Combined Effect of CVR and DG Penetration in the Voltage Profile of Low-Voltage Secondary Distribution Networks

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***Abstract*—In this paper, the voltage profile of secondary networks under conservation voltage reduction and distributed-generation (DG) penetration is studied for the first time. Three networks in New York City, modeled in detail, are used as study cases. Interconnection of DG is proposed to eliminate localized low-voltage violations due to a voltage reduction of 4%, 6%, and 8% from the normal schedule. The selection of the type of DG is based on the requirements imposed by the various interconnection standards, most notably IEEE 1547, public service commission, and local utility regulations. It is found that a small percentage of DG penetration would alleviate voltage violations. The study shows that DGs installed in distributed networks improve voltage regulation, allowing utilities to use deeper voltage reductions during critical conditions. It is also shown that the network power factor is reduced when penetration of DG is high and, thus, the line drop compensation needs to be adjusted for the characteristics of the new power demand.**

***Index Terms*—Conservation voltage reduction (CVR), distributed-generation (DG) allocation, DG penetration, distributed power generation, energy conservation, load model, secondary network, voltage profile, ZIP coefficients.**

I. Introduction

As THE penetration of distributed generation (DG) in electric power systems (EPS) increases, so do the reliability and economic benefits. Utility regulators have been a driving force toward accelerating the implementation of DG [1]. The DG interconnection requirements began with the IEEE Standard 929 in 1988 [2]. Uniform mandatory interconnection requirements at the point of common coupling (PCC) were developed in 2003 for all types of DGs in IEEE Standard 1547 [3]. Due to the large variations in distribution system configurations and situations where DG may be connected, a series of standards was developed as the guide on impact studies for DG interconnection [4], [5]. The recommendations for DG interconnection with secondary networks are given in IEEE Standard 1547.7 [4].

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Penetration is a percentage/dynamic measure of the amount of power delivered/generated by interconnected DG compared with the total generation resources on a power system for a specific time of loading [1]. Penetration is not a static measure since a small percentage of DG penetration during peak load could be a high level of penetration under light load conditions. Different types of DGs have the potential to substantially affect system performance. For instance, conventional-type synchronous generators can have a greater effect on customer voltage than inverter-based DG or induction generators. However, regulation, cost, and reliability impose limitations on synchronous DG deployments in distribution systems as the short-circuit capacity of the installed breakers may be exceeded.

The compromise between DG interconnection requirements for the avoidance of islanding and the security of the EPS have been studied in [6]–[8]. Numerous studies have investigated the optimal placement of distributed generation in power systems [9]–[11].

The benefits of DG interconnection can be summarized as [1], [9], [10]:

- standby/backup power availability and reliability;
- peak load shaving;
- combined heat and power;
- sales of power back to utilities or other users;
- renewable energy;
- power quality, such as reactive power compensation and voltage support;
- dynamic stability support.

Voltage variation studies when a significant portion of the total generation is DG have been performed in [11]–[15]. Previous efforts introduced a comprehensive analysis of the possible impacts of different penetration levels of DG on voltage profiles in low-voltage secondary distribution networks [16]. The work aimed to explore the maximum amount of DG that secondary distribution networks can withstand in a probabilistic fashion. A field-validated load model for the calculation of conservation voltage reduction (CVR) in several secondary networks was presented in [17]. Both studies [16], [17] concluded that the implementation of DG or CVR will provide energy and economic savings for the utility and the customers. Many power utilities are moving toward implementing CVR [18]–[22]. The benefits of CVR in terms of energy savings and loss reduction have been studied in [23]–[25] while different implementation methods of CVR are described in [26] and [27].

