Field-Validated Load Model for the Analysis of CVR in Distribution Secondary Networks: Energy Conservation

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***Abstract*—This paper presents a field-validated load model for the calculation of the energy conservation gains due to conservation voltage reduction (CVR) in highly meshed secondary networks. Several networks in New York City are modeled in detail. A time resolution of one hour is used to compute the energy savings in a year. A total of 8760 power flow runs per year for voltage reductions of 0%, 2.25%, 4%, 6%, and 8% from the normal schedule are computed. An equivalent ZIP model is obtained for the network for active and reactive powers. The most important finding is that voltage reductions of up to 4% can be safely implemented in the majority of the New York City networks, without the need of investments in infrastructure. The networks under analysis show CVR factors between 0.5 and 1 for active power and between 1.2 and 2 for reactive power, leading to the conclusion that the implementation of CVR will provide energy and economic savings for the utility and the customer.**

***Index Terms*—Conservation voltage optimization (CVO), conservation voltage reduction (CVR), load model, system losses reduction, ZIP coefficients model.**

I. INTRODUCTION

CONSERVATION of energy in distribution systems is at the top of the list of issues that power utilities face today. Conservation voltage reduction (CVR) is known as a method of energy conservation by reducing voltage at the substation level [1]. CVR has been studied at different utilities with inconsistent results since its success depends on the nature of the load and the topology of the network. Constant impedance loads are better suited for CVR than motor loads demanding constant power. The CVR factor ($\mathrm{CVR_f}$) is used to determine how effective CVR is for a particular system. It is calculated from the percent energy savings divided by the percent voltage reduction. The same factor can be defined for reactive power ($\mathrm{CVRQ_f}$), calculated from the percent of reactive power reduction by the percent of voltage reduction.

A. History of CVR

Conservation voltage reduction has been in use as a technique for reducing energy consumption for a long time. Many utilities and public service commissions have tested and tried to implement CVR on their system; see, for example, [2]–[4]. The first wide-scale implementation of CVR was in 1973, during the oil embargo, when the Public Service Commission of New York ordered its utilities to implement 3%–5% reduction in voltage in order to reduce energy consumption [5]. However, in 1974, the order was lifted and the effects of CVR were not properly documented. Since then, many utilities have tried to implement CVR on their system using different strategies. The results of these studies vary widely and, so far, there has been only one documented case of successful system-wide implementation, by BC Hydro [6].

The reported results in [6] show almost 1.3 GWh ($\sim 1\%$) of reduction in energy per year, while the peak demand was reduced by 1.6 MW (1.1%), for a 1% voltage reduction. Utilities other than BC Hydro have also reported savings in energy using CVR. In 1973, American Electric Power (AEP) conducted its own study on CVR and found 3%–4% reduction in demand [7]. However, the investment cost for the implementation of CVR was not justified against the savings at that time. Also, California PUC in 1976 reported savings of 2,686 GWh (1.7%) on their system for one year [1], based also on a 1% voltage reduction.

More recently, in 2005, Hydro-Quebec implemented a pilot project for CVR and reported close to 1.5 TWh (0.4% for 1% voltage reduction) of reduction in energy on its system [8]. A recent simulation study by the Department of Energy in 2010 also shows a reduction in annual energy of 3.04%. However, this simulation study does not show any substantial decrease in losses [8].

B. Implementation and Advantages of CVR

When implementing CVR, the voltage at the customer terminals is reduced within appropriate limits to prevent damage to any sensitive appliances or equipment. According to ANSI standards [9], service voltage must be at a minimum of 114 V, which is 5% below 120 V and utilization voltage, under contingency, must be at a minimum of 108 V which is 10% below nominal voltage.

There are two methods for the implementation of CVR that have been considered in the past [10]. The first is through line drop compensation (LDC), by adjusting underload tap changers (ULTCS) (or other voltage controllers) such that the end of the

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line voltage is set at the desired lower voltage. ULTC transformers have controls that use an X and an R setting to create a model for the impedance of the feeder. Based upon the current or load, the voltage at the substation is calculated using the model so that the end of the line voltage is held at a specific minimum voltage. The controller adjusts the tap position on the transformer to hold end-of-line voltage at a set point. The end-of-line voltage is not directly measured with this technique, but is calculated based on the model. The settings of the LDC have to be updated for each voltage reduction level. The second method is voltage spread reduction (VSR), in which the limit is narrowed to a smaller percentage change via regulators or ULTC controls. Usually, with this technique, some modifications to the system are necessary. Distribution lines may need capacitors to correct power factor and maintain voltage profile, reconducting, or other changes.

A newer method, adaptive voltage control (AVC) uses automatic control and communications to control the voltage at the substation [11]. Its main components are a substation data collector and controller (SDCC), an adaptive voltage controller (AVC), a line voltage monitor (LVM), and a voltage regulator. The SDCC monitors feeder kilowatt-hours, kvarh, kilowatts, kvar, current, and voltage. The AVC unit runs an algorithm and communicates with the LVM and possible line regulator interface units to obtain real-time data from the end of the line, critical loads, or locations that may be known to have low voltage. The AVC unit then controls the voltage regulator or ULTC to adjust voltage to a set voltage point in order to maintain minimum end-of-line voltage.

