



21, rue d'Artois, F-75008 PARIS

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**Distribution System Monitoring for CVR Operation and Performance
Evaluation: A Utility Experience**

**W. FAN, M. S. HOSSAN, L. WORKMAN, A. COOK, P. PABST, E. A. PAASO
Commonwealth Edison Company
USA**

SUMMARY

Electric utilities deploy conservation voltage reduction (CVR) in the distribution systems in several applications, including achieving energy savings and reducing peak load. The control devices, such as substation transformer load tap changers (LTC) and capacitor (CAP) banks, are guided by volt-var optimization (VVO) in the CVR control platform. In practice, when a mechanical issue or equipment failure occurs on one or more control devices, the CVR operation can become abnormal. The irregular CVR operation can reduce energy saving impact, affect the relationship of CVR-on and CVR-off data, and further impact the quantification of CVR effects. Therefore, it is paramount to monitor the CVR devices and operation for a successful CVR program. This paper presents a utility experience of monitoring CVR devices, operation, and performance. Field measurements and communication signals are brought to the back-end environment, where analytics are conducted. Then, the results are displayed on the front-end dashboards for direct visualization. This monitoring tool has been applied on more than 164 substations for a major utility located in the Midwest region of the U.S.

KEYWORDS

Conservation voltage reduction (CVR), SCADA systems, operation, monitoring, measurement, evaluation.

wen.fan@comed.com

I. INTRODUCTION

Conservation voltage reduction (CVR) is a technique that promotes energy efficiency by operating the distribution feeders in a tighter voltage band (i.e., 114 to 120 V) using advanced controls [1,2], without adverse impact on customer devices. Since many customer devices consume less energy when voltage is low, CVR deployment and operation will enable energy savings and shed peak demand. Many electric utilities have adopted CVR in their distribution feeders through pilots or large-scale programs. A recent paper [3] surveyed 37 utilities in the U.S. about their CVR program.

In general, CVR operation is realized through the coordination of several types of control devices, including the substation transformer load tap changers (LTC), line voltage regulators (LVR) and capacitor (CAP) banks deployed across the feeders. Such coordination follows the real-time volt-var optimization (VVO) analysis carried out in the CVR control platform. A mechanical problem or equipment failure on one or more CVR control devices can interrupt the CVR operation. For example, the substation transformer LTC can get locked at the bottom tap position, which prevents the LTC from participating in the coordination to regulate the feeder head voltage. A CAP bank failure can affect the amount of var injected, the coordination with other CAP banks on the same feeder, and result in abnormal CVR operation as well.

The irregular CVR operation (e.g., interrupted days-ON/days-OFF CVR testing) can affect the relationship of CVR-on and CVR-off power/voltage data, and further impacts the accuracy of energy saving estimations and CVR factor (CVRf) calculation [4]. The inaccurate estimation results not only damage the CVR program credibility but also put risks to the future CVR deployment.

Monitoring the CVR devices and operation can help utility crews detect mechanical issues and failed equipment. This allows maintenance requests to be created and performed in a timely manner to prevent further damages on the control devices, bring the CVR operation back to normal, and contributes to the distribution system stability. Furthermore, less abnormal CVR operation means less anomaly data to be dealt with when quantifying the CVR effects. Thus, CVR devices and operation monitoring is of great importance for a successful CVR program.

This paper presents a utility experience of monitoring CVR equipment, operation, and performance. First, the measurements collected from the field devices and communication signals sent by the control platform are brought to the back-end environment. In this environment, a hierarchy of distribution circuits are built, and essential analytics are developed and performed. The developed analytics are performed automatically either with a pre-set time interval or event-based, aiming to monitor the device conditions, operation status, and CVR performance. The analytic results along with the field measurements and communication signals are then being displayed on the developed dashboards for direct visualization. The gained visibility into CVR operation and performance promotes situational awareness, allows for timely actions, and thus maximizes the potential energy savings. This monitoring tool has been applied on more than 164 CVR activated substations located in the Midwest region of the U.S. as its effectiveness has been proved.

The rest of this paper is organized as follows. Section II presents the developed analytics, followed by the illustration and demonstration in Section III. The paper is concluded in Section IV.