A recent study on peak demand reduction and energy conservation favored volt/var optimization via power factor correction

TABLE I
NETWORK TOPOLOGY AND DEMAND

Network	Sutton	Madison Sq.	Yorkville
High voltage	69 kV	138 kV	138 kV
No. of substation transformers	7 (69/13.8 kV)	5 (one spare) (138/13.8 kV)	4 (3-winding transformers) (138/13.8 kV)
No. of breakers	27	45	45
No. of network transformers	224	462	542
No. of primary feeders	12	24	29
Light load demand	47 MW	90.7 MW	118.4 MW
Peak load demand	141.7 MW	307 MW	250 MW

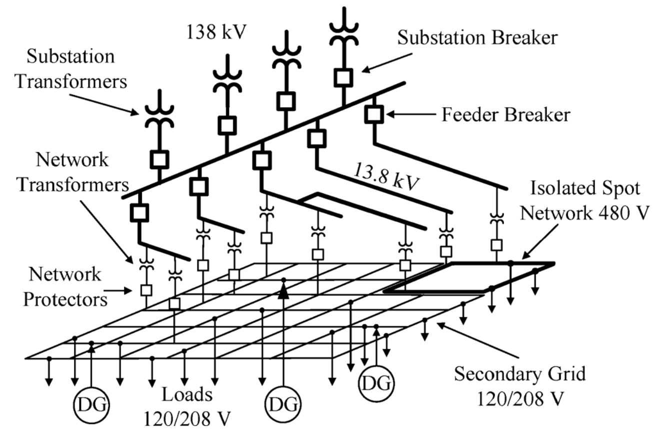

Fig. 1. Illustration of an LV secondary network, including high voltage, substation, loads, transformers, DG, and a typical structure of an isolated spot network. In New York City, the LV networks operate at 208/120 V and isolated spot networks are fed at 460 V.

over CVR via active voltage regulation [28]. The study used load model-based approaches for the application of CVR using two load categories: with and without thermal cycles. A comparison of the polynomial static load model against the physical load model gave credit to the latter model when dynamic load behavior is considered. Another study highlighted the role of feeder characteristics for CVR applications [29]. It was concluded that short feeders on densely populated networks would be most convenient to achieve the economical goal of CVR. A counter opinion was presented in [30]. Reference [31] shows that CVR provides energy and economic savings for the utility and the customer. The results of [16] and [17] led to a challenge to study the behavior of low-voltage distribution networks with the combined effect of CVR and DG penetration.

The interaction of DG implemented in a secondary grid can become more challenging when the EPS is under different operating voltage conditions; for example, CVR or in periods of stress in the network due to contingencies. This becomes more pronounced with a higher DG penetration as the network power factor reduces. This causes further reduction in the line-drop compensation (LDC) setting compromising the voltage limits. Thus, research on the integration of customer generation in a distributed network with different types of interconnected DGs is needed to determine the impact on the steady-state behavior of the system.

The main contribution of this paper is to show how a small percentage of DG penetration can alleviate voltage violations when CVR is applied. This enables further reducing the voltage and, therefore, increasing the energy savings. The study is performed on several secondary networks in New York City, taking into account the behavior of different types of DG distributed in realistic scenarios.

All simulations are performed with the open-source simulation package developed by EPRI: OpenDSS [32]. The networks and DG models were validated against New York City utility records and the models developed in previous studies [16], [17].

II. NETWORK MODELING

A. Topology of the Networks Under Study

The networks under study are: Madison Square, Sutton, and Yorkville, all located in Manhattan. The selection of networks was made to test different load compositions and a varied number of customers. Some details of the networks are described in Table I.

TABLE II
NETWORKS' TOTAL LOAD AND LOAD COMPOSITION

Network		Sutton		Madison		Yorkville	
No. of Structure/ Load points	LT loads (120/ 208V)	311	284	1122	1102	2282	2272
	HT loads (460V)		27		20		10
Load composition	Small residential	6.3 %		11.1 %		16.3 %	
	Large residential	3.9 %		9.7 %		0.0 %	
	Small commercial	1.9 %		3.8 %		16.4 %	
	Large commercial	87.9 %		75.3 %		61.2 %	
	Industrial	0.0 %		0.0 %		6.1 %	

Power is fed into the low voltage grid network serving low tension (LT) customers at 120/208 V and a small percentage of high tension (HT) local building buses (spot networks at 460 V). Detailed description of the load composition of the three networks is given in Table II. Fig. 1 shows a simplified topology of the network with loads, transformers, and the typical structure of an isolated spot network. For reliability purposes, the distribution system of New York City and the downtown core of many cities in North America, use large interconnected low-voltage (208/120 V) networks to supply loads of hundreds of megawatts. This is different from most other locations where the systems are mostly radial and supply loads of only a few hundreds of kilowatts.