The expected advantages of CVR in highly meshed secondary networks are numerous. Due to the stiffness of the mesh topology, reduced or no investments are expected when implementing CVR. First of all, there are direct consequences, such as a reduction of power demand during peak periods and accumulated energy savings during the complete year. This is also directly linked to a reduction of carbon emissions. Moreover, with reduced voltages, transformer life is extended since iron losses are a function of voltage [12]. Especially during peak demand where there is a significant amount of stress on the system, CVR may be a way to reduce this strain and potentially prevent outages. Energy consumption is on an upward trend and is projected to continue in this manner. CVR could potentially delay the building of new powerplants or system reinforcements by offsetting the increased demand.

In this paper, the feasibility and the possible benefits of the implementation of CVR in the New York City networks operated by Consolidated Edison, Inc. are investigated. This analysis is performed for each of the 8760 hours in a year. A precise analysis on losses, voltage distribution, voltage violations, and active/reactive power demand reduction is undertaken. These analyses are year-wide and for particular load situations. Such an extensive study for power systems with highly meshed secondary distribution networks, like the New York City networks, has never been reported.

II. NETWORK MODELING

New York City's electrical system represents a unique case study because of the widespread use of highly meshed secondary networks. Secondary networks are used by utilities in the core of cities, but the majority of distribution systems in the U.S. are radial [12]. This study uses real data from Consolidated Edison Inc. of New York. The network models are built using the known physical characteristics of each network, such as: cable impedances, transformer reactances, connectivity, precise location of each load, and even daily load variation by customer classes during the year.

For each network under study, a five-step procedure has been followed: 1) processing of the raw data files; 2) translation of all network characteristics and topology into OpenDSS; 3) validation of the load-flow results with respect to Consolidated Edison's internal load-flow program; 4) construction of the yearly load shapes for each of the customers of the network; and 5) running the CVR study on OpenDSS.

A. Topology of the Network

The topology of the different networks under study has been built using: 1) characteristics and ratings of all area substation transformers; 2) characteristics and ratings of all primary feeders and their connectivity; 3) characteristics and ratings of all network transformers and their connections; 4) characteristics and ratings of all secondary feeders; and 5) yearly load values, their P-V and Q-V characteristics and their connection points to the secondary mesh. The switches have been maintained with their default status or control logic.

These models have been translated into OpenDSS input files. OpenDSS is an electrical system simulation software developed by EPRI [13]. In 2008, EPRI released the software under open-source license to encourage grid modernization efforts in the "smart grid" field. OpenDSS was designed mainly for conducting yearly load-flow simulations and, hence, is suitable for this study. The area substation transformers are modeled as two-winding transformers with 0.1% no-load losses. Primary feeders and secondary cables are modeled as standard *pi* sections. The network transformers are also modeled as two-winding transformers with their known no-load loss. Finally, the loads connected at the secondary mesh are modeled as ZIP loads that represent the P-V and Q-V behavior of each customer class [14], [15]. These load models have been obtained from many voltage reduction tests performed in our laboratory on many domestic appliances. These load models are further described in Section III.

B. Voltage Regulator, Capacitor Switching, and Network Protectors

The voltage in the secondary networks is controlled from the area substation ULTCs, which are operated with line-drop compensation mechanisms. The voltage reduction levels for each network are given in the voltage schedule specifications, which are followed by the network operators. The operation of the ULTCs has been mimicked in the OpenDSS model through a voltage schedule that properly reproduces the hourly voltage variation during the day and year.

Capacitors are connected and disconnected everyday to correct power factor and release transformer capacity. The actual capacitor switching sequences have been included in the model.

The operation of the network protectors is represented in detail in the load-flow simulations. When reverse power is sensed,

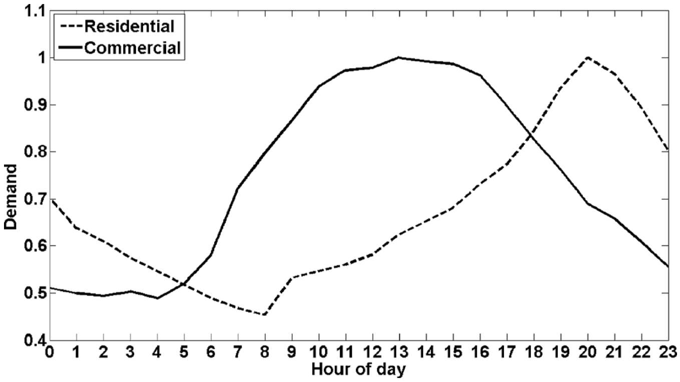

Fig. 1. The 24-h demand pattern for residential and commercial customers.

the protectors open and when the conditions are right for forward power delivery, the network protectors close.

III. LOAD MODELS

A. Yearly Consumption for Each Customer

This section describes how the yearly evolution of the demand of each customer in the network is obtained. Two different models are described and compared next.

