Unveiling Impacts of High-PV and EV Penetrations on Conservation Voltage Reduction in Distribution Grids

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***Abstract*—Conservation Voltage Reduction (CVR) is widely implemented by utilities to reduce energy consumption and peak load demand by operating distribution feeders at the lower end of the acceptable voltage range. However, extensive integration of photovoltaic (PV) generation and electric vehicle (EV) charging has significantly altered feeder voltage profiles and CVR performance. As a result, the impact of PV and EV on CVR performance needs to be further investigated. This paper evaluates the impact of the integration of PV and EV on CVR performance using the simulation-based method leveraging real utility feeder and real load and EV charging data. A comprehensive simulations of multiple scenarios are evaluated to quantify the performance of CVR under varying penetration levels of PV and EV. To accurately capture load–voltage sensitivity, ZIP load models are employed for the feeder loads. The results show that increasing PV and EV penetration reduces power import and line losses by providing active and reactive power locally. In addition, CVR can further reduce total energy consumption and line losses even in the presence of high penetration of PV and EV.**

***Index Terms*—Conservation voltage reduction, photovoltaic, electric vehicle, load-voltage sensitivity**

I. Introduction

Conservation Voltage Reduction (CVR) is widely implemented by utilities as an effective method to reduce energy consumption and peak demand in distribution systems [1]. The fundamental idea of CVR is to intentionally operate the distribution system at the lower end of the acceptable service voltage range. Due to the voltage sensitivity of the loads, the power and energy consumption of distribution system loads will decrease when operating at lower voltage levels. According to the American National Standards Institute (ANSI) C84.1 voltage standard, residential customer service voltage is typically required to be maintained between 114 V and 126 V [2], [3]. Under CVR, customer voltage is reduced but remains within this allowable range; specifically, it is not allowed to drop below 114 V, which is approximately 5% below the nominal 120 V utilization voltage.

In general, CVR is achieved through Volt/VAr optimization (VVO), which controls the operation of Volt/VAr regulation devices such as capacitor banks (CBs), voltage regulators, and on-load tap changers (OLTCs) to simultaneously regulate voltage and reactive power [4]- [6]. Currently, line drop compensation (LDC) is an efficient and simple technique to achieve CVR without requiring any modifications to the system circuit. However, this approach may result in substantial voltage drops along feeders that are heavily loaded or dominated by loads with poor power factors. In [7], OLTCs and switched CBs are utilized to regulate the feeder voltage and implement CVR at locations with relatively high node voltages [8]. To quantify the sensitivity of energy consumption to voltage reduction, the CVR factor is proposed as a metric for utilities to evaluate and compare CVR effectiveness under different operating conditions. A higher CVR factor signifies greater energy savings achieved for the same voltage reduction when CVR is implemented.

To accurately estimate the CVR factor, several methods have been proposed in the literature, including regression-based approaches, load modeling-based approaches, comparison-based approaches, and simulation-based approaches [9], [10]. In this work, a simulation-based method is adopted. Power flow simulations are used to estimate energy consumption with and without CVR, and then the simulation results are used to compute the CVR factor. In our study, the load of the distribution system is represented using a combination of constant power, constant impedance, and constant current models to capture different levels of voltage sensitivity. However, with the extensive integration of photovoltaic (PV) generation and electric vehicle (EV) charging, the composition and behavior of distribution systems have changed significantly. PV and EV have altered the feeder load, voltage profiles, and reactive power flow, which in turn affected CVR performance. Therefore, to effectively implement CVR in distribution systems, it is essential to figure out the impact of PV and EV on CVR performance.

This paper investigates the impact of PV and EV penetration on CVR performance using a real utility distribution system. A simulation-based method is used to estimate the CVR factor at multiple penetration levels of PV and EV. The loads are modeled as constant power, constant impedance, and ZIP loads to accurately capture the load-voltage sensitivity, including the nearly constant power behavior of EV charging. The study compares operating conditions with and without CVR to quantify the changes in voltage profiles. The results show that increasing PV and EV penetration reduces substation

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import and feeder losses by providing active and reactive power locally. In addition, CVR can further reduce total energy consumption and line losses even in the presence of high penetration of PV and EV.