The three networks selected are of various sizes and demands: a small network (Sutton), a medium network (Madison Square), and a large network (Yorkville) with different load compositions.

B. Network Model

In a previous study carried out by the authors, a polynomial static load model with ZIP coefficients was used to represent the power consumed by a load as a function of voltage [17], [33]. ZIP parameters are the coefficients of a load model comprised of constant impedance Z, constant current I, and constant power P loads. ZIP-based load models were developed for residential,

TABLE III
SAMPLE OF THE IMPLEMENTED VOLTAGE SCHEDULE

Total 13.8 kV Bus Load (MW)	No CVR		2.25% reduction		4 % reduction		6% reduction		8 % reduction	
	Feeder Bus Voltage (kV)	% Reduction	Feeder Bus Voltage (kV)	% Reduction	Feeder Bus Voltage (kV)	% Reduction	Feeder Bus Voltage (kV)	% Reduction	Feeder Bus Voltage (kV)	% Reduction
0-50	13.3	0 %	13.0	2.26 %	12.76	4.06 %	12.50	6.02 %	12.23	8.05 %
51-90	13.4	0 %	13.1	2.24 %	12.86	4.03 %	12.59	6.01 %	12.32	8.02 %
91-130	13.5	0 %	13.2	2.22 %	12.96	4.00 %	12.69	6.00 %	12.42	8.00 %
131-170	13.6	0 %	13.3	2.21 %	13.06	3.97 %	12.78	5.99 %	12.51	7.98 %
171-210	13.7	0 %	13.4	2.19 %	13.16	3.94 %	12.88	5.99 %	12.61	7.96 %

commercial, and industrial loads [33]. The models were validated in the field for the networks under study. Experimentally validated network models are used to analyze the behavior of the distribution networks under the combination of CVR and DG penetration. The DG models used in the study are selected from the OpenDSS library, and they have been validated against Electromagnetic Transients Program (EMTP) results in [16].

Using actual data, the network model was built in OpenDSS. The data include primary feeders, transformers, network protectors, and secondary mains with each customer represented as a ZIP coefficients load. The behavior of the DG (synchronous generators and inverter-based DG) is considered using the existing models from the OpenDSS library. Capacitors are modeled based on the network load demand. As an example, the Sutton network has two switching capacitors, one of them is connected at medium load (50% to 75% of demand), two are connected at peak load, and no capacitors are connected at light load.

The network voltage is controlled exclusively from the area substation onload tap changer transformers. CVR is implemented by reducing voltage at the substation by controlling the line-drop compensation (LDC) mechanism. A lower LDC setting at the substation allows voltage reduction to be implemented. Table III shows a sample voltage schedule with the voltage reduction level for various network demands.

C. Load Models

To obtain reliable results, a voltage-sensitive load model was used for all networks. Both watts and vars vary with voltage based on typical residential, commercial, and industrial customers in New York City. The loads connected on the secondary network are represented as a static load model with their polynomial ZIP coefficients. The models have been obtained from numerous voltage reduction tests performed in the laboratory on many domestic appliances performed on typical residential, commercial, and industrial customers in New York City. These experiments are described and documented in [33].

The polynomial expressions for active and reactive powers of the ZIP coefficients model are

$$P = P_0 \left[Z_p \left(\frac{V_i}{V_0}\right)^2 + I_p \left(\frac{V_i}{V_0}\right) + P_p \right] \quad (1)$$

$$\text{Subject to} \quad Z_p + I_p + P_p = 1 \quad (2)$$

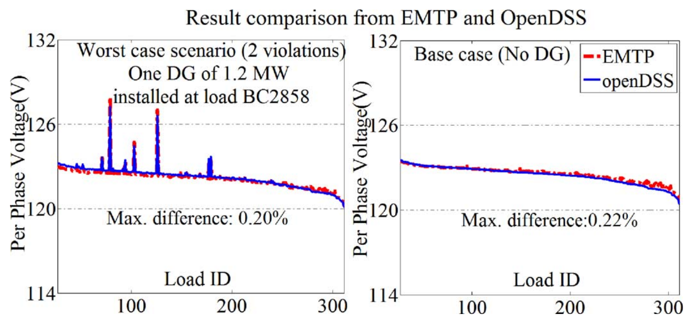

Fig. 2. Comparison of results for the customer voltage profile at 120 V from OpenDSS and EMTP for the worst case scenario (left) and base case with no DG (right) reported in [16].

