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Investigating the Practical Bounds of the CVR Factor

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SUMMARY

The distribution grid monitoring and control has been significantly enhanced over the past decade, primarily due to the smart grid efforts led by electric utilities and modern measurement technologies such as advanced metering infrastructure and phasor measurement units. These enhanced capabilities have further enabled multiple practices, most notably conservation voltage reduction (CVR) and volt-var optimization (VVO). However, the measurement and verification of CVR/VVO effects is a highly challenging task, fuelled by a lack of standard practices and the wide variety of approaches used to tackle this problem. Moreover, there is no benchmark to determine whether the CVR impact studies offer valid results. This paper attempts to show an approach on identifying a practical range, i.e., lower and upper bounds, for CVR factors calculated in a CVR-enabled distribution grid. The studies are conducted based on underlying CVR factor calculation mathematical models benefiting from ZIP load models. The studies using practical ZIP coefficients further provide the sought-after bounds.

KEYWORDS

Conservation voltage reduction, energy efficiency, ZIP load model

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1. 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. It is done by reducing the voltage and operating the grid in the lower half, i.e., 114–120 Volts based on ANSI standard, as many customer appliances draw less energy at lower voltages [1]. This results in energy savings without adversely impacting consumer appliances. CVR is an effective way to improve system energy efficiency and provide benefits to customers without the need for costly investments. Studies have shown that widespread implementation of CVR/VVO can lead to up to 4% energy savings in the U.S. [2].

An ongoing technical challenge in CVR application is the verification of its effects. CVR factor (CVRf) is a widely accepted metric to quantify the impacts of CVR, defined as the ratio between the percentage change in energy and the associated percentage change in voltage [3]. However, it is a challenge to provide a reasonable estimation of CVRf. This stems from a lack of benchmark load consumption measurement during the CVR period, combined with the complexity in distinguishing the changes in load and energy consumption due to voltage reduction from other impact factors. Electric utilities collect a substantial amount of load and voltage data in CVR-enabled circuits to estimate the CVRf. However, there is no guarantee that CVRf is correctly estimated since many other factors can impact CVRf calculation, such as the quality of data. Missing data, presence of outliers, imperfect CVR on/off activation and low data collection resolution are just some of the factors that can significantly impact CVRf calculations. The choice of the measurement and verification (M&V) methodology also impacts the results, with some methods being more sensitive to the data quality and external factors. It is known that different methods find different results, and there is currently no reliable way of knowing which method has achieved more accurate results compared to others or if a method has found CVRf values that are impractical.

In this paper, we aim to discuss an approach for determining a practical range, i.e., an upper and a lower bound, for CVRf. This range would significantly help examine if the CVRf results obtained by a methodology make a practical sense or need to be revisited. To do so, we use a ZIP load model, which represents the real power consumption as a function of voltage variations and can be used for CVRf determination. Section 2 of this paper provides an overview of some of the publicly available CVRf values by various electric utilities in the U.S. As CVR is commonly applied to a feeder, an aggregate ZIP load model is needed for CVRf calculation which is studied in Section 3. This aggregate ZIP load model is used to derive the CVRf in Section 4. Using practical ZIP coefficients of residential appliances and the developed CVRf model, associated CVRf bounds are determined in Section 5. Finally, the paper is concluded in Section 6.

2. CVR M&V BENCHMARKING

Electric utilities primarily leverage one or more of the three common CVR assessment methods, including comparison-based, regression-based, and simulation-based methods. The comparison-based methods leverage operational data under CVR (treatment) and non-CVR (control) conditions and accordingly determine the CVR factor by comparing these two cases. The major benefit of comparison-based methods is being straightforward and easy to implement. Correlated-feeder and correlated-weather are the two general categories for comparison-based methods. Regression-based methods model load and nodal voltage as a function of various factors, including temperature and CVR impact. The CVRf is calculated by generating this function using data associated with CVR-on and CVR-off conditions. Linear regression and difference-in-differences are the commonly-used approaches to estimate the load model in regression-based methods. Physical interpretations are potentially embedded in the regression models, so electric utilities can understand the model behavior based on impact factors. Simulation-based methods simulate the load consumption in CVR-off conditions and further use this model within power flow calculations to find the difference with measured load consumption and accordingly calculate CVRf. Simulation-based methods show high precision if the load models are highly accurate while allowing the system to run continually.