The rest of this paper is organized as follows: Section II presents the methodology used to estimate the CVR factor. Section III introduces the modeling of loads, PV, and EV. Section IV provides the simulation results and corresponding analysis. Section V concludes the paper.

II. Estimation of the CVR Factor

A. CVR Definition

To distinguish the impact of voltage reduction from other factors that influence CVR, the CVR factor is used to quantify the effectiveness of voltage reduction in achieving energy and demand savings. The CVR factor is the primary metric used for the CVR evaluation and is defined as:

$$\mathrm{CVR}_f = \frac{\Delta E(\%)}{\Delta V(\%)} \tag{1}$$

where

$$\Delta E(\%) = \frac{E_{\text{cvroff}} - E_{\text{cvron}}}{E_{\text{cvroff}}}, \quad \Delta V(\%) = \frac{V_{\text{cvroff}} - V_{\text{cvron}}}{V_{\text{cvroff}}} \tag{2}$$

E_{cvron} and E_{cvroff} represent the energy consumption with/without CVR, respectively; V_{cvron} and V_{cvroff} represent the measured voltage with/without CVR, respectively.

B. Simulation-Based method

A simulation-based approach is used to evaluate the CVR factor by performing power flow analyses under operating conditions with and without CVR. All simulations are conducted using the open-source distribution system analysis tool OpenDSS. As illustrated in Fig. 1, the assessment begins with developing detailed ZIP load models, DER models (including PVs, EVs, etc.), and tap changer settings at the feeder head. Power flow simulations are then executed in OpenDSS for both CVR-on and CVR-off scenarios.

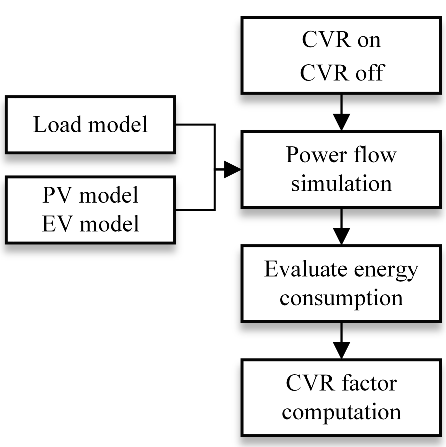

Fig. 1. CVR factor estimation using simulation-based methods..

CVR is activated by enabling the tap changers to regulate feeder voltage and deactivated by disabling tap changer control. For each scenario, the total load demand and energy consumption are computed, and the CVR factor is subsequently estimated based on the change in energy consumption corresponding to the reduction in voltage.

III. System Modeling

A. ZIP Load Model

The ZIP load model provides a more accurate representation of real load behavior, especially under varying voltage conditions. Hence, it is used to capture load–voltage sensitivity. The model characterizes the relationship between voltage magnitude and power consumption through a combination of constant-impedance, constant-current, and constant-power components, as:

$$P_{ZIP} = P_0 \left[\alpha_P \left(\frac{V}{V_0} \right)^2 + \beta_P \frac{V}{V_0} + \gamma_P \right]. \tag{3}$$

Here, P_{ZIP} is the active power of the ZIP load model; P_0 is the nominal active power; V is the measured voltage magnitude; V_0 is the nominal voltage. The parameters α_P, β_P, and γ_P represent the constant-impedance, constant-current, and constant-power coefficients of the ZIP model, respectively, such that $\alpha_P + \beta_P + \gamma_P = 1$. Similarly, reactive power of the ZIP load could also be established.

B. PV Model

PV are interfaced with the grid through power electronic inverters. Typically, they operate in unity power factor, although, utilities are adopting smart inverter functionalities such as V–Q control to accommodate high PV penetration. In this study, two primary control modes defined in *IEEE Std 1547-2018* are considered: (i) the power factor (PF) mode and (ii) the voltage-reactive power (VRP) mode.

