise, it can create risks because there may not be enough CVR-off voltage remaining for energy savings calculations.

F. CVR Status

To calculate the change in volage or load consumption, CVR-on data need to be estimated while CVR is OFF, and vice versa [2,3,9]. Moreover, the data eliminated from the analysis due to data quality issues and irregular CVR events will need to be reconstructed. Indices including season, temperature, weekday type, hour, and most importantly, the CVR ON/OFF status is required for reconstruction. The inaccurate status will impact the reconstruction results, and eventually impact the M&V results as well. Therefore, accurate CVR on/off status is required along with the additional data cleaning for accurate M&V.

3. CASE STUDIES

This section presents CVR energy savings results based on real utility feeders and data from a utility located in the U.S. Midwest. The substation/transformer/feeder names are anonymized due to security concerns. The described real-world events and developed CVR additional data cleaning methods have been applied on selected substations and feeders to demonstrate the CVR energy saving results. Note that the results can either increase or decrease. The dataset used is in a 30-minute interval, so the energy saving is calculated for each time interval, and summations were taken to obtain the annual savings.

A. Feeder Baseline Decrease During Covid Lockdown

Fig.7. presents the percentage difference of CVR energy savings based on a dataset of pre- and post-additional cleanings on 42 CVR-deployed feeders under 12 substations. The impacted load consumption data during the lockdown period between March 15, 2020, and May 28, 2020, were excluded from the analysis and got reconstructed before feeding into the M&V calculation. It is observed that most feeders have improved results except feeder #27. A closer inspection of this feeder's power profile reveals that the feeder had an additional feeder baseline decrease.

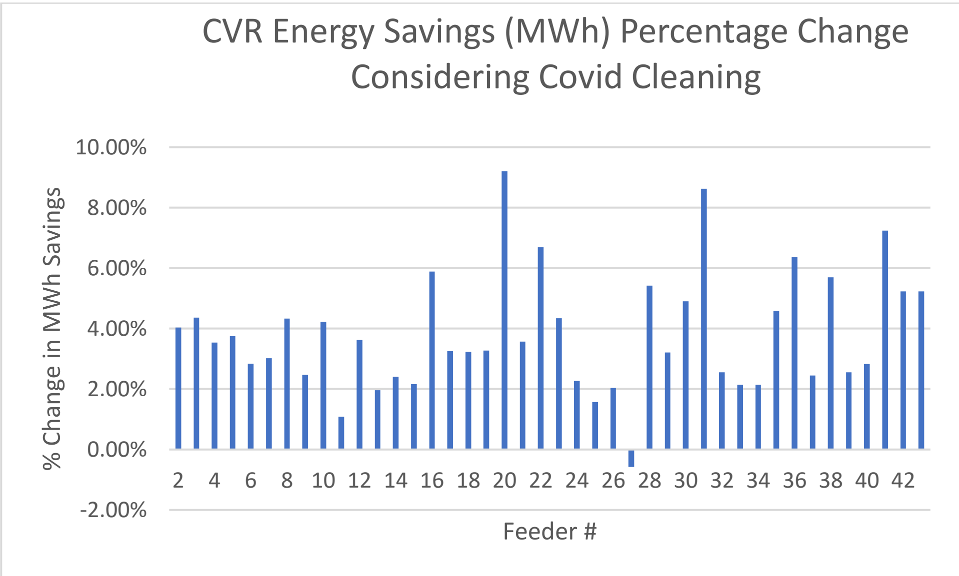

Fig. 7. The percentage change of CVR energy savings considering the additional cleaning on power data affected by Covid Lockdown in the year 2020

The total CVR energy savings on these 42 feeders are presented in Table 2, where the savings increase after Covid Cleaning is 737.8 MWh, or the percentage increase is 3.26%. Someone may argue the energy results increase is insignificant as a result of Covid Cleaning, this may not necessarily be true considering the CVR program scale. The extra 737.8 MWh energy savings weights about 2~4 feeders' CVR energy savings depending on the feeders, which can improve the CVR program benefit-cost ratio.

Table 2Total CVR Energy Savings Before and After Covid Cleaning

CVR energy savings (MWh) before Covid cleaning	22600.7
CVR energy savings (MWh) after Covid cleaning	23338.5

B. Feeder Baseline Change due to Load Shift

A case study was carried out on a feeder with a permanent load shift. The load profile is illustrated in Fig.3. in subsection II.B. This feeder took over all the load from another feeder due to a feeder merge. Its peak load has been increased from 99 to 281 amperes. To accommodate the feeder load condition change, all power data before this permanent load shift were excluded from the analysis and reconstructed before calculating the annualized savings. Results are presented in Table 3. The savings increased from 221.9 MWh to 495.5 MWh, or 123.3%.

Table 3 Total CVR Energy Savings Before and After Load Shift Cleaning

CVR energy savings (MWh) before load shift cleaning	221.9
CVR energy savings (MWh) after load shift cleaning	495.5

Note that the savings increase is not linearly proportional to peak load increase. This is because the load RCI mix (i.e., residential, commercial, and industrial) has also been altered. The load online/offline time could also be a factor. Another thing worth to be pointed out is that the load can be either shifted up or down, resulting in increased or decreased baseline, and accordingly energy savings.

C. LTC No Load Tap (NLT) position change

Fig.8. presents the percentage difference of CVR energy savings based on a dataset of pre- and post- additional cleanings on 119 CVR-deployed feeders under 6 substations. The voltage and power data prior NLT adjustment completion are excluded from the savings analysis and reconstructed. It is observed that all substations had savings increase, with the maximum increase of 25% occurring on substation #1. Table 4 summarizes the total CVR energy savings of these 6 substations, with an increase of 6402.6 MWh or 11.0%.