1) Model 1: Detailed Representation of Load Shapes: This model aims at representing as precisely as possible the consumption behavior of each one of the customers in the network. Each customer belongs to a service class depending on the use of its property: residential, commercial or industrial. Each class is divided into subclasses or strata, according to the measured annual energy consumption and the average peak demand of summer months. In order to do so, four sets of data are used:

1) Historical monthly energy consumption and peak demand, for each customer of the network, for 2010.
2) Typical 24-h consumption values (daily load curves) for each stratum, different for each daily average temperature range.
3) Average daily temperature for each day of 2010.
4) Load values for all customers of the network for the peak hour of the year.

Each customer is classified in the network according to their particular service class stratum using the historical monthly consumption and peak load data for all the customers. Next, a yearly load curve for each stratum is generated by assigning the typical 24-h consumption to each day of 2010 according to the daily average temperature. The yearly load curves for each stratum are then normalized to have a value of 1 at the yearly peak hour of the network. Finally, the normalized curves are scaled for each customer by multiplying the yearly curve of the stratum they belong to by their estimated yearly peak. This gives 8760 load values for each customer; one per hour in the year.

Fig. 1 shows the load curves for a peak day for a residential customer and a large commercial user. It can be observed that the typical residential customer peaks at the twenty-first hour of the day (9:00 P.M.) while the large commercial customer peaks at the 13th hour of the day (1:00 P.M.). These curves are representative of the historic daily consumption pattern of different types of customers.

An energy normalization factor is defined as the ratio of the recorded yearly energy consumption of the network to the modeled yearly energy consumption. Then, each customer's curve is normalized by this factor, so that the modeled yearly energy consumption matches that of the actual recorded data.

2) Model 2: Network-Wide Load Shape: This second modeling scheme forces the network behavior to coincide with the one recorded in 2010. To do so, we use the following data:

a) network-measured demand for the entire year of 2010;
b) load values for all customers of the network for the peak hour of the year.

First, the peak hour of the year is identified and the percentage participation of each customer for that hour computed. Second, this same percentage is applied for each customer for each hour of the year following the network recorded curve. This method assures that the hourly network energy consumption matches the recorded energy consumption for each network in 2010.

3) Comparison of the Two Models: The first model provides realistic operating conditions differentiating the consumption time pattern of different users across the network. Thus, in this scenario one is capable of modeling the real behavior of each customer according to its stratum and with its specific daily consumption pattern. This method is more accurate from a customer load pattern standpoint. On the other hand, the second model reproduces perfectly accurately the consumption pattern at a network level, for each hour. This second model is more adequate to conduct a precise study on the consequences of CVR for 2010 specifically, especially at the area substation level. Overall, the absolute difference of the aggregate percentage drop in energy consumption between the methods is less than 0.3%. Therefore, the two methods can be considered equivalent. In this study the full results using Model 2 will be presented because it can be programmed more efficiently.

B. Zip Model: P-V *and* Q-V *Characteristics*

The general assumption that the opponents of CVR have is that the majority of the loads in the power system are predominantly constant power. But this is not the case in reality. Laboratory experiments on different appliances and pieces of equipment have been conducted and the results show that no load is entirely a constant-power, neither a constant-impedance nor a constant-current load. Each appliance or piece of equipment in the system has its own P-V and Q-V characteristics, which can be represented by its ZIP coefficients [14], [15]. These are the coefficients of a quadratic approximation of the P-V and Q-V curves. The ZIP coefficients can be obtained by applying a least-square fitting on the test data obtained from voltage reduction laboratory experiments. These experiments are described and documented in [16].

The P-V and Q-V curves for a particular service class depend on the load composition of customers in such class, for example, type of appliances, rating of appliances, duty cycle, and use factor. With all of this information, one can generate an equivalent ZIP model for each class depending on the percentage contribution of each appliance to the total load of the typical customers of the class and the ZIP coefficients of each appliance. Taking into account the percent load of users of each class in specific networks, a network-equivalent

TABLE I
ZIP COEFFICIENTS FOR EACH CUSTOMER CLASS

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 II
VOLTAGE REDUCTION MEASUREMENTS

Network & Year	*V* [%]	*P* [%]	*Q* [%]
Fulton 2012	-4.89	-1.80	-6.86
Fulton 2010	-2.45	-1.09	-3.59
Yorkville 2008	-3.0	-1.47	-5.30
Yorkville 2008	-5.0	-2.45	-8.84
Yorkville 2008	-8.0	-4.83	-16.86

ZIP model can be obtained. The validity of such an aggregate ZIP model has been confirmed experimentally by comparing our simulations with available voltage reduction tests. The ZIP coefficients model used can be written with the following quadratic expressions:

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

$$Q = Q_0\left[Z_q\left(\frac{V}{V_0}\right)^2 + I_q\frac{V}{V_0} + P_q\right]. \tag{2}$$

The ZIP coefficients for each customer class modeled in this study are listed in Table I.

IV. RESULTS

A. Validation of the Model

The validity of the model is assessed by comparison of voltage reduction tests performed by Con Edison in six networks against the results obtained by the simulations with OpenDSS. The networks under study are Fulton, Yorkville, Madison Square, West Bronx, Central Bronx, and Borough Hall. These networks were selected because they represent the spectrum of the load compositions in the Con Edison service area, from predominantly residential to predominantly commercial (large and small). The measurements are performed in the context of the ISO tests performed every June by the utility and consist of 20 minute voltage reduction tests normally at around noon. The differences between the measurements and the simulations, in active and reactive power, are below 0.8%. In the following section, the specific results of this validation are shown for Fulton and Yorkville networks.