Considering that electric utilities use one or a combination of the methods described above, we expect CVRf range to be consistent across different utilities and service territories. However, the available benchmarking studies show otherwise. Our previous work in [4] shows this divide. This benchmarking study provides an overview of CVR/VVO deployments by several electric utilities within the U.S. and looks at the type of initiative, year(s) of the application, and the methodology used for CVRf assessment. Also, when available, a more detailed discussion on the initiative, e.g., the number of feeders with CVR/VVO deployments, electric utility's future plans, and the recorded CVRf values, are provided. Table 1 shows a summary of CVRf values by these utilities.

Table 1 A Summary of CVRf for Several U.S. Electric Utilities

Utility/Project	Type	Year	Methodology	No. of Feeders	CVR Factor	Reference
Central Lincoln People's Utility District	Pilot	2013-2014	Comparison-based	2	0.43 (summer); 1.05 (winter)	[5]
Ameren	Pilot/Program	2012-2013/2017-2019	Regression-based	4, 70	0.148-1.48, 0.8	[6]-[8]
Commonwealth Edison	Program	2018-2025	Regression-based	176	0.8	[8]-[10]
Idaho Power Company	Program	2009-2016	Constant CVR factor/ Comparison-based	30	0.41-5.75 (residential); 0.19-2.89 (commercial)	[11]-[13]
West Penn Power Company	Study	2012-2014	Regression-based	110	0.86	[14]-[15]
Indianapolis Power & Light	Program	2012-2013	Comparison-based	-	0.85 (2012); 0.75 (2013)	[16]
Philadelphia Electric	Program	2009-2012/2013-2016	Regression-based	-	1.08	[17]-[19]
Duke Energy Ohio	Program	2008-2016	Constant CVR factor	400	0.58-3.78	[20]-[22]
Xcel Energy	Pilot/Plan for program	2011-2012/2015-2020/2019	Simulation-based method/Statistical analysis	-	1.7 (2011); 2.7 (2012)	[23]-[24]
Avista Utilities	Program/Plan for program	2013-2014/2019	Regression-based/Simulation-based	-	0.833-0.881	[25]-[26]
Pacific Gas and Electric	Pilot/Plan for program	2013-2016	Regression-based	14	0.6-0.8	[27]-[28]
Southern California Edison	Demonstration Project/Plan for program	2012-2015/2019	Regression-based	8	1.56	[29]
Puget Sound Energy's	Program	2015-2016	Regression-based	14	0.475	[30]
Dominion Energy	Program	2009-2011	Comparison-	-	0.92	[31]

[45]			based			
Indiana Michigan Power Company	Program	2014-2015/2019	Regression-based	53	-1.13-11.38 (2015); -0.43-4.48 (2018)	[32]-[34]
Kansas City Power and Light	Demonstration Project	2015	Comparison-based	-	0.14-2.073 (overall 0.889)	[35]-[36]
National Rural Electric Cooperative Association	Test	2012-2014	Comparison-based	-	1.04-1.05	[37]

As this table indicates, there is a large discrepancy among the CVRf values calculated by different utilities. In extreme cases, some utilities have reached a minimum CVRf of -1.13 and a maximum CVRf of 11.38. This raises the question of an acceptable range for CVRf.