- PF mode: In the constant power factor mode, PV units operate at a fixed power factor.
- VRP mode: In the voltage–reactive power (V–Q) control mode, the inverter adjusts its reactive power output according to local voltage measurements following a predefined V–Q droop characteristic. We adopted parameters specified in *IEEE Std 1547-2018* to model them with V–Q control mode.

C. EV Model

In this study, EVs are modeled in OpenDSS using a constant-power load representation. The EV charging profiles are derived from real datasets collected from residential EV chargers. These datasets were provided by MiEnergy Cooperative in Linn County, Iowa, whose smart meters record detailed charging behavior for both Level-1 and Level-2 chargers with power ratings ranging from 0.56 kW to 15.7 kW [11].

EVs are assigned to residential customers who also have PV units, following the common observation that customers with rooftop PV systems are more likely to own EVs. This observation illustrated in Fig. 2, is used locate EVs to generate different penetration levels in the distribution feeder.

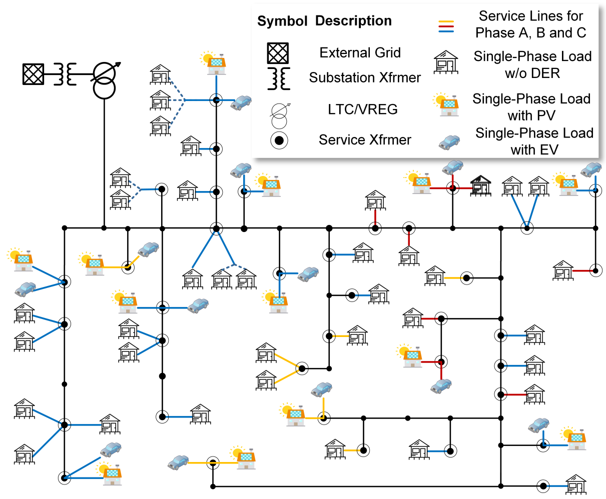

Fig. 2. A real distribution feeder located in Iowa, provided courtesy of Algona Municipal Utilities.

D. OLTC Model

The feeder voltage can be regulated using an on-load tap changer (OLTC), typically located at the substation. This regulation is generally not automatic and instead requires supervised operator intervention. A typical OLTC provides 32 tap positions, allowing the secondary voltage to be adjusted within a range of 0.90 to 1.10 pu, with a resolution of 0.00625 pu per step. Utilities often use the OLTC to enable or disable CVR.

IV. Case Studies

A real utility feeder located in the Algona Municipal Unitilies, Iowa, is modeled in OpenDSS for this study. The feeder has a total length of 67,350 ft and includes 39 service transformers, consisting of 2 three-phase units and 37 single-phase center-tapped transformers. It serves 52 customers, with 9 customers on phase A, 7 on phase B, and 34 on phase C, while 2 customers are connected across all three phases. PV and EV are colocated at the same customer locations, as illustrated in Fig. 2. The feeder is supplied by a 69/13.8-kV three-phase step-down substation transformer.

Case studies are performed on this feeder to evaluate the CVR performance. The CVR is implemented using OLTC at the substation. The OLTC reference voltage is set to 0.985 pu during CVR operation, which lowers downstream voltages below 0.975 pu while ensuring that all node voltages remain above the minimum acceptable limit of 0.95 pu.

The CVR case studies are conducted using the July data set. We have the real load demand of all 53 customers, out of which three profiles are shown in Fig. 3, where short-duration peaks frequently reach 8–10 kW and minimum values remain below 1 kW during low-consumption hours. The three PV generation profiles are presented in Fig. 4, exhibiting clear-sky daytime peaks around 0.9–1.1 kW. The three EV charging power profiles are shown in Fig. 5, where irregular charging events of 2–3 kW occur intermittently throughout the month,

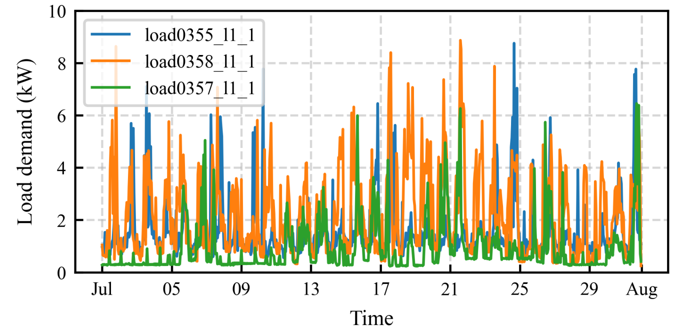

Fig. 3. Three load demand profiles of the EC3 feeder in July.