$$Q = Q_0 \left[Z_q \left(\frac{V_i}{V_0}\right)^2 + I_q \left(\frac{V_i}{V_0}\right) + P_q \right] \quad (3)$$

$$\text{Subject to} \quad Z_q + I_q + P_q = 1 \quad (4)$$

where P and Q are the active and reactive powers at operating voltage (V_i); P_0 and Q_0 are the active and reactive powers at rated voltage (V_0); Z_p, I_p, and P_p are the ZIP coefficients for active power; and Z_q, I_q, and P_q are the ZIP coefficients for reactive power.

The networks under study are highly integrated with diverse residential, commercial, and industrial loads. Each load is classified into one of the four following categories: small or large residential, commercial, or industrial. Each load is then represented with the appropriate ZIP coefficients model.

III. DG STUDY UNDER CVR

A. Network Model Validation

The analysis presented here is based on the detailed three-phase model developed in [17] using network characteristic and real data records (for 2010). The results of steady-state (power-flow) simulations under DG penetration were verified against EMTP time-domain simulations reported in [16]. Reproduction of several events and DG penetrations of the same network were compared and validated. Fig. 2 shows the voltage profile comparison between OpenDSS and EMTP for the base case (with no DG) and the worst case scenario reported in [16].

B. Voltage Violation Study

The application of CVR in highly meshed secondary networks is known to have a satisfactory impact on energy savings and losses [17]. However, voltage reduction can produce undervoltage violations at some loads. Utilities are mandated to keep voltage values within acceptable ranges across all of the nodes in the network, both on the primary and secondary sides. For the purpose of this study, voltage reduction simulations of each network were performed to identify all loads/structure points with violations on the peak hour of the year. Voltage reduction operations are performed for voltage levels of 2.25%, 4%, 6%, and 8% and a voltage violation of 5% (under 114 V) and 10% (under 108 V) is monitored for all loads.

The utility of New York City regulates the minimum voltage on distribution feeders so that the delivery voltage at the customer's meter will stay within ±5% of nominal (i.e., 120 V ±5% or 126 V to 114 V) during normal operating conditions and 10% below nominal voltage (108 V) for emergency conditions [34]. The national standard related to these voltage levels is ANSI C84.1 where 114 V (95%) is defined as the minimum service voltage and 108 V (90%) is defined as the minimum utilization voltage [35]. In this study, we have computed voltage violations for both of these levels for loads with a voltage base of $V_{LN} = 120$ V.

The investigation is aimed at identifying voltage violations of 5% and 10% under different voltage reduction levels for the three networks. Fig. 3 shows the voltage violations exceeding 5% (under 114 V) when a 4% voltage reduction is applied. Fig. 4 shows voltage violations exceeding 10% (under 108 V) when 8% voltage reduction is used. These figures are shown for the peak-load hour of the year. The plots show that the voltage violations are localized in small geographical areas. Then, an investigation was launched to find if the problems can be solved with a small percentage of DG penetration. This stems from the fact that the interconnection of DG is known to produce localized overvoltages. A win-win situation is expected since both techniques (CVR and DG) save energy, but their potential bad-side effects may cancel each other.

Fig. 3. Geographical voltage distribution in the Yorkville network for 4% voltage reduction during the peak hour of the year. Twenty-six voltage violations are detected, exceeding 5% (under 114 V) out of 2282 structure points. Underlying map ©2014 by Google.

Fig. 4. Geographical voltage distribution in the Yorkville network for 8% voltage reduction of the peak hour of the year. Eight voltage violations are detected, exceeding 10% (under 108 V) out of 2282 structure points. Underlying map ©2014 by Google.