3. ZIP LOAD MODEL

Load modeling is instrumental in CVR assessment by explaining the sensitivity of loads to voltage. One of the frequently used load models in both steady-state and dynamic studies in the power system is the ZIP load model. Voltage-dependency of the load is expressed as a second-order polynomial consisting of constant impedance (Z), constant current (I), and constant power (P) components. Equations (1) and (2) show the ZIP load model structure. Z, I, and P coefficients are shown with *a*, *b*, and *c*, respectively.

$$p_i = p_{i0}\left(a_i\left(\frac{v}{v_{i0}}\right)^2 + b_i\left(\frac{v}{v_{i0}}\right) + c_i\right) \quad (1)$$

$$q_i = q_{i0}\left(a'_i\left(\frac{v}{v_{i0}}\right)^2 + b'_i\left(\frac{v}{v_{i0}}\right) + c'_i\right) \quad (2)$$

where v_{i0} is the nominal voltage, and p_{i0} and q_{i0} are the real and reactive powers at v_{i0}. a_i, b_i, and c_i are the real power ZIP coefficients, and a'_i, b'_i, and c'_i are the reactive power ZIP coefficients. ZIP coefficients show the proportion of three parts of the composite load model, thus their summation should equal one as in (3):

$$a_i + b_i + c_i = a'_i + b'_i + c'_i = 1 \quad (3)$$

There are various levels of granularity in determining the ZIP load models, e.g., for each load using AMI data or for each feeder using feeder-head data. Feeder-head data aggregates individual real and reactive powers, which will accordingly result in mixing the ZIP coefficients. If there are *i* appliances behind a meter, the aggregate ZIP load model for that meter *m* can be represented as follows:

$$\begin{aligned} p_m &= \sum_i p_i \\ &= \sum_i \left[p_{i0}\left(a_i\left(\frac{v}{v_0}\right)^2 + b_i\left(\frac{v}{v_0}\right) + c_i\right)\right] \\ &= \sum_i p_{i0}a_i\left(\frac{v}{v_0}\right)^2 + \sum_i p_{i0}b_i\left(\frac{v}{v_0}\right) + \sum_i p_{i0}c_i \\ &= p_{m0}\left(a_m\left(\frac{v}{v_0}\right)^2 + b_m\left(\frac{v}{v_0}\right) + c_m\right) \end{aligned} \quad (4)$$

Therefore, the coefficients of the aggregate load will be obtained as follows:

$$a_m = \sum_i p_{i0} a_i / p_{m0} \quad (5)$$
$$b_m = \sum_i p_{i0} b_i / p_{m0} \quad (6)$$
$$c_m = \sum_i p_{i0} c_i / p_{m0} \quad (7)$$
$$p_{m0} = \sum_i p_{i0} \quad (8)$$

These equations demonstrate that the ZIP coefficients of the aggregate load are determined as a weighted sum of individual loads. Each weight is equivalent to the share of that load (p_{i0}) in the entire pool of loads. Let's define this weight as α_i, where $\alpha_i = p_{i0}/\sum_i p_{i0}$. We will accordingly have the following updated equations for aggregate ZIP coefficients:

$$a_m = \sum_i \alpha_i a_i \quad (9)$$
$$b_m = \sum_i \alpha_i b_i \quad (10)$$
$$c_m = \sum_i \alpha_i c_i \quad (11)$$
$$p_{m0} = \sum_i p_{i0} \quad (12)$$

It is worth noting that these equations are for real power, however, the ones associated with the reactive power can be obtained similarly. Moreover, the aggregation is done at the meter level based on appliance ZIP models, while the same equations can be used at the meter level to achieve feeder-level ZIP coefficients.

Based on the definition of α_i, we will always have $0 \leq \alpha_i \leq 1$, so the lower and upper bounds of the ZIP coefficients can be found using equations below, in which lower and upper bars represent lower and upper bounds, respectively.

$$\underline{a}_m = \min \{\sum_i \alpha_i a_i\} = \min_i \{a_i\} \qquad \overline{a}_m = \max \{\sum_i \alpha_i a_i\} = \max_i \{a_i\}\,; \quad (13)$$
$$\underline{b}_m = \min \{\sum_i \alpha_i b_i\} = \min_i \{b_i\} \qquad \overline{b}_m = \max \{\sum_i \alpha_i b_i\} = \max_i \{b_i\} \quad (14)$$
$$\underline{c}_m = \min \{\sum_i \alpha_i c_i\} = \min_i \{c_i\} \qquad \overline{c}_m = \max \{\sum_i \alpha_i c_i\} = \max_i \{c_i\} \quad (15)$$

Note that the ZIP coefficients may change with voltage variations so the lower and upper bounds would change as the mix of loads and voltage values change. Moreover, when these coefficients are considered at the meter level, all the appliances behind that meter should be considered to help determine the lower and upper bounds.