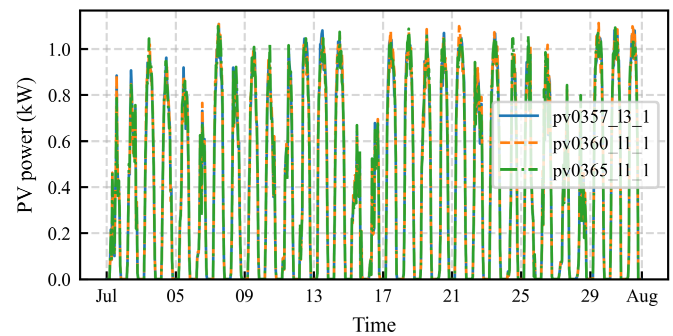

Fig. 4. Three PV generation profiles in July.

primarily during night and evening hours. Note that the EV charging profiles are obtained from field measurement with dedicated smart meters.

A. CS1: CVR without distributed PVs and EVs

The CVR factor is evaluated without PVs and EVs for three different load types: constant-power, constant-impedance, and ZIP loads. These load models have fundamentally different voltage sensitivities, which directly influence CVR performance.

Fig. 6 presents the feeder voltage profiles under the constant-impedance load model. The CVR operation produces a persistent voltage reduction of approximately 100 V at the feeder head. The corresponding power import in Fig. 7 shows that the CVR-on curve remains consistently below the CVR-off case, with the largest deviation occurring during daytime peaks. This behavior reflects the inherent voltage sensitivity

TABLE I
CVR PERFORMANCE UNDER DIFFERENT LOAD MODELS

Load	Total customer load (kWh)		Total losses (kWh)		CVR factor
	w/ CVR	w/o CVR	w/ CVR	w/o CVR	
Con. P	55511.76	55511.76	846.07	838.74	-0.012
Con. Z	53460.88	54301.35	793.82	805.26	1.48
ZIP	54470.52	54896.22	819.07	821.33	0.74

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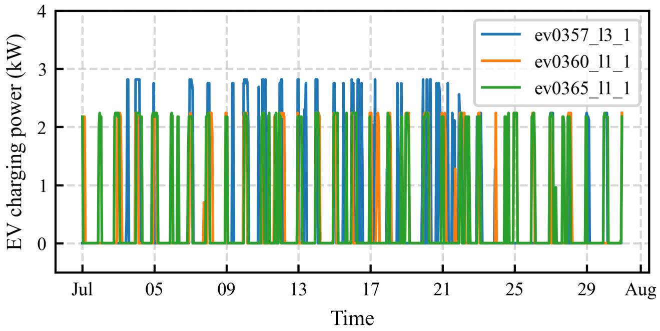

Fig. 5. Three EV charging profile in July, provided courtesy of MiEnergy Cooperative, Iowa.

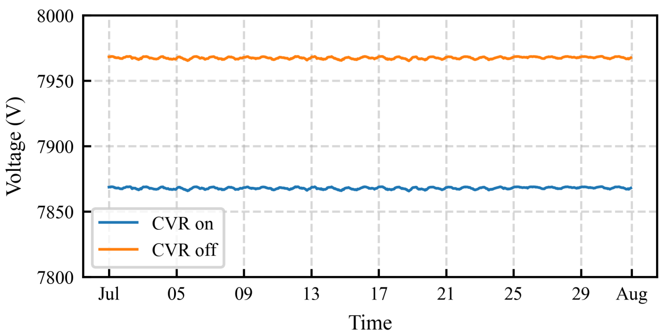

Fig. 6. feeder voltage with and without CVR for constant impedance load.

of constant-impedance loads, for which lower voltage directly results in reduced power demand.

