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Conservation Voltage Reduction and Volt-VAR Optimization: Measurement and Verification Benchmarking

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ABSTRACT The ongoing efforts in grid modernization, which is accompanied by upgrading distribution grids through employment of advanced distribution grid technologies, further provide the necessary tools to employ Conservation Voltage Reduction (CVR) and Volt-VAR Optimization (VVO) programs and ensure that the system is operating continuously at an optimized voltage. This paper provides an overview of CVR/VVO deployments by several electric utilities within the U.S. The paper looks at three major areas: (i) type of the initiative, including pilot, plan, program, study, and test case; (ii) year(s) of the application; and (iii) methodology used for CVR factor assessment. When available, a more detailed discussion on the initiative is provided. Based on the studied cases, it is concluded that majority of utilities use either a regression-based or a comparison-based method. The day-on/day-off approach is common within both methods in which CVR is applied every other day to generate CVR-on and CVR-off data that can be used for comparison and model fitting.

INDEX TERMS Conservation voltage reduction, demand reduction, distribution network, energy saving, volt-VAR optimization.

I. INTRODUCTION

Conservation Voltage Reduction (CVR) and Volt-VAR Optimization (VVO) enable electric utilities to reduce energy and peak demand by lowering the voltage at the distribution system. This is a cost-effective way to improve system energy efficiency and to provide benefits to customers. The fundamental principle in CVR is that the acceptable voltage band can be operated in the lower half (114–120 Volts based on ANSI standard [1]), without causing any harm to consumer appliances. Many customer devices draw less energy at lower voltages resulting in energy savings [2]. The U.S. DOE reports savings from 1 to 4% based on prior implementation of CVR and VVO programs [3].

Assessment and verification of CVR effects has always been a technical challenge in its application, considering that there is a lack of benchmark load consumption measurement during the CVR period. In addition, distinguishing the changes in load and energy consumption due to voltage reduction from other impact factors is a challenging task but is required for quantifying CVR effects. CVR effects can be evaluated by a CVR factor, which is an indicator of the relationship between energy savings and changes in voltage from CVR operations. The CVR factor (CVR_f) is defined as the ratio between the percentage change in energy and the associated percentage change in voltage, i.e.,

$$CVR_f = \frac{Percentage\ of\ change\ in\ energy\ consumption}{Percentage\ of\ change\ in\ voltage} \tag{1}$$

Utilities may need to collect a substantial amount of data of load and voltage over an extended period of time and for each

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CVR-enabled circuit to be able to estimate the CVR factor. However, there have been cases that utilities have calculated the CVR factor for a selected number of circuits and used the result, commonly an averaged CVR factor, for other circuits in their service territory.

This paper provides an overview of CVR/VVO deployments by several electric utilities within the U.S. The paper looks at the type of the initiative, year(s) of the application, and the methodology used for CVR factor assessment. When available, a more detailed discussion on the initiative, e.g., the number of feeders with CVR/VVO deployments and electric utility's future plans, is provided. VVO uses CVR techniques to reduce energy and peak demand, so the scope of this paper is limited to the existing and planned CVR assessment initiatives. In particular, the methods used for CVR factor assessment are reviewed and discussed. The calculated energy savings and CVR factors by each utility are further provided when available. The paper does not include the cases that do not provide information on their methodology.

The rest of the paper is organized as follows. Section II provides a review of the most common methodologies in CVR factor assessment. Section III provides a summary of studied cases associated with practical CVR/VVO deployments. Section IV concludes the paper.

II. METHODOLOGY REVIEW

The electric utilities primarily leverage three CVR assessment methods as discussed in the following.

A. COMPARISON-BASED METHODS

The comparison-based methods leverage operational data under CVR-on and CVR-off conditions and accordingly determine the CVR factor by comparing these two cases. These two cases are called 'treatment' and 'control', respectively. There are two general categories for comparison-based methods, correlated-feeder and correlated-weather.

1) CORRELATED-WEATHER APPROACH

Correlated-weather approach compares operation of a feeder under the CVR-on (treatment) and CVR-off (control) conditions. Under the treatment condition, CVR is applied to a test feeder, and under the control condition normal voltage is applied to the same feeder but during another time period with similar weather conditions. Comparison between the measurements in these two tests helps calculate the CVR factor. In this approach, day-pairing is carried out to find the baseline day for an on-day. The baseline day can be any of the off-days with the same operating conditions including primarily load and temperature, and sometimes other factors (such as same season, day of the week, snow, and humidity) as for on-day.

2) CORRELATED-FEEDER APPROACH

Correlated-feeder approach compares operation of a feeder under the CVR-on (treatment) with another CVR-off feeder (control) at the same time. The control feeder should be strongly correlated to the treatment feeder in terms of feeder characteristics and load composition. In this approach, control feeder is chosen based on its similarity and correlation to the treatment feeder in terms of customer and load characteristics, load shapes and level, and power factor, among other factors. In selecting the control feeder, the experts in utilities should consider customer and load characteristics and ensure that treatment and control pairings are generally adjacent. Other considerations can be made to ensure that all pairings are in a single jurisdiction (or geographically close to each other) and many factors which affect consumption (e.g., economic factors) are similar between pairings in each customer class to decrease variability. Some studies show that residential customer load profiles are very similar to each other in terms of their shape and level in treatment and control feeders, while non-residential customer load profiles are very similar to each other in terms of their shape, but they differ in terms of the level of usage. This observation demonstrates that load composition in matched feeders should be similar especially for feeders with non-residential customers. Correlated-feeder approach is a faster and clearer approach than correlated-weather approach. However, finding correlated feeders is commonly a challenging task.

A correlation analysis can be further used to find strongly correlated pairs of feeders. Correlation is a statistical measure of how much two datasets are close and dependent to each other. The most familiar measure of dependence between two quantities is the Pearson product-moment correlation coefficient, or "Pearson's correlation coefficient", commonly called simply "the correlation coefficient". It is obtained by dividing the covariance of the two variables; i.e., $\boldsymbol{X}$, $\boldsymbol{Y}$; by the product of their standard deviations; i.e., σ_X, σ_Y; as in (2).

$$\rho_{X,Y} = corr = \frac{cov\left(\boldsymbol{X}, \boldsymbol{Y}\right)}{\sigma_X \sigma_Y} = \frac{E\left[\left(\boldsymbol{X} - \mu_X\right)\left(\boldsymbol{Y} - \mu_Y\right)\right]}{\sigma_X \sigma_Y} \tag{2}$$

where μ_X, μ_Y, E, and cov are the expected value of $\boldsymbol{X}$, the expected value of $\boldsymbol{Y}$, the expected value operator, and covariance function, respectively. *corr* is a widely used alternative notation for the correlation coefficient. The Pearson correlation is defined only if both standard deviations are finite and positive. Pearson correlation can be rewritten as in (3):

$$\rho_{X,Y} = \frac{E\left(\boldsymbol{XY}\right) - E\left(\boldsymbol{X}\right)E\left(\boldsymbol{Y}\right)}{\sqrt{E\left(\boldsymbol{X}^2\right) - E\left(\boldsymbol{X}\right)^2}\sqrt{E\left(\boldsymbol{Y}^2\right) - E\left(\boldsymbol{Y}\right)^2}} \tag{3}$$

The absolute value of Pearson correlation coefficient of two datasets is a value within [−1, 1] interval. The correlation coefficient of +1 shows a perfect direct (increasing) linear relationship (correlation), while −1 means a perfect decreasing (inverse) linear relationship (anti-correlation). Other values in the open interval (−1, 1) indicate the degree of linear dependence between the variables. As the correlation coefficient approaches zero, there is less of a relationship (closer to uncorrelated). The closer the coefficient is to either −1 or 1, the stronger the correlation between the variables.