The measurement data used for the validation of the Yorkville network are the voltage reduction tests performed on this network on June 8, 2008. These tests were performed for three different voltage reduction levels, i.e., 3%, 5% and 8%. In the case of Fulton, the voltage reduction tests were performed in June 2010 and June 2012, with voltage reductions of 2.45% and 4.89%, respectively. The recorded reductions in active power and reactive power are summarized in Table II.

These measurements are compared to the output of the Yorkville and Fulton model built for this study. The model includes the complete network topology with all of its primary and secondary feeders together with all of the network transformers as well as the totality of the loads in the network. These models are then simulated from the case with no voltage reduction (0%) up to the case of 8% voltage reduction. These simulations are done for the light load case, the medium load case, and the peak load case. The results of these simulations, together with the measurements, are plotted in Fig. 2 for both networks. The results are plotted for active power and reactive power and are practically independent of loading level. It can be observed that the evolution of the active power follows the measurements very precisely and the mismatch between the measurements and the model is below 0.5%. In the case of the reactive power, the mismatch is also below the 0.5% except for the specific case of 8% for the Yorkville network, when the mismatch between the model and the measurements is around 4%. This mismatch is explained by the capacitor switching that occurred during the voltage reduction measurements and changed the base for the calculation of Q. This little mismatch does not cause a problem for the study because as will be described, CVR would be implementable only up to 4%, where the model is replicating the measurements within the 0.5% error for both active and reactive powers.

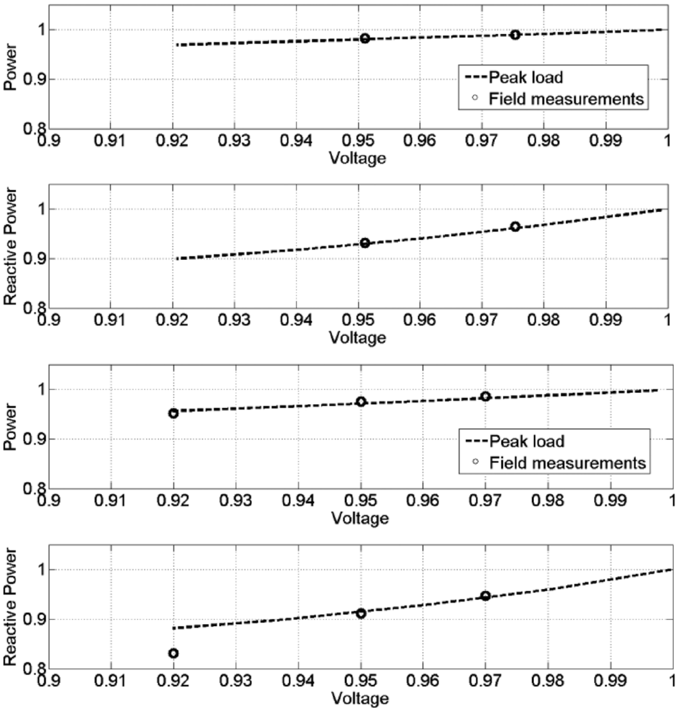

Fig. 2. Comparison of the evolution of P and Q while performing voltage reductions down to 8% for the Fulton (top two plots) and Yorkville (top bottom plots) network. Black dots show the voltage reduction measurements.

B. Network Behavior

The percent of voltage reduction experienced by a particular customer of the network and the overall effect on the network is determined mainly by two factors: 1) overall load composition of the network and 2) network topology.

Since different customers are connected at different geographical locations, at different distances from the area station

TABLE III
NETWORK CHARACTERISTICS

Network	Number of customers	Num. Primary Feeders	Num Network Transf.	Peak demand
Fulton	4874	24	220	105 MW
Yorkville	92315	29	535	270 MW

(through primary feeders, network transformers and secondary feeders), the effect of voltage reduction experienced by the customers is not the same.

The overall load of the network is a composite of the percent contribution from each of the service class (i.e., residential customer, small commercial and large commercial customers). In turn, the behavior of each service class P-V and Q-V depends on the percentage of each set of appliances and equipment available in each type of customer. Not only does the load composition contribute to the overall P-V and Q-V characteristics of each network, but also its topology. Since the topology is different for each network, the average effect on the customers varies from network to network. The overall reduction in energy is hence both load and network dependent.

In this paper, two different networks in New York City, Fulton, and Yorkville are analyzed. These two networks are both located in Manhattan but have very different characteristics as summarized in Table III. Fulton is one of the smallest networks in Manhattan and its customers are mainly commercial (86.73% are large commercial, 6.38% are small commercial, 3.06% are residential, and 3.83% are industrial customers). At the same time, Fulton is a network with high robustness to contingency situations. On the other hand, Yorkville is one of the largest networks in the island of Manhattan and has a large number of residential and small commercial customers (roughly 40%). Specifically, it has 61.21% large commercial customers, 16.38% are small commercial, 16.27% are residential, and 6.14% are industrial customers. Every single customer is modeled individually in detail with its corresponding class ZIP coefficient model. Each customer is connected to their appropriate service point (manhole) in the secondary grid. Customer loads are not lumped or grouped in any way for this study.