II. DEVELOPED ANALYTICS AND DASHBOARDS

This section presents the developed analytics for monitoring CVR devices, operation, and performance. All analytics are running automatically in the back-end environment, either in a fixed time interval (e.g., every 5 minutes) or event-based. The analytic results can be historized to the PI data points, which enables trending of historical results in the front-end dashboards. In addition, the historized results can be utilized for further off-line analyses.

A. CVR ON/OFF Status Detection Calc

The popular intended CVR activation schedule can be divided into two categories, 24 hours a day and 7 days a week (24/7), or ON/OFF testing (e.g., 4-days-ON/4-days-OFF). At a time when a distribution feeder starts to have CVR deployment, it first undergoes ON/OFF activation cycles to collect testing data. Then, the data is utilized to quantify the energy savings using CVR measurement and verification (M&V) methodologies such as, comparison-based, or regression-based [3, 5]. Once the testing phase is completed, the feeder starts to run CVR 24/7 to obtain maximum energy savings.

Despite the type of CVR activation schedule, CVR ON/OFF status needs to be detected for the CVR operation monitoring and performance evaluation. The detected CVR status is also an important condition being used in other analytics.

The CVR status detection algorithm developed in our previous work [4], has been implemented in the back-end environment to enable the automatic status detection. The signals and measurements utilized are as follows,

- VO_{active} stands for voltage optimization active indicator signal, which is a manual point in the control platform. It is a binary variable which is ON when CVR is intended to be turned on, and vice versa.
- *Heartbeat* is a communication signal sent from the control platform to the transformer LTC as a time limit, which allows the LTC to have CVR running until the limit is reached.
- *Setpoint* is an active bandcenter sent from the control platform to control LTC.
- *Secondary load voltage* is the measurement captured from the transformer remote terminal units (RTU).

Below shows the basic idea of the developed algorithm,

The basic idea of the developed CVR status detection algorithm (full algorithm can be found in previous work [4])

1:	at a substation transformer,
2:	if VO_{active} is ON, and <i>heartbeat</i> is greater than the lower threshold, and <i>setpoint</i> is smaller than the default bandcenter, and the <i>secondary load voltage</i> is smaller than the default bandcenter
3:	CVR status is detected as ON
4:	else
5:	CVR status is detected as OFF
6:	end if

This algorithm considers not only the field measurements but also the communication signals and proved to be working effectively on more than 200 substation transformers. The implemented CVR status detection Calc is set to run every 5 minutes in the back-end environment. Since a substation may have multiple voltage control zones (VCZ) separated by circuit breakers (CB), the Calc is applied at the transformer level for maximum accuracy. The automatically determined CVR status is then being utilized in the following analytics presented in latter subsections.

B. CVR On Time Percentage Calc

Once CVR status is determined, the percentage time of CVR ON operation can be calculated. This Calc is implemented as a 30-day moving average using the formula below,

$$CVR_{ON}\% = \frac{TM\{CVR\ ON\ time\ in\ 30\ days\}}{TM\{30\ days\}} \times 100 \quad (1)$$

where, $CVR_{ON}\%$ is the percentage time when CVR was ON in the past 30 days. $TM\{.\}$ is the total minutes of its argument.

The Calc is applied at the transformer level, and this percentage number $CVR_{ON}\%$ reveals how the CVR operated comparing with the intended activation schedules.

If $CVR_{ON}\%$ is far less than 50% while running ON/OFF testing, it indicates the CVR ON operation was disturbed or stopped by some reasons. In practice, this is most likely due to the substation transformer LTC being put in manual by the operation center for maintenance work or equipment upgrade. Rarely, the $CVR_{ON}\%$ can also be far greater than 50% while ON/OFF testing is running. In this scenario, the transformer LTC being locked at the bottom tap position is the main cause.

If CVR is intended to run in 24/7 mode, the $CVR_{ON}\%$ would be 100%, ideally. However, mechanical problems, equipment failures, or operation center temporary overrides can lead to a smaller $CVR_{ON}\%$. When $CVR_{ON}\%$ is far less than 100%, the CVR equipment needs to be investigated to identify any maintenance or adjustment is required.