Table I summarizes the CVR performance across different load models. As expected, the constant-power load exhibits negligible sensitivity to voltage changes, yielding a CVR factor near zero. The constant-impedance load demonstrates the strongest response, achieving substantial reductions in both customer energy and feeder losses, with a CVR factor of 1.48. The ZIP model yields a CVR factor of 0.74, consistent with its blended representation of constant-power, constant-current, and constant-impedance components. These results underscore the dominant role of load voltage sensitivity in determining CVR effectiveness.

B. CS2: CVR with distributed PVs

Figs. 8 and 9 illustrate the power import with and without CVR under the unity power factor and VVC control modes,

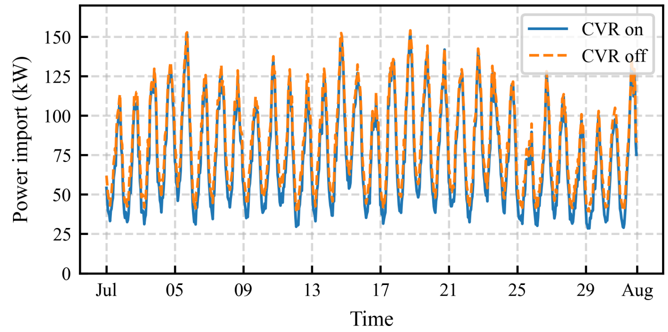

Fig. 7. power import with and without CVR for constant impedance load.

respectively. Although the two curves nearly overlap, the CVR-on case consistently exhibits slightly lower power import across all hours and PV penetration levels.

Tables II and III summarize the CVR performance under unity power factor and VVC control modes, respectively, while all other loads are have ZIP characteristics. In unity PF mode, increasing the penetration of PV from 25% to 75% leads to progressively higher CVR factors, increasing from 0.74 to 0.98. A similar pattern is observed under VVC operation. Although the absolute energy and loss values differ slightly from those under unity PF, the resulting CVR factors follow nearly identical trends, ranging from 0.74 to 0.97.

Therefore, distributed PV reduces line losses and import power by supplying active and reactive power locally, while CVR provides an additional layer of demand reduction. The combined effect improves overall system efficiency and improves the effectiveness of CVR in PV-rich feeders.

C. CS3: CVR with distributed PVs and EVs

Fig. 10 illustrates the power import with and without CVR under scenarios where both PV generation and EV charging are present. Note that all the PVs are in unity PF mode in this case study.The CVR-on curve remains consistently lower than the CVR-off case across the entire month. The reduction is particularly evident during afternoon and evening hours when feeder loading is highest.

Table IV summarizes the corresponding energy consumption and loss metrics under two representative PV–EV penetration levels. At 50% penetration, the CVR reduces total customer energy consumption from 56021.63 kWh to 55537.68 kWh, yielding a CVR factor of 0.79. When the

TABLE II
CVR PERFORMANCE UNDER DIFFERENT PV PENETRATION LEVELS (UNITY PF MODE)

PV level	Total customer load (kWh)		Total losses (kWh)		CVR factor
	w/ CVR	w/o CVR	w/ CVR	w/o CVR	
25%	54499.79	54925.47	787.63	789.85	0.74
50%	54495.21	54969.32	729.83	732.65	0.79
75%	54339.36	55006.95	684.03	688.93	0.98

TABLE III
CVR PERFORMANCE UNDER DIFFERENT PV PENETRATION LEVELS (VVC MODE)

PV level	Total customer load (kWh)		Total losses (kWh)		CVR factor
	w/ CVR	w/o CVR	w/ CVR	w/o CVR	
25%	54504.57	54927.91	783.72	787.46	0.74
50%	54510.38	54977.80	718.07	725.57	0.79
75%	54366.13	55019.17	663.96	678.94	0.97

