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Conservation Voltage Reduction in Secondary Distribution Networks with Distributed Generation and Electric Vehicle Charging Loads

Barry Hayes, *Senior Member, IEEE*
Dept. of Electrical and Electronic Engineering
National University of Ireland Galway
Galway, Ireland
barry.hayes@nuigalway.ie

Kevin Tomsovic, *Fellow, IEEE*
Dept. of Electrical Engineering and Computer Science
The University of Tennessee
Knoxville (TN), United States of America
tomsovic@utk.edu

***Abstract*—This paper investigates the potential for Conservation Voltage Reduction (CVR) in Low Voltage (LV) secondary distribution networks. CVR is a well-established technique where the voltage in LV networks is managed at a reduced, but still acceptable level in order to obtain energy savings. In this paper, a component-based load modelling approach is used to create time-varying models of residential loads designed to accurately represent the changes in electrical characteristics of LV customer loads over time. The proposed CVR approach is analysed in several scenarios with high penetrations of residential PV (Photovoltaic) units and Electric Vehicle (EV) charging loads in order to assess the impact of these technologies on CVR. Simulations are carried out using a detailed three-phase model of a typical European LV residential distribution network. The results quantify the CVR energy savings and the effects of CVR on LV network voltage quality. The sensitivity of the CVR results to the load model parameters is also analysed.**

I. Introduction and Literature Review

Conservation Voltage Reduction (CVR) has been used as a means of improving energy efficiency in power distribution networks for several decades [1]. The principle of CVR is simple: since certain loads consume less energy when the supply voltage is reduced, utilities can achieve energy savings by supplying users with a reduced voltage level. CVR is regarded as one of most cost-effective means of achieving energy efficiency in electricity distribution networks. Many electrical utilities worldwide have implemented CVR initiatives, reporting kWh energy savings of 3-4% [2], [3], [4]. However, not all electrical devices operate more efficiently with reduced voltages. The effectiveness of CVR is therefore highly-dependent on the exact load type and composition in a particular network. Previous work has shown that CVR energy savings are difficult to accurately measure and validate, since it can be difficult to distinguish changes in energy consumption due to CVR from other factors which impact energy consumption, such as temperature and seasonal load changes [5].

Recent years have seen a significant renewal of interest in CVR due to an increasing focus on energy efficiency and power system environmental impacts, and with the new distribution network monitoring and control possibilities enabled by advanced metering infrastructure [6], [7], [8]. A comprehensive review of the state of the art in CVR and its implementation in distribution networks is provided in [9]. CVR can be applied as a constant, "all-day" voltage reduction or as a "dispatchable" peak load reduction measure [10]. A recent large-scale demonstration project in England examined both CVR and demand response via dispatchable voltage reduction [2]. Energy savings of 3-4% were obtained in residential UK secondary distribution networks without customers noticing any negative effects. A field-validated CVR model was presented in [3], which reported an energy reduction of 4% based on yearly kWh savings in highly-meshed urban secondary distribution networks. Despite promising results in a number of studies and field demonstrations, significant barriers to the implementation of CVR remain. In deregulated electricity markets where a large component of utility revenue is based on total kWh consumption, CVR is not incentivised financially. CVR is therefore not viable unless there is a means of repaying the utility for lost revenue [9]. Technical barriers to CVR may also exist. In some distribution networks, voltage control capability is limited, and there can be an increased risk of reliability impacts (e.g. voltage collapse) if CVR is not implemented properly.

Many utilities use a distribution network voltage optimisation, or Volt/VAR Optimization (VVO) scheme, aimed at optimally controlling voltage levels across the entire network in order to minimise total distribution system losses. A significant amount of literature has been published in this area in recent years, e.g. [11], [12], [13]. Several authors have investigated the impact of increasing penetrations of Distributed Energy Resources (DER) on CVR [14], [15]. The effect of solar

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photovoltaic (PV) generation on energy consumption, peak load reduction, and voltage profiles is examined in [14]. The inclusion of CVR in a VVO scheme where DER provide reactive power support via inverter VAR dispatch is examined in [15] and [16].