C. CVR Average Voltage Reduction Percentage Calc

The average voltage reduction percentage $\Delta V\%$ is one of the most important measures of CVR performance. It is not only used for quantifying the CVR effects, but also gives a direct overview of the CVR performance as many customer devices consume less energy when voltage is lower.

The average voltage reduction percentage Calc is implemented as a 30-day moving average using the formula below,

$$\Delta V\% = \frac{AVE\{V_{CVR_{OFF}}\} - AVE\{V_{CVR_{ON}}\}}{AVE\{V_{CVR_{OFF}}\}} \times 100 \quad (2)$$

where, $AVE\{.\}$ takes the average value of its argument in the past 30 days. $V_{CVR_{OFF}}$ and $V_{CVR_{ON}}$ denotes the CVR-off and CVR-on voltages, respectively.

If a substation transformer is running in 24/7 mode, $V_{CVR_{OFF}}$ can be obtained by taking the average of the CVR-off voltages prior 24/7 activation. This can be done either online or offline.

Depending on the size of a substation, its transformer can have more than one bus connected. In such cases, the Calc is implemented at the bus level instead of the transformer level. Then, the bus level results are rolled up to the transformer level by taking the average of them. Similarly, the results can be further rolled up to the substation level, substation type level, and to the CVR program level, eventually.

The average voltage reduction at different levels reveals valuable information for monitoring CVR devices and performance, which is summarized in Table I.

Table I. The information revealed by the average voltage reduction at different level

Level of the Results	Revealed Information
Substation transformer level	Indicate whether a transformer/substation is working as intended, and if any equipment maintenance or reconfiguration is required
Substation level	
Substation type level	Provide an expectation of the average voltage reduction for a specific substation type or at the system level for future analysis (e.g., cost-benefit-ratio)
Program level	

D. LTC Locked at Bottom Tap Position Calc

The substation transformer LTC is a key piece of equipment to regulate the feeder voltage. Each tap position gives LTC the ability to adjust the secondary voltage by 0.75 volts on a 120 V base. When CVR is activated, LTC brings its tap to a lower tap position to reduce the feeder voltage, in coordination with LVRs and CAP banks. Sometimes, the LTC must reach its bottom tap position in order to bring down the voltage to the desired range. When CVR is deactivating, LTC raises its tap position to bring the voltage back to CVR-off level. In practice, however, there is a chance that the LTC getting locked at the bottom tap position. This mechanical problem requires manual work to unlock the LTC tap.

Before the LTC is unlocked from its bottom tap position, coordination with LVRs and CAP banks will be affected, and the feeder header voltage will remain in the CVR-on voltage range or in between the range of CVR-on and CVR-off, even when the CVR is scheduled to be OFF. This behavior is especially disturbing when CVR is running ON/OFF testing. It can dilute the relationship of CVR-on and CVR-off data and further impacts the accuracy of M&V analysis. Therefore, monitoring whether the LTC is locked is of great importance. Considering there would be hundreds of substation transformers, so is the number of LTCs, in a moderate- or large- scale CVR program, monitoring the LTC automatically is preferred.

A Calc is developed to automatically monitor whether a LTC is locked at the bottom tap position. The Calc is described as follows. For a time-instance t , if the string value of $LOLM_{Alarm}$ is ALARM-METER, and VO_{Calc} is OFF, then the substation transformer LTC is determined to be locked at the bottom tap position.

Where, VO_{Calc} is the detected CVR ON/OFF status. $LOLM_{Alarm}$ stands for low-limit alarm, which is a PI point in the SCADA systems that historizes the alarms captured from LTC. The

alarms are transmitted in digital set and displayed in strings. The relationship of the digital set and string expression for the most common occurrences are shown in Table II.

Table II. String expressions of the digital set of $LOLM_{Alarm}$

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

The CVR status is considered in this Calc to avoid false positives. This is because an LTC can reach the bottom tap position to reduce the voltage while CVR is ON, but it does not necessarily mean the 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.

By monitoring whether an LTC is locked, it allows the working request to be created in a timely manner to notify the substation operators.

E. LTC No Load Tap (NLT) Warning Calc

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 get locked too frequently, it will not only add 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 are changing from time to time, the NLT settings need to be reviewed and reconfigured if necessary.

