Energy and Economic Impacts of the Application of CVR in Heavily Meshed Secondary Distribution Networks

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***Abstract*—This paper presents an economic model, based on a field-validated load model, for the assessment of impact of conservation voltage reduction (CVR) implemented continuously during both on-peak and off-peak hours. The model evaluates the impact on individual customers and the utility, taking into account the different billing structures, including service class, monthly rates, and reactive power billing. The model considers as well the impact of the utility's revenue decoupling mechanism. The hourly operation of three New York City networks of the Consolidated Edison Company of New York (ConEd) for an entire year has been simulated for the purpose of this study. The results presented for voltage reductions between 2.25% and 8% indicate that for individual customers, the larger the original bill, the greater the relative savings in percentage of the original bill. For the utility, the main advantages are the reduction in aggregated energy consumption and peak power demand with corresponding avoided investment and operating costs. The study and results presented are the first of their kind for a meshed power system. In addition, the economic model presented can be used for any utility system where distribution is separated from generation ownership.**

***Index Terms*—Billing structures, conservation voltage optimization (CVO), conservation voltage reduction (CVR), economic impact, revenue decoupling.**

I. Introduction

CONSERVATION of energy in distribution systems is at the top of the list of issues that power utilities face today. This has forced many utilities to explore new energy-saving avenues, such as energy efficiency programs, demand response, demand-side management, smart metering, and conservation voltage reduction (CVR) [1]. In the Appendix, we tabulate and briefly comment on the CVR programs in North America initiated from 1973 to 2010.

Manuscript received April 22, 2013; revised August 22, 2013 and December 02, 2013; accepted January 23, 2014. Date of publication February 25, 2014; date of current version July 21, 2014. Paper no. TPWRD-00479-2013.

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Digital Object Identifier 10.1109/TPWRD.2014.2304501

In a CVR study, there must be an accurate model of the system, and the actual energy savings associated with lower voltage must be determined. Also, the utility should consider whether it is willing to spend capital to install modifications to enable CVR with any associated operations and maintenance costs that may be incurred. The economic impact on the customer and the utility must be assessed in detail. To estimate energy savings that CVR can yield, energy consumption at rated voltage should be compared with consumption at reduced voltage levels. Ideally, for a valid comparison, the same conditions must be repeated (daily temperature, day of the week, etc.) so that the two simulations differ only in their voltage levels. It is also beneficial to study the energy consumption by customer type, categorized as service class (SC), as the billing rates for each are different, as is the nature of the load. Concerns regarding CVR are wide ranging. In the worst case, customers may experience low voltage to the point where equipment loses its functionality or appliances are damaged.

From an economic point of view, the desire to reduce electricity sales through tools, such as CVR, may appear counterintuitive for an electric distribution utility. However, increased awareness by regulators of the benefits of reduced energy consumption has led to energy efficiency targets that encourage utilities through penalties, incentives, and adjustments to allowed rate of return to seek lower electricity consumption. In many states, these have been accompanied by revenue decoupling mechanisms, under which any difference between forecast and actual energy sales is reconciled via a customer charge so that a utility's target revenue is met, regardless of actual sales. This impact is included in the economic model proposed here.

Where the utility does not already employ voltage reduction during peak periods, CVR provides a way to delay investment in infrastructure. As of now, there is a lack of readily available models to analyze the financial aspects of CVR implementation.

This paper presents a model for analyzing the economic impact of CVR on the customers and utility for a deregulated electricity market, such as the New York Independent System Operator (NYISO), deregulated since the late 1990s.

II. Economic Impact Model

The customer bill depends in a complicated way on the customer service class and on the electricity regulatory structure and, hence, involves multiple line items. However, these can be simplified into two primary components [1]:

1) energy or supply component;

2) delivery component, with possible reactive power charge. The supply component is directly related to a customer's energy consumption. This component pays for the energy that is utilized in the system. In a deregulated energy market, the generation of power, the transmission, and the distribution are undertaken by different entities. The distribution utility is responsible for delivering power. Where it processes payments on behalf of energy suppliers, this is a pass-through transaction.

