Smart-Grid-Enabled Distributed Reactive Power Support with Conservation Voltage Reduction

Hao Jan Liu, Student, IEEE, and Thomas J. Overbye, Fellow, IEEE

***Abstract*—As solar energy continues to increase in the current power grid, the reactive power support capability from their grid-tie inverters may be used to regulate feeder voltage and reduce system losses on medium- and low-voltage distribution systems. The focus of this paper is to develop a smart-grid-enabled control algorithm that will determine the amount of reactive power injection required at each node to minimize the deviation from the control voltage level. Once the voltage level is being achieved, implementing Conservation Voltage Reduction (CVR) further benefit the system by increasing energy saving. The method is tested on a modified IEEE-13 node feeder system and simulations are performed in OpenDSS using the same system to validate the results.**

***Index Terms*—Photovoltaic (PV) systems, distributed power generation, reactive power support, voltage control, conservation voltage reduction (CVR), OpenDSS, distributed control, distribution network.**

I. INTRODUCTION

SOLAR photovoltaic (PV) power systems are one of the fastest growing renewable energy sources in the world. Industry statistics show that the total capacity of grid-connected PV power systems has grown rapidly between 2005 and 2012, reaching a total of 3313 MWdc in 2012, as shown in Fig.1 [1]. Before 1999, PVs were mostly used in off-grid applications, such as rural electrification, telecommunications, water pumping systems, and sign lighting. However, with advancing technologies and the issues of green house gas emissions, over 78% of existing PVs are used in grid-connected applications where the power is fed into the electrical network [2]. As the prices for the solar modules continue to fall, this will mostly likely to lead to increase penetration of PV in the power system. Since most distributed PV systems are in the distribution network, understanding its impact on the stability and operation of the grid is vital.

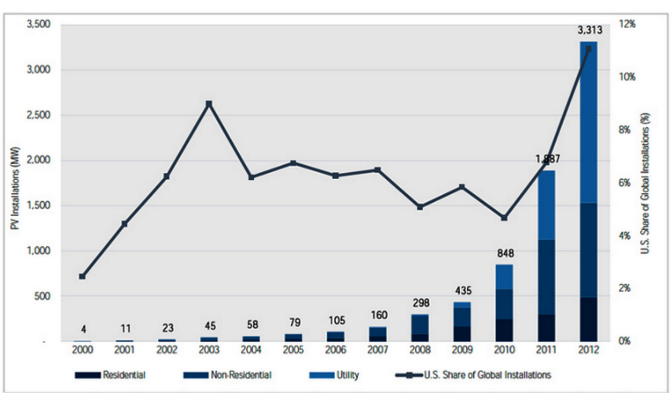

Figure 1. U.S. PV Installations and Global Market Share, 2000-2012 [1]

The impacts of high penetration of PV have been studied in existing literature, and can be classified into two groups: impacts on distribution and impacts on transmission. These impacts affect distribution system protection planing, voltage profiling, system stability, energy quality, network planning, and economics [3]. Voltage irregularities are one of the major power quality issues and 95% of the problems in electrical systems stem from voltage problems. An overvoltage caused by reverse power flow may reduce the life of electronic devices, increase the energy consumption of certain loads, and reduce light bulb life [4]. It also limits the active power output from PV systems. A typical 3-6 kW PV systems will inject most of its power back to the grid on a clear day. Therefore, reverse power flow causes a voltage rise among feeder lines. In the case of light loading, voltage may exceed the upper limit of ANSI Range A at the Point of Common Coupling (PCC) [5],[6]. On the other hand, a low steady-state voltage under heaving loading may lower lighting levels, shrink TV pictures, and overheat motors [7]. Therefore, it is imperative that the feeder voltage is monitored and controlled in order to minimize potential voltage problems.

Traditionally, there are several voltage control techniques used to keep feeder voltages within permissible limits in the distribution systems. The voltage regulator at the distribution substations and primary feeders can raise or lower its voltage depending on the current loading conditions to maintain the desired feeder voltage. Adding capacitor banks at feasible locations along the feeder would also alleviate undervoltage problem and decrease system losses. Other techniques include increasing feeder conductor size, changing feeder from single-phase to multi-phase, and rerouting loads to new feeders [3]. Different system topologies may require different control schemes to regulate its voltage.