4. CVR FACTOR CALCULATION

To calculate the CVRf for each time interval, energy and voltage reductions are first determined using (16) and (17).

$$\Delta E\ (\%) = \frac{E_2 - E_1}{E_1} \times 100 \quad (16)$$
$$\Delta V\ (\%) = \frac{V_2 - V_1}{V_1} \times 100 \quad (17)$$

CVRf is then calculated by dividing the percentage of energy reduction by percentage of voltage reduction as in (18):

$$CVR_f = \frac{\Delta E\ (\%)}{\Delta V\ (\%)} \tag{18}$$

CVRf is calculated over the one-year period by averaging over all time interval-specific CVRf's. The consumed energy at each time interval can be determined from the power at that time interval times the time interval duration, i.e., $E = p\Delta t$. Therefore, the CVRf can be written as:

$$CVR_f = \frac{\frac{p_2-p_1}{p_1}}{\frac{v_2-v_1}{v_1}} \tag{19}$$

We can benefit from the ZIP load model developed in (4) to update (19). Now let's assume that the pre-CVR load is at the nominal value, i.e., $p=p_0$. By changing the voltage to a new value v, the load will also change, and accordingly, the CVRf will be obtained as:

$$CVR_f = \frac{a_m(\frac{v}{v_0})^2+b_m(\frac{v}{v_0})+c_m-1}{(\frac{v}{v_0})-1} = \frac{a_m((\frac{v}{v_0})^2-1)+b_m((\frac{v}{v_0})-1)}{(\frac{v}{v_0})-1} = a_m((\frac{v}{v_0})+1)+b_m \tag{20}$$

The last equation calculates the CVRf based on the Z and I coefficients and the ratio of change in voltage relative to the nominal voltage. The minimum and maximum CVRf can be accordingly calculated as:

$$\begin{aligned} CVR_f^{min} &= \min\left\{a_m((\frac{v}{v_0})+1)+b_m\right\} = \min\left\{\textstyle\sum_i \alpha_i a_i\ ((\frac{v}{v_0})+1)+\sum_i \alpha_i b_i\right\} \\ &= \min\left\{\textstyle\sum_i \alpha_i \left(a_i((\frac{v}{v_0})+1)+b_i\right)\right\} = \min_i\left\{a_i((\frac{v}{v_0})+1)+b_i\right\} \end{aligned} \tag{21}$$

$$\begin{aligned} CVR_f^{max} &= \max\left\{a_m((\frac{v}{v_0})+1)+b_m\right\} = \max\left\{\textstyle\sum_i \alpha_i a_i\ ((\frac{v}{v_0})+1)+\sum_i \alpha_i b_i\right\} \\ &= \max\left\{\textstyle\sum_i \alpha_i \left(a_i((\frac{v}{v_0})+1)+b_i\right)\right\} = \max_i\left\{a_i((\frac{v}{v_0})+1)+b_i\right\} \end{aligned} \tag{22}$$

These two equations clearly show that the minimum and maximum values for CVRf can be easily calculated using individual appliance's ZIP coefficients while considering the impact of voltage change.

A more generic version of the above equation can be achieved by assuming that the voltage change is from v_1 to v_2 (in which both are different from v_0), and accordingly the load changes from p_1 to p_2. Using (19), the CVRf is obtained as follows:

$$CVR_f = \frac{a_m\frac{v_1(v_1+v_2)}{v_0^2}+b_m\frac{v_1}{v_0}}{a_m(\frac{v_1}{v_0})^2+b_m\frac{v_1}{v_0}+c_m} \tag{23}$$

If we assume $v_1=v_0$, this equation would be simplified to the one obtained in (20).