The main contributions of this paper are: (i) the development of a residential user load model with PV and EV incorporated in the model; (ii) an analysis of the impact of PV and EV on CVR using a typical European configuration secondary distribution network; (iii) an analysis of the sensitivity of the CVR study to load ZIP model coefficients and load power factor. The paper is structured as follows: Section II discusses the development of the load model incorporating PV and EV and the modelling of the secondary distribution network, Section III provides the results of the network simulations and load sensitivity analysis, and Section IV concludes.

II. Methodology

The CVR factor, CVR_f is defined as the ratio of the change in energy consumption to the change in supply voltage:

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

where $\Delta E\%$ is the change in energy consumption (typically measured in terms of active power only), and $\Delta V\%$ is the change in voltage applied. In a given distribution network, CVR_f can be calculated by a comparison of the power consumption and voltage with CVR on and with CVR off over a period of time T:

$$CVR_f = \sum_{t=1}^{T} \frac{1}{T} \frac{(P_{cvroff}(t) - P_{cvron}(t))/P_{cvroff}(t)}{(V_{cvroff}(t) - V_{cvron}(t))/V_{cvroff}(t)} \tag{2}$$

A typical industry standard value of CVR_f is 0.7, indicating 0.7% kWh savings for a reduction in voltage of 1%. However, CVR_f can vary from 0-1.5, depending on a range of factors. These factors include the load type and mixture, daily and seasonal load changes, weather effects, and user behaviour effects. Residential and commercial sector loads generally provide the best results for CVR [9]. The accurate modelling of these loads is a crucial part of any CVR study. This paper focuses on CVR for residential loads.

A. Residential User Load Modelling

In order to predict, analyse and validate the energy savings from CVR, it is necessary to accurately model the load-voltage dependency of the supplied demand. The load-voltage dependency and therefore the CVR factor is different for each load. A summary of CVR factors for common residential appliances is shown in Figure 1 [17]. Appliances with simple resistive loads (e.g. electric cooking appliances, incandescent bulbs) have high CVR factors. Energy consumption in motor loads such as pumps in heating and refrigeration is reduced by CVR, but these effects are often non-linear. Finally, appliances with power electronics-based voltage regulation are considered “constant power” devices, with CVR factors close to zero.

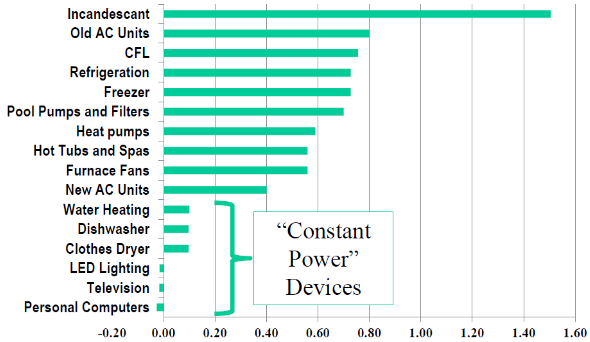


Figure 1. Examples of CVR factors for common residential appliances [17].

In this paper, the component-based load modelling approach developed in [18], [19] is applied to create time-varying models of residential loads which are capable of capturing the changes in electrical characteristics of Low Voltage (LV) customer load over time. Load statistics on appliance ownership and usage patterns are used to estimate the percentage of each load category (e.g. consumer electronics, cooking, wet loads) present in the aggregate load. Figure 2 shows an example of a typical UK winter peak residential demand decomposed into each load category [20].