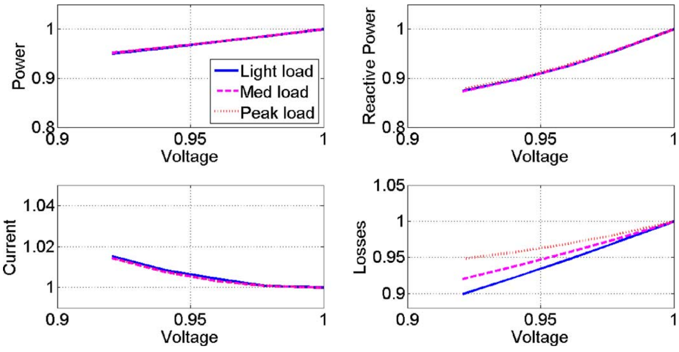

Fig. 3. Evolution of P, Q, I and losses while performing voltage reductions down to 8%, for the Fulton network.

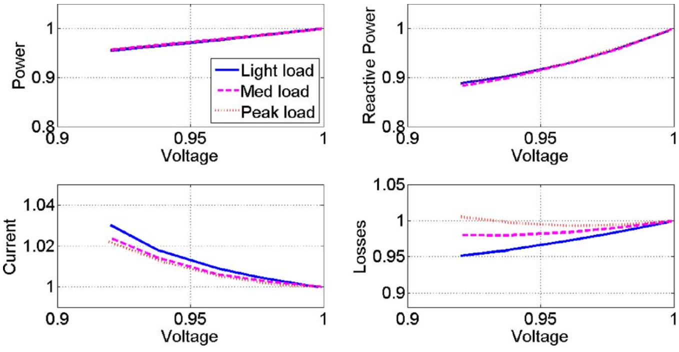

Fig. 4. Evolution of P, Q, I and losses while performing voltage reductions down to 8%, for the Yorkville network.

The analysis of the network behavior is carried out for three different load scenarios: 1) peak load (summer), 2) medium load (winter), and 3) light load (spring/fall) conditions. Power-flow simulations are run for different voltage reduction cases, from base case (no voltage reduction) down to an 8% reduction in voltage. In Fig. 3, one can observe that for 4% reduction, the Fulton network presents a demand reduction of nearly 2.52% ($\mathrm{CVR_f} = 0.63$), whereas, in Fig. 4, the power reduction in Yorkville is slightly above 2% ($\mathrm{CVR_f} = 0.5$). The evolution of the reactive power in both networks shows that for a voltage reduction of 4%, the reactive power in the network is reduced by 8% ($\mathrm{CVRQ_f} = 2$). The Fulton network experiences an increase of the current flow of under 1% (similar for the three load scenarios), while the light load case (only) for Yorkville shows an increase of 1.5% in current–all of these values are based on a 4% voltage reduction scenario. For the peak case, in Yorkville, one can observe that the current increases by just 1%. Finally, the behavior of the total network losses (losses in primary and secondary cables and both core losses and no-load losses in network transformers and area substation transformers) differs quite substantially from network to network, and even more important, from peak load to light load scenarios. Specifically, in Fulton, the decrease in power losses for the peak hour is only 3.5%, but this improvement increases to 6% for light load situations. In contrast, for Yorkville, losses for peak load are fairly constant (within the 1% margin) but are reduced by more than 3% for light load periods–also based on a 4% voltage reduction.

C. *Voltage Distribution*

Another important aspect to study is the voltage distribution across all loads in the network. These profiles are shown in Fig. 5 for Fulton and Yorkville, respectively. This figure shows the statistical distribution of the voltage level at all customer loads in per-unit values. These statistical distributions are shown for every demand level (x axis). The dark solid line shows the average voltage level in the network. The opacity of the plot reflects the density of loads at each specific voltage level. The limits show the maximum voltage level and the minimum voltage level recorded in the network. In each plot, the voltage distribution is shown for base case (0% voltage reduction)–in blue (top graph)–and for 8% reduction–in pink (bottom graph). Note that the maximum voltage increases in steps as the network load increases due to the line drop compensation mechanism that operates the ULTCs.

For a small network like Fulton, the voltage of the great majority of loads (99%) lies within ±1% of the average, and this