Under the current regulation in the US, PVs are only allowed to inject real power back to the grid [8]. However, there have been many suggestions to change standards which are unsustainable and even inhibit certain PV benefits such as reactive power support capability from the PV's grid-tie inverter [9]. Since the inverter must be sized for peak sun conditions, it will practically always have spare reactive power support capacity during the daytime and full reactive power support capacity at night. Reactive power is mostly used to minimize system losses and provide voltage regulation in transmission systems. Since reactive power is very local, it is most efficient to have the support scheme dispersed throughout the systems. As the X/R ratio is lower in the

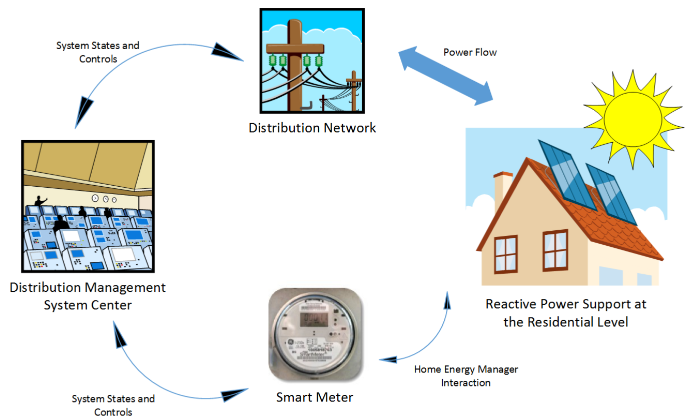

Figure 2. Smart-Grid Communication Scheme

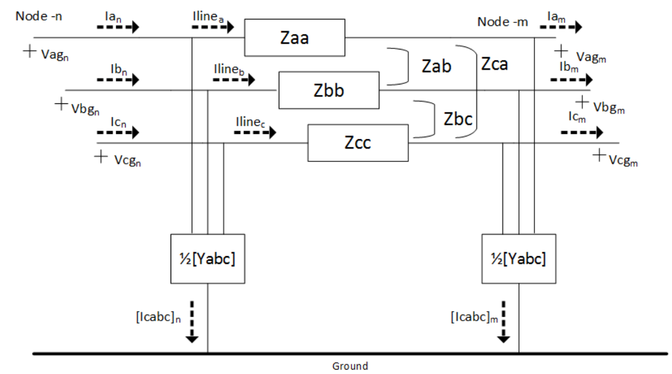

Figure 3. Three-phase Exact Line Segment Model

distribution network, voltage is sensitive to both active and reactive power. In this work, the reactive power support from grid-tie inverters is considered as an alternative way to control the voltage profile. With the communication advantages and system feedback provided by smart-grid devices as shown in Figure 2, the idea is to find an optimal reactive power support level to improve power factors and obtain the desired voltage profile.

One of the major issues most electric utilities are facing today is conservation of energy in distribution systems. The idea of conservation voltage reduction (CVR) may decrease the total power consumption by reducing voltage at the substation level [10]. This method has been studied and performed by many utilities; however, the results are inconsistent with each other due to highly dependencies on network topology and nature of the load. CVR is best suited for constant impedance loads since the energy consumption is directly proportion to its voltage. On the other hand, some motor loads are less sensitive to CVR. The small decrease in load power consumption may be very beneficial to distribution utility companies if it is performed during peak loading condition across a wide area in a competitive market environment.

Many electric utilities have practiced CVR as an emergency measure to reduce loading during critical loading periods. During the severe shortage of generating capacity in the 1960's, CVR was frequently used to balance power supply and demand. The first wide scale implementation of CVR was conducted by the American Electric Power Service Corporation (AEP) in New York during the Arab oil embargo in 1973. The report shows an average 3% drop in load when the voltage was reduced by 5% for 4 hours. However, the study neglected CVR capital costs when calculating the savings [11]. Since then CVR was adopted by many utility companies using different strategies, the results of these studies were not well documented until BC Hydro's 2010 report. BC Hydro is one of the pioneers in North America in implementing Voltage VAR Optimization (VVO) in distribution systems. The first project was carried out with the main objective of minimizing distribution substation peak loading conditions and alleviating the transmission system capacity constraints. The report shows that for a 1% voltage reduction, the energy saving per year is around 1.3 GWh (~1%) while the peak winter demand was reduced by 1.6MW (1.1%). In 2005, Hydro-Quebec also launched a CVR pilot project; results show that for 1% voltage reduction, the reduction in energy is about 1.5 TWh (0.4%) on its tested system [12]. The more recent studies from EPRI shows an annual energy reduction of between 0.16% and 1.2% in active energy when CVR is implemented in a given test feeder system [13]. In [14], authors shows that a 4% reduction in voltage can be implemented in most of New York City without any further financial investment in the current network, and the energy saving is around 2.5 % for the whole year. The goal of this paper is to strategically use distributed reactive power control to flat the voltage profile. After the desire voltage level is achieved, the substation voltage is regulated at its lowest permissible level without any voltage violation in the system in order to minimize the system energy consumption and losses.

