# Review on Implementation and Assessment of Conservation Voltage Reduction

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***Abstract*—Conservation voltage reduction (CVR) is widely adopted by utilities for peak demand reduction and energy savings through reducing the voltage level of the electrical distribution system. This paper presents an in-depth review on implementing and assessing CVR. The methodologies to quantify CVR effects are categorized into comparison-based, regression-based, synthesis-based and simulation-based methods. The implementation strategies for voltage reduction are classified into open-loop and closed-loop methods. The impacts of emerging smart-grid technologies on CVR are also discussed. The paper can provide researchers and utility engineers with further insights into the state of the art, technical barriers and future research directions of CVR technologies.**

***Index Terms*—Conservation voltage reduction (CVR), demand reduction, distribution system, energy saving.**

## I. Introduction

CONSERVATION voltage reduction (CVR) is an established idea and one of the most cost-effective ways to save energy. By lowering voltages on the distribution system in a controlled manner, CVR can reduce peak demand, losses and achieve more energy savings while keeping the lowest customer utilization voltage consistent with levels determined by regulatory agencies and standards-setting organizations [1], [2]. Considerable CVR tests were performed in the 1980s and 1990s, and achieved significant peak demand or energy reduction. More efforts have been made in the industry and academia in CVR recently, which is particularly influenced by the increasingly stringent requirements for energy saving and environmental protection as well as accommodating emerging smart monitoring and control technologies in distribution systems.

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The earliest reported CVR test was performed by American Electric Power System (AEP) in 1973 [3]. After that, many utilities such as Southern California Edison (SCE) [4], Northeast Utilities (NU) [5], Bonneville Power Administration (BPA) [6], BC Hydro [7], Northwest Energy Efficiency Alliance (NEEA) [8], Hydro Quebec (HQ) [9], and Dominion Virginia Power [10] conducted their CVR tests and obtained significant outcomes of energy savings associated with voltage reduction, usually ranging from 0.3% to 1% load reduction per 1% voltage reduction. Recent studies show that deployment of CVR on all distribution feeders of the United States could provide a 3.04% reduction in the annual national energy consumption [11]. CVR was also widely tested in other countries, such as Australia [12] and Ireland [13]. It was found that 2.5% voltage reduction resulted in 1% energy savings on residential circuits in Australia. Applying CVR to circuits in Ireland could achieve 1.7% energy reductions.

Besides the above successful experiences, there still exists skepticism on CVR performance and its potential negative effects on system reliability and power quality [14]–[16]. Moreover, in some European countries, distribution systems are operated at the upper voltage limit levels due to the lack of incentives to reduce load consumption and concerns on possible increase of system losses (which may not be true for certain types of loads as discussed in detail in the following section). However, increasing interests on CVR can be found in some European countries. For example, the Electricity North West Limited in the United Kingdom, has launched a demand response project with CVR trials on 60 substations with the purpose to manage electricity consumption through voltage reduction [17].

The technical barriers related to CVR can be summarized into three aspects: 1) coordination of different Voltage/Var devices to reduce voltage in a reliable and optimal way; 2) assessment and verification of CVR effects; 3) coordination between CVR and distributed generation (DG). Although there are many publications introducing CVR field experiences and assessing its effects, to the authors’ best knowledge, a comprehensive literature survey on CVR is widely desired. The purpose of this paper is to show the latest development of field experiences and research in performing voltage reduction, quantifying CVR effects and analyzing impacts of smart grid technologies on CVR.

The remainder of this paper is organized as follows. Section II introduces the basic concepts of CVR and investigates electrical components’ reaction to CVR. Assessment of CVR effects is reviewed and compared in Section III. Section IV discusses existing techniques to reduce voltage. Section V analyzes the impacts of DGs on CVR. Section VI recommends some directions for future work.

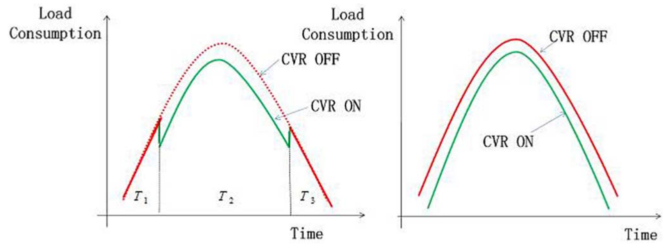


Fig. 1. (left) Peak demand reduction and (right) 24-hr energy reduction.

## II. Concepts of CVR

### A. Definition of CVR

American National Standards Institute (ANSI) Standard C84.1 [18] sets the range for voltages at the distribution transformer secondary terminals at 120 Volts ±5% or between 114 Volts and 126 Volts. CVR works on the principle that the acceptable voltage band can be easily and inexpensively operated in the lower half (114–120 Volts), without causing any harm to consumer appliances [19]. CVR effects can be evaluated by the conservation voltage regulation factor $(CVR_f)$, which is defined as follows:

$$CVR_f = \frac{\Delta E\%}{\Delta V\%} \tag{1}$$

where $\Delta E\%$ is the percentage of energy reduction and $\Delta V\%$ is the percent voltage reduction.

There are two ways to perform CVR: short-term demand reduction and long-term energy reduction, as shown in Fig. 1. The left plot of Fig. 1 shows the short-term CVR, voltage reduction is applied during peak hours $(T_2)$ to reduce peak demand. In long-term energy reduction, as shown in the right plot of Fig. 1, the voltage is reduced permanently to save energy. The peak demand and energy reduction are compared in several papers [3], [20], [21]. It is found that CVR is effective in both energy and demand saving, but the effects of reduction are different.

### B. Electrical Equipments and CVR Effects

Transformers are a critical and widely deployed electrical equipment in power systems. Applying CVR can reduce the core losses including eddy current losses and hysteresis losses of the transformer [15], [22]–[24]. As far as transmission line losses are concerned, while the line current may increase when voltage is reduced for constant-power loads, thus resulting in the increase of line losses, this is not true for constant-impedance and constant-current loads. According to studies in [15], CVR can reduce the net system losses when transformer losses are taken into account, and line losses only increase slightly (typically less than 0.1 percent). Therefore, there are obvious energy savings on the utility side of meter.

Benefits of CVR are also linked to the voltage sensitivity of the loads, i.e., the CVR factor will increase when the voltage dependence of the load changes from a constant power type to a constant impedance type. EPRI [14], [25] measured the power consumption of electric appliances by varying the service voltage so as to quantify the energy consumption of electric load components as a function of supply voltage. For open-loop loads, there is no control mechanism that would change the operation of the load to correct or compensate for the reduction of the input voltage, while this control mechanism exists in closed-loop loads. Typical open-loop loads include lighting loads (e.g., incandescent lamps, fluorescent lamps and high intensity discharge lamps) and unregulated motors (e.g., ventilation motors). Both incandescent lamps and fluorescent lamps tend to absorb less energy at a reduced supply voltage. Another beneficial side effect is that the recued temperature can increase the life of the lamp [11], [14], [23]. For high intensity discharge lamps, reduced voltage may lead to decreased life [14]. The change of energy consumption of unregulated motors with CVR depends on many factors such as motor type, size, load and speed. If a motor is operating at less than full load (which is usually the case), CVR can reduce its losses and increase efficiency [16], [23]. Typical closed-loop loads include motor drives, loads with thermal cycles (such as electric water heaters) and regulated constant power loads (such as furnaces). No energy reduction effects are found for this kind of loads [11], [14]. The study in [23] claimed that a small amount reduction of isolation transformer losses and switching losses may be found in loads with modern electronics.