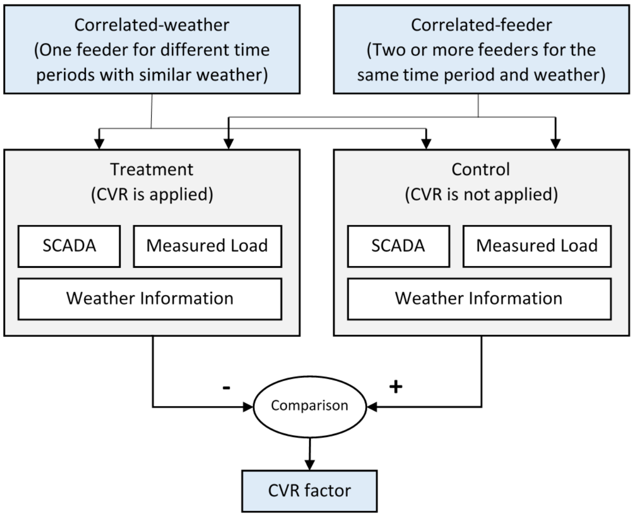

FIGURE 1. **Comparison-based methods.**

Based on the characteristics of the data, both negative and positive values of correlation coefficient may have similar meaning. This is the case for feeder-pairing. In this regard, it is perfectly fine to use an alternative coefficient called R-squared (R^2). R^2 equals the square of the Pearson correlation coefficient as in (4) and has a value within [0,1] interval, where the closer the R^2 coefficient is to 1, the stronger the correlation between the variables. R^2 can be expressed as a percent value to measure the strength of the relationship between two variables in a 0-100% scale.

$$R^2 = \left(\rho_{X,Y}\right)^2 \tag{4}$$

Based on raw correlation analysis and by defining a proper threshold for the correlation, each two feeders that have greater correlation coefficient, or higher R^2, compared to the threshold are picked as correlated feeders. It should be noted that additional analysis is required to ensure that no load transfers or other unusual patterns occurred between treatment and control feeders. Additional analysis can be done either manually or automatically. In the former, experts/engineers manually check the data and search for any sign of load transfers amongst feeders or unusual patterns. For instance, by checking the number of connected customers to each feeder during the test period, load transfers can be identified. In addition, outages and unusual load and voltage spikes can be referred as unusual patterns. Information about outage intervals is also commonly available, so outage periods can be excluded from the data accordingly. Spikes in the data could be excluded by defining proper cutoff thresholds for load and voltage. Mentioned procedures can be coded and applied automatically to the data. Figure 1 shows the flowchart for comparison-based methods.

3) PROS AND CONS

The major benefit of comparison-based methods is being straight-forward and easy to implement. However, on the downside, other factors, such as weather differences in the correlated-weather approach or load differences in the correlated-feeder approach, may add noise to the measurements and result in erroneous CVR calculations. Given the commonly small CVR effect, this noise may completely mask the CVR. Moreover, the time-dependency nature of the CVR factor may be lost as the data is averaged.

Several electric utilities, including Central Lincoln People's Utility District, Idaho Power Company, Indianapolis Power & Light Company, Portland General Electric Company, Sacramento Municipal Utility District, Glendale Water & Power, Dominion Energy, Kansas City Power and Light, and Choptank Electric Cooperative use or have used this method for CVR factor assessment.

B. REGRESSION-BASED METHODS

Regression-based methods model loads as a function of various factors, such as temperature. This function is commonly obtained using a linear regression. The CVR factor is calculated by comparing the output of the load model under CVR-on and CVR-off conditions. Commonly used approaches to estimate the load model in regression-based methods; i.e., linear regression and Difference in Differences approaches, are explained as follows:

1) LINEAR REGRESSION APPROACH

By modeling the load as a linear function of temperature, regression-based methods start with a model estimation as in (5).

$$\boldsymbol{L}\,(MW) = \beta_0\mathbf{1} + \beta_1\left[T_{fh}\mathbf{1} - \boldsymbol{T}\right] + \beta_2\left[T_{fc}\mathbf{1} - \boldsymbol{T}\right] + \boldsymbol{\varepsilon} \tag{5}$$

where T_{fh} and T_{fc} are the heating and cooling reference temperatures, respectively. Training data for the model are $\boldsymbol{L}$ and $\boldsymbol{T}$ which represent the vector of measured CVR-off load data and vector of recorded ambient temperature, respectively. β_0, β_1, and β_2 are the regressors' coefficients that need to be calculated, and ε represents the errors.

To calculate regressors' coefficients, errors can be minimized based on least squares method as in (6)-(8).

$$\hat{\boldsymbol{\beta}} = \left(\boldsymbol{X}^T\boldsymbol{X}\right)^{-1}\boldsymbol{X}^T\boldsymbol{L} \tag{6}$$

$$\boldsymbol{X} = \left[\mathbf{1}\,T_{fh}\mathbf{1} - \boldsymbol{T}\,T_{fc}\mathbf{1} - \boldsymbol{T}\right] \tag{7}$$

$$\hat{\boldsymbol{\beta}} = \left[\hat{\beta}_0\;\hat{\beta}_1\;\hat{\beta}_2\right]^T \tag{8}$$

where $\hat{\boldsymbol{\beta}}$ consists of the estimated coefficients. Based on estimated coefficients, new load consumption without CVR can be calculated for a new temperature; i.e., $\boldsymbol{T}*$.

$$\boldsymbol{L}_{N\_CVR}\,(MW) = \hat{\beta}_0\mathbf{1} + \hat{\beta}_1\left[T_{fh}\mathbf{1} - \boldsymbol{T}^*\right] + \hat{\beta}_2\left[T_{fc}\mathbf{1} - \boldsymbol{T}^*\right] \tag{9}$$

$\boldsymbol{L}_{N\_CVR}$ refers to estimated load consumption if CVR is not applied, while load consumption when CVR is implemented is measured directly from the feeder; i.e., $\boldsymbol{L}_{CVR}$. CVR factor can be calculated as follows:

$$CVR_f = \frac{\Delta \boldsymbol{L}\%}{\Delta \boldsymbol{V}\%} \tag{10}$$

where

$$\Delta \boldsymbol{L}\% = \frac{\boldsymbol{L}_{N\_CVR} - \boldsymbol{L}_{CVR}}{\boldsymbol{L}_{N\_CVR}} \times 100 \tag{11}$$

Other variables including voltage, temperature, day of the week, month, daylight and dark hours, humidity, and solar intensity also can be considered in the linear model to analyze their impacts in load consumption and consequently improve accuracy. Considering voltage and temperature, multivariable regression can be used to formulate and calculate regressors' coefficients associated with each variable. Multivariate regression is often used to detect sensitivities of load to its impact factors. Equation (12) shows a multivariable regression model estimation:

$$\boldsymbol{L}\,(MW) = \alpha_0\mathbf{1} + \alpha_1\boldsymbol{T} + \alpha_2\boldsymbol{\Delta V} + \boldsymbol{\varepsilon} \tag{12}$$

where α_1 and α_2 are the load-to-temperature (LTT) dependence and load-to-voltage (LTV) dependence, respectively. $\Delta\mathbf{V}$ represents the measured voltage reduction at the substation transformer. α_2 can be used to estimate CVR factor.

The load's nonlinear relations to its impact factors can be shown using more complex models, for example by using a log function instead of a linear function. Similar to comparison-based methods, regression-based methods can use treatment and control measurements, where the treatment feeder's load is a function of control feeder's load. Model estimation in (13) shows the load of a treatment feeder ($\boldsymbol{L}^{Tr}$) as a nonlinear function of control feeder's load ($\boldsymbol{L}^{C}$).

$$\mathrm{Log}(\boldsymbol{L}^{Tr}) = \beta_0 + \beta_1\mathrm{Log}\left(\boldsymbol{L}^{C}\right) + \ldots + \varepsilon \tag{13}$$

2) DIFFERENCE IN DIFFERENCES APPROACH

Difference in Differences (DID) approach is another statistical regression-based method to estimate CVR factor. This approach uses observable data (i.e., control feeder's load, weather data, and other factors) to mimic an experimental event (i.e., load of treatment feeder if CVR was not applied). In other words, the effect of a specific treatment such as applying CVR on the feeder is calculated through comparison between the average change over time in the feeder's load for the treatment feeder, compared to the average change over time for the control feeder. Data from pre-/post-treatment are required in this approach, such as cohort or individual level data over time. This approach is considerably effective in removing biases. Biases can exist in post-treatment period comparisons between the treatment and control group that could be the result from permanent differences between those groups, and also biases from comparisons over time in the treatment group that could be the result of trends due to other factors impacting the load. Figure 2 shows a graphical explanation of DID. Intervention represents treatment or CVR.