Table 4 Total CVR Energy Savings Before and After NLT Cleaning

CVR energy savings (MWh) before NLT cleaning	51664.1
CVR energy savings (MWh) after NLT cleaning	58066.7

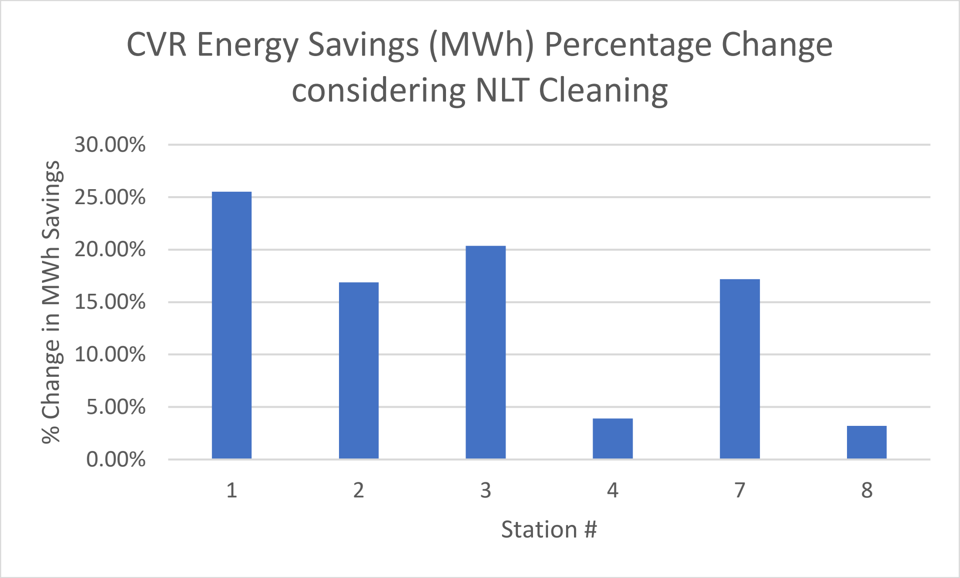

Fig. 8. The percentage change of CVR energy savings considering the addtional cleaning voltage and power data prior NLT adjustment completion

D. Voltage shift

A case study was carried out on two feeders under the same substations. Both feeders had voltage shift during CVR-related construction work. The voltage profile of one feeder is illustrated in Fig.6. in subsection II.E. The voltage profile of another feeder is similar to the voltage shift that occurred 8 days after the other feeder. Voltage data prior to voltage shift completion were excluded from the analysis, and the results are presented in Table 5. The energy increase is 550.4 MWh or 50.1%.

Table 5 Total CVR Energy Savings Before and After Voltage Shift Cleaning

CVR energy savings (MWh) before voltage shift cleaning	1097.6
CVR energy savings (MWh) after voltage shift cleaning	1648.0

It is worth noting that the voltage can be shifted up or down, and so are the energy savings calculated.

4. DISCUSSIONS

It is important to note that this paper is not aiming to identify additional CVR energy savings through additional data cleaning. Instead, the paper estimates the energy savings accurately by excluding the voltage or power data affected by irregular CVR events. Based on the results presented in Section III, the CVR energy savings can either increase or decrease after additional cleaning, except for NLT cleaning. The reason is that once NLT positions are adjusted, it increases the CVR voltage reduction potential and thus savings.

Once the additional cleaning processes are done, the empty data entries will be reconstructed before feeding into the M&V methodology for annualized savings calculation. The reconstruction approach is provided in [8]. Additionally, the studies in references [8] and [13] have demonstrated that the M&V results are sensitive to data quality. So, the additional cleaning approaches developed in this paper contribute to true CVR energy savings assessment.

It is understood that the CVR will only be CVR activated on a substation after the relevant construction work is done. To accumulate adequate CVR on data for M&V with or without these developed addtional cleaning scenarios, the construction work should be scheduled to be completed as early as possible. The necessary NLT adjustment and voltage shift actions should be identified before the CVR construction work begins to avoid any delay in accumulating the required CVR on data for M&V. This requires extensive collaboration between the CVR M&V team, planning, and project management teams.

It is popular that once the evaluators verify the CVR savings on a feeder, it will carry over through the CVR program measure life (e.g., 20 years). Therefore, it is ultra-important to not let a one-time thing such as equipment reconfiguration required by CVR deployment impact the savings, which will also be used for the future. Inaccurate estimation would put the program's credibility at risk. The additional cleaning approaches provided by this paper can be utilized to address this concern.

5. CONCLUSIONS

CVR is a popular energy efficiency measure employed by electric utilities to promote energy savings and reduce peak load. CVR also contributes to grid modernization as the construction work installs/reconditions control devices (LTC, LVR, Cap bank) as necessary and enables communications between these devices and the control platform. In practice, voltage or power data can become abnormal due to real-world CVR events. These impacted data may jeopardize studies related to CVR M&V and provide wrong estimation about the system's actual performance.

This paper presents additional cleaning approaches to identify such anomalies to maintain the accuracy of the CVR assessment. Several irregular CVR events are described, additional cleaning approaches are elaborated, and extensive case studies and discussions are presented. Results reveal that the additional cleaning can assess the true CVR savings. The developed additional cleaning methods set an exemplary approach for utilities, especially utilities with or are going to have a large-scale CVR program and participant in the energy savings evaluation. The methods ensure the CVR energy savings is not falsely counted towards the future measure life years, thus increasing the program credibility, and helps the utility to get the benefit-cost ratio to the maximum accuracy, and supporting future CVR program expansion.

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