### C. CVR Benefits

Consumers can benefit from the reduced energy consumption from CVR. However, the utilities may lose revenues, which is a common problem for many demand-response programs [15]. The CVR benefits for utilities can be summarized as: peak loading relief of distribution network; net loss reduction considering both the transformers and distribution lines; potential incentives and requirements from regulatory bodies (e.g., California Public Utilities Commission encouraged utilities to implement CVR, Northwest Power and Conservation Council performed extended research on CVR incentives [15]); increasing social welfare such as fuel consumption and emission reduction. Moreover, CVR can be combined with system improvements (such as adding capacitors, load and phase balancing) to achieve optimal Voltage/Var control, which is the future trend of distribution efficiency programs and discussed in Section IV.

## III. Assessment of CVR Effects

Assessing the performance of CVR on feeder circuits has always been a critical issue in deciding its implementation, selecting target feeders to apply voltage reduction and performing cost/benefit analyses. The load consumption without voltage reduction during the CVR period cannot be measured and provide a benchmark for comparison. How to quantify a credible estimated energy-saving effect is the driving force for research and implementation of CVR. Skepticism regarding the effect of CVR remains a barrier to its acceptance. The major challenge to quantify CVR effects is to distinguish the changes in load and energy consumption due to voltage reduction from other impact factors. The methodologies for assessing CVR effects can be classified into four categories: comparison-based, regression-based, synthesis-based and simulation-based. There are also papers that combine two of these methods to analyze CVR effects. This section reviews and compares the existing methodologies. The impact factors for CVR effects are also discussed.

### A. Comparison-Based Methods

There are two basic comparison methods for measuring CVR effects. The first one is to select two similar feeders in the same performance period. In other words, the two feeders have similar configurations, topologies, load conditions, load mix and are close in location. Voltage reduction is applied to one feeder (treatment group), while normal voltage is applied to the other feeder at the same time (control group). The second way is to perform a CVR test on a feeder (treatment group) and apply normal voltage to the same feeder but during another time period with similar weather conditions (control group). The CVR effects can then be calculated based on the measurements from the two tests. The problems with the basic comparison methods are that load changes due to factors other than voltage reduction, such as weather differences and measurement noises are included in the calculation, which can blur the small CVR effect.

In [26], the averages of data on test and non-test days are used for comparison to analyze CVR test results of Detroit Edison. Power consumptions of low-voltage days and high-voltage days in a season were averaged, and then the averaged data were compared to calculate the CVR factor. In [27], the CVR tests were employed on each circuit of Snohomish County Public Utility District (Snohomish PUD) on an alternating 24-h cycle of normal voltage and reduced voltage. Their tests started in the early winter when it tended to be colder. To offset the impact of temperature, they paired a test day with a colder non-test day and a warmer non-test day, respectively. Then a weighted average of the two was computed to obtain the CVR factor.

The comparison-based methodology is the most straightforward to calculate the CVR factor. However, there are some shortcomings: 1) a good control group may not exist; 2) the noises such as weather impacts are not very well considered and simple averages may not be sufficient to cancel noises; 3) after averaging the data, it is not possible to obtain the CVR factor for a particular time on a particular test day, which loses the time-dependant nature of the CVR factor.

### B. Regression-Based Methods

In regression-based methods, loads are modeled as a function of their impact factors. In [15], [16], and [28], loads are modeled as a function of temperature. Models for the normal-voltage load process are identified using linear regression, and their outputs are compared with the measured reduced-voltage load to calculate the CVR factor. The overall procedure can be summarized as follows [15]:

Step 1) Model parameters estimation

$$\mathbf{L} = \beta_0 \mathbf{1} + \beta_1 [T_{fh}\mathbf{1} - \mathbf{T}] + \beta_2 [T_{fc}\mathbf{1} - \mathbf{T}] + \boldsymbol{\varepsilon} \tag{2}$$

where $\mathbf{L}$ and $\mathbf{T}$ are training data for the model, $\mathbf{L}$ represents the vector of measured normal-voltage load data, $T_{fh}$ is the heating reference temperature, $T_{fc}$ is the cooling reference temperature (e.g., in [15], $T_{fh}$ and $T_{fc}$ are set to be 60F and 70F, respectively), $\mathbf{T}$ is the vector of recorded ambient temperature, the resolution of $\mathbf{L}$ and $\mathbf{T}$ depends on measurement devices and user preferences (e.g., the resolution is 15 min in [15]), $\beta_0$, $\beta_1$ and $\beta_2$ are parameters that need to be calculated using linear regression, $\boldsymbol{\varepsilon}$ represents the errors.

Step 2) Parameter estimation: The parameters $\beta_0$, $\beta_1$ and $\beta_2$ can be estimated by minimizing the errors. For example, if an ordinary least squares method is used, the parameters can be calculated as follows:

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{L}$$
$$\mathbf{X} = [\mathbf{1}\; T_{fh}\mathbf{1} - \mathbf{T}\; T_{fc}\mathbf{1} - \mathbf{T}] \tag{3}$$

where $\hat{\boldsymbol{\beta}} = [\hat{\beta}_0\; \hat{\beta}_1\; \hat{\beta}_2]^T$ represents the estimated parameters.

Step 3) Calculation of load consumption without CVR: With a new vector of temperature $\mathbf{T}^*$ on test days, the load consumption without CVR on those days can be calculated as follows:

$$\mathbf{L}_0^* = \hat{\beta}_0 \mathbf{1} + \hat{\beta}_1 [T_{fh}\mathbf{1} - \mathbf{T}^*] + \hat{\beta}_2 [T_{fc}\mathbf{1} - \mathbf{T}^*] \tag{4}$$

where $\mathbf{L}_0^*$ is the estimated load if CVR is not implemented.

Step 4) CVR factor calculation: With the measured load on test days with CVR on, denoted as $\mathbf{L}_1^*$, and the $\mathbf{L}_0^*$ calculated in (4) from Step 3, we can calculate the CVR factor as follows:

$$CVR_f = \frac{\Delta\mathbf{L}\%}{\Delta\mathbf{V}\%}$$
$$\Delta\mathbf{L}\% = \frac{\mathbf{L}_0^* - \mathbf{L}_1^*}{\mathbf{L}_0^*} \times 100\%. \tag{5}$$

The most established regression-based methodology is "Protocol #1 for automated CVR" [15], [16], [28].