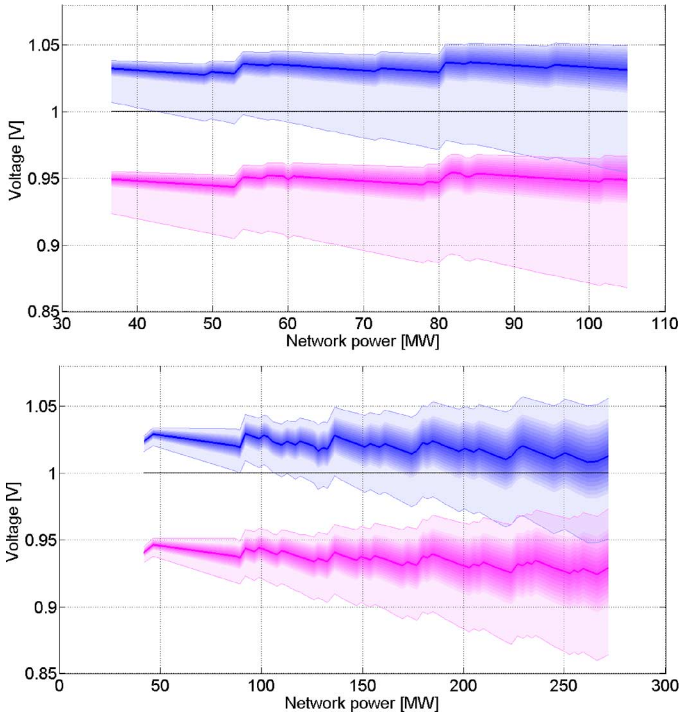

Fig. 5. Distribution of voltage values for different demand levels. Fulton network (top), Yorkville network (bottom). The graph in blue (top graph in each figure) shows the voltage distribution for a case with no voltage reduction (0%) and the graph in pink (bottom) shows the voltage distribution for 8% voltage reduction. The solid line shows the average voltage level and the opacity of the plot represents the density of loads at the specific voltage level.

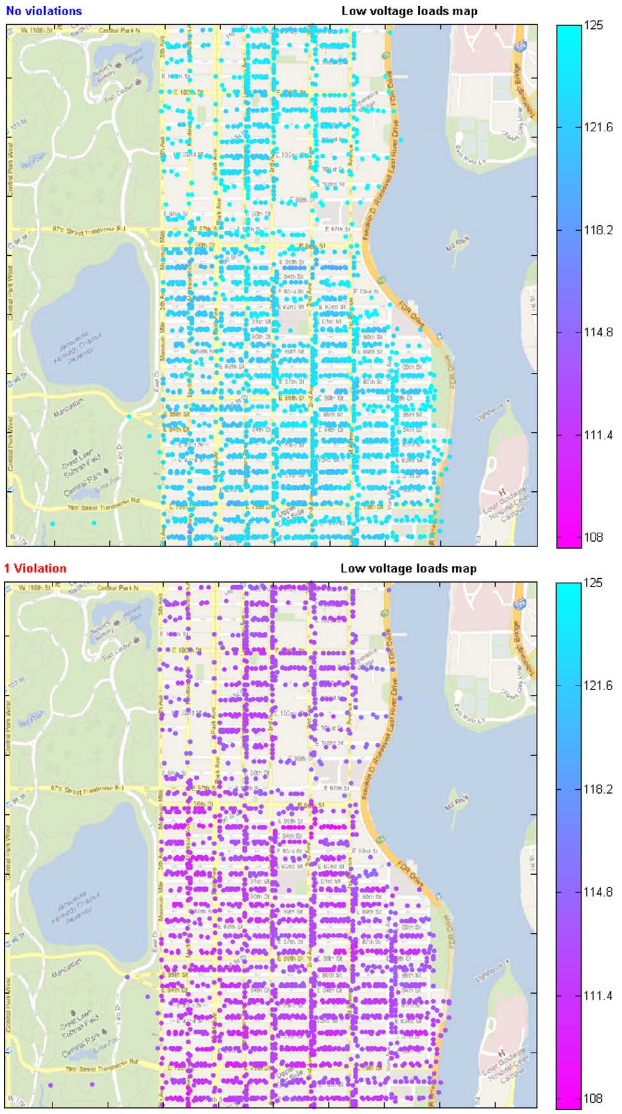

Fig. 6. Geographical voltage distribution in the Yorkville network. The top plot shows the voltage distribution for the base case (no voltage reduction) and the bottom plot shows the distribution for 8% voltage reduction. ©2012 by Google.

distribution is narrower (lower standard deviation) for light load periods. This behavior is also observed in Yorkville but the voltage distribution has a larger standard deviation. In this case, the majority of loads (99%) are within ±2% of the average. Another important aspect to note here is the average voltage level for both networks for the base case. While the Fulton network has an average voltage level of 1.03 p.u, Yorkville has an average value of 1.01 p.u. This situation offers important operative implications, since voltage violations are more likely to occur in Yorkville when implementing CVR. This aspect will be discussed in Section V. It is important to emphasize that low-voltage values are observed only at very few nodes (less than 1% of the loads are out of the dark area).

In Fig. 6, one can observe the geographical voltage distribution in the Yorkville network, first for a case where no voltage reduction is applied (top plot), and second, for a voltage reduction case of 8%. The plot shows that the voltage violations are localized in a small geographical area. This means that the problem can be solved locally, perhaps using a voltage regulator, distributed generation [17], [18], or a capacitor bank. Low-voltage loads are localized in the same geographical region, not only for Fulton and Yorkville, but for the other four networks studied as well (not presented in this paper). Local voltage-control solutions to solve these isolated effects are being investigated and will be the subject of a sequel paper.

D. Loss Study

The evolution of the losses under CVR is critical because they relate directly to the efficiency of the network. Fig. 7 shows the evolution of the total losses for the network for peak (dotted red line), medium (pink dashed line), and light load (blue solid line) when the voltage is reduced.