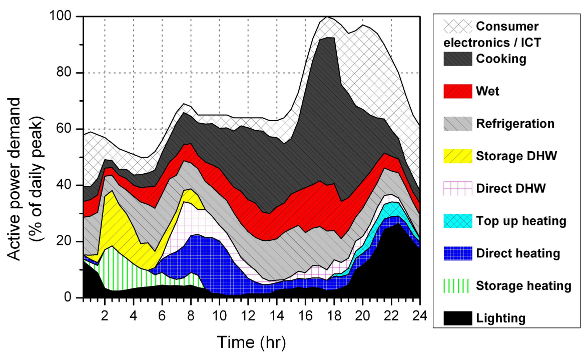


Figure 2. Residential demand decomposed into load categories based on statistical data [20].

The LV residential user load model is developed in ZIP form since this better represents modern nonlinear loads [21]. This is then expressed in exponential form, with a set of 48 time-varying exponential coefficients for both active and reactive power, expressing the changes in load composition at each 30-minute interval over the course of the day:

$$P(t) = P_o(t)\left(\frac{V(t)}{V_o}\right)^{n_p(t)} \quad for \quad t = 1, ..., 48 \tag{3}$$

$$Q(t) = Q_o(t)\left(\frac{V(t)}{V_o}\right)^{n_q(t)} \quad for \quad t = 1, ..., 48 \tag{4}$$

where $n_p(t)$ and $n_q(t)$ are the exponential model coefficients n_p and n_q at time interval t:

$$n_p \approx \frac{(2 * Z_p + 1 * I_p + 0 * P_p)}{(Z_p + I_p + P_p)} \tag{5}$$

$$n_q \approx \frac{(2 * Z_q + 1 * I_q + 0 * P_q)}{(Z_q + I_q + P_q)} \tag{6}$$

B. Modelling of residential PV generation and EV charging loads

In this paper, models of residential PV generation and EV charging loads are added to the component-based, time-varying load model described in [18], [19], [20]. Residential PV units are modelled as active power injections at each load point in the LV network. The PV production data is based on actual measurements of rooftop PV outputs at residential homes recorded by domestic smart meters in the SmartHG project [22]. The PV units use maximum power point tracking and operate at fixed unity power factor. The EV charging data used in this paper is taken from actual vehicle charging data from the Test-an-EV project [23].

C. Low Voltage Network Simulation with CVR

The LV secondary distribution networks are modelled Open Distribution System Simulator (OpenDSS), where three-phase, time series simulations are carried out with a time resolution of one minute. OpenDSS is interfaced with Matlab using a COM interface as illustrated in Figure 3. Matlab is used for data input/output, load modelling, and the analysis and visualisation of simulation results.

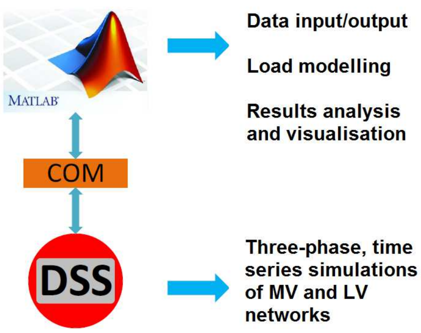


Figure 3. Overview of load modelling and network simulation approach.

In this paper, two cases are analysed:

- **Base Case (No CVR)**: Current utility practice of controlling voltage in the “upper range” (1.0 - 1.1 p.u.), using the voltage at the feeder head as the reference.
- **Proposed Approach (CVR)**: CVR is applied in order to achieve energy savings by controlling voltage in the “lower range” (0.94 - 1.0 p.u.), using the voltage at end of LV feeder as the reference.

The proposed CVR approach is simulated in various scenarios with high penetrations of PV and EV chargers in order to analyse the impact of these technologies on CVR, Section III.

D. Sensitivity Analysis

A sensitivity analysis is presented in Section III-D, which varies the load model parameters and examines the effects on the CVR factor and on the voltages at all load points in the LV distribution network. The impact on network voltages is calculated by:

$$\Delta V_{max} = max_j \left| \frac{V_j - V_0}{V_0} \right| \tag{7}$$

where ΔV_{max} is the maximum voltage deviation in the secondary network, expressed as the largest voltage difference between the node voltages and the voltage at the feeder head, V_0, measured at the LV side of the MV/LV substation transformer.