References [20] and [21] assume a linear model for the load with a linear dependence on voltage, temperature as well as other factors. Multivariate regression is used to detect sensitivities of load to its impact factors. Such a model can be formulated using the following equation:

$$\mathbf{L} = \alpha_0 \mathbf{1} + \alpha_1 \mathbf{T} + \alpha_2 \boldsymbol{\Delta}\mathbf{V} + \boldsymbol{\varepsilon} \tag{6}$$

where $\boldsymbol{\Delta}\mathbf{V}$ represents the measured depth of voltage reduction, at the substation transformer, $\alpha_0$ is the basic load component, $\alpha_1$ is the load-to-temperature (LTT) dependence, $\alpha_2$ is the load-to-voltage (LTV) dependence, $\boldsymbol{\varepsilon}$ represents the errors. The estimated parameter $\alpha_2$ can be used to calculate the CVR factor.

The nature of the multivariate method is to identify LTV. Besides using temperature as a regression variable, load consumption of a "reference feeder" or "reference day" can also be used to formulate the multivariate model. References [7] and [8] used the multivariate model to obtain LTV and calculate the CVR factor. Markushevich *et al.* [29] improved the above LTV method. The calculated LTV was input into a power flow program to verify its accuracy.

Other impact factors can also be included in a multivariate regression model. For example, [21] analyzed the data from California Public Utilities Commission (CPUC) using a multivariate regression model including voltage, temperature, day of the week, month and other impact factors. Only the resulting coefficient for voltage change was used in calculating the CVR factor. Preiss and Warnock [3], [20] used the regression method to analyze CVR tests in AEP. They applied regression to find the LTT dependence to remove the masking effect of temperature and obtained new energy consumption data. Then, a base case was established on the non-reduction days for CVR factor calculation.

As the regression methods are based on linear regression models that decompose the load, usually into basic and weather dependent components, they are widely used to assess CVR effects because some physical interpretations may be attached to model components, allowing utilities to understand the model behavior. The regression models can also be used to forecast the CVR factors. However, since the CVR effects are usually a few percent of energy reduction, it may fall within the error bound of the regression models. It is necessary to distinguish CVR effects from the estimation errors. Moreover, the regression methods are heavily dependent on the accuracy of regression models. Models used by most papers are basically linear, but the load series they try to explain are known to be distinctly nonlinear functions of the exogenous variables. Recent developments of nonlinear regression methods such as artificial neural network (ANN) and support vector regression (SVR) provide an opportunity to approximate the nonlinear behaviors of load [30]–[33]. Impact factors of loads such as weather information and historic load can be used as inputs to train these nonlinear regression models. There are a large number of papers using ANN and SVR to forecast load, however, only a few of them applied these methods to analyze CVR effects [34]. ANN and SVR may have better estimation results of CVR effects than linear regression based methods.

### C. Synthesis-Based Methods

Synthesis-based methods aggregate LTV behaviors to estimate the CVR effects of a circuit. There are two ways to perform the aggregation: synthesis from load components and synthesis from customer classes. In the component-based synthesis, the energy consumption of major appliance loads is modeled as a function of voltage, which is identified through laboratory tests. The load shares of each appliance are obtained through surveys. The total energy consumption at the circuit level can be computed as

$$E_c(V) = \sum_i E_i(V) S_i \tag{7}$$

where $E_i(V)$ represents the energy consumption of appliance $i$ at voltage $V$, $S_i$ is the load share of appliance $i$. Energy saving effects can be estimated by applying reduced and normal voltages to (5).

Chen *et al.* [35], [36] investigated the relationship between energy consumption and voltage of major appliances and provided a preliminary overview on estimating aggregated energy consumption using assumed load compositions.

TABLE I
CVR FACTORS OF DIFFERENT CUSTOMER CLASSES

| References | Residential | Commercial | Industrial |
|---|---|---|---|
| California [40] | 0.76 | 0.99 | 0.41 |
| BPA [38] | 0.77 | 0.99 | 0.41 |
| AEP [3] | 0.61 | 0.89 | 0.35 |
| CPUC [21] | 1.14 | 0.26 | N/A |
| SCE [4] | 1.30 | 1.20 | 0.50 |
| Snohomish [27] | 0.33-0.68 | 0.89-1.10 | N/A |
| HQ [9] | 0.06-0.67 | 0.80-0.97 | 0.10 |
| NEEA [8] | 0.63 | 0.37 | N/A |
| Detroit [26] | 0.96-1.11 | 0.75-0.80 | 0.50-0.83 |

Types of customers can be classified into residential (R), commercial (C), and industrial (I). Different classes of customers have different percentages of appliance load composition. CVR effects are closely related to classes of customers on the feeder. Table I summarizes published results of CVR factors of each customer class. Although the quantitative CVR effects of each customer type may vary, there is a basic conclusion that, compared with industrial loads, reducing voltage could reduce more energy consumption for composite residential and commercial customers since they have larger voltage sensitivities [37]. The circuit-level CVR factor can be estimated as a linear combination of CVR factors and load shares of each customer class:

$$CVR = RCVR_R + CCVR_C + ICVR_I \tag{8}$$

where $R$, $C$, and $I$ represent the load share of residential, commercial, and industrial customers, respectively. $CVR_R, CVR_c$, and $CVR_I$ represent the CVR factor of residential, commercial, and industrial customers, respectively.

Kirshner [1] and Steese [38], [39] applied both of the two synthesis methods to quantify CVR effects at BPA. They found that the first method, in which energy savings were synthesized from equipment-level performance, produced estimates that were 35% lower than those from the customer-class level of the second method. Reference [2] found the following formula could be used to estimate CVR effects:

$$CVR_f = 0.7 + 0.5 \times N_{RSC} \tag{9}$$

where $N_{RSC}$ is a percentage of residential and small business customers on a feeder. Thus, $CVR_f$ varies between 0.7% and 1.2% as $N_{RSC}$ varies between 0 and 1.

Synthesis-based methods can be used to obtain a quick estimation of CVR effects before its implementation. The basic assumptions of synthesis methods are that all of the appliances behave as they did during the lab test and the load composition information is correct. However, it is difficult to collect accurate load share information as well as the LTV response of every existing electric appliance. Thus, the results obtained from synthesis methods should be used with caution.

### D. Simulation-Based Methods

Simulation methods are based on system modeling and power flow calculation. This method simulates what the load consumption would be if there is no CVR. Fig. 2 shows the flowchart of

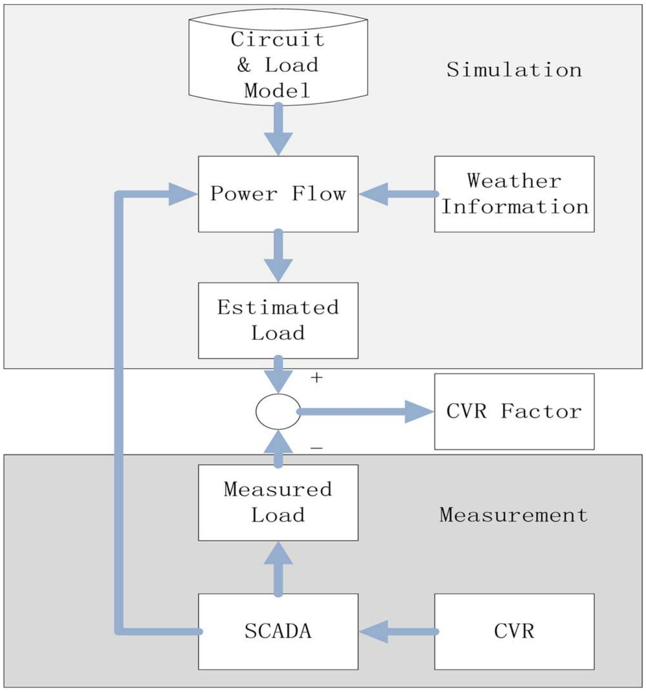


Fig. 2. Simulation based methods.