5. NUMERICAL ANALYSIS

A comprehensive list of ZIP coefficients for modern residential, commercial, and industrial loads is provided in [38]. A shorter version of the calculated ZIP coefficients is provided in

Table 2 below. Considering that the load could be any combination of the listed equipment, the lower and upper limits of CVRf can be obtained based on (21) and (22) by calculating $a_i((\frac{v}{v_0}) + 1) + b_i$ for individual equipment/component and then selecting the overall minimum and maximum values. Note that the voltage ratio can reach 1.05 as its highest value and 0.95 as its lowest. Using values provided in Table 2, the lower and upper limits of CVRf are calculated as -0.399 and 2.3345, respectively.

Table 2: Real Power ZIP Model

Equipment/Component	v_0	p_0	Z	I	P
Air compressor 1ph	120	1109.01	0.73	0.38	-0.11
Air compressor 3ph	208	1168.54	1.16	-1.81	1.65
Air conditioner	120	496.33	1.6	-2.69	2.09
CFL bulb	120	25.65	-0.63	1.66	-0.03
Coffeemaker	120	1413.04	0.98	0.03	-0.01
Copier	120	944.23	0.52	0.45	0.03
Electronic ballast	120	59.02	-0.07	0.08	0.99
Elevator	208	1381.17	2.36	-4.15	2.79
Fan	120	163.25	0.26	0.9	-0.16
Game console	120	60.65	0.36	-0.58	1.22
Halogen	120	97.36	0.51	0.55	-0.06
High pressure sodium HID	120	276.09	-0.16	1.2	-0.04
Incandescent light	120	87.16	0.54	0.5	-0.04
Induction light	120	44.5	0.18	-0.75	1.57
Laptop charger	120	35.94	0.25	-0.48	1.23
LCD television	120	208.03	0.33	-0.57	1.24
LED light	120	3.38	0.69	0.92	-0.61
Magnetic ballast	120	81.23	-3.16	6.85	-2.69
Mercury vapor HID light	120	268.27	-0.16	2.33	-1.17
Metal halide HID electronic ballast	120	113.7	-0.03	-0.06	1.09
Metal halide HID magnetic ballast	120	450	-0.2	1.35	-0.15
Microwave	120	1365.53	-0.27	1.16	0.11
Minibar	120	90.65	3.95	-6.46	3.51
PC (monitor and CPU)	120	118.9	0.18	-0.26	1.08
Projector	120	253	0.19	-0.45	1.26
Refrigerator	120	119.55	5.03	-8.48	4.45
Resistive heater	120	914.78	0.92	0.1	-0.02
Tungsten light	120	256.2	0.45	0.66	-0.11
Vacuum	120	855	0.92	0.07	0.01

We further employ (23) to consider a more comprehensive case, in which the initial voltage is not restricted to the nominal value. Simulation results show that the maximum CVRf occurs at v_1=0.95 and v_2=1.05 with a value of 2.4641, and the minimum CVRf occurs at v_1=1.05 and v_2=0.95 with a value of -0.4175.

6. DISCUSSIONS AND CONCLUSION

We leveraged the ZIP load model and the CVRf model to derive the minimum and maximum possible values for CVRf mathematically. Using real power ZIP coefficient values, the CVRf bounds were respectively calculated as 2.4641 and -0.4175. These values can provide a recommended practice to electric utilities that deploy CVR/VVO in their grids to ensure the validity of the calculated results. This was done for a set of mainly residential appliances; however, the results can be extended to a set of meters without loss of generality. There are several points to consider when using these values:

- The ZIP coefficients are calculated in a laboratory environment. The practical ZIP coefficients in the field may differ from the values used in this paper due to different voltage levels, resulting in different CVRf limits.
- The considered list of ZIP coefficients in this paper is not comprehensive as it mainly focuses on residential customers. However, in practical cases, the feeders may have a mix of residential, commercial, and industrial customers, thus seeing different ZIP coefficients.
- In line with the previous point, not all meter and appliance data can be captured accurately, and therefore, a generic statistical boundary may need to be utilized at the feeder level.
- The studies in this paper were based on a ZIP load model. If a different load model is used, e.g., an exponential model, a different set of CVRf limits may be obtained.

Despite these points, the studies in this paper could help electric utilities plan, pilot, and scale their CVR/VVO efforts.

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