III. Results

A. Case Study Network and Input Data

The LV secondary network and residential demand data used in this paper is taken from the IEEE European Low Voltage Test Feeder [24], Figure 4. This is based on actual measurements from residential LV customers in a European secondary distribution network. A sample of the demands recorded at one-minute intervals on a typical winter day for 55 individual users is given in Figure 5. The time-varying exponential load models described in (3)-(6) are applied at 30-minute intervals. The power factor for the residential loads is obtained from the component-based load model and varies from 0.96-0.995, depending on time of day and load mix.

Supply voltages in the secondary LV network are regulated to 1.0 per unit (p.u.) $\pm$ 10%. It is standard practice for utilities to maintain the voltage at the feeder head (i.e. at the MV/LV substation) above 1.0 p.u., and often this voltage is kept near to the upper voltage limit of 1.1 p.u.. This allows a sufficient margin to account for voltage drops across the LV distribution network, so that users connected to the end of the feeder receive an acceptable voltage level. Typically, CVR attempts to reduce the supply voltage so that voltages across the secondary distribution system are in the “lower range” of the acceptable limits (0.9 - 1.0 p.u.).

In order to model voltage regulation in the MV distribution network, the IEEE Low Voltage Test Feeder is modified to include a representation of part of the upstream MV network. The MV network is modelled as a delta-wye connected 33:11 kV Online Tap Changing (OLTC) transformer and a three-phase, 10 km line (R=2.13 Ω/km, X=1.55Ω/km). This connects the transformer to the MV substation in the IEEE test feeder model. The MV substation contains a delta-wye connected 11:0.416 kV transformer, which has no voltage regulation capability.

B. PV and EV Scenarios

Figure 6 shows a sample of the PV injections and EV charging demands, taken from actual recorded data in [22] and [23]. The following Scenarios 1-4 are applied in order to assess the impacts of PV and EV on the CVR factor and on the voltage in the secondary distribution network.

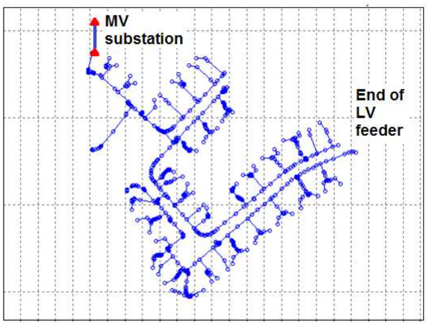
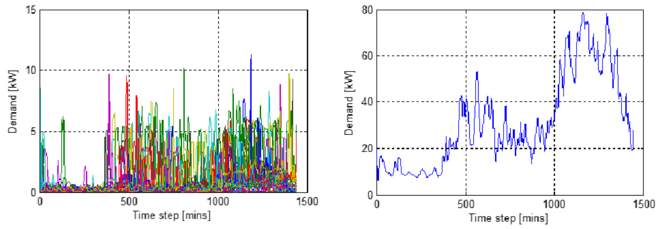


Figure 4. IEEE European Low Voltage Test Feeder network map.



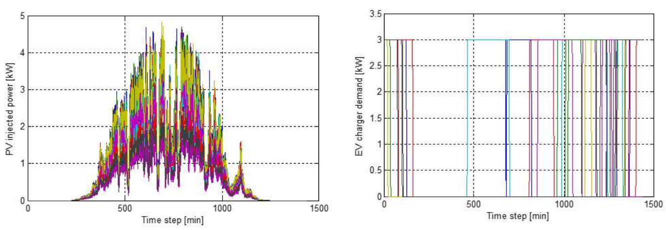
(a) (b)

Figure 5. Sample of the demand data a typical winter day: (a) 55 individual residential users; (b) aggregated demand profile.