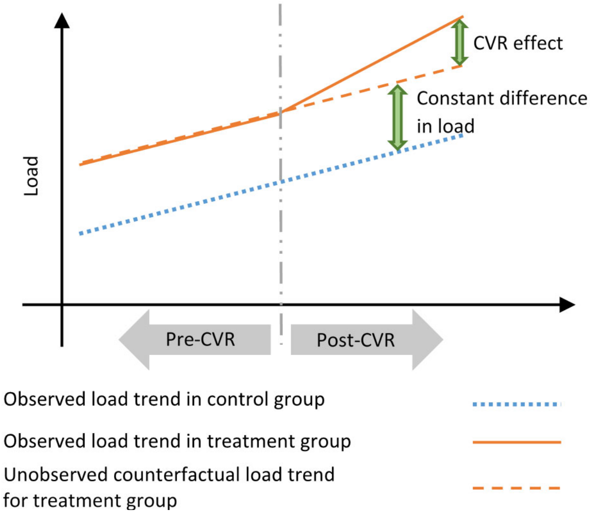

FIGURE 2. Graphical explanation of DID technique. Intervention here is treatment or CVR.

Although DID is intended to mitigate the effects of selection bias, depending on how the treatment group is chosen, this method may still be subject to certain biases such as omitted variable bias. To ensure that the estimated coefficients from the regression model are unbiased, Fixed Effects (FE) routine can be used, which assumes that the unobservable factor in the error term is related to one or more of the model's independent variables, and accordingly removes the unobserved effect from the error term prior to model estimation (using a data transformation process). In FE approach it is assumed that the means of each group is fixed rather than being random.

The FE regression allows controlling for time-invariant unobserved individual characteristics that can be correlated with the observed independent variables. Consider a relationship between a vector of observable random time-variant variables X_{it} and a dependent random time-variant variable L_{it} as in (14):

$$L_{it} = \boldsymbol{\beta}X_{it} + \mu_{\mathbf{i}} + \varepsilon_{it} \tag{14}$$

where μ_i is an unobserved random variable (individual effect), $i = 1, \ldots,$ N is used for observations, and ε_{it} is the stochastic error uncorrelated with X_{it}. When μ_i is a time-invariant variable correlated with X, regressors' coefficients $\boldsymbol{\beta}$ cannot be estimated by using Ordinary Least Squares (OLS), as the standard assumption of no correlation between the error term and the regressors is violated. The FE regression suggests subtracting the time mean (i.e., average over time) of each variable in the model and rewriting the model as in (15) and then estimating the transformed model by OLS. The upper bar denotes the time mean of respective variables.

$$L_{it} - \bar{L}_i = \boldsymbol{\beta}\left(X_{it} - \bar{X}_i\right) + (\mu_{it} - \bar{\mu}_i) + (\varepsilon_{it} - \bar{\varepsilon}_i) \tag{15}$$

As μ_i is a time-invariant variable, then $\mu_i - \bar{\mu}_i = 0$. This procedure drops the unobserved variable μ_i from the model, so the model can be rewritten as (16). Based on this new model, regressors' coefficients $\boldsymbol{\beta}$ can be estimated by OLS.

$$\tilde{L}_{it} = \boldsymbol{\beta}\tilde{X}_{it} + \tilde{\varepsilon}_{it} \tag{16}$$

where $\tilde{L}_{it} = L_{it} - \bar{L}_i$, $\tilde{X}_{it} = X_{it} - \bar{X}_i$, and $\tilde{\varepsilon}_{it} = \varepsilon_{it} - \bar{\varepsilon}_i$.

3) AUTOMATED CVR PROTOCOL NO. 1

Regional Technical Forum (RTF) [4] Protocol No. 1 has been the most established regression-based methodology, although currently deactivated. This methodology has been used by several electric utilities. It should be noted that deactivation status does not imply that the protocol's method is unreliable [5]. The proposed method by the automated CVR protocol No. 1 measures and verifies energy savings from CVR voltage reductions and experimental data produced by alternating the voltage set-points on a set of distribution circuits on successive days. The data, collected through extended cycling, are used in time-series and statistical analysis to estimate energy savings.

To estimate energy savings, other factors that affect load such as climate variations and customer behavior, are eliminated and the system is operated at different voltage levels on alternating days. The initial verification period is considered to be one year, where in the first 3 months CVR is applied every other day (day-on/day-off), followed by 9 months of continuous automated CVR application. Three out of these 9 months are then selected, based on season and geographic weather patterns, to operate the system so that on alternate days the system is at full voltage reduction, and the next day at the controlled nominal midpoint. The energy saving is accordingly determined by comparing energy use on similar days at different voltage levels, which is done through time-series and robust statistical analysis, as well as temperature compensation methods. Calculated CVR factors are verified during similar periods in following periods by running alternating days with full end-of-line voltage reduction and 2 volts above full end-of-line voltage reduction for two- to four-week periods.

4) PROS AND CONS

A benefit of regression-based methods is that physical interpretations are potentially embedded in the regression models, so electric utilities can understand the model behavior based on impact factors. As a disadvantage, regression models may have estimation errors that are higher than the CVR effects, thus masking the effect. Moreover, these models are mostly linear while the loads are known to be nonlinear in nature.

Several electric utilities, including American Electric Power, East Kentucky Power, Ameren Illinois Company, Potomac Electric Power Company, Commonwealth Edison Company, West Penn Power Company, Avista Utilities, Pacific Gas and Electric Company, Southern California Edison, Puget Sound Energy's, and Indiana Michigan Power Company use or have used this method for CVR factor assessment.

C. SIMULATION-BASED METHODS

Simulation-based methods simulate the load consumption in case of CVR-off. These methods employ system models and power flow calculations, and load models that are a function of voltage, time and weather factors. The CVR factor is calculated through the difference analysis between power flow results and measured load consumption. Figure 3 shows the flowchart of simulation-based methods.

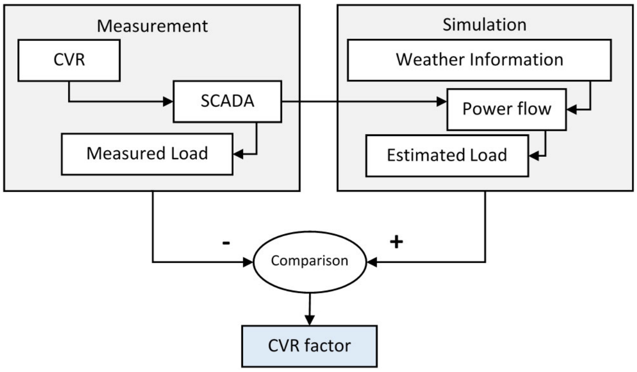

FIGURE 3. Simulation-based methods.

Simulation-based methods calculate feeder's load using a real-time power flow engine to estimate what would have occurred on the feeder without CVR. It then calculates the energy reduction by comparing the measured system's load under CVR-on, with the simulated baseline model.

1) PROS AND CONS

Simulation-based methods show high precision if the load models are highly accurate, while further allowing the system to run continually. However, it may be inefficient to build models for all existing and emerging load components. Application of aggregated load models at the circuit level is a potential solution. The developed models are further not adaptive to dynamic changes of feeders and load behaviors. In addition, the power flow model requires a load-voltage sensitivity (CVR factor) that is unknown until the analysis is complete. Constant CVR factor can be used for the power flow model, and by refining the CVR factor, energy savings would be calculated based on new CVR factor.

Few electric utilities, including Avista Utilities have used this method for CVR factor assessment.