Network losses are mainly made up of losses in cables and transformer losses in cores and windings. Losses in cables and transformer windings are proportional to the square of the current, while losses in transformer cores are proportional to the square of the voltage. As discussed in previous sections, when the voltage reduces, the current increases and thus the series losses increase. On the other hand, the losses in transformer cores reduce when the voltage reduces. These two types of losses display opposite behavior with respect to voltage reduction.

For peak load in Fulton, the network transformer core losses represent 45% of the total losses and the cable losses only represent 19%. On the other hand, for peak load in Yorkville, the series losses represent 57% and the contribution of the losses in the network transformer cores is 21%. The remaining share

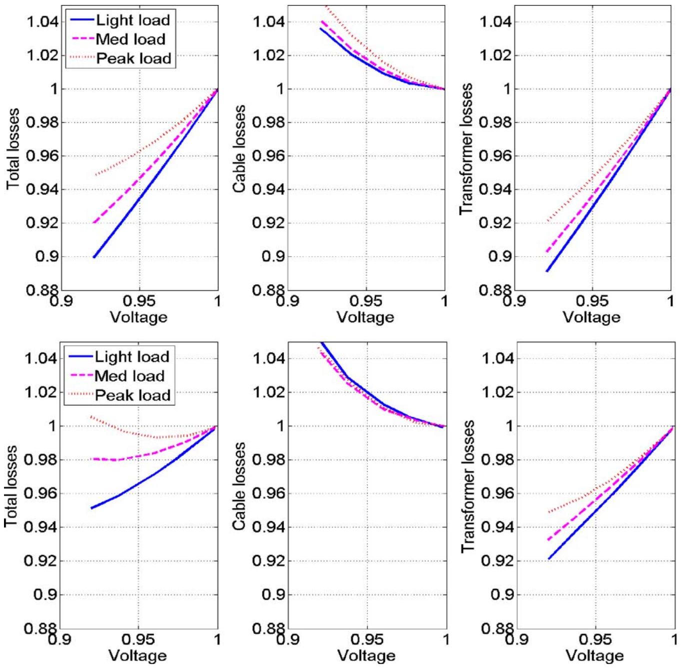

Fig. 7. Evolution of per-unit total losses, cable losses and transformer losses while performing voltage reduction down to 8%. The results are shown for Fulton (top) and Yorkville (bottom) networks.

TABLE IV

PARAMETERS REDUCTIONS FOR THE 4% VOLTAGE REDUCTION CASE. ENERGY AND LOSSES SAVINGS ARE AGGREGATED CALCULATIONS FOR THE WHOLE YEAR. ACTIVE POWER AND REACTIVE POWER DEMAND REDUCTIONS ARE ONLY FOR THE PEAK HOUR OF THE YEAR

Network	**Energy (GWh)**	**Active power (peak) (MW)**	**Reactive power (peak) (MVAr)**	**Losses (MWh)**
Fulton	9.61 (2.50%)	2.20 (2.44%)	2.10 (7.88%)	560.49 (4.51%)
Yorkville	21.54 (2.33%)	4.56 (1.96%)	5.50 (7.82%)	764.56 (1.69%)

of the losses (22%) is due to the area substation transformers. During light-load periods the losses in the network transformer cores represent more than 85% of the losses in both networks. In other words, for both networks, the losses for light load conditions reduce as the voltage is reduced. Nevertheless, for heavy load periods, the losses in the cables are more significant. For Fulton, the latter do not overtake the network transformer losses, but the total savings in losses are reduced from 6% (for 4% voltage reduction at light load) to 3.5% (for 4% voltage reduction at peak load). On the other hand, in the case of Yorkville, at light load the total losses are reduced by 3% (for 4% reduction in voltage). Nevertheless, one can see that for peak load, losses remain constant while voltage is reduced. This is because the increase of losses in the cables is compensated by the decrease of transformer losses. All this can be observed in Fig. 7, where the basis (1.0 p.u.) corresponds to the case of full voltage (0% voltage reduction). The top three plots represent the losses for Fulton and the bottom three plots refer to Yorkville. From left to right, the per-unit total losses, the per-unit losses in cables and the per-unit losses in transformers are presented.

This study shows that the behavior of losses vary from network to network, because they are driven by different factors that are related to size of the network, load, and topology. Fulton is an exceptional network in terms of loading, since the loading at the head of the feeders (limiting sections) at peak load is of 49% of their full capacity. On the other hand, Yorkville is loaded at an average 88%. Yorkville is the most heavy-loaded network in NYC. The average loading considering all primary sections (not only the limiting sections) in Fulton is 20%, for Yorkville is 50%, while the average of the other networks is 30%. Even in the worst case scenario represented by Yorkville, since the network feeders are not close to their full capacity, the losses are constant or reduced. Therefore, it can be stated that the operation of the secondary distribution networks becomes more efficient under CVR.