This paper is presented as follows: Section II provides an overview of distribution network power flow modeling. Section III proposes the distributed reactive power support algorithm with CVR, and in Section IV, a modified IEEE 13-node feeder system with PV is examined in Matlab and OpenDSS. The paper is concluded in Section V.

II. Distribution Network Power Flow Modeling

It is critical to understand the models and equations used to represent overhead and underground line segments in distributions system since most of the lines are untransposed and the loadings are unbalanced. The following equations are derived and formulated in [15]. Figure 3 represents the total impedance and admittances for a three-phase line segment. Applying Kirchhoff's Current Law (KCL) and Voltage Law (KVL), the following equations will be obtained:

$$[VLG_{abc}]_n = [a] \cdot [VLG_{abc}]_m + [b] \cdot [I_{abc}]_m \quad (1)$$

$$[I_{abc}]_n = [c] \cdot [VLG_{abc}]_m + [d] \cdot [I_{abc}]_m \quad (2)$$

$$[VLG_{abc}]_m = [a]^{-1} \cdot ([VLG_{abc}]_n - [b] \cdot [I_{abc}]_m) \quad (3)$$

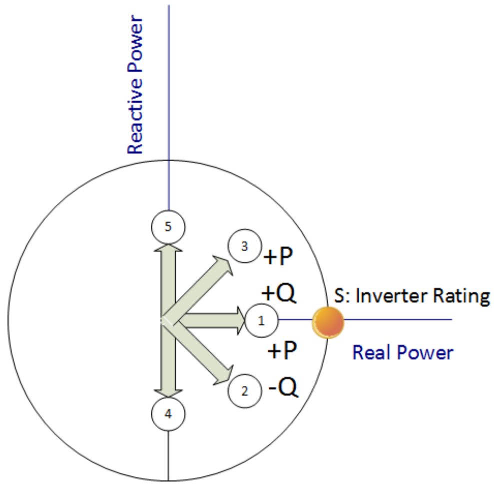

Figure 4. PV Inverter P/Q Capability Curve

$$[a] = [u] + \frac{1}{2}[Z_{abc}] \cdot [Y_{abc}] \tag{4}$$

$$[b] = [Z_{abc}] \tag{5}$$

where $[u]$ is an identity matrix, and

$$[c] = [Y_{abc}] + \frac{1}{4} \cdot [Y_{abc}] \cdot [Z_{abc}] \cdot [Y_{abc}] \tag{6}$$

$$[d] = [u] + \frac{1}{2} \cdot [Z_{abc}] \cdot [Y_{abc}] \tag{7}$$

Since most distribution feeders are radial, the iterative Newton-Raphson and Gauss-Seidal methods are not suitable for distribution power flow analysis [16]. Instead, the ladder iterative technique is used. It has two basics steps: the backward sweep using Equations 1 and 2 to find the corresponding voltage and current, while the forward sweep uses Equation 3 to calculate voltages in a distribution feeder. The sweep process is continued until the difference between the specified and computed source voltage is below a given tolerance.

The load is then represented in classic voltage dependent ZIP model [17]:

$$P = P_o \cdot [Z_p \cdot (\frac{V}{V_0})^2 + I_p \cdot (\frac{V}{V_0}) + P_p] \tag{8}$$

where P_o is the real power consumption at rated voltage, and $Z_p + I_p + P_p = 1$ are normalizing constraints to ensure that load model consumes rated power at its rated voltage.