To detect such scenarios where NLT settings need a review automatically, a 30-day moving average Calc is developed.

$$LTC_{Locked}\% = \frac{TM\{LTC_{Locked} \text{ in } 30 \text{ days}\}}{TM\{30days\}} \times 100 \quad (3)$$

where, $LTC_{Locked}\%$ is the percentage time of the LTC got locked in the bottom tap position.

If $LTC_{Locked}\%$ of a substation transformer is greater than the pre-determined threshold, then the NLT setting of its LTC needs a review and possibly a reconfiguration. This threshold can be determined based on the substation operators' experience and historical performance of the LTC. In this study, the threshold used is 20%.

F. CAP Bank Neutral Current Calc

Cap bank is a vital equipment for CVR operation. It can flatten the voltage across the feeder to maintain the voltage level at the end of the line (EOL), which allows the feeder head voltage to be further reduced, achieving more energy savings. A CVR-enabled distribution circuit usually has one or more CAP banks installed. When one of the CAP banks fails, the coordination

between CAP banks and with LTC or LVRs can be affected, resulting in abnormal CVR operation.

To monitor the CAP bank conditions, a Calc was developed based on the CAP bank neutral current (NC). The basic idea is that when the magnitude of NC is beyond a certain threshold, it indicates the CAP bank is experiencing issues. The Calc is described as follows.

If the NC of a CAP bank is greater than the pre-determined threshold, then $NC_{warning} = \text{True}$. Otherwise, $NC_{warning} = \text{False}$, where, $NC_{warning}$ denotes the neutral current magnitude warning. The threshold used in this study is 5 Amperes.

As a large-scale CVR program can have thousands of CAP banks involved, this Calc provides visibility into CAP banks by generating warnings. The calculated $NC_{warning}$ reveals whether a CAP bank needs a work request created for maintenance. It can also help to detect when a CAP bank is near the edge of failure, where timely decision can be made.

G. CAP Bank OPEN CLOSE Count Calc

Since frequently OPEN and CLOSE operations on a cap bank can increase the amount of maintenance needed, it is desired to distribute such operations as evenly as possible to all CAP banks installed on the same feeder.

A Calc was developed to monitor the total number of OPEN and CLOSE operations on CAP banks. It utilizes the information captured at the CAP bank and historized in the SCADA systems. Based on the total counts of OPEN and CLOSE operations, whether one or more cap banks are preferred to be switched can be pinpointed. Then, adjustments can be made in the CVR control platform to distribute such operations to other less preferred CAP banks. As a result, less maintenance and longer equipment lifetimes are expected, thus deferring the needs of equipment replacement.

H. Substation Heath Score Calc

A few types of results from the previous introduced Calcs are utilized to create another Calc to track the substation condition and performance. The score is determined based on four variables, including the CVR ON percentage time $CVR_{ON}\%$, average voltage reduction $\Delta V\%$, whether LTC is locked LTC_{Locked} , and LTC NLT $LTC_{Locked}\%$. Each variable has a weighted factor w , which can be determined based on the experience of substation types and historical performance. In general, the substation health score (SHS) Calc is determined using the following formula:

$$SHS = w_1\Delta V\% + w_2CVR_{ON}\% + w_3LTC_{Locked} + w_4LTC_{Locked}\% \quad (4)$$

where, w_1 to w_4 are the weighted factors of their associated variables.

Based on the magnitude of the obtained SHS, a color code can be assigned to each substation. In this study, color code Orange indicates a substation needs attention or action required, color code Yellow indicates there was a minor concern(s) of a substation, and Green indicates no issue. Then, the SHS are displayed in the front-end dashboards to give a quick visual recognition of how a substation performs.

I. Developed Front-End Dashboards

The field measurements, communication signals, and analytic results are brought to the front-end developed dashboards for direct visual access. Two main dashboards were created, the program dashboard and the substation dashboard.

The program dashboard provides an overview of the entire CVR activation at all substations. It displays analytic results rolled up to the program level, such as CVR ON percentage time and average voltage reductions. Analytic results at the substation type level are also included in this dashboard.

The substation dashboard provides a clear visual of all CVR equipment status, SCADA point trends, and the analytic results at a substation. Since all CVR activated substations are added to the hierarchy in the back-end environment, each substation can be selected to be displayed in the dashboard.