D. REQUIRED DATA IN CVR ENERGY SAVING ASSESSMENT

Depending on the method, various data are needed for CVR energy saving assessment. Data need to be recorded in a proper time interval; i.e., 1- to 60-min. Common data used in discussed methods consist of:

- SCADA data: time-series values of real power, reactive power, voltage, and current from each voltage regulating device on the CVR substation/feeder,
- Interval energy (kWh) and voltage specific to each customer service point,
- Feeder characteristic data, such as conductor length, rated load, load factor, feeder conditioning data, regional, and customer-type load composition data,
- Weather data for each substation zip code; including temperature and humidity,
- Indicator of CVR status for each interval, i.e., "on/off",

- Precise time stamp of all collected data; including year, month, day of week, and hour.

III. STUDIED CASES

This section provides a summary of 26 studied cases, all associated with practical CVR/VVO deployments of electric utilities within the U.S.

A. AMERICAN ELECTRIC POWER (AEP)

AEP has deployed VVO on approximately 172 circuits, out of the 6,000 circuits on its system, as of March 2019, and has proposed 1600 more circuits for VVO implementation across the company's service territory. AEP has experience of working with three vendors: Cooper Yukon VVO, GE VVO, and Utilidata AdaptiVolt$^{\mathrm{TM}}$VVO. AEP Ohio started its VVO program in 2014 by using Utilidata AdaptiVolt system and achieved an energy savings of 4.27% using a day-on/day-off basis. The other AEP company, Kentucky Power Company (KPCo), retained AEG Applied Energy Group to assess energy savings obtained from VVO implementation as part of its Integrated Resource Plan (IRP, 2017-2031). Public Service Company of Oklahoma (PSO) is the other AEP company that expanded its CVR program using data from its AMI to better determine problems that may affect power quality for customers. PSO has currently implemented this on 52 circuits.

AEP affiliate operating companies show a range of 0.7-1.2% of energy demand reduction for each 1% voltage reduction. CVR program for AEP Ohio showed that 3-5% reduction in voltage, yields 2.9% energy reduction, while 3-4% drop in voltage, causes 2-3% peak demand reduction [6]–[11].

B. CENTRAL LINCOLN PEOPLE's UTILITY DISTRICT (Oregon ELECTRIC UTILITY)

Central Lincoln People's Utility District implemented a CVR pilot in 2014 in partnership with Landis+Gyr, the District's AMI vendor, and Dominion Voltage Inc. (DVI) as energy solutions partner. The pilot benefitted from the DVI's then-recently patented voltage control methodology called EDGE which uses AMI data and encompasses planning, operation and validation functions.

After sufficient summer and winter operating data were collected, the validation phase began in January 2014. Pairs of hours with similar weather conditions were found using EDGE Validator. Each pair had two data points, associated with CVR-on and CVR-off cases (including data during or prior to the pilot). For each pair of hours, the percent change in load was divided by the percent change in voltage to calculate the respective hourly CVR factor. The entire group of CVR factors were statistically analyzed to determine the overall CVR factor. From that, the overall change in voltage was used to calculate the total energy savings. Table 1 shows the energy savings and calculated CVR factors of this CVR program [12].

TABLE 1. Customer savings.

Lincoln Beach	CVR Factor	Energy Savings
Summer	0.43	1.49%
Winter	1.05	2.49%

C. EAST KENTUCKY POWER (EKPC)

EKPC is currently piloting Conservation Voltage Optimization (CVO) in two substations. The energy savings are assessed using a regression analysis based on two hourly substation energy (kWh) logs With and Without CVO. The savings are estimated to be 50 kW demand impact (0.3% more demand reduction) for Downline Regulator CVO and 310 kW demand impact (2% more demand reduction) for Feeder Regulation [13].

D. AMEREN ILLINOIS COMPANY (AIC)

Ameren has implemented a VO pilot in 2012-2013 and launched its VO program in 2017, while the first few years of VO program focused on better understanding current marketed VO technologies and solutions. Ameren is currently applying VO program in the system and plans to implement it on 1,047 circuits by the end of 2024. Ameren worked with the Electric Power Research Institute (EPRI) to provide analysis support for its VO Pilot. EPRI used regression methods to create voltage-sensitive models of test-feeder loads based on either weather variables or a suitably comparable feeder. Discussion with EPRI about Ameren's VO pilot allowed EPRI and Ameren to determine that the best method to perform the analysis of the project was to utilize the Comparable Circuit Regression methodology. Comparable Circuit method provides a model that utilizes comparable feeder load, voltage-state, and time variables. The CVR factor is then calculated from the voltage-state variable.

Tables 2 and 3 show the energy savings for two of the tested circuits. The last column in these two tables shows average kW savings per each percent of voltage reduction. The CVR test was performed in two sets: a) voltage reduction of 2% in a set of days during a selected month, and b) voltage reduction of 4% in another set of days during the same month; Then kW savings obtained from these two sets are averaged to give the average kW savings per % of voltage reduction.

The implementation for the VO program 2018-2025 included the installation of new voltage regulator controllers with two-way radio communications, installation of voltage sensors at end of-line locations, modifications to the LTC controller at the University substation in Peoria, Illinois, to provide remote control capabilities, and implementation of automatic voltage control using Ameren's ADMS system. The energy and demand savings of VO program are planned to be evaluated by Opinion Dynamics starting in 2019 using two different approaches: a) Algorithmic Approach, that estimates savings based on results from Ameren's pilot study and a survey of the literature that assumes a CVR factor

TABLE 2. University substation monthly CVR results.

Month - Year	CVR factor	kW/%ΔV
May-12	1.37	85
Jun-12	0.79	55
Jul/Aug-2012	0.75	76
Sep-12	1.12	63
Oct-12	1.48	74
Nov-12	0.91	48
Dec-12	1.16	68
Jan-13	0.8	50.5
Feb-13	N/A	N/A
Mar-13	N/A	N/A
Apr-13	N/A	N/A
May-13	N/A	N/A
Jun-13	N/A	N/A
Jul-13	0.71	56.5

TABLE 3. Mt. Zion substation Rt. 121 Monthly CVR Results.

Month - Year	CVR factor	kW/%ΔV
May-12	N/A	N/A
Jun-12	N/A	N/A
Jul-12	0.82	39
Aug/Sep-12	0.8	25
Sep/Oct-12	0.63	14
Nov-12	0.86	22
Dec-12	0.26	7.5
Jan-13	0.148	14.5
Feb-13	N/A	N/A
Mar-13	N/A	N/A
Apr-13	N/A	N/A
May-13	N/A	N/A
Jun-13	N/A	N/A
Jul-13	0.88	32

of 0.80, and b) On/Off Regression Approach, that develops a regression model using VO-on and VO-off testing data that will be used to obtain seasonal and annualized savings estimates. The results of the two approaches will be compared and the on/off regression approach results will be used to validate the algorithmic approach [14], [15].

E. COMMONWEALTH EDISON COMPANY (ComEd)

ComEd has planned to install VVO on a total of 2,958 feeders at 450 substations for its voltage optimization program over the 2018-2025 timeframe. Navigant was selected to evaluate the energy savings of this program. For 2018, as the data was not sufficient, Navigant suggested that saving estimates be based on the best information available at the time, which included empirical estimates developed from other ComEd VO feeders, and empirical estimates developed in other jurisdictions that are available in the published literature. In this regard, by considering CVR factor of 0.8, Navigant proposed a statistical modeling method for energy baseline prediction. It should be noted that the CVR factor of 0.8 is consistent with the result that ComEd identified by analyzing measured data during a pilot VO project at one of its substations, i.e., Oak Park substation. In addition, this value is the same as the Commission-approved CVR factor applicable to Ameren Illinois. This method consisted of data cleaning, model selection and tuning, and impact estimation. Data cleaning is done to remove incorrect data and fill missing data, while the goal of model selection and tuning is to generate models that can be utilized to simulate following three states:

- VO-enable state: estimating the feeder load and voltage assuming that VO had been enabled for the entire year,
- Feeder conditioned state: estimating the load and voltage assuming that feeder conditioning had been completed prior to the start of 2018,
- VO and feeder conditioned state: estimating the load and voltage assuming that VO had been enabled for the entire year and feeder conditioning had been completed prior to the start of 2018.