this method. Load can be modeled as a function of voltage, time and weather factors. Power flow is run based on measured operation data and weather information. The difference between power-flow results and measured load consumption is used to calculate the CVR factor. The circuits that have detailed models can be of high precision. The challenge is how to model the load which contributes to the major energy saving effect. Traditional load models such as exponential and ZIP models can be used to represent open-loop appliances. For closed-loop loads such as heating, ventilation, and air conditioning (HVAC) systems, the equivalent thermal parameter (ETP) model should be used. In ETP, the power demand of the HVAC system is modeled as a function of solar input, temperature, humidity, voltage and thermostatic set points [41], [42].

Chen *et al.* [36], [43] proposed a load flow program to estimate CVR effects of a Taipower feeder. Their program requires two kinds of information: the power consumption as functions of voltage and temperature for major electric appliances [35], [44]; load composition describing the percentage of power consumption by each type of appliances during a certain time interval. Markushevich *et al.* [29] used the power flow program to verify the LTV calculated from a regression-based method. EPRI [45] modeled the load as an exponential function of voltage and attempted to replicate the operation of the CVR system under the test days and non-test days to analyze CVR effects. Schneider *et al.* [46] incorporated the ETP model to represent loads with closed-loop controls into an open-source simulation software to analyze CVR effects.

It can be seen that the simulation methods have high precision if the models can accurately represent the load behaviors. However, the current simulation methods are component-based while it may be too difficult to build models for all existing and emerging load components. A better method is to identify the aggregated load models at the circuit level. Moreover, it is clear that CVR effects change with time, but the current load models are all time-invariant, which may impact the estimation results of the CVR factor. Thus, it is necessary to make the model adaptive to dynamic changes of feeders and load behaviors.

TABLE II
CVR FACTORS OF DIFFERENT SEASONS

| References | Type | Spring | Summer | Fall | Winter |
|---|---|---|---|---|---|
| AEP [20] | R | 0.79 | 0.79 | 0.45 | 0.87 |
| | C | 0.91 | 1.01 | 0.64 | 0.82 |
| | I | 0.89 | 0.83 | 0.33 | 0.53 |
| NEEA [15] | M | 0.57 | 0.78 | 0.60 | 0.51 |
| HQ [9] | R | N/A | 0.67 | N/A | 0.12 |
| | C | N/A | 0.97 | N/A | 0.80 |
| | I | N/A | 0.10 | N/A | 0.10 |
| BC Hydro [7] | M | 0.60 | 0.77 | N/A | N/A |

### E. Seasons and CVR Factor

Seasonal variations of CVR factors are due to different weather and human behaviors in various seasons. Table II summarizes published CVR factor results by season. There are four types of feeders: residential (R), commercial (C), industrial (I) and mixed (M). CVR effects change from season to season as the load compositions of appliances vary. For test results from NEEA [15] and HQ [9], it can be seen from the table that CVR factors in summer are relatively higher and those in winter are lower. Reference [15] provides a possible reason for this phenomenon: it may be due to the large portion of electric motor loads, such as air conditioners in summer. As heating loads with thermal cycles come to dominate the load composition in winter, CVR effects are expected to decrease, since this kind of loads reacts to voltage reduction with a longer operation time. CVR factors in spring and fall are between the other two seasons. However, the results from AEP [20] show that CVR factors in fall could be smaller, while those of the other three seasons are similar. More tests are still necessary to make a conclusion on the relationship between CVR factors and seasons.

Table III summarizes the existing assessment methodologies. In fact, there are two basic ideas. The first one is to determine what the load consumption would be if CVR was not applied. The comparison methods based on the single-variate regression model in Section III-B and simulation-based methods all belong to this category. The second idea is to detect LTV sensitivities. The multivariate regression method in [20] and [21] is a representative of this idea. Since it is impossible to know the load consumption under normal voltage during the CVR period, lack of validity becomes the common roadblock for all assessment methodologies. The comparison-based methods are not very popular due to the lack of accuracy. The synthesis-based methods require load-share information which is difficult to be obtained. The regression-based methods are widely used in assessing CVR effects. Simulation methods have the potential to be used for validation, if the load behaviors could be accurately modeled. Some of the four methods can be combined in certain cases, e.g., simulation-based methods can be used to validate regression-based methods. If there is no benchmark for comparison, the reported CVR effects cannot be well accepted. Using

TABLE III
ASSESSMENT METHODOLOGIES

| References | EST | Attributes | CVRf |
|---|---|---|---|
| Snohomish [19] | CO | (+) easy and straightforward, (-) dependent on control group, (-) noise vulnerable | 0.50 |
| NU [5] | CO | | 1.00 |
| AEP [3] | RE | (+) clear physical meaning, (+) capable of forecasting CVR effects, (-) regression error, (-) load model is linear | 0.62 |
| California [40] | RE | | 1.00 |
| NEEA [8] | RE | | 0.61 |
| Avista [47] | RE | | 0.84 |
| BC Hydro [7] | RE | | 0.70 |
| SCE [4] | RE | | 1.00 |
| BPA [38] | SY | (+) quick estimation and forecast of CVR effect, (-) accurate load information is difficult to collect | 0.99 |
| Australia [12] | SY | | 0.40 |
| EPRI [45] | SI | (+) maybe highly accurate, (-) precise load modeling is difficult, (-) load model is time-invariant | 0.70 |
| Taipower [43] | SI | | 0.57 |

**EST**: assessment methodology, **RE**: regression based, **CO**: comparison based, **SY**: synthesis based, **SI**: simulation based, $(+)$ means positive attributes, $(-)$ means negative attributes.

LTV for assessing CVR effects is another attractive method, since it can reflect the nature of CVR. More sophisticated identification algorithms are needed to filter out noises and detect LTV.

## IV. IMPLEMENTATION STRATEGIES OF CVR

The early techniques to reduce voltage are open-loop without voltage feedback, such as load tap changer (LTC), line drop compensation (LDC), voltage spread reduction (VSR) [48], capacitor-based reduction and home voltage reduction (HVR). The installation of SCADA and advanced metering infrastructure (AMI) has led many utilities to implement closed-loop Voltage/Var control (VVC), such as SCADA-based VVC and AMI-based VVC. CVR becomes an operation mode in these close-loop VVCs, while many other control objectives such as loss reduction, power factor improvement and voltage deviation minimization are also included. For example, "AdaptiVolt" is a typical closed-loop VVC product with a CVR function [49].