E. Yearly Simulations

Finally, in this section, the yearly results are presented. These results are obtained by simulating 8760 cases (one case for each hour of the year) for each of the networks taking into account the hourly load models presented and described in Section III. Also, these simulations are done for all voltage reduction cases presented above. The results of energy savings, network peak reduction, reactive power reduction and losses reduction for each of the network and for the 4% voltage reduction case are summarized in Table IV. If a 4% voltage reduction is applied throughout a typical year, Fulton network will save 9.6 GWh which represents a 2.5% energy reduction, whereas Yorkville network will save 21.54 GWh (2.33%). Peak demand and reactive power are also reduced substantially which would delay the investment for newer infrastructure. Losses are reduced more than 500 MWh per year per network. Carbon emissions are normally proportional to energy reductions; therefore, carbon emissions would be reduced also around 2.5% in both networks. The results confirm that the implementation of CVR is beneficial in terms of energy savings and network efficiency.

V. VOLTAGE VIOLATIONS STUDY

The feasibility of CVR is determined by the occurrence or not of voltage violations at each of the load points of the system. Therefore, in order to assess what the implementable CVR levels are in each of the networks, the minimum voltage for the peak-load hour (worst case), under normal operation–first contingency and second contingency–for four voltage reduction cases have been computed. The ANSI standard defines 114 V (95%) as the minimum service voltage and 108 V (90%) as the minimum utilization voltage [9]. In this study, we have computed violations for both of these levels under contingency for loads with a voltage base of $V_{LN} = 120$ V.

The results for the two networks under study are summarized in Tables V–VII. The violations under 108 V are shown first and the violations under 114 V are shown in parentheses. None of the network presents voltage violations under 108 V for the 2.25% and the 4% reduction cases (only 23 nodes under 114 V for 4% for Yorkville network). For the 6% case, there are still no violations under 108 V but Yorkville presents 802 nodes under 114 V. The minimum calculated voltages are 111.75 V (Fulton) and 108.33 V (Yorkville). In these cases, all violations occurred in electrically and geographically neighboring nodes.

TABLE V
Number of Voltage Violations Under 108 V for the Base Case. Violations Under 114 V are Shown in Parentheses

Network	**0%**	**2.25%**	**4%**	**6%**	**8%**
Fulton	0 (0)	0 (0)	0 (0)	0 (2)	0 (78)
Yorkville	0 (0)	0 (3)	0 (23)	0 (802)	17 (2159)

TABLE VI
Number of Voltage Violations Under 108 V for First Contingency. Violations Under 114 V are Shown in Parentheses

Network	**0%**	**2.25%**	**4%**	**6%**	**8%**
Fulton	0 (0)	0 (0)	0 (1)	0 (2)	1 (95)
Yorkville	0 (0)	0 (2)	0 (56)	3 (1080)	95 (2103)

TABLE VII
Number of Voltage Violations Under 108 V for Second Contingency. Violations Under 114 V are Shown in Parentheses

Network	**0%**	**2.25%**	**4%**	**6%**	**8%**
Fulton	0 (0)	0 (0)	0 (1)	1 (10)	12 (87)
Yorkville	0 (0)	5 (42)	7 (128)	76 (1199)	343(1903)

Finally, if the analysis is extended to 8%, Fulton presents only 78 nodes with violations under 114 V (minimum of 109.16 V), but Yorkville presents 17 nodes under the 108 V level (minimum of 105.39 V).

The same study has been performed for all first and second contingency cases. In both cases, the minimum voltages for the peak-load hour have also been recorded.

For the first contingency analysis, all possible cases with one feeder disconnected are simulated. Then the hour of the year that shows the largest number of voltage violations is selected. The results are presented in Table VI. The Fulton network exhibits an acceptable performance down to a voltage reduction of 4% where only one node with voltage violation is found. On the other hand, the Yorkville network presents unacceptable figures for reductions beyond 4%, because violations are not geographically close and the number of customers affected is larger than 1% (1080 voltage violations).

Finally, the second contingency analysis is presented in Table VII. Analogously to the first contingency study, all network configurations with two feeders disconnected are simulated and the combination that presents the most voltage violations is selected.

In summary, it can be stated that voltage reductions down to 4% can be implemented in most of New York City, without the need of important investments in the infrastructure of the network. This is possible because only a few voltage violations are present and only occur for the peak hours of the year. In the second contingency case, for the peak hour, the load under 108 V is only 0.21% of the total demand. Note also that the utility could decide to operate only at 2.25% voltage reduction for these peak hours if necessary.

VI. Conclusion

In this paper, a complete study of conservation voltage reduction in some of the highly meshed secondary networks that exist in New York City is undertaken. The analysis covers the behavior of losses, voltage distribution, voltage violations, yearly energy savings, and active/reactive power throughout the year. This paper presents the first voltage-reduction validated model with field measurements in highly meshed distribution networks. The results show that the implementation of CVR up to 4% is satisfactory because active and reactive power demands are reduced. Moreover, due to the stiffness of the highly meshed secondary networks, direct savings are obtained because there is no need for capital investments.

The CVR factor for active power varies from 0.5 to 1.0 and the CVR factor for reactive power ranges from 1.2 to 2.0. Therefore, voltage reduction in highly meshed secondary distribution networks is feasible and beneficial. Nevertheless, localized low-voltage violations may occur. Consequently, these situations can be easily identified and locally solved by adding voltage regulators or distributed generators. Contingency analyses show that reductions up to 4% could be implemented safely without the need for costly infrastructure investments and attaining significant savings in energy.

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