Moreover, individual grid-tie inverter is able to provide reactive power locally when operating within the power rating limit. A PV inverter operates in two quadrants (modes 1-5) dependent upon its power rating as shown in Figure 4. Mode 1 is the base case where only the real power is produced and no reactive power is injected into the system. Modes 2 and 3 show power injection at a lagging and leading power factor respectively. Both the current magnitude and angle can be adjusted with appropriate power electronics controls. Modes 1, 2, and 3 are mostly likely to be in operation during the day, when there is some real power injection coming from the solar isolation, while modes 4 and 5 are solely reactive power absorption and injection (respectively) and will be used during the nighttime when there is no real power output from the PVs.

$$Q_i^{maxinj} = \sqrt{(S_i^{rate})^2 - (P_i^{inj})^2} \tag{9}$$

Equation 9 determines the instantaneous capability of reactive power support in the i^{th} PV inverter, where Q_i^{maxinj} is the maximum reactive power support, S_i^{rate} is the power rating of the inverter, and P_i^{inj} is the real power output from the PV.

The smart-grid technologies enable systems to coordinate reactive power resources over a secure communication infrastructure. The goal of residential smart meters is to provide two-way communication between the end-users and the control center. This opens the door to system feedback, which can be used to achieve some optimal control strategies, e.g. minimize the feeder losses or maintain a voltage at a certain bus. Since each load in the distribution system is served from different feeders or circuits and the system is usually radial, the analysis is different from that of the transmission system. The following section will focus on smart-grid-enabled reactive power support with CVR algorithms that assume piecewise steady state operating conditions, full knowledge of system states, and two-way communications between the end-users and the control center in the distribution system.

III. Distributed Reactive Power Support with CVR

Implementing CVR improves energy saving in the system, since system losses are inversely related to reduction in voltage, it is difficult to find an operating point which maximizes energy saving and minimizes the total system losses. The maximum energy reduction occurs when each node is at its lowest allowable voltage level. System losses may also behave differently depending on the network topology. System losses under CVR are critical because they have a direct impact on the efficiency of the network. The losses include losses in cables and losses in trnsformer cores and windings. The losses from cables and transformer windings are proportional to the square of the current, while transformer core losses are proportional to the square of the voltage. When the voltage reduces due to CVR, the cable and winding losses increase due to the increase in current. On the other hand, the core losses reduce as a result of voltage reduction. These two types of losses behaves oppositely with CVR. Results in [14] shows that the size of network, load, and topology influence the behavior of system losses. However, CVR in secondary distribution networks improve the overall system efficiency. To overcome this issue, a distributed voltage support framework with CVR is proposed. Equation 10 is a constrained nonlinear optimization problem which can be solved using Sequential Quadratic Programing (SQP). The goal is to use distributed reactive power resources at each available node to flatten out the feeder voltage profile to 1 p.u. and then the substation voltage is to be controlled at its lowest setting so no voltage violations would occur in the given feeder. This method ensures that every node is at its lowest permissible voltage level which in turn maximizes energy saving.

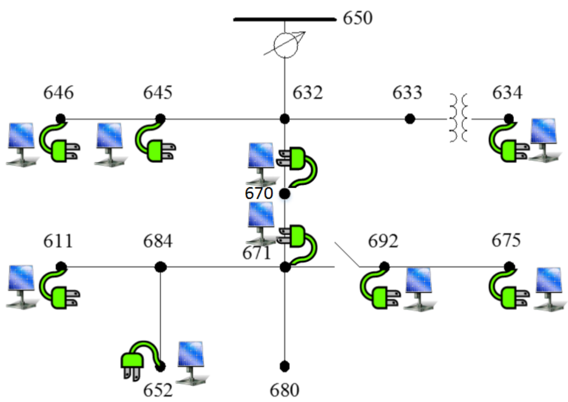

Figure 5. IEEE Modified 13 Nodes Feeder

Class	Z_p	I_p	P_p	Z_q	I_q	P_q
Large Commercial	0.47	-0.53	1.06	5.30	-8.73	4.43
Small Commercial	0.43	-0.06	0.63	4.06	-6.65	3.59
Residential	0.85	-1.12	1.27	10.96	-18.73	8.77
Industrial	0	0	1	0	0	1