### A. LTC, LDC, and Capacitor

LTC/LDC is the most used method to implement voltage reduction. LTC is typically used to control the secondary voltage of a substation and almost available in all substations, which means there is no additional cost for system improvement. However, to apply voltage reduction merely by LTC, the circuits should be carefully selected. For a feeder with large voltage drops, the depth of voltage reduction may be limited. LDC can lower the average voltage by 2% to 3% [50]. LDC involves setting the controls on substation voltage regulators or LTC to keep the most distant portion of the circuit at some minimum acceptable voltage levels, such as 114 volts, while the rest of the circuit voltage is allowed to vary with load conditions. Although LDC is an easy way to control voltage, it has some drawbacks. Settings of LDC are difficult to determine and cannot adapt to the dynamic nature of distribution loads and changes of network configurations. As most utilities include some safety margin to ensure that the voltage levels remain above the minimum requirements, the voltage reduction potential is relatively small, which will decrease CVR effects.

Capacitors can provide Var compensations for CVR. Switched capacitors can be coordinated with voltage control methods to conduct VVC to implement CVR. For a feeder with a certain CVR factor, deeper voltage reduction within the permissible range can lead to more energy-savings. The depth of voltage reduction is limited for circuits that experience a significant voltage drop. A relatively flat voltage profile along the feeder is preferable to achieve an effective implementation of CVR. By placing capacitors at multiple locations, it is possible to flatten the voltage profile, correct the power factor to near unity, and reduce power losses. Capacitor placement has been extensively researched [51]. However, few papers discuss the placement of capacitors for CVR. Reference [52] proposed optimal capacitor placement for CVR. A multi-objective optimization problem was formulated as (10). One genetic algorithm was applied to solve the following problem:

$$\begin{aligned} F &= Min(f_{pload}, f_{Ploss}, f_c) \\ s.t.\ &\mathbf{G}(\mathbf{x}) = \mathbf{0} \\ &\mathbf{H}(\mathbf{x}) \leq \mathbf{0} \end{aligned} \tag{10}$$

where $f_{Pload}$ represents active power consumed by loads while load is modeled as an exponential function of voltage, $f_{Ploss}$ represents active power losses on the feeder, $f_c$ represents capacitor investment, $\mathbf{x}$ represents the vector of system state variables, $\mathbf{G}(\mathbf{x})$ represents the equality constraints such as power flow, $\mathbf{H}(\mathbf{x})$ represents the inequality constraints such as allowable ranges of bus voltages.

Reference [53] proposed a two-step Voltage/Var optimization algorithm for CVR. The first step is to schedule capacitor bank commitment to correct power factor and flatten the voltage profile, the second step is to change LTC tap ratio to achieve voltage reduction. Georgia Power Company (GPC) [54], Oneida-Madison Electric Cooperative (OMEC) [55] and Snohomish PUD [19] combined LDC and capacitors to implement CVR.

For feeders without LTC or voltage regulators, capacitor banks can be used to reduce voltage directly, which can provide 1% feeder voltage reduction [56]. SCE [4] implemented a closed-loop capacitor optimal control system and achieved a 3.8% reduction. However, this method requires a large number of voltage sensors and switched capacitors, which limits its application.

The voltage can also be regulated at customer meters, which is called HVR [28]. In HVR, a device is installed at the customer meter and used to regulate the voltage at the lower level within the customer premises. NEEA [15] installed HVR devices in 395 homes in its service area, and the voltage reduction was 3.5% to 5.2%. A drawback of HVR is that it depends on the customers to install equipment on their sites and to pay the capital costs. Additionally, it does not have the benefit of less distribution system losses. Hence, HVR is not widely implemented.

In general, open-loop voltage reduction is a convenient and cost-effective way to implement CVR. However, there are three major drawbacks of open-loop voltage reduction: 1) the depth of voltage reduction is limited; 2) as control of all devices is based on local data and disjointed from one another, it is not optimized, or at least not systematically optimal; 3) it cannot adapt to dynamic changes of distribution networks.

### *B. Closed-Loop Voltage/Var Control (Close-Loop VVC)*

The SCADA-based or AMI-based close-loop VVC can be run in CVR mode. The closed-loop VVC takes advantage of various measurements to determine the best Voltage/Var control actions during certain time periods [57]. VVC is studied in many papers and some of them discuss optimal algorithms for CVR implementation. Roytelman *et al.* [58] proposed a centralized VVC algorithm for accomplishing energy saving in distribution systems. The algorithm was based on the oriented discrete coordinate decent method. The objective functions such as minimum power losses, power demand and number of control steps were taken into account. Souza and Almeida [59] used GA to solve a multi-objective volt/var optimization problem to minimize power losses and voltage drops along the feeder.

There are several utilities implementing closed-loop VVC in their distribution systems and operating them in the CVR mode. Inland Power and Clatskanie PUD [47], [60] implemented a SCADA-based closed-loop VVC system to achieve a 3% voltage reduction. The emerging of AMI extends the measurements and system models to every customer [61]. As a new technology, AMI-based VVC is used by some utilities and runs in the voltage reduction mode, such as Dominion Virginia Power [10], SCE [62] and Duke energy [63]. It was found that AMI could improve the overall distribution operation, enable more precise voltage optimization and provide additional room for voltage reduction, thereby improve the energy-savings of CVR without AMI by approximately 40% [64].

Compared with LTC and LDC, the advantages of closed-loop VVC are clear: systematically optimal voltage reduction, greater energy-saving effect and adaptive to dynamic system changes. The only shortcoming may be its complexity and high cost. Table IV summarizes voltage reduction techniques. The selection of suitable methods depends on the existing infrastructure of the targeted system, availability of equipment and budget.

TABLE IV
VOLTAGE REDUCTION TECHNIQUES

| References | VR | Attributes | VD |
|---|---|---|---|
| California [40] | LT | (+) easy and economical, (-) small volt reduction, (-) no volt feedback, may result in low volt | 2.5% |
| NEEA [8] | LD | (+) end-of-line voltage is controlled, (+) larger volt reduction than LT, (-) complicated settings, (-) no volt feedback, (-) cannot adapt to dynamic changes | 2-3.9% |
| Australia [12] | LD | | 3% |
| CPUC [21] | LD | | 2.5% |
| Duke [63] | LD | | 2% |
| Snohomish [19] | LD,CA | (+) end-of-line voltage is controlled, (+) larger volt reduction than LD, (+) less power losses, flattened volt profile and improved power factor (-) capacitor placement is complicated, (-) no volt feedback, (-) lack of coordination between LD and CA, (-) cannot adapt to dynamic changes, (-) high cost | 2.1% |
| BPA [38] | LD,CA | | 4.6% |
| NU [5] | LD,CA | | 3% |
| GPC [54] | LD,CA | | 4.1% |
| BC Hydro [7] | VVO | (+) larger volt reduction, (+) more reliable with volt feedback, (+) adaptive to dynamic changes, (-) complicated and high cost | 3% |
| Avista [47] | VVO | | 2.3% |
| Dominion [10] | VVO | | 4% |

**VR**: voltage reduction methodology, **VD**: percentage of voltage reduction, **LT**: LTC, **LD**: LDC, **CA**: capacitor, **VVO**: closed-loop VVC. (+) means positive attributes, (-) means negative attributes.