- **Scenario 1**: No PV or EV.
- **Scenario 2**: PV at 50% penetration. PV generators are modelled as time-varying (1-min interval) P injections with unity power factor. Network nodes with PV are randomly-selected.
- **Scenario 3**: EV at 50% penetration. EV charging points are modelled as time-varying (1-min interval) with unity power factor. EV nodes are randomly-selected.
- **Scenario 4**: PV and EV both 50% penetration.

C. *Results of Scenarios 1-4*

1) Scenario 1: The impact on energy savings and secondary network voltages for the “No CVR” case (using the voltage at the feeder head as the control reference), and for the proposed “CVR” approach (using the voltage at the end of the LV feeder as the control reference) are shown in Table I. This shows the impacts on net kWh and kVarh imported into the secondary network, the maximum (daily peak) kW and kVA, and the total number of instances where LV network customers experience high ($V > 1.10$) or low ($V < 0.94$) voltage violations. The results in Table I show that CVR reduces the total energy imported over the course of the day by 22.43 kWh, or 4.2%, and reduces the peak demand by 1.6%. In Scenario 1, there are no voltage violations for either the No CVR or CVR case. However, the total number of OLTC transformer tap changes over the course of the day is significantly increased in the CVR case[1]. Figure 7 shows the simulated voltage in each phase at the head of the feeder in Figure 7(a) and at the end of the feeder in Figure 7(b).

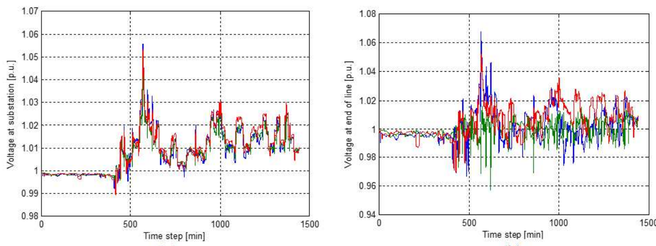


(a) (b)

Figure 6. Samples of input data: (a) PV injections; (b) EV charging demands.

TABLE I. SUMMARY OF SCENARIO 1.

	No CVR	CVR
Net energy imported (kWh)	534.55	512.12
Reactive power imported (kVArh)	142.95	140.68
Max active power (kW)	63.34	62.30
Max complex power (kVA)	66.32	65.27
Total low voltage violations ($V < 0.94$)	0	0
Total high voltage violations ($V > 1.10$)	0	0
Customers affected by low voltages (%)	0	0
Customers affected by high voltages (%)	0	0
Total MV transformer taps	2	79



(a) (b)

Figure 7. Simulated three phase voltages in secondary distribution network for Scenario 1: (a) at LV feeder head; (b) at end of LV feeder

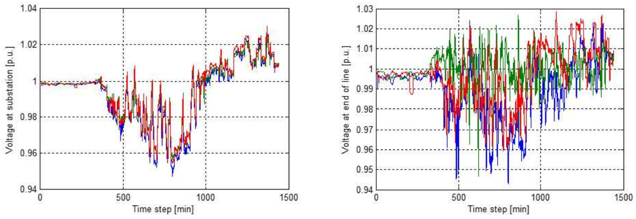
2) Scenario 2: In Scenario 2, 50% of the residential network users have rooftop PV installed and the PV power injection profiles shown in Figure 6(a) are applied. This high penetration of PV results in a net export of power from the MV substation over the course of the day, Table II. The voltage results in Table II show that in the No CVR case, there are a large number of high voltage violations, affecting 33 of the 55 customers in the LV network. High voltage violations are recorded for every 1-minute time slot in the simulation where the voltage at one of the LV load points exceeds 1.10 p.u.[2]. The CVR approach reduces the number of voltage violations in the LV network, but results in 151 transformer tap changes over the course of the day. Figure 8 shows the voltages in each phase at both ends of the feeder when CVR is applied.