Feeder conditioning in these states refers to various steps undertaken on a VO-on feeder prior to deployment and may include modifying LTC controls, capacitor banks, and voltage regulators, as well as load balancing, phase balancing, and reconductoring.

Several approaches were considered to model the mentioned states by taking the available data into account, including structural linear regression models, simple CVR factor-based approaches, and supervised machine-learning approaches. Amongst these approaches, the machine-learning methods was selected because of their ability to consider multiple, complex model specifications, including lagged terms and interaction terms, and make more accurate predictions. A Random-Forest approach was used to estimate the voltage models, and a Gradient-Boosted Decision Trees approach was used to estimate the load models. The general specification for these models is shown in (17).

$$X_{it} = f(load-shape,\ weather,\ VO\ status,\ FCstatus,\ feeder\ characteristics,\ Events,\ \Delta\ LRs) \quad (17)$$

where i and t are the feeder and time interval indices, respectively. X_{it} is the interval load or voltage measured on feeder i during time interval t. Interval power is measured at feeder heads at the substation, while voltage is measured as the load-weighted average of interval voltage readings from the AMI meters at the customer-ends on each feeder. VO status indicates VO-on and VO-off time intervals. Events comprises a set of binary flags for load-shifting event within time interval t. FC status refers to whether time interval t falls before, during, or after the feeder conditioning phase, and ΔLR comprises a set of binary flags indicating load-regime changes.

Bootstrapped cross-validation is then used to tune the models. Based on this technique, a series of k models are fitted to different bootstrapped resamples drawn with replacement from a subset of the dataset. For each bootstrap resample, 20 percent of the data was randomly selected and held back to permit out-of-sample prediction model testing. After fitting the models, predictions were made using the hold-out validation samples, by comparing each of the k model predictions produced to the hold-out sample data. After fitting each model to the bootstrap resamples drawn from the training data set, the counterfactual simulations were produced. Simulations of load and voltage for 2018 were made at 30-minute time intervals for three scenarios: pre-feeder conditioning, post-feeder conditioning/pre-VO, and VO-on. Three annualized load and voltage profiles were calculated for entire 2018 based on the scenarios and differencing these profiles yielded the impact of VO without feeder conditioning, feeder conditioning without VO, and both VO and feeder conditioning.

For 2019, ComEd used a constant CVR factor of 0.8 in energy savings calculations. Energy savings are obtained by multiplying the constant CVR factor to the energy baseline as well as voltage reduction percentage. To estimate the counterfactual energy consumption and voltage reduction from the counterfactual voltage profiles, a clustering algorithm is used based on the temperature, season, time of the day, day type, and VO status. The energy baseline is then obtained from the sum of the annual energy consumption utilizing the actual energy measurement during VO-off condition (this includes the actual measurements prior to VO activation during the given program year) and a calculated VO-off value for VO-on condition. VO-off energy consumption calculation for VO-on condition will be calculated as in (18):

$$E_{VO-off} = \frac{E_{VO-on}}{1-(CVR_f \times \Delta V)} \tag{18}$$

where E_{VO-off} is the calculated VO-off energy consumption for VO-on condition, while E_{VO-on} is the actual measured energy consumptions during VO-on condition. ΔV and $\mathrm{CVR_f}$ also denote voltage reduction and CVR factor, respectively [16]–[18].

F. IDAHO POWER COMPANY (IPC)

In 2007, IPC was involved in the Northwest Energy Efficiency Alliance (NEEA) CVR demonstration project. After that, IPC implemented three CVR programs. IPC initially began the CVR project in 2009. The project focused on feeders where CVR could be implemented at minimal cost by simply changing the settings on distribution substation transformer load tap changers (LTC) (referred to here as ''one control point''). For this project, the CVR energy reduction was calculated by using the CVR factor identified in the NEEA study (0.55) and applying it to the loads over the entire base year of 2009. After the initial project, the CVR Enhancement Project began with project design in early 2014 and equipment installation in late 2014/early 2015. The selected power by the IPC was similar to that described in the EPRI's Green Circuit Distribution Efficiency Case Study document for validating CVR energy savings. Among 264 potential candidates, CVR was implemented on 30 feeder circuits. This was done by implementing new LTC settings. A comparison-based (correlated-feeder) method was used in which aggregated AMI data on separate treatment transformers were compared with a set of control transformers to produce CVR factors for each customer class and weather zone. A 2-day-on/2-day-off protocol was used to allow for the load to recover from the voltage change as it was thought that a day-on/day-off cycling protocol wouldn't allow for the load to fully recover before switching into a different operating voltage.

TABLE 4. Summary of commercial and residential CVR factor.

Feeder Name	CVR Factor	
	Commercial	Residential
Boise	0.78	0.86
Pocatello	0.87	0.63
Twin Falls	0.65	0.41
Ketchum	1.11	1.16
McCall	2.89	5.75
Ontario	0.19	0.91

The effects of CVR were determined on commercial and residential customers in all six company-identified weather zones, including Boise, Twin Falls, Pocatello, McCall, Ontario, and Ketchum. One treatment transformer in each weather zone was studied for each rate class. Additionally, one transformer dedicated to irrigation loads was studied. Data collection was performed on all treatment and control transformers for an entire year. Control transformers were selected in a way to be similar to treatment transformers in the same weather zone, having sufficient residential, commercial, or industrial (in this case irrigation) customers above the line regulators on each associated feeder. Control and treatment transformer loads were matched as closely as possible for each customer class. Additionally, control transformers were chosen such that they were geographically close to each other to decrease weather-caused variability.

For the final CVR program, two CVR factors; i.e., residential and commercial, were calculated for each feeder, as shown in Table 4. The commercial CVR factor for Ontario Weather Zone is 0.19 which is relatively small, considering the small size of commercial sample (77 customers) compared to the residential sample (431 customers). In addition, residential CVR factor for McCall Weather Zone is 5.75 and this extreme result was caused by the LTC settings and is subject to further studies [19]–[21].

G. POTOMAC ELECTRIC POWER COMPANY (PEPCO)

PEPCO piloted a CVR program in 2012-2014 and used a regression-based method for CVR factor assessment based on treatment and control substations. To match treatment and control substations, customer and load characteristics were considered to ensure that treatment and control pairings are generally adjacent. All pairings were in a single jurisdiction, assuring that factors that affect consumption, such as economic factors and weather, are similar between pairings. Seven substation pairs were identified (14 feeders in total) by

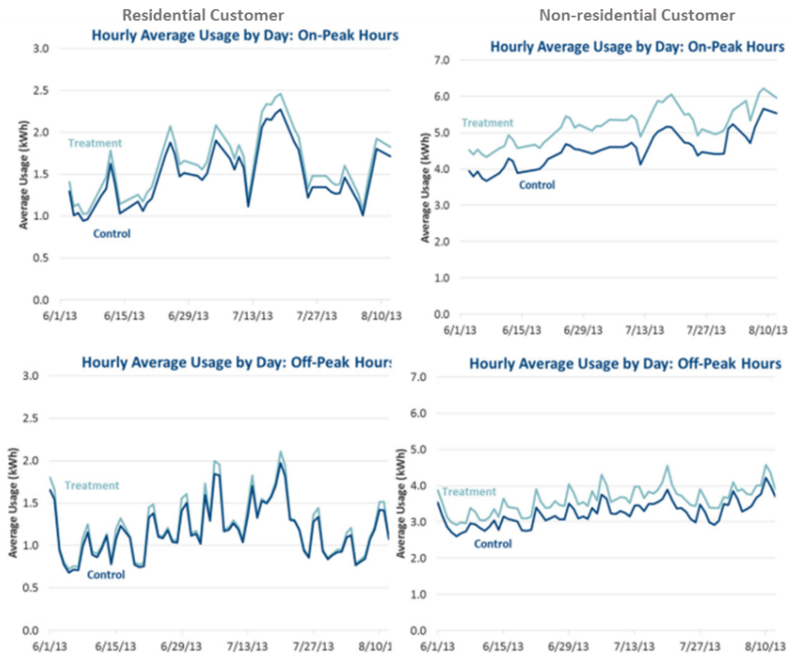

FIGURE 4. Comparisons for consumption profile of residential and non-residential control and treatment groups using hourly AMI data for the peak analysis [22].