Table I
ZIP COEFFICIENTS FOR DIFFERENT CUSTOMER CLASS [14]

$$min\ f(\underline{x}, \underline{u}) = \parallel \underline{V} - \underline{V}_{control} \parallel_2 \tag{10}$$

$$s.t.\ \underline{g}(\underline{x}, \underline{u}) = 0$$

$$\underline{h}(\underline{x}, \underline{u}) \leq 0$$

In Equation 10, $\underline{x}$ is the unknown system state vectors obtained by solving distribution power flow equations, and $\underline{u}$ is the control vector; in this case, it is the controllable reactive power injection from each node. $f(\underline{x}, \underline{u})$ is the objective function and $\underline{g}(\underline{x}, \underline{u})$ and $\underline{h}(\underline{x}, \underline{u})$ represent the equality constraints from power equations and the inequality constraints from system physical limitations, respectively. $\underline{V}_{control}$ is set to 1 p.u. In a more general case, reactive power support is not always available at each node. Due to the lack of reactive power support at certain locations, the voltage profile may not be flat, but it is the best voltage profile that can be achieved for a given case.

IV. SIMULATION

The method described in the previous section is applied to the modified IEEE-13 node feeder system, as shown in Figure 5. Each individual load is modeled as an aggressive residential ZIP model. The ZIP coefficient and load information are obtained from Table I. As in a more general case, reactive power support is not available at every single node in the system. The voltage limits of $V_{min} = 0.95$ and $V_{max} = 1.05$ are chosen accordingly with ANSI standard for distribution networks.

As shown in Figure 6, the total power consumption decreases at the substation as a result of the control algorithm. On the other hand, due to excess amount of reverse reactive

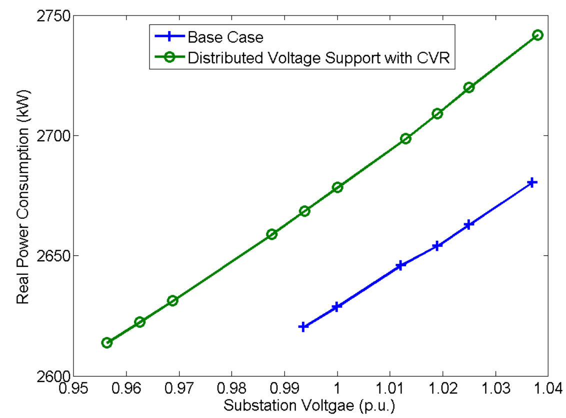

Figure 6. Real Power Consumption at Substation: Distributed Voltage Support with CVR

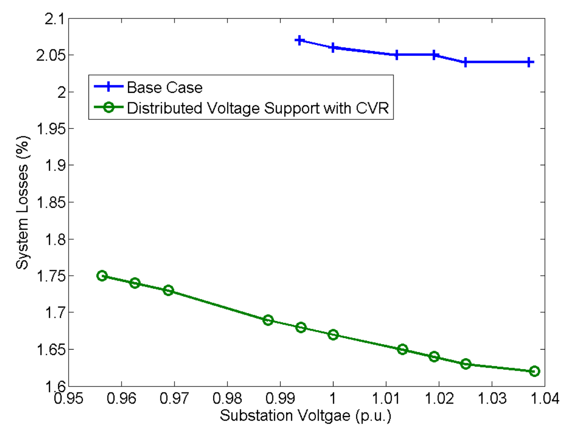

Figure 7. System Losses at Substation: Distributed Voltage Support with CVR

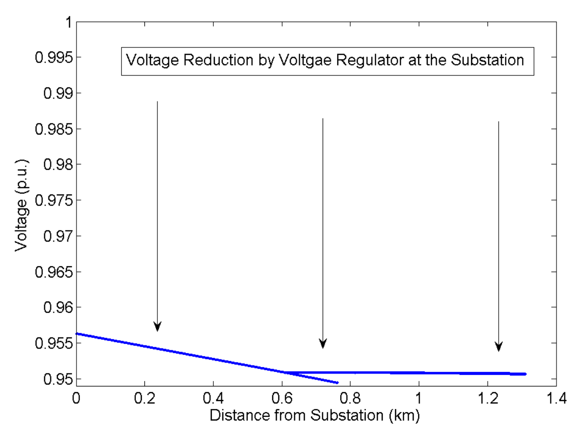

Figure 8. Voltage Profile after Distributed Voltage Support with CVR

Table II
CVR METHODOLOGIES COMPARISON

	Sub. Voltage	Load (kW)	Losses (%)
No CVR	1.037	2680.5	2.04
Base Case CVR	0.9936	2620.4	2.07
Losses Min. with CVR	0.9688	2618.3	1.58
Dist. Volt. Support with CVR	0.9563	2613.7	1.75

power flow in the network, the system losses increase compared with losses minimization with CVR method. Overall, distributed voltage support with CVR maximizes the energy saving in the system and improves the system losses when compared with implementing CVR alone, as shown in Figure 7. Table II summarizes the overall effectiveness of the CVR methodologies. Compared with the case without CVR, the proposed distributed voltage support with CVR reduces power consumption by 66.8kW in the current loading condition while improving the system losses by 0.29%.