[1]The lower voltage limit of 0.94 p.u. is selected rather than the regulatory limit of 0.9 p.u. in order to allow some margin for further voltage sags in the LV network and reduce the risk of voltage collapse. It may be possible to reduce the number of OLTC taps required by reducing the low voltage violation limit used in the analysis from 0.94 p.u. to 0.9 p.u.

[2]For instance, if the voltage exceeds 1.10 p.u. for 10 LV network customers over a 5 minute period, 50 high voltage violations are recorded.

TABLE II. SUMMARY OF SCENARIO 2 (50% PV).

	No CVR	CVR
Net energy imported (kWh)	-75.98	-80.66
Reactive power imported (kVArh)	147.44	141.72
Max active power (kW)	50.88	50.41
Max complex power (kVA)	79.82	73.70
Total low voltage violations (V < 0.94)	0	19
Total high voltage violations (V > 1.10)	1578	0
Customers affected by low voltages (%)	0	16
Customers affected by high voltages (%)	33	0
Total MV transformer taps	2	151



(a) (b)

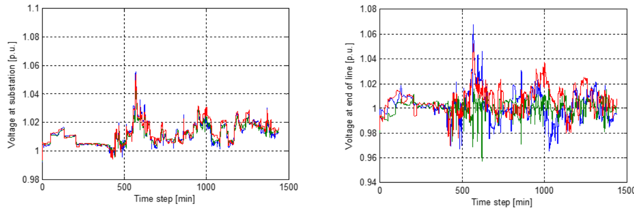
Figure 8. Simulated three phase voltages in secondary distribution network for Scenario 2 (50% PV): (a) at LV feeder head; (b) at end of LV feeder.

3) Scenario 3: In Scenario 3, 50% of the residential customers in the LV network have EV chargers installed, where each EV has a charging demand of 2 kW as shown in Figure 6(b). Table III shows that CVR reduces the net energy imported by 38.73 kWh and the peak demand by approximately 2.5%. Figure 9 shows the resulting voltages in each phase for the CVR case.

TABLE III. SUMMARY OF SCENARIO 3 (50% EV).

	No CVR	CVR
Net energy imported (kWh)	774.34	735.61
Reactive power imported (kVArh)	169.40	165.70
Max active power (kW)	68.84	67.01
Max complex power (kVA)	71.07	69.27
Total low voltage violations (V < 0.94)	0	0
Total high voltage violations (V > 1.10)	0	0
Customers affected by low voltages (%)	0	0
Customers affected by high voltages (%)	0	0
Total MV transformer taps	3	85

4) Scenario 4: Scenario 4 analyses the impact of 50% PV and 50% EV penetration in the secondary distribution network. Table IV shows that the total energy imported is reduced by 23.8 kWh in the CVR case and that the maximum peak demand is reduced by 2.5%. There are 1094 high voltage violations in the No CVR case affecting 35 customers. In the CVR case, there are a large number of transformer tap changes, and 69 low voltage violations (V < 0.94). Figure 10 shows the per phase voltages for the CVR case.



(a) (b)

Figure 9. Simulated three phase voltages in secondary distribution network for Scenario 3 (50% EV): (a) at LV feeder head; (b) at end of LV feeder.

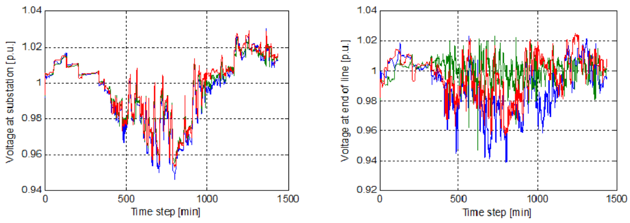
TABLE IV. SUMMARY OF SCENARIO 4 (50% PV + 50% EV).