C. *Overview of the DG Interconnection Under CVR*

The operation of DG has an influence on the distribution system voltage levels by changing the current levels on the system [8]. This influence is defined by the size, type, and location of the DG, the network topology, DG operation strategy, and the characteristics of the distribution system. The operation of the generator should not cause the distribution system voltage (utilization voltage) to go outside the steady-state voltage limits specified by ANSI Standard C84.1. The Public Utilities Commission establishes service voltage (customer voltage) limits for the utility. However, during severe voltage reduction (or contingency), service voltage supplied by the utility could go below specified limits for customers connected at the end of feeder due to voltage drop.

The interconnection of DG must meet the basic requirements imposed by the various standards, most notably IEEE 1547 [3]–[5], public service commission [36], and local utility regulation [37], while providing a foundation on which higher levels of penetration can be built. As dictated by Consolidated Edison Inc. of New York, the default voltage operating range for the DG shall be from 88% to 110% of nominal voltage magnitude and be operated in a manner that does not cause the voltage regulation to go outside the applicable limits.

DG allocation with constraints of maximum 2-MW output power or less on each DG is considered in this study. Note that

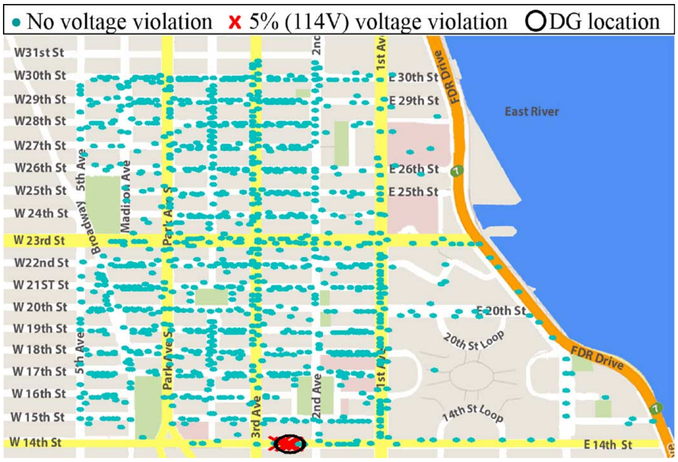

Fig. 5. Geographical voltage distribution in Madison Square network for 4% voltage reduction of the peak hour of the year with three voltage violations detected exceeding 5% (under 114 V). Only one DG allocated on the structure point under voltage violation. Underlying map ©2014 by Google.

no power can be exported from the secondary network to primary because network protectors will trip.

D. DG Allocation Approach

The following key operations are performed to obtain the minimum DG penetration required to solve localized voltage violations.

1) Looking up the geographical and electrical location of structures under LV violation.
2) Low-voltage structures that are electrically close to each other are treated together.
3) One DG is installed for a group of structures to reduce the overall number of DGs.

Only two types of DG systems are used: the inverter type and synchronous machine type. The inverter-type DG operates at a unity power factor, and the synchronous machine-type DG operates at power factor 0.9 leading. Structure points that have lower demands of less than 100 kW are allocated inverter-type DG, with the lowest DG size not being less than 50 kW. Structure points with heavier loads are allocated synchronous machines, with a limit of 2 MW. LV structures that are electrically connected are not allocated as separate DGs, rather a single DG is installed for all of the structure points that are electrical neighbors. This helps reduce the overall number of DGs, and reduces the cost of installation and maintenance. However, if a particular group of electrically close structure points has a combined load value of more than 2 MW, more than one DG of similar type are connected in order to improve the voltage profile.

For the Yorkville network, nine DGs were allocated in the LV distribution network with a total power of 1.25 MW representing 0.5% of the total peak demand. Voltage reductions of 4% and 8% were simulated with DG penetration to solve voltage violations exceeding 5% (under 114 V) and over 10% (under 108 V). A similar DG allocation approach was applied on the Madison Square network to solve the over 5% and 10% voltage violations resulting from 4% and 8% voltage reduction. This network is robust to voltage violation with only three voltage violations clustered in one location. Fig. 5 shows the voltage map