PEPCO's experts to have closely matched customer and load characteristics. These treatment and control substation pairs were generally adjacent to each other and the communities that they served were similar in nature in terms of homes. Moreover, since all the treatment and control substations were in the PEPCO Maryland service territory, many factors that may affect consumption, such as rates and economic factors, were similar between treatment and control substations.

As the impact of CVR could vary between residential and non-residential customers, for both peak hours and conservation savings, CVR analyses was broken down between peak and all other hours, and was also done for residential and non-residential customers separately. An *ex-post* comparison of control-treatment pairings on pre-treatment period (June-August 2013) were carried out to validate the control group. Figure 4 shows the comparisons for consumption profile of residential and non-residential control and treatment groups using hourly AMI data for the peak analysis.

As shown in Figure 4, the residential treatment and control group load profiles were very similar to each other in terms of their shapes and levels, which implies that the residential control group customers reasonably represented the residential treatment customers (in case of CVR-off). However, for the non-residential customer load profiles, the groups are similar to each other in terms of their shapes, but different in the level of usage. To estimate the parameters in regression model, Difference in Differences (DID) technique was used through a panel data regression analysis. The usage of the treatment and control group customers before and after the CVR treatment were compared using a regression model, while accounting for other factors that could potentially confound the estimated impact such as weather conditions, DSM program participation, and AMI activation. The most important factor to account for in this regression is the impact of weather conditions on the electricity usage of the customers. A temperature humidity index (THI) which combines dew point and dry bulb temperatures into one variable was used in this case. In addition, customer participation and enrollment in utility demand-side management programs were accounted for, as the participants of these programs reduce their electricity usage after the installation/implementation of demand-side management measures. To ensure that the estimated coefficients from the resulting model were unbiased, the Fixed Effects (FE) estimation routine was used, which assumes that the unobservable factor in the error term is related to one or more of the model's independent variables, and accordingly removes the unobserved effect from the error term prior to model estimation (using a data transformation process).

The results showed that a 1.5% reduction in voltage is estimated to result in a 1.4% and 0.9% reduction in consumption for residential customers and non-residential customers, respectively. The results further showed that a 1.5% reduction in voltage is estimated to result in a 1.1% and 2.5% reduction in *peak* consumption for residential customers and non-residential customers, respectively. PEPCO has continued its CVR program and plans to expand its CVR program through the 2023/2024 timeframe. As of 2018, PEPCO implemented CVR on approximately 85% of its Maryland substations [22], [23].

H. WEST PENN POWER COMPANY

West Penn Power Company studied CVR deployment in its system in 2012-2014 by a reduced voltage of 1.5% doing in a day-on/day-off approach for one week in spring and summer, and a week-on/week-off approach for two weeks in winter. It used regression-based method based on the difference in energy usage in treatment and control substations for CVR factor assessment.

Results showed a range of CVR factors, with an average of 0.86. CVR factors for winter, spring, and summer were calculated as 0.64, 1.11, and 0.85, respectively [22] and [24].

I. INDIANAPOLIS POWER AND LIGHT COMPANY (IPL)

Simultaneous comparison between treatment and control load profiles improves the accuracy and eliminates uncertainty of weather corrections, and this is what IPL adopted for carrying out its CVR program in 2012-2014. Furthermore, it was observed that repeating the tests on several days and treating different representative groups further improves confidence in the load response. Also, careful monitoring of individual circuits during a CVR test assures the results do not inadvertently include emergency load transfers, power outages, etc.

IPL applied the CVR for a few short periods (two detailed tests over five near peak days) in 2012 and 2013 and compared drop in usage during those periods to predict an impact. The aggregate CVR factor was estimated to be 0.85 in 2012 and 0.75 in 2013. IPL chose to use a CVR factor of 0.8 until additional tests justify changes [22], [25].

J. PHILADELPHIA ELECTRIC COMPANY (PECO)

PECO, an Exelon Company, implemented an Energy Efficiency and Conservation Plan in two phases in 2009-2012 and 2013-2016. PECO formed a CVR working group, consisting of PECO personnel, Navigant, and representation from the state-wide evaluator to develop a protocol for CVR assessment. The CVR working group focused on development an enhanced version of the NEEA CVR protocol, adapted for use at PECO for energy and demand savings, through research, data collection, statistical sampling, and objective reviews. The working group estimated separate protocols for energy and demand savings, and developed an EM&V protocol that follows Option C as described in International Performance Measurement and Verification Protocol where savings are determined by measuring energy use at the whole-facility or sub-facility level.

Option C requires a regression analysis to account for independent variables such as temperature. The evaluation team performed a statistical regression analysis study using hourly loads and voltage data collected for substation transformers and circuits treated under the CVR program. The data set for this analysis included hourly loads and voltage values for the weeks immediately prior and after the voltage reduction week, for the entire group of stations and circuits treated in the program. The data was further used to statistically estimate an average system-wide CVR factor. The regression model used to calculate this factor considers average hourly heating and cooling degree days to control for weather-related influences on change in hourly energy consumption, metered voltage, and CVR factor for energy measuring the average percentage change in MWh, for every one-percentage change in voltage over all hours on the PECO system. Alternative model specifications were tested, including different segmentations of the data, to test the robustness of the calculated CVR factor.

The CVR factor was ultimately calculated as 1.08 and the overall impact of the program was estimated to be around 320 GWh/year [26]–[28].

K. PORTLAND GENERAL ELECTRIC COMPANY (PGE)

PGE piloted a CVR project in 2014. The CVR was applied in a day-on/day-off operation basis to provide a data comparison between CVR-off and CVR-on modes.

The results for winter and summer seasons and for two different substations show a range of energy reduction from 0.87% kWh to 0.99% kWh per 1% voltage reduction. PGE is making progress on its CVR program as an integrated function of grid modernization and anticipates meeting its 1 MWa (average MW) 2020 target [20], [29].

L. SACRAMENTO MUNICIPAL UTILITY DISTRICT (SMUD)

SMUD piloted a VVO/CVR test in 2010-2014. CVR and VVO were used in conjunction with each other. CVR used the LTC within the substation. Operators could remotely lower the voltage output at the substation while substation and line capacitor banks provided voltage support on the distribution lines. In order to test both the CVR and VVO benefits, SMUD carefully designed the tests so that there were days when only CVR or VVO was implemented, days when both were enforced, and days when neither was active. CVR tests were conducted at three different voltage reduction levels (CVR Level 1-3). Each level represented a corresponding percentage voltage reduction set-point change in the LTC on the power transformer. The energy saving was carried out by comparing matched days with and without CVR.

In summer 2011, SMUD CVR program resulted in an estimated 2.5 percent reduction of peak demand on one of the pilot substations (In addition, two separate regression methods produced similar results). SMUD has continued to deploy volt-VAR optimization technologies throughout the SGIG program and estimates a 1 percent average load reduction across 14 substations and approximately 1.5 MWh of energy savings per day [30], [31].

M. DUKE ENERGY OHIO

Duke Energy Ohio piloted integrated VVO in a few locations in Ohio territory from 2008 to 2016. Previous studies indicated energy savings from 0.50% to 0.79% for a 1% drop in voltage, with common mode values of 0.65%. These three constant CVR factor values (0.50, 0.65, and 0.79) were used by MetaVu Inc. in low case, base case, and high case estimates, respectively. System energy reduction was estimated to be between 1.00% and 1.58% with 8760-h operation. As of 2018, Duke Energy Ohio has planned to expand its VVO program [32]–[34].

N. XCEL ENERGY

Xcel Energy piloted a Distribution Voltage Optimization (DVO) in 2011-2012. The demand and energy savings were verified in two ways during this project: a) DVO was conducted in week-on/week-off basis, and EPRI verified the demand and energy savings using its statistical models, and b) Savings were verified through the DVO Software Platform used in the pilot projects, using its power flow based measurement and verification engine. The results of both methods were then compared. Initial results were close but over the longer period of time the results varied by approximately 40 percent.

