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Investigating the Practical Bounds of the CVR Factor

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Conservation voltage reduction (CVR)

- ✓ Conservation voltage reduction (CVR) enables electric utilities to reduce energy and peak demand by lowering the voltage at the distribution system.

- ✓ 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.

- ✓ 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.

CVR factor

- ✓ CVR factor (CVRf) is a widely accepted metric to quantify the impacts of CVR
- ✓ It is defined as the ratio between the percentage change in energy and the associated percentage change in voltage.

- ✓ It is a challenge to provide a reasonable estimation of CVRf, due to
  - lack of benchmark load consumption measurement during the CVR period
  - complexity in distinguishing the changes in load and energy consumption due to voltage reduction from other impact factors.

- ✓ There is no guarantee that CVRf is correctly estimated since many other factors can impact CVRf calculation
  - Missing data, presence of outliers, imperfect CVR on/off activation, low data collection resolution, choice of the measurement and verification (M&V) methodology, …

- ✓ 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.

Objective of this paper

- ✓ 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.
- ✓ A ZIP load model is used to represent the real power consumption as a function of voltage variations, and is further used for CVRf determination.

CVRf Benchmarking

- ✓ Electric utilities primarily leverage one or more of the three common CVR assessment methods:
  - comparison-based
  - regression-based
  - simulation-based

- ✓ Considering that electric utilities use one or a combination of the above methods, we expect CVRf range to be consistent across different utilities and service territories.
- ✓ However, benchmarking studies show otherwise.

- ✓ CVRf values range from negative values to as high as 11.3.

CVRf Benchmarking

Utility/Project	Type	Year	Methodology	CVR Factor
Central Lincoln People's Utility District	Pilot	2013-2014	Comparison-based	**0.43 (summer); 1.05 (winter)**
Ameren	Pilot/Program	2012-2013/2017-2019	Regression-based	**0.148-1.48, 0.8**
Commonwealth Edison	Program	2018-2025	Regression-based	**0.8**
Idaho Power Company	Program	2009-2016	Constant CVR factor/ Comparison-based	**0.41-5.75 (residential); 0.19-2.89 (commercial)**
West Penn Power Company	Study	2012-2014	Regression-based	**0.86**
Indianapolis Power & Light	Program	2012-2013	Comparison-based	**0.85 (2012); 0.75 (2013)**
Philadelphia Electric	Program	2009-2012/2013-2016	Regression-based	**1.08**
Duke Energy Ohio	Program	2008-2016	Constant CVR factor	**0.58-3.78**
Xcel Energy	Pilot/Plan for program	2011-2012/2015-2020/2019	Simulation-based method/Statistical analysis	**1.7 (2011); 2.7 (2012)**
Avista Utilities	Program/Plan for program	2013-2014/2019	Regression-based/Simulation-based	**0.833-0.881**
Pacific Gas and Electric	Pilot/Plan for program	2013-2016	Regression-based	**0.6-0.8**
Southern California Edison	Demonstration Project	2012-2015/2019	Regression-based	**1.56**
Puget Sound Energy’s	Program	2015-2016	Regression-based	**0.475**
Dominion Energy [45]	Program	2009-2011	Comparison-based	**0.92**
Indiana Michigan Power Company	Program	2014-2015/2019	Regression-based	**-1.13-11.38 (2015); -0.43-4.48 (2018)**
Kansas City Power and Light	Demonstration Project	2015	Comparison-based	**0.14-2.073 (overall 0.889)**
National Rural Electric Cooperative Association	Test	2012-2014	Comparison-based	**1.04-1.05**

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Our Approach

- ✓ We leverage a ZIP load model, where the voltage-dependency of the load is expressed as a second-order polynomial consisting of constant impedance, constant current, and constant power components.

- ✓ We define the ZIP load model of meter data using an aggregation of individual behind-the-meter devices.
- ✓ We further define the ZIP load model of feeder-head using an aggregation of individual meters load models.

→ Feeder-head load model is represented as a function of ZIP load models associated with individual behind-the-meter devices

→ Knowing CVRf range for individual devices, we can calculate the CVRf range for meter and also feeder-head

Numerical Analysis

A list of ZIP coefficients for modern residential, commercial, and industrial loads

Borrowed from “A. Bokhari et al., "Experimental Determination of the ZIP Coefficients for Modern Residential, Commercial, and Industrial Loads," in IEEE Transactions on Power Delivery, vol. 29, no. 3, pp. 1372-1381, June 2014.

Equipment/Component	Voltage	Power	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

Numerical Analysis

Case 1: Base voltage is restricted to the nominal value.

✓ The voltage ratio can reach 1.05 as its highest value and 0.95 as its lowest.

✓ Using the proposed approach, the lower and upper limits of CVRf are calculated as **-0.399** and **2.3345**, respectively.

Case 2: Base voltage is not restricted to the nominal value.

✓ The voltage ratio can reach 1.05 as its highest value and 0.95 as its lowest.

✓ Using the proposed approach, the lower and upper limits of CVRf are calculated as **-0.4175** and **2.4641**, respectively.

✓ The results show that the highest CVRf value that can be achieved is **2.4641.**

Discussions

✓ The obtained CVRf range can provide a recommended practice to electric utilities that deploy CVR/VVO in their grids to ensure the validity of the calculated results.

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 mainly focuses on residential customers. In practical cases, the feeders may have a mix of RCI customers.

✓ 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.