The delivery component of the economic structure is the part which the utility imposes on its customers for distribution services. This charge is received by the utility to cover the cost of capital projects, operations, maintenance, and other costs. The delivery component is typically composed of three different charges:

1) a fixed monthly connection charge;
2) an energy delivery charge;
3) for larger customers, a demand charge based on peak monthly demand.

In this study, the methodology for calculating the impact of CVR on individual customer bills and utility revenues takes each of these components into consideration.

The first step in this CVR study involved establishing a "base case" with energy and demand measurements for each customer in the three Manhattan networks under study (Fulton, Yorkville, Madison Square). Monthly bills were then generated using the rate structure applicable to each customer. Subsequently, "reduction" cases were run (corresponding to a 2.25, 4, 6, and 8% voltage reduction), and the monthly bills were recalculated. The difference in each component was then used to determine the immediate and permanent impact on customer bills.

The permanent savings to the customer relate to the reduction in energy use and appear in a reduced supply (energy) component of the customer bill. Any reduction in the delivery component experienced by the customer is, however, only temporary. This is due to the capital-intensive nature of utilities, where a reduction in consumption will not lead to a significant reduction in overall costs. It is also due to the utility business model, where individual customer charges are set (with agreement from the state public utility commission) based on projected utility-wide electricity sales. Customer charges are designed to ensure total revenues (a utility's revenue requirement) equal to the utility's costs plus an appropriate rate of return for its shareholders. To the extent that actual sales do not match forecast sales, the utility will experience an over or under-collection of revenue. This discrepancy can be factored into rates in a subsequent rate setting period or more frequently through a revenue decoupling mechanism (RDM). In the case of ConEd, RDM adjustments occur every six months. The result is that while customers might experience an immediate drop in the delivery component of their bill, this will be later reversed. An exception would be where CVR is only applied to a portion of the utility's service territory; the revenue shortfall will be met collectively by all customers, so customers experiencing CVR will receive some benefit in the form of wealth transfer.

From the point of view of the distribution utility, it will thus experience no direct economic impact from CVR, neither in the form of reduced power sales (since they are a passthrough cost) nor delivery charges (since they are adjusted to ensure the revenue requirement is met).

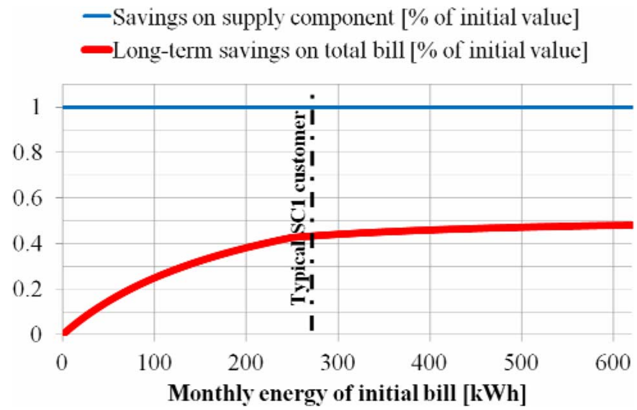

Fig. 1. Reduction in bill components with a 1% reduction in monthly total energy for SC1 customers.

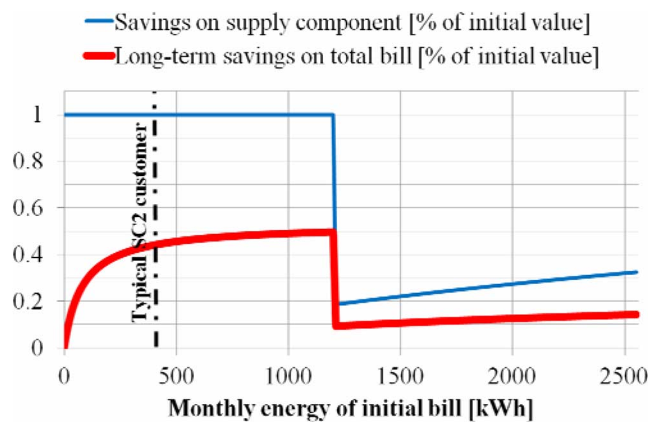

Fig. 2. Reduction in bill components with a 1% reduction in monthly total energy for SC2 customers.