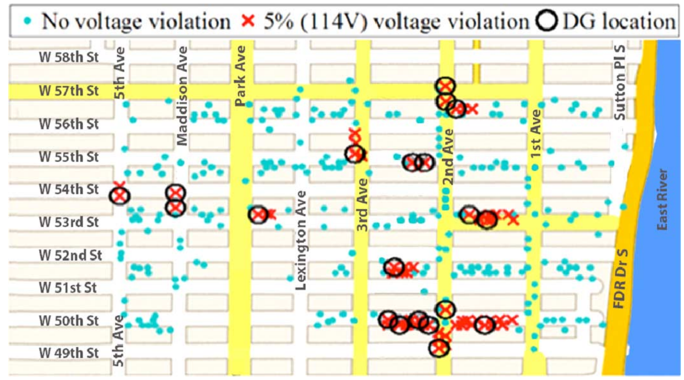

Fig. 6. Geographical voltage distribution in the Sutton network for 6% voltage reduction of the peak hour of the year with 62 voltage violations detected more than 5% (under 114 V). Twenty-nine localized DGs are allocated on structure points under voltage violation. Underlying map ©2014 by Google.

TABLE IV
SUMMARY OF IDENTIFIED VOLTAGE VIOLATION AND ALLOCATED DGs

Network	Sutton	Madison Sq.	Yorkville
Voltage violation level	5% (114V)	5% (114V)	5% (114V), 10% (108V)
No. of violation (CVR %)	62 (6%)	3 (4%)	26 (4%), 8 (8%)
No. of allocated DGs	29	1	9
Total allocated DGs output power	3.4 MW	250 kW	1.25 MW
% of DGs to peak load demand	2.3%	0.08%	0.5%

with the voltage violation being more than 5% (under 114 V) in the Madison Square network when 4% voltage reduction operation is conducted. Only one DG of 250 kW (0.08% of peak demand) was needed to remove the 5% and 10% voltage violations. Finally, the smallest network (Sutton) has a weak characteristic with 62 voltage violations of more than 5% (under 114 V) when 6% voltage reduction was applied. Twenty-nine DGs with a total power of 3.4 MW (2.3% of the total peak demand) were used to solve voltage problems. Results for the Sutton network are shown in Fig. 6. The results for the three networks under study and allocated DGs are summarized in Table IV.

E. Simulation Results of the Proposed DG Allocation

In this section, load-flow simulation results showing the voltage profile of all loads for each network are presented. The results are obtained for the voltage violation study (with no DG) described in Section III-A, and compared with the results with DG penetration presented in Section III-C. In addition, these simulations are performed for all voltage reduction levels. With proper DG allocation, the utility can implement reduction in voltage that was not acceptable (due to voltage violations) for the case without DG being implemented. For example, some medical equipment, such as X-ray and MRI machines, have a small range of operating voltage which makes them sensitive to voltage variations. DG could be an inexpensive solution to health-care facilities and hospitals since no medical equipment will drop out due to CVR implementation during emergency situations.