III. ILLUSTRATIONS AND DEMONSTRATIONS

In this section, examples of back-end analyses and front-end displays are presented for illustration and demonstration. The results presented are based on real CVR deployed distribution feeders located in the Midwest region of U.S. The names of substation/transformer/feeder are redacted due to security concerns. This monitoring tool has been applied to more than 164 CVR-enabled substations.

A. CVR Status Detection and ON Time Percentage

Fig. 1 demonstrates the CVR ON/OFF status detection Calc. In the time frame of 60 days, the CVR was first running ON/OFF testing and later operating in 24/7 CVR mode. In the figure, there is a spike of CVR active indicator signal VO_{active} at the very beginning of the first CVR-on cycle, which attempted to turn on the CVR operation. However, communication signal heartbeat was not sent, and the CVR operation was not activated. Therefore, the CVR status was determined as OFF by the Calc at that time. As seen in the figure, the Calc can detect status accurately regardless whether CVR runs ON/OFF testing or 24/7.

Once the CVR status are detected, the percent time of CVR running in the past 30 days, $CVR_{ON}\%$, can be calculated using (1).

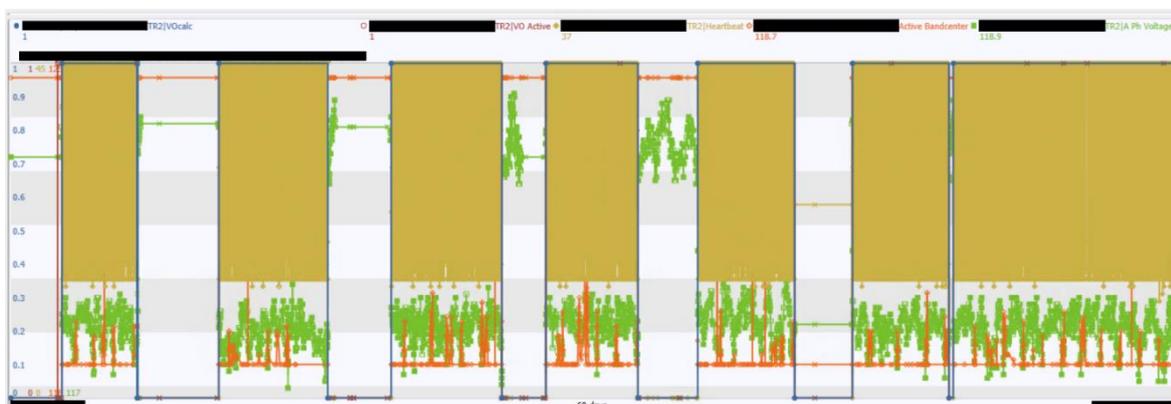


Fig. 1. CVR ON/OFF status detection Calc determines the CVR status using communication signals and field measurements

B. Average Voltage Reduction

Fig. 2 presents an example of the primary feeder head voltage and the detected CVR status. The figure suggests the status detected is accurate based on the trend of the feeder-head voltages, despite CVR running mode.

The CVR-on and CVR-off voltages are classified into two categories based on the ON/OFF status. The average voltage reduction is then calculated using (2). If a substation transformer is running fully in 24/7 mode, the CVR-off voltage can be obtained by taking the average of the CVR-off voltages prior 24/7 activation.