	No CVR	CVR
Net energy imported (kWh)	163.82	140.02
Reactive power imported (kVArh)	172.37	165.39
Max active power (kW)	68.84	67.01
Max complex power (kVA)	71.07	69.27
Total low voltage violations (V < 0.94)	0	69
Total high voltage violations (V > 1.10)	1094	0
Customers affected by low voltages (%)	0	31
Customers affected by high voltages (%)	35	0
Total MV transformer taps	3	159

D. Sensitivity Analysis

The overall average CVR factor for the IEEE LV test case using the time-varying residential load model described in Section II-A was 0.76. This value corresponds with residential load CVR values reported in the literature in [3]-[9]. The sensitivity of CVR_f and ΔV_{max} to the load model parameters is examined in this section.

Figure 11(a) shows the sensitivity of the CVR factor to the load coefficient n_p and load power factor (PF). It is clear from the results that CVR_f is highly sensitive to the load model used in the analysis. For a constant power load (n_p=0), the CVR factor is 0, for a constant current load (n_p=1), the CVR factor is in the 0.7-0.8 range, and for a constant impedance load (n_p=2), the CVR factor is in the 1.4-1.5 range. This matches the CVR factors for common residential appliances provided in Figure 1 and [17]. Figure 11(b) shows the sensitivity of the maximum voltage deviation in the LV



(a) (b)

Figure 10. Simulated three phase voltages in secondary distribution network for Scenario 4 (50% PV + 50% EV): (a) at LV feeder head; (b) at end of LV feeder.

network, ΔV_{max}, to the load model parameters. The main observations are that voltage deviation has a low sensitivity to the load model coefficient n_p but is highly sensitive to the power factor. It was shown in the results for Scenarios 1-4 in Section III-C that ΔV_{max} is also sensitive to PV injections and EV charging demands.

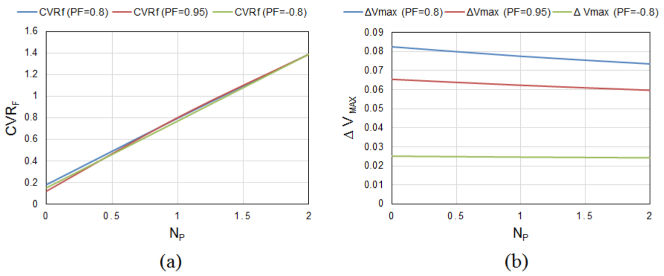


Figure 11. Sensitivity of (a) CVR factor and (b) maximum voltage deviation to the load model coefficient n_p and load power factor.

IV. Discussion and Conclusions

This paper analyses the potential for CVR in secondary distribution networks with high penetrations of PV generation and EV charging loads. The analysis compares the current utility practice of controlling voltage in the "upper range" of 1.0 - 1.1 p.u. using the voltage at the feeder head as the reference to a CVR approach where voltage is managed at a lower, but still acceptable level using the voltage at end of the LV feeder as the reference. The results for Scenarios 1-4 in Section III suggest that energy savings of 4.2% in total kWh and 2.5% in maximum kVA demand can be obtained in this LV network without significant impacts on the voltage quality at residential customer load points.

The results in Section III-C demonstrate that voltage control is a major challenge in secondary networks with high penetrations of PV and EV. A large number of OLTC tap changes are required in order to maintain voltage within acceptable limits for the PV and EV scenarios tested. A limitation of this study is that the PV and EV units are modelled as time-varying power injections with fixed power factor. Future work will investigate the possibility of additional voltage control being provided at LV load points via advanced PV inverters [16]. The results of the sensitivity analysis in Section III-D demonstrate the importance of accurate load modelling in the CVR study. In this paper, time-varying, component-based load models are used to estimate the load voltage dependency. Further research will develop and improve these models for use in CVR studies and include a more accurate representation of motor loads, loads with advanced control cycles, and emerging load types.

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