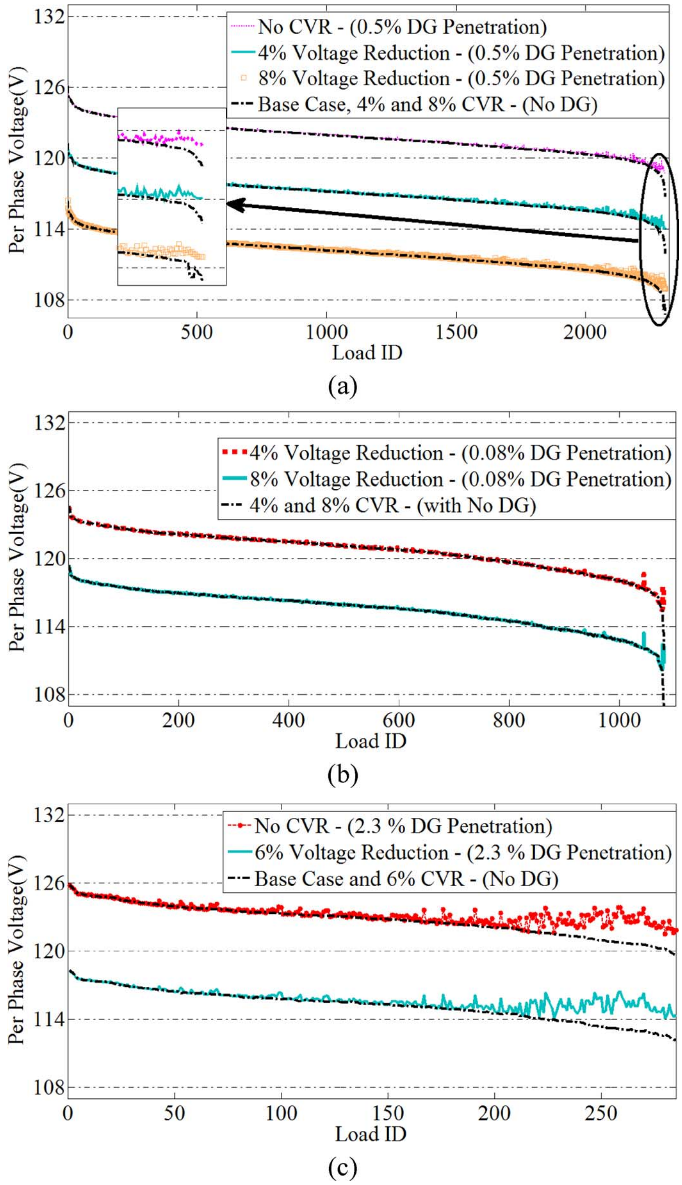

Fig. 7. Comparison of the voltage profile for loads at 120 V without DG penetration (dash dotted lines) and with DG penetration. Results are shown for the base case with no voltage reduction, 4% and 8% CVR: (a) for Yorkville, (b) Madison Square, and (c) Sutton with no voltage reduction and 6% CVR.

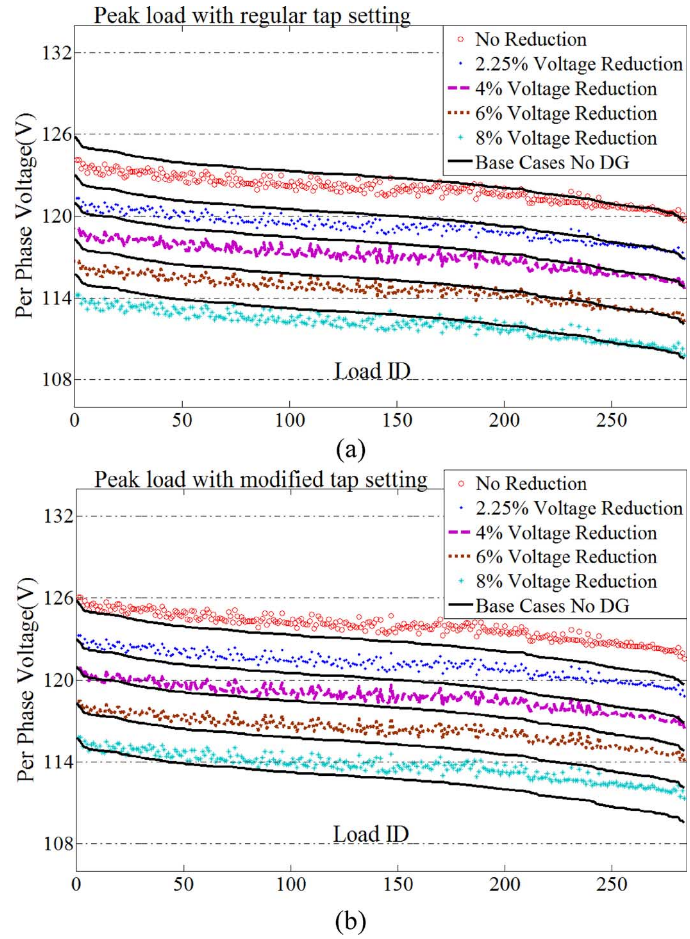

Fig. 8. Sutton network voltage profile for customers at 120 V during the peak load hour: (a) regular tap setting and (b) modified tap setting. Results for the base case and CVR with no DG penetration are in solid lines.