In NCAR substation, it was observed that voltage can be lowered on average about 2.5%, resulting in energy reduction range of 1.6-2.7%. Results from the Englewood substation show a voltage reduction of 1.5% and a CVR factor of 1.7 (2.55% energy saving) in 2011 and 2.7 (4.05% energy saving) in 2012.

After this pilot, Xcel Energy initiated to start a DVO program in which it plans to use the power flow-based method that can continuously calculate the savings. It will use the EPRI results of Xcel Energy's historical pilots (CVR factor of 0.8) to help refine the CVR factor. Then that CVR factor will apply the actual usage data by substation to calculate the savings for each substation where DVO is implemented. As of 2018, Xcel energy has planned to deploy 4350 VVO Varentec's ENGO units as part of its CVR project and it is expected to cut energy consumption by about 2% [35], [36].

O. AVISTA UTILITIES

Avista Utilities piloted an Integrated Volt-VAR Control (IVVC) program in 2013-2014. Avista assessed the energy savings of its pilot based on three methods: a) RTF's Automated CVR Protocol No. 1, b) Washington State University (WSU) Voltage Optimization Validation Methodology, and c) Navigant Regression Methodology. The temperatures at each substation to which experimental circuits connect were collected, as well as at the feeder end-of-line locations, in order to reduce the possibility of confounding due to localized microclimates and based on the protocol's recommendation.

The RTF Automated CVR Protocol No. 1 resulted in a CVR factor of 0.881. The calculated CVR factor by the Navigant Regression Methodology was 0.833 [37], [38].

P. PACIFIC GAS AND ELECTRIC COMPANY (PG&E)

PG&E piloted VVO in 2013-2016 by using DVI's EDGE solution. PG&E contracted with a third-party consultant to perform the M&V of the VVO pilot circuits. The consultant's model utilized regression models for each hour. The model incorporated SCADA data, smart meter data, weather data, VVO operation and transition time, as well as solar potential index as a proxy for solar PV generation impacts not captured in other variables. The use of smart meter voltage and energy consumption data supported breakouts of voltage reductions and energy savings by customer class. It was determined that further study is needed to determine whether the uncertainty in the cause of voltage and energy changes during high loading can be addressed through statistical modelling.

The VVO pilot circuits exhibited a CVR factor in the 0.6 to 0.8 range. Across all test periods and pilot banks (excluding Dinuba), the weighted average CVR factor was 0.7. PG&E has planned to deploy advanced VVO in 2018-2020 [39], [40].

Q. SOUTHERN CALIFORNIA EDISON (SCE)

SCE tested a Distribution VVC (DVVC) under its Irvine Smart Grid Demonstration project. The DVVC was operated based on a week-on/week-off approach. When the DVVC was off, capacitors were returned to their normal settings, which gave a clear comparison of voltage control in the two modes. Furthermore, energy consumption for each week was recorded and temperature was adjusted.

The DVVC operation achieved a two-volt reduction on a 120-volt basis and reduced voltage fluctuations. The average CVR ratio observed over 32 weeks of testing was 1.56. Average voltage reduction while running DVVC was 1.58% in the test year (2014) compared to the base year (2012). Average energy savings while running DVVC was 2.53% in the test year (2014) compared to the base year (2012) [38], [41].

R. GLENDALE WATER AND POWER (GWP)

GWP implemented CVR as part of an AMI Initiative Project in 2014-2015. The pilot realized 2.95% in energy savings on two feeders over the baseline suggesting that a full-scale program could save a minimum 14,500 MWh a year, equivalent to net power costs savings of $470,000 to $1.2 million per year. After its CVR pilot, GWP started working with DVI to expand its CVR program system wide in 2015. As of June 2018, average savings per feeder is 2.2% [42], [43].

S. PUGET SOUND ENERGY's (PSE)

PSE implemented a VO program in 2015-2016. The program relied on the RTF Protocol No. 1. Energy consumption data for three selected substations were accessed for the same period used in the reported savings (July 2014-June 2015 and July 2015-May 2016). The July 2015-May 2016 period was analyzed to ensure that no significant changes to the customer class had occurred since the implementation of the CVR projects, and it was concluded that no significant changes to feeder load characteristics were identified.

The applicable VO factor was calculated as 0.475 [44].

T. DOMINION ENERGY

Dominion Energy implemented and evaluated VVO project in Midlothian, Charlottesville, and Northern Virginia in 2009-2011. The Voltage optimization integrates between the existing DMS Software and AMI and adds DVR (Short-term - minimal peak day hours - reductions) to CVR and VVO. The adaptive voltage control is implemented using AMI to collect the needed customer voltage readings, the DVI's EDGE to control setpoint changes, and a Distribution Management System (DMS) or SCADA to control the local substation LTC controller, circuit voltage regulator and/or capacitor. Evaluation phase read DMS and weather data to calculate savings. The objective of the Measurement and Verification phase is to confirm through verifiable statistical analysis that the expected energy savings by circuit was achieved. The rigorous statistical method incorporates a paired difference test that compares daily/hourly samples of the baseline circuit data (OFF condition) to the CVR circuit data (ON condition) under matched operating conditions. The results of the demonstration prove that there are measurable reductions in energy usage using voltage optimization.

Dominion's demonstration shows an average of 2.8% reduction in annual energy. CVR factor of 0.92 was achieved [45].

U. INDIANA MICHIGAN POWER COMPANY (I&M)

I&M implemented a VVO program in 2014-2015 as part of Electric Energy Consumption Optimization (EECO). VVO program used Utilidata's AdaptiVolt VVO platform installed at three substations and leveraging real-time data measurement and communications. An on/off procedure was used for voltage reductions during various parts of the year.

Given the calculated baseline values for voltages and currents, baseline power demand (MW) for a 5-minute interval when VVO was On were calculated; similarly for the actual power demand, for each circuit/phase and by type of day (weekday, weekend). The analysis was conducted for four scenarios: a) Heating season (January-March, October-December) weekdays; b) Heating season (January-March, October-December) weekends; c) Cooling season (June-September) weekdays; d) Cooling season (June-September) weekends.

For each station/circuit, the temperature value used for each hour was the average temperature for that hour over the number of days in the seasonal period (i.e., either weekdays or weekends). For each scenario for each station/circuit/phase, energy savings for a weekday or weekend with typical temperatures was calculated. For each of the two voltage conditions, the 24-hour power demand values were aggregated to give daily totals for power usage. The percentage savings from reducing voltage was calculated and divided by the percentage reduction in voltage to provide the estimate of the daily CVR factor for a day.

Estimated daily CVR factor ranges from −1.13 to 11.38 for different station/circuit/phase/season/day of week. Although the CVR factors seem off the expected range, I&M's report mentions that these values are consistent with evidence from previous studies of the voltage reduction strategy; i.e., EPRI's Green Circuits collaborative project and Northwest Energy Efficiency Alliance (NEEA)'s CVR project.

After this CVR program, I&M continued its CVR deployment and as of July 2019. I&M has currently approximately 50 distribution circuits with CVR installed in its Indiana service territory and 3 distribution circuits in its Michigan jurisdiction. Estimated daily CVR factor for 2018 ranges from −0.43 to 4.48 [46]–[48].

V. PUBLIC SERVICE ELECTRIC AND GAS COMPANY (PSE&G)

PSE&G in New Jersey had planned to pilot a VVO program in 2018, and has already completed phase I of VVO study for North Bellmore area. PSE&G plans to run the pilot for a minimum of two years to allow the collection of evaluation data during a full range of test conditions: all four seasons, weekdays and weekends/holidays, and a broad range of weather conditions. PSE&G and a third-party implementation contractor will work with an evaluation consultant to develop a mutually acceptable measurement and verification plan. VVO impacts are determined by the characteristics of the individual substations and feeders on which they are installed, as well as the characteristics of the dominant load type(s) they are serving. Thus, they are expected to vary across feeders, seasons, times of day, types of day, system contingencies, as well as weather conditions. PSE&G is planning to deliver the interval test data from the pilot to the independent evaluator in regular basis (weekly or biweekly). Given the variability of potential volt-VAR approaches and the need to further study this innovative offering in a pilot setting, no specific participation or savings estimates are available at this time. However, based on indicative levels of energy savings achieved at other utilities, it was estimated that the energy savings associated with the pilot, depending on final design, could be in the range of 0.75% to 2.0% of baseline energy [49].