The utility may experience a temporary negative revenue impact due to an initial period of undercollection with the implementation of CVR. However, under its RDM, ConEd will recover that revenue at a future point, including any forgone interest.

III. Energy and Peak Power Billing per Customer Class

In this study, the effect of voltage reduction on energy and peak power is first determined, based on the methodology presented in [2] and [3], using a ZIP coefficients model. This is, in turn, used to calculate the economic impact.

The results on three different SCs which together make up the majority of the total load under study:

1) residential/religious (SC1);
2) small commercial/industrial (SC2);
3) large commercial/industrial (SC9).

are discussed in this paper. Figs. 1–3 show the effect on the bill of a 1% reduction in energy. While the customer bill for SC1 and SC2 is a function of consumption (kilowatt-hours), SC9 customers have another input to their bills: peak power demand (kW).

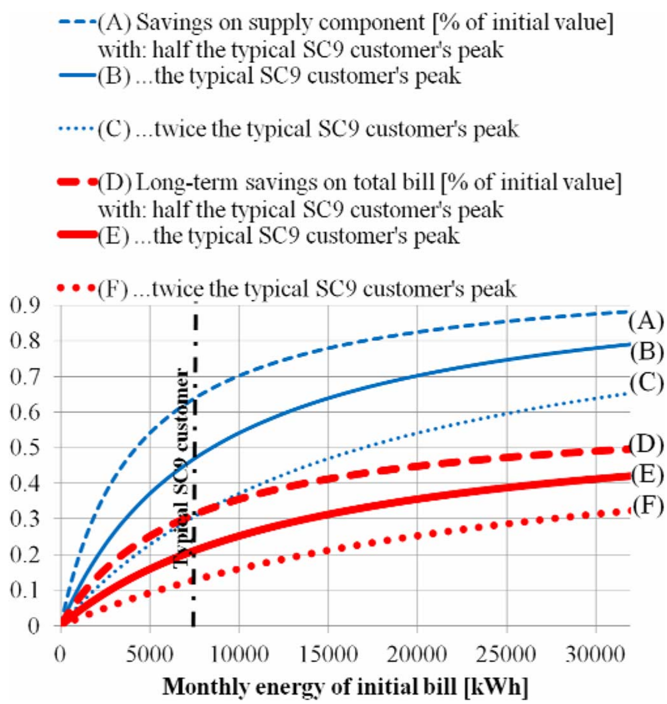

Fig. 3. Reduction in bill components with a 1% reduction in monthly total energy and monthly peak power for SC9 customers.

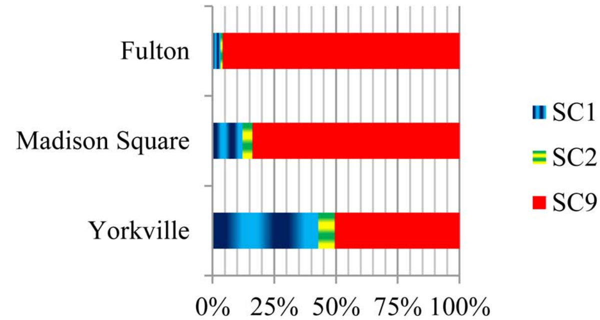

Fig. 4. Networks' load composition according to average energy consumption.

TABLE I
CONED FACTS: ENERGY AND PEAK POWER (2010) [4]

	Energy		Peak power	
	[TWh]	[%]	[GW]	[%]
Fulton	0.57	2.1	0.12	2.1
Yorkville	1.42	5.1	0.30	5.1
Madison Square	1.11	4.0	0.31	5.3
Sum of all three	3.10	11	0.73	12
ConEd	27.6	100	5.82	100

TABLE II
MONTHLY VALUES FOR A TYPICAL CUSTOMER (2010)

	Energy [kWh]	Peak power [kW]	Supply [$]	Delivery [$]	Total bill* [$]
SC1	266	Not a bill input	27.7	44.7	75.6
SC2	429		60.6	67.8	140
SC9	7435	15.3	774	569	1462

(*): includes sales tax, and reactive power charge if applicable.

The