## V. DISTRIBUTED GENERATION AND CVR

Integrating DG into distribution networks is a major trend in a Smart Grid. Impacts of DG integration on distribution systems are well analyzed, however, there are few papers discussing the relationship between DG and CVR. For impacts of CVR on DG, it was found that PV systems would not be adversely influenced by CVR, since power inverters can be set to generate constant power [56]. The output of DG such as PV and wind power depends on weather, and cannot be anticipated accurately. The integration of DG makes the voltage profile along the feeder change more quickly, thus, may interfere with the control scheme and performance of CVR. Singh [65] discussed the impacts of adding PV to a feeder on CVR effects using simulations. In their test, the CVR factor was insignificant with a high PV penetration, which was attributed to the failure of the voltage control strategy to keep the voltage levels within the desired range. Markushevich and Berman [66] applied simulations to find that LTV of a feeder with a high penetration of DG would vary a lot from time to time due to the stochastic nature of DG outputs.

There are two major research topics on the relationship between DG and CVR: 1) sizing and placement of DG for loss reduction and voltage profile improvement; 2) the coordination between controls of DG and VVC to further optimize CVR effects. A number of objectives can be associated with sizing and placement of DGs, among which, to minimize voltage deviation along the feeder and to minimize power losses are closely related to CVR. References [67] and [68] applied a harmony search algorithm [69] and sensitivity analysis to achieve optimal DG placement with the objective to minimize power losses and voltage deviation. It should be noted that only a few papers considered the stochastic nature of DG output when solving the DG placement problem [70].

The inconsistent output of DG does have impacts on VVC. Traditional VVC is designed for slow and gradual changes of loads on a distribution feeder due to the slow reaction of capacitors and LTC [71], [72]. The random and rapid change of DG output requires a faster controller, such as an inverter [71]–[73]. The coordination of traditional VVC and inverters is a new challenge when CVR is applied to a feeder with a high penetration of DG. Reference [73] proposed a two-timescale optimal control algorithm for loss and load reduction. Slow time-scale control is designed for VVC, while the fast one is designed for inverters. In order to deal with the stochastic output of DG, a stochastic multi-objective framework was presented in [74]. Scenario-based methods and evolutionary algorithms were used to minimize voltage deviation and energy loss.

## VI. Future Work

With the advent of smart-grid technologies, CVR is a convenient and cost-effective way to save energy. As CVR is initiated by utilities, it is different from price-driven demand response programs which depend on the sensitivity of customers' energy consumption to electricity prices and their choices to turn off some electrical equipments during high-price periods. Although CVR is an established idea, a lot of work is still needed to analyze and improve its performance.

The regression-based methodologies are the most established and popular ways to assess CVR effects. More sophisticated regression models are needed to improve the estimation accuracy. ANN and SVR might be used to analyze CVR effects considering the complex relationship between loads and the impact factors. Simulation methods have the potential to accurately quantify CVR outcomes, if the system and load models can be more precise and adaptive to dynamic changes. The idea to use LTV to estimate CVR effects is relatively new and can reveal the nature of CVR. How to accurately identify LTV is a topic that needs to be studied. Another major advantage of the LTV method is that the CVR effects of any test time can be estimated, if LTV is calculated using recursive algorithms.

Open-loop voltage reduction is still the dominant technique to implement CVR. Closed-loop VVC incorporating the dynamic information on distribution network configuration from Geographical Information Systems (GIS), detailed real-time measurements from AMI, advanced optimal power flow algorithms and CVR operation mode is the trend of VVC in the future. It is necessary to study how to use a large amount of system information from smart meters to coordinate voltage and reactive power control to realize real-time system-wide optimal operation.

The impact of DG penetration on CVR is an emerging research topic. How to improve VVC schemes to maintain a desired voltage profile along the feeder with DG needs to be studied. How to coordinate VVC and controls of DG to further optimize CVR operations becomes a new research area. Considering the uncertainty of DG output, stochastic optimization may be applied.

## Appendix

### List of Acronyms

| | |
|---|---|
| AMI | Advanced metering infrastructure. |
| ANN | Artificial neural network. |
| CVR | Conservation voltage reduction. |
| CVRf | CVR factor. |
| DG | Distributed generator. |
| ETP | Equivalent thermal parameter. |
| GA | Genetic algorithm. |
| HVAC | Heating, ventilation, and air conditioning. |
| LDC | Line drop compensation. |
| LTC | Load tap changer. |
| LTT | Load-to-temperature dependence. |
| LTV | Load-to-voltage dependence. |
| SVR | Support vector regression. |
| VSR | Voltage spread reduction. |
| VVC | Voltage/Var control. |
| VVO | Voltage/Var optimization. |

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## References

[1] D. Kirshner, "Implementation of conservation voltage reduction at Commonwealth Edison," *IEEE Trans. Power Syst.*, vol. 5, pp. 1178–1182, 1990.
[2] M. Begovic, D. Novosel, B. Milosevic, and M. Kostic, "Impact of distribution efficiency on generation and voltage stability," in *Proc. 33rd Annual Hawaii Int. Conf. System Sciences, 2000*, 2000, p. 7 pp.
[3] R. Preiss and V. Warnock, "Impact of voltage reduction on energy and demand," *IEEE Trans. Power App. Syst.*, pp. 1665–1671, 1978.
[4] B. Williams, "Distribution capacitor automation provides integrated control of customer voltage levels and distribution reactive power flow," in *Proc. IEEE Power Industry Computer Application Conf., 1995*, 1995, pp. 215–220.
[5] D. Lauria, "Conservation voltage reduction (CVR) at Northeast utilities," *IEEE Trans. Power Del.*, vol. 2, pp. 1186–1191, 1987.
[6] J. De Steese, Assessment of Conservation Voltage Reduction Applicable in the BPA Service Region, 1987.
[7] A. Dwyer, R. E. Nielsen, J. Stangl, and N. S. Markushevich, "Load to voltage dependency tests at BC hydro," *IEEE Trans. Power Syst.*, vol. 10, pp. 709–715, 1995.
[8] T. A. Short and R. W. Mee, "Voltage reduction field trials on distributions circuits," in *Proc. 2012 IEEE PES Transmission and Distribution Conf. Expo. (T&D)*, 2012, pp. 1–6.
[9] S. Lefebvre, G. Gaba, A.-O. Ba, and D. Asber, "Measuring the efficiency of voltage reduction at Hydro-Québec distribution," in *Proc. 2008 IEEE Power and Energy Society General Meeting—Conversion and Delivery of Electrical Energy in the 21st Century*, 2008, pp. 1–7.
[10] M. A. Peskin, P. W. Powell, and E. J. Hall, "Conservation voltage reduction with feedback from advanced metering infrastructure," in *Proc. 2012 IEEE PES Transmission and Distribution Conf. Expo. (T&D)*, 2012, pp. 1–8.
[11] J. F. K. Schneider, F. Tuffner, and R. Singh, 2010, Evaluation of Conservation Voltage Reduction (CVR) on a National Level. [Online]. Available: http://www.pnl.gov/main/publications/external/technical_reports/PNNL-19596.pdf.
[12] W. Ellens, A. Berry, and S. West, "A quantification of the energy savings by conservation voltage reduction," in *Proc. 2012 IEEE Int. Conf. Power System Technology (POWERCON)*, 2012, pp. 1–6.
[13] E. Diskin, T. Fallon, G. O'mahony, and C. Power, "Conservation voltage reduction and voltage optimisation on Irish distribution networks," in *Proc. CIRED 2012 Workshop Integration of Renewables into the Distribution Grid*, 2012, pp. 1–4.
[14] EPRI, 2001, PQ Commentary. [Online]. Available: http://www.smartgridnews.com/artman/uploads/1/sgnr_2007_1208.pdf.
[15] R. W. Beck, Distribution Efficiency Initiative Final Report, 2007. [Online]. Available: http://neea.org/docs/default-source/rfp's/long-term-monitoring-and-tracking-distribution-efficiency.pdf?sfvrsn=4.
[16] T. L. Wilson, "Measurement and verification of distribution voltage optimization results," in *Proc. 2010 IEEE Power and Energy Society General Meeting*, 2010, pp. 1–9.
[17] E. N. W. Limited, 2012, Customer Load Active System Services (CLASS). [Online]. Available: http://www.enwl.co.uk/class.
[18] ANSI, "ANSI Standard C84.1-1995 Electric Power Systems and Equipment Voltage Ratings (60 Hz)," 1995.
[19] B. Kennedy and R. Fletcher, "Conservation voltage reduction (CVR) at Snohomish county PUD," *IEEE Trans. Power Syst.*, vol. 6, pp. 986–998, 1991.
[20] V. Warnock and T. Kirkpatrick, "Impact of voltage reduction on energy and demand: Phase II," *IEEE Trans. Power Syst.*, vol. 1, pp. 92–95, 1986.