V. Conclusion

This paper proposes a distributed reactive power support with CVR algorithm that uses a two way communication provided by smart-grid technology. The solutions are obtained from SQP to minimize the deviation from the control voltage level. The control algorithms are tested in the modified IEEE-13 node feeder system; results show that voltage reduction with distributed reactive power support in the given system is feasible and beneficial. The proposed method not only solves undervoltage issues locally but also attains significant savings in energy while reducing system losses.

For future work, the current method will be incorporated with a distributed control mode combining decentralized and centralized schemes. The distributed control scheme will not only determine the amount of reactive power injection required at each node to achieve the objective function, but also reduce communication since the numerous distributed resources do not communicate with the higher-level control. Several cyber-security issues will also be examined to ensure a "smarter" future power grid.

References

[1] *U.S. Solar Market Insight - 2012 Year in Review*, GTM Research Std.

[2] R. McMonagle, *The Potential of Solar PV in Ontario*, The Canadian Solar Industries Association Std., January 2006.

[3] J. S. N. Hadjsaid, *Electrical Distribution Networks*. John Wiley & Sons, Inc., 2011.

[4] J. Peas Lopes, "Integration of dispersed generation on distribution networks-impact studies," in *Power Engineering Society Winter Meeting, 2002. IEEE*, vol. 1, 2002, pp. 323–328 vol.1.

[5] Y. Ueda, K. Kurokawa, T. Tanabe, K. Kitamura, and H. Sugihara, "Analysis results of output power loss due to the grid voltage rise in grid-connected photovoltaic power generation systems," *Industrial Electronics, IEEE Transactions on*, vol. 55, no. 7, pp. 2744–2751, 2008.

[6] C. L. Masters, "Voltage rise: the big issue when connecting embedded generation to long 11 kv overhead lines," *Power Engineering Journal*, vol. 16, no. 1, pp. 5–12, 2002.

[7] T. Gonen, *Electric Power Distribution System Engineering*. CRC, 2008.

[8] "Ieee standard for interconnecting distributed resources with electric power systems," *IEEE Std 1547-2003*, pp. 1–16, 2003.

[9] K. Rogers, R. Klump, H. Khurana, A. Aquino-Lugo, and T. Overbye, "An authenticated control framework for distributed voltage support on the smart grid," *Smart Grid, IEEE Transactions on*, vol. 1, no. 1, pp. 40–47, 2010.

[10] G. Park and R. Colony, "Voltage reduction as a means of reducing distribution load," *Power Apparatus and Systems, IEEE Transactions on*, vol. 96, no. 2, pp. 628–634, 1977.

[11] R. F. Preiss and V. J. Warnock, "Impact of voltage reduction on energy and demand," *Power Apparatus and Systems, IEEE Transactions on*, vol. PAS-97, no. 5, pp. 1665–1671, 1978.

[12] S. Lefebvre, G. Gaba, A.-O. Ba, D. Asber, A. Ricard, C. Perreault, and D. Chartrand, "Measuring the efficiency of voltage reduction at hydro-quebec distribution," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1–7.

[13] W. Sunderman, "Conservation voltage reduction system modeling, measurement, and verification," in *Transmission and Distribution Conference and Exposition (T D), 2012 IEEE PES*, 2012, pp. 1–4.

[14] M. Diaz-Aguilo, J. Sandraz, R. Macwan, F. de Leon, D. Czarkowski, C. Comack, and D. Wang, "Field-validated load model for the analysis of CVR in distribution secondary networks: Energy conservation," *Power Delivery, IEEE Transactions on*, vol. 28, no. 4, pp. 2428–2436, 2013.

[15] W. H. Kersting, *Distribution System Modeling and Analysis*. New York, NY: CRC Press, 2001.

[16] K. Balamurugan and D. Srinivasan, "Review of power flow studies on distribution network with distributed generation," in *Power Electronics and Drive Systems (PEDS), 2011 IEEE Ninth International Conference on*, 2011, pp. 411–417.

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