W. KANSAS CITY POWER AND LIGHT (KCP&L)

KCP&L implemented a VVC demonstration project in 2015. The evaluation phase was conducted based on a day-on/day-off approach. The baseline day for an on day could be any of the off days with the same load, temperature and other characteristics such as the on day. The major criteria to establish a baseline day were temperature and real power.

Conservative 2.05% drop in voltage resulted in 1.63% decreases in energy use. KCP&L also studied peak energy use reduction, achieving 1.13% energy use reduction from a reduction of voltage of an average of 1.64% over numerous peak days. It was found that CVR is less effective on high peak load days. CVR factor for each pair of matched days was in the range of 0.140-2.073 with an overall CVR factor of 0.889 [50], [51].

X. CHOPTANK ELECTRIC COOPERATIVE

Choptank Electric Cooperative implemented a system-wide VVO program, partnering with DVI. The initiative resulted in an average 3.1 percent voltage reduction and accordingly a 5 percent reduction in peak demand [52].

TABLE 5. Summary of studied cases.

Utility/Project	Type	Year	CVR Factor Assessment Method	CVR Factor
AEP [6]-[11]	Program	2014/2016/2019	Regression-based	*
Central Lincoln People's Utility District [12]	Pilot	2013-2014	Comparison-based	0.43 (summer); 1.05 (winter)
EKPC [13]	Test case	2019	Regression-based	*
AIC [14]-[15]	Pilot/Program	2012-2013/2017-2018/2018-2025	Regression-based	0.148-1.48
ComEd [16]-[18]	Program	2018-2025	Regression-based/Constant CVR factor	0.8
IPC [19]-[21]	Program	2009-2016	Constant CVR factor/ Comparison-based	0.41-5.75 (residential); 0.19-2.89 (commercial)
PEPCO [22]-[23]	Pilot	2012-2014/2018	Regression-based	*
West Penn Power Company [22], [24]	Study	2012-2014	Regression-based	0.86
IPL [22], [25]	Program	2012-2013	Comparison-based	0.85 (2012); 0.75 (2013)
PECO [26]-[28]	Program	2009-2012/2013-2016	Regression-based	1.08
PGE [20], [29]	Pilot/Plan for program	2014/2018	Comparison-based	*
SMUD [30]-[31]	Test/Plan for program	2010-2014/2017	Comparison-based	*
Duke Energy Ohio [32]-[34]	Pilot	2008-2016	Constant CVR factor	0.50-0.79
Xcel Energy [35]-[36]	Pilot/Plan for program	2011-2012/2015-2020/2019	Simulation-based method/Statistical analysis	1.7 (2011); 2.7 (2012)
Avista Utilities [37]-[38]	Program/Plan for program	2013-2014/2019	Regression-based/Simulation-based	0.833-0.881
PG&E [39]-[40]	Pilot/Plan for program	2013-2016	Regression-based	0.6-0.8
SCE [41]	Demonstration Project/Plan for program	2012-2015/2019	Regression-based	1.56
GWP [42]-[43]	Pilot/Program	2014-2015/2015-2018	Comparison-based	*
PSE [44]	Program	2015-2016	Regression-based	0.475
Dominion Energy [45]	Program	2009-2011	Comparison-based	0.92
I&M [46]-[48]	Program	2014-2015/2019	Regression-based	-1.13-11.38 (2014-2015); -0.43-4.48 (2018)
PSE&G [49]	Plan for pilot	2018-2025	Regression-based	*
KCP&L [50]-[51]	Demonstration Project	2015	Comparison-based	0.14-2.073 (overall 0.889)
Choptank Electric Cooperative [52]	Program	2018	Comparison-based	*
NRECA [53]	Test	2012-2014	Comparison-based	1.04-1.05
NEEA [19]	Pilot	2006-2007	Comparison-based	0.17-1.12

* No CVR factor was found

Y. NATIONAL RURAL ELECTRIC COOPERATIVE ASSOCIATION (NRECA)

NRECA implemented VVO program involving several cooperatives in 2012-2014. Involved cooperatives were Adams-Columbia Electric Cooperative (ACEC), Owen Electric Cooperative (OEC), and Iowa Lakes Electric Cooperative (ILEC). VVO via power factor correction was preferred strongly to CVR via active voltage regulation. CVR schemes were primarily SCADA actuated but were initiated by human operators. The verification scheme was based on testing across correlated feeders. The benefits of the method were identified as uniqueness of the pairing algorithm, simplicity of implementation, and weather and day-of-week load correction were not necessary because the pairs of SCADA measurements under comparison were taken at the same time. Based on the analyses, for each of the features for which CVR was implemented, there were multiple other feeders in the system whose load behavior was strongly correlated ($R^2 > 0.9$), which could be used as controls. In cases for which, due to the system design, highly correlated feeders do not exist, an alternate day treatment verification protocol was proposed. Results for a single feeder in NRECA project showed that CVR factor ranges 1.04-1.05 for load levels at and below 2.2 MW [53].

Z. NORTHWEST ENERGY EFFICIENCY ALLIANCE (NEEA)

NEEA implemented a Distribution Efficiency Initiative (DEI) Pilot Study involving 14 Pacific Northwest utilities in 2007-2008. The DEI study was intended to quantify the effects of power consumption in relation to the applied voltage or CVR. CVR was implemented in day-on/day-off basis. The results of energy savings were within expected values of 1-3% total energy reduction, 2-4% reduction in kW demand, and 4-10% reduction in reactive power demand. Computer model simulations showed that by performing selected system improvements, between 10 and 40% of the total energy savings occurs on the utility side of the meter. Based on the results of NEEA pilot study CVR factors were calculated for Avista as 0.93, Clark, as 0.88, Douglas for two substations, as 0.17 and 1.12, Idaho Power for three substations as 0.55, 0.61, and 0.74, PSE for two substations as 0.8 and 0.85, and SnoPUD as 0.74 [19].

1) SUMMARY OF STUDIED CASES

A summary of the studied cases is provided in the table 5. It should be noted that although other utilities may have worked on CVR programs/pilots, sufficient public information is not available about their methods of CVR factor calculation. As the focus of this paper is on CVR factor assessment, these utilities are not discussed. These utilities include, but are not limited to, Consolidated Edison (ConEd), FirstEnergy, PacifiCorp, Middle Tennessee Electric Membership Corporation, Huntsville Utilities, National Grid, Oklahoma Gas & Electric (OG&E), Jones-Onslow Electric Membership Corporation (JOEMC), NorthWestern Energy (NWE), and Evergy (Electric utility through operating companies KCP&L and Westar Energy).

IV. CONCLUSION

Electric utilities are constantly looking into methods of increasing system energy efficiency and reducing peak load to help system operations while supporting end-use customers. CVR and VVO are exceptionally effective methods in achieving this goal by lowering the voltage at the distribution system. This paper provided a measurement and verification benchmark of CVR/VVO deployed by several electric utilities in the U.S. The specific focus of the paper was on the electric utilities that discussed their method of CVR factor calculation and further provided relevant results. The studies in this paper can be used by other electric utilities as well as the research community to (i) become familiar with the most common approaches in CVR factor calculations, (ii) understand the important factors and common challenges in CVR factor assessment, and (iii) have a clear idea of the possible range of CVR factors in practical systems. This would provide a substantial background for other electric utilities as they plan and develop their own CVR/VVO efforts.

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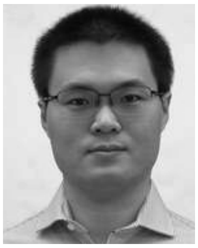

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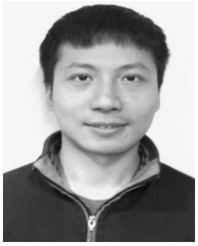

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