[21] J. Erickson and S. Gilligan, "The effects of voltage reduction on distribution circuit loads," *IEEE Trans. Power App. Syst.*, pp. 2014–2018, 1982.

[22] R. J. Smith and R. C. Dorf, Circuits, Devices and Systems, 2009. [Online]. Available: http://www.wiley.com.

[23] T. Wilson, 2003, AdaptiVolta Based CVR in Industrial Applications Technical Synopsis. [Online]. Available: http://utilidata.com/assets/docs/white_papers/UtiliData_Technical_Synopsis_Industry_.pdf.

[24] C. Concordia and S. Ihara, "Load representation in power system stability studies," *IEEE Trans. Power App. Syst.*, pp. 969–977, 1982.

[25] M. Chen, R. Shoults, and J. Fitzer, "Effects of reduced voltage on the operation and efficiency of electric loads," in *EPRI, Arlington: University of Texas, EL-2036 Volumes*, 1981, vol. 1, p. 1419-1.

[26] T. J. Krupa and H. Asgeirsson, "The effects of reduced voltage on distribution circuit loads," *IEEE Trans. Power Syst.*, vol. 2, pp. 1013–1018, 1987.

[27] B. Kennedy and R. Fletcher, "Conservation voltage reduction (CVR) at Snohomish county PUD," in *Proc. IEEE/PES 1991 Winter Meeting*, New York, NY, USA, 1991.

[28] K. Fagen and C. Bernier, "Efficiencies in distribution design and operating practices mid-study analysis (February 2007)," in *Proc. 2007 IEEE Rural Electric Power Conf.*, 2007, p. B6-B6-14.

[29] N. Markushevich, A. Berman, and R. Nielsen, "Methodologies for assessment of actual field results of distribution voltage and var optimization," in *Proc. 2012 IEEE PES Transmission and Distribution Conf. Expo. (T&D)*, 2012, pp. 1–5.

[30] B.-J. Chen and M.-W. Chang, "Load forecasting using support vector machines: A study on EUNITE competition 2001," *IEEE Trans. Power Syst.*, vol. 19, pp. 1821–1830, 2004.

[31] S. Fan and L. Chen, "Short-term load forecasting based on an adaptive hybrid method," *IEEE Trans. Power Syst.*, vol. 21, pp. 392–401, 2006.

[32] H. S. Hippert, C. E. Pedreira, and R. C. Souza, "Neural networks for short-term load forecasting: A review and evaluation," *IEEE Trans. Power Syst.*, vol. 16, pp. 44–55, 2001.

[33] D. C. Park, M. El-Sharkawi, R. Marks, L. Atlas, and M. Damborg, "Electric load forecasting using an artificial neural network," *IEEE Trans. Power Syst.*, vol. 6, pp. 442–449, 1991.

[34] Z. Wang, M. Begovic, and J. Wang, "Analysis of conservation voltage reduction effects based on multistage SVR and stochastic process," *IEEE Trans. Smart Grid*, to be published.

[35] M. Chen, R. Shoults, J. Fitzer, and H. Songster, "The effects of reduced voltages on the efficiency of electric loads," *IEEE Trans. Power App. Syst.*, pp. 2158–2166, 1982.

[36] C. S. Chen, "The effect of voltage control to the efficiency and operation of electric distribution system," Ph.D. dissertation, Univ. Texas at Arlington, Arlington, TX, USA, 1984.

[37] W. Price, S. Casper, C. Nwankpa, R. Bradish, H. Chiang, and C. Concordia *et al.*, "Bibliography on load models for power flow and dynamic performance simulation," *IEEE Power Eng. Rev.*, vol. 15, p. 70, 1995.

[38] J. De Steese, S. Merrick, and B. Kennedy, "Estimating methodology for a large regional application of conservation voltage reduction," *IEEE Trans. Power Syst.*, vol. 5, pp. 862–870, 1990.

[39] J. G. De Steese, J. E. Englin, and R. D. Sands, "Conservation voltage reduction potential in the Pacific Northwest," in *Proc. Proc. 25th Intersociety Energy Conversion Engineering Conf., 1990 (IECEC-90)*, 1990, pp. 43–47.

[40] D. Kirschner, "Implementation of conservation voltage reduction at Commonwealth Edison," in *Proc. IEEE PES 1990 Winter Meeting*, Atlanta, GA, USA, 1990.

[41] R. C. Sonderegger, "Dynamic models of house heating based on equivalent thermal parameters," Ph.D. dissertation, Center for Environmental Studies, Princeton Univ., Princeton, NJ, USA, 1978.

[42] K. P. Schneider, J. C. Fuller, and D. P. Chassin, "Multi-state load models for distribution system analysis," *IEEE Trans. Power Syst.*, vol. 26, pp. 2425–2433, 2011.

[43] C.-S. Chen, T.-H. Wu, C.-C. Lee, and Y.-M. Tzeng, "The application of load models of electric appliances to distribution system analysis," *IEEE Trans. Power Syst.*, vol. 10, pp. 1376–1382, 1995.

[44] C. Alvarez, R. P. Malhame, and A. Gabaldón, "A class of models for load management application and evaluation revisited," *IEEE Trans. Power Syst.*, vol. 7, pp. 1435–1443, 1992.

[45] W. Sunderman, "Conservation voltage reduction system modeling, measurement, and verification," in *Proc. 2012 IEEE PES Transmission and Distribution Conf. Expo. (T&D)*, 2012, pp. 1–4.

[46] K. P. Schneider, J. C. Fuller, and D. Chassin, "Evaluating conservation voltage reduction: An application of GridLAB-D: An open source software package," in *Proc. 2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 1–6.

[47] L. Global Energy Partners, 2005, Distribution Efficiency Initiative. [Online]. Available: http://www.smartgridnews.com/artman/uploads/1/sgnr_2007_08011.pdf.

[48] T. Wilson, "Energy conservation with voltage reduction-fact or fantasy," in *Proc. 2002 IEEE Rural Electric Power Conf., 2002*, 2002, p. C3-C3_6.

[49] T. Wilson, K. Benson, D. Bell, P. E. E. P. Engineer, P. UtiliData, and P. C. Timber *et al.*, "Saving megawatts with voltage optimization," in *Proc. 32nd Industrial Energy Technology Conf.*, New Orleans, LA, USA, 2010.

[50] R. H. Fletcher and A. Saeed *et al.*, "Integrating engineering and economic analysis for conservation voltage reduction," in *Proc. 2002 IEEE Power Engineering Society Summer Meeting*, 2002, pp. 725–730.

[51] L. Du, L. He, and R. G. Harley, "A survey of methods for placing shunt capacitor banks in power network with harmonic distortion," in *Proc. IECON 2012—38th Annual Conf. IEEE Industrial Electronics Society*, 2012, pp. 1198–1203.

[52] B. Milosevic and M. Begovic, "Capacitor placement for conservative voltage reduction on distribution feeders," *IEEE Trans. Power Del.*, vol. 19, pp. 1360–1367, 2004.

[53] M. J. Krok and S. Gene, "A coordinated optimization approach to Volt/VAr control for large power distribution networks," in *Proc. Amer. Control Conf. (ACC), 2011*, 2011, pp. 1145–1150.

[54] C. McCarthy and J. Josken, "Applying capacitors to maximize benefits of conservation voltage reduction," in *Proc. Rural Electric Power Conf., 2003*, 2003, pp. C4-1–C4-5.

[55] J. Triplett and S. Kufel, "Implementing CVR through voltage regulator LDC settings," in *Proc. 2012 IEEE Rural Electric Power Conf. (REPC)*, 2012, pp. B2-1–B2-5.

[56] K. Fagen, "Distribution efficiency voltage optimization supports lowest cost new resource," in *Proc. 2010 IEEE Power and Energy Society General Meeting*, 2010, pp. 1–6.

[57] R. Uluski, "VVC in the smart grid era," in *Proc. 2010 IEEE Power and Energy Society General Meeting*, 2010, pp. 1–7.

[58] I. Roytelman, B. Wee, and R. Lugtu, "Volt/Var control algorithm for modern distribution management system," *IEEE Trans. Power Syst.*, vol. 10, pp. 1454–1460, 1995.

[59] B. A. de Souza and A. M. F. de Almeida, "Multiobjective optimization and fuzzy logic applied to planning of the volt/var problem in distributions systems," *IEEE Trans. Power Syst.*, vol. 25, pp. 1274–1281, 2010.

[60] T. Wilson and D. Bell, "Energy conservation and demand control using distribution automation technologies," in *Proc. Rural Electric Power Conf., 2004*, 2004, p. C4-1-12.

[61] R. C. Dugan and M. McGranaghan, "Sim city," *IEEE Power and Energy Mag.*, vol. 9, pp. 74–81, 2011.

[62] R. Neal, "The use of AMI meters and solar PV inverters in an advanced Volt/VAr control system on a distribution circuit," in *Proc. 2010 IEEE PES Transmission and Distribution Conf. Expo.*, 2010, pp. 1–4.

[63] R. Belvin and T. Short, "Voltage reduction results on a 24-kV circuit," in *Proc. 2012 IEEE PES Transmission and Distribution Conf. Expo. (T&D)*, 2012, pp. 1–4.

[64] V. Dabic, C. Siew, J. Peralta, and D. Acebedo, "BC Hydro's experience on Voltage VAR Optimization in distribution system," in *Proc. 2010 IEEE PES Transmission and Distribution Conf. Expo.*, 2010, pp. 1–7.

[65] R. Singh, F. Tuffner, J. Fuller, and K. Schneider, "Effects of distributed energy resources on conservation voltage reduction (CVR)," in *Proc. 2011 IEEE Power and Energy Society General Meeting*, 2011, pp. 1–7.

[66] N. Markushevich and A. Berman, "New aspects of IVVO in active distribution networks," in *Proc. 2012 IEEE PES Transmission and Distribution Conf. Expo. (T&D)*, 2012, pp. 1–5.

[67] K. Nekooei, M. M. Farsangi, H. Nezamabadi-pour, and K. Y. Lee, "An improved multi-objective harmony search for optimal placement of DGs in distribution systems," *IEEE Trans. Smart Grid*, vol. 4, pp. 557–567, 2013.

[68] H. Hedayati, S. Nabaviniaki, and A. Akbarimajd, "A method for placement of DG units in distribution networks," *IEEE Trans. Power Del.*, vol. 23, pp. 1620–1628, 2008.

[69] Z. W. Geem, J. H. Kim, and G. Loganathan, "A new heuristic optimization algorithm: Harmony search," *Simulation*, vol. 76, pp. 60–68, 2001.

[70] R. S. Al Abri, E. F. El-Saadany, and Y. M. Atwa, "Optimal placement and sizing method to improve the voltage stability margin in a distribution system using distributed generation," *IEEE Trans. Power Syst.*, vol. 28, pp. 326–334, 2013.

[71] H.-G. Yeh, D. F. Gayme, and S. H. Low, "Adaptive VAR control for distribution circuits with photovoltaic generators," *IEEE Trans. Power Syst.*, vol. 27, pp. 1656–1663, 2012.

[72] J. M. Carrasco, L. G. Franquelo, J. T. Bialasiewicz, E. Galván, R. P. Guisado, and M. A. Prats *et al.*, "Power-electronic systems for the grid integration of renewable energy sources: A survey," *IEEE Trans. Ind. Electron.*, vol. 53, pp. 1002–1016, 2006.

[73] M. Farivar, C. R. Clarke, S. H. Low, and K. M. Chandy, "Inverter VAR control for distribution systems with renewables," in *Proc. 2011 IEEE Int. Conf. Smart Grid Communications (SmartGridComm)*, 2011, pp. 457–462.

[74] T. Niknam, M. Zare, and J. Aghaei, "Scenario-based multiobjective Volt/Var control in distribution networks including renewable energy sources," *IEEE Trans. Power Del.*, vol. 27, pp. 2004–2019, 2012.

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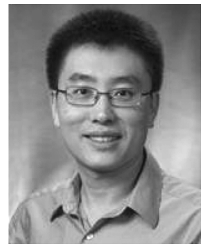

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