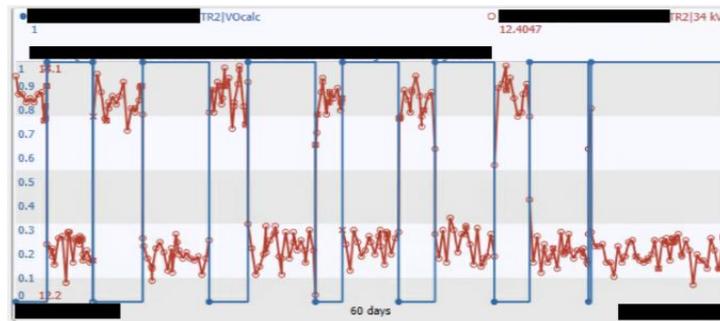


Fig. 2. Feeder-head voltage against CVR status

C. Detection of Locked LTC and NLT Warning

Fig. 3 presents an example of detecting the locked LTC. As observed in the circled time frame, when $LOLM_{Alarm}$ is of digital set 16 (i.e., ALARM-Meter) and CVR status is OFF, the LTC_{Locked} is detected as True. This detection is accurate as the primary feeder head voltage was not able to rise back to CVR OFF voltage range while CVR is supposed to be OFF. As such, LTC_{Locked} can also help to flag this kind of anomaly data for data cleaning for accurate M&V results. The percentage of time that the LTC got locked in the bottom tap position in the past 30 days can then be calculated using (3).

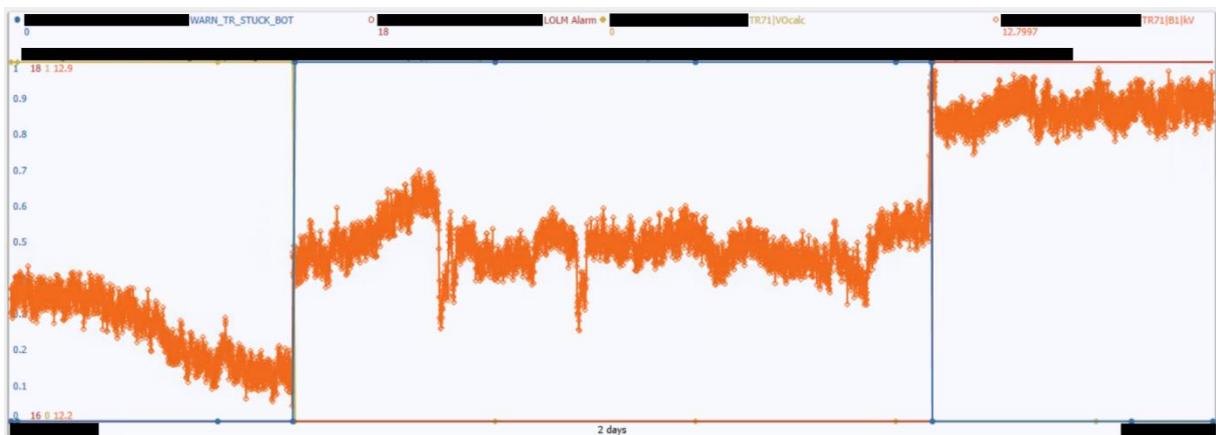


Fig. 3. Detection of locked LTC based on $LOLM_{Alarm}$ and the detected CVR status VO_{Calc}

D. Developed Station dashboard

Fig. 4 illustrates the developed station dashboard. In the dashboard, several parameters are listed for quick reference, including the station name, type, number of transformers and CAP banks, CVR go live year, CVR activation mode, and the average voltage reduction target. The detected CVR status, calculated voltage reduction, and the percentage time of $LOLM_{Alarm}$ in ALARM-METER and LTC get locked at the bottom tap position are also displayed in the dashboard.



Fig. 2. An example of the station dashboard in the front-end

The trended primary and secondary voltages are displayed on the top middle of the dashboard. Besides, the CAP bank secondary voltage, neutral current, and the counts of OPEN-CLOSE are summarized in the Capacitor Banks table, shown at the bottom middle of the dashboard. A list of warning indicators can be found in the right-hand side columns. Since there is no abnormality at this station, the indicators are displaying False.

The program dashboard is developed in a similar way with rolled-up program level and station type level results displayed on it, offering a single place to get an overview of the CVR program and its performance.

IV. DISCUSSIONS AND CONCLUSIONS

This paper presents a utility experience of monitoring the CVR devices, operation, and performance. The field measurements and communication signals are brought to the back-end environment to perform analyses. Then, the analytic results are displayed in the front-end along with the measurements and signals. This monitoring tool helps to track the performance of CVR control devices, including substation transformer LTC and CAP banks, and raise situation awareness to promote timely actions. As a result, the CVR can be operated in a manner that is closer to the intended activation schedule, which further reduces the anomaly scenarios and data for M&V evaluation. This monitoring tool is an exemplary model for other electric utilities that have or are planning large-scale CVR programs.

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