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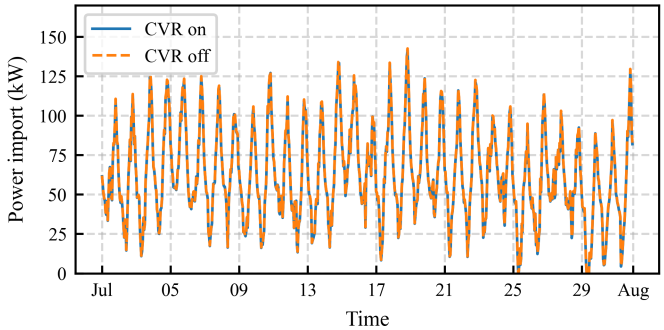

Fig. 8. Power import with and without CVR for unity power factor control at 50% PV penetration.

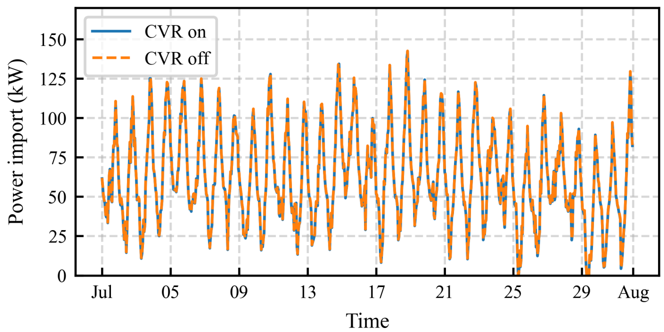

Fig. 9. Power import with and without CVR for the VVC mode at 50% PV penetration.

penetration increases to 75%, the CVR benefit becomes more pronounced, with the CVR factor rising to 0.98. This upward trend indicates that higher PV–EV penetration increases the feeder's sensitivity to voltage adjustments, enabling greater demand reduction during CVR operation. The results also show that increasing PV and EV penetration reduces substation import and feeder losses by providing active and reactive power locally. In addition, CVR can further reduce total energy consumption and line losses even in the presence of high penetration of PV and EV.

TABLE IV
CVR PERFORMANCE UNDER COMBINED PV–EV PENETRATION LEVELS

PV-EV level	Total customer load (kWh)		Total losses (kWh)		CVR factor
	w/ CVR	w/o CVR	w/ CVR	w/o CVR	
25%	55134.63	55562.91	833.41	837.52	0.74
50%	55537.68	56021.63	759.63	762.74	0.79
75%	57401.73	58106.44	704.25	715.87	0.98

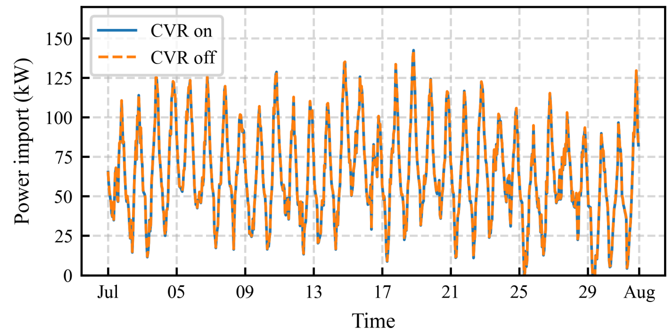

Fig. 10. Power import with and without CVR under 50% PV–EV penetration.

V. Conclusion

This paper evaluates the performance of CVR on a real utility distribution feeder while considering the impacts of PV generation and EV charging. A simulation-based method is used to estimate the CVR factor by modeling the feeder in OpenDSS under different PV and EV penetration levels. The results show that the effectiveness of the CVR strongly depends on the characteristics of the load and the amount of PV. Constant-power loads exhibit almost no voltage sensitivity, whereas constant-impedance and ZIP loads have higher CVR factors. Distributed PV reduces line losses and power import by supplying active and reactive power locally, and CVR can further decrease energy consumption and losses when PV is present. EV charging, modeled as a constant-power load, shows very low voltage sensitivity and therefore has only a minor impact on CVR performance. Future work will investigate coordinated CVR and smart-inverter control to improve voltage regulation and enhance energy savings in high-DER distribution feeders.

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