Fig. 7(a) shows the voltage profile of all loads in the Yorkville network. With 0.5% (1.25 MW) DG penetration of the total network peak demand (250 MW), 26 violations of 5% (under 114 V) and 8 violations of 10% (under 108 V) for 4% and 8% voltage reduction levels, respectively, are now removed. Similar analysis is shown for the Madison Square network during peak demand (307 MW) with one DG to solve violations of 5% and 10% occurring in 4% and 8% voltage reductions. Finally, the proposed DG allocation is also applied to the Sutton network (141.7 MW peak demand) to solve 62 violations of under 114 V for the 6% voltage reduction using only 2.3% DG penetration.

IV. Effect of High DG Penetration on the Power Factor

In [16], it was shown that high penetration of randomly allocated DG results in overvoltage and undervoltage violations. It was also shown that 100% of the load could be fed from DGs when allocated in a way that the load is negated. In this section, it is shown how voltage reduction can be applied under high DG penetration.

With no DG, the total peak load demand of the Sutton network is 141.7 MW and the reactive power demand is 72.74 Mvar, giving a power factor of 0.89 lagging. The substation transformers setting is 13.6 kV (see Table III). Let us assume a total power supplied by DGs at 24.73 MW and 3.17 Mvar at a power factor of 0.99 leading (which corresponds to 50% of the light load). The new power demand seen by the substation is 116.97 MW and 69.57 Mvar at a power factor of 0.86. The power factor of the network has been lowered from 0.89 to 0.86 due to the high penetration of DGs. The substation transformer setting for this demand is 13.5 kV (see Table III). However, the original tap settings were designed assuming a power factor of 0.89. At 0.86 power factor, more reactive power is supplied (in proportion) than originally foreseen, which causes a larger voltage drop in the feeders and offsets the effect of DG.

From Fig. 8(a), it can be seen that the voltage profile at this DG penetration level is becoming flatter, that is, the structure points that previously had lower voltages have a higher voltage now, while the structure points that previously had higher voltages now have a lower voltage. The decrease in voltage of the

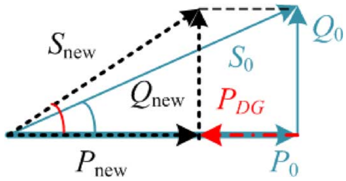

Fig. 9. Illustration of the network power triangle with no DG penetration (solid lines), total power supplied by all DGs (dash-dotted line), and the new network power triangle DG penetration (dashed lines).

structure points that were previously higher is caused by the lowering of transformer taps. This scenario is more favorable for a utility since the difference between highest voltage and lowest voltage is reduced, which allows the utility to control the voltage of the loads more effectively. The phenomenon of *flattening* of the voltage profile is favorable at normal operation with no voltage reduction. However, when 8% voltage reduction on peak load demand hour is applied, more structure points violate the low voltage limit as can be seen in Fig. 8(a). Therefore, adding more DGs will not improve the voltage profile if no modification is made to the LDC settings.

Fig. 8(b) shows improvements in the voltage profile for the same DG allocation by modifying the tap setting such that it considers the new power factor of the load in addition to the active power demand. The aforementioned cases show that distribution networks have not been designed for connecting a large percentages of DG. This issue reveals that modification of the substation transformers setting is needed to achieve the desired results for large DG penetrations.

Fig. 9 shows the power triangle of the network and the increase of the power angle due to high DG penetration. The original tap setting was designed assuming a power factor of 0.89. With DG penetration, the power factor of the system becomes smaller; hence, a higher voltage at the substation is needed to compensate for the increased proportion of reactive power. This effect is further pronounced when DG penetration is increased.

V. Conclusions

A new technique to solve voltage violations in a highly meshed network when CVR is implemented using a small percentage of DG penetration is investigated. It is shown that a win-win situation exists when combining DG and CVR. On one hand, in an unregulated secondary network, the limit of the voltage reduction is given by the LV violations. It has been shown that in secondary networks, loads experiencing voltage violations are strongly correlated and usually occur in localized pockets in the network. On the other hand, it is known that the interconnection of DG produces localized overvoltages. Small amounts of DG can alleviate voltage violations; therefore, enabling deeper voltage reductions and, as a consequence, larger energy and economic savings.

The study has also revealed new issues related to LDC settings when DG penetration increases. When the network's power factor is reduced under high DG penetration, mitigation of the effects of the previous tap scheduling is needed to control the voltage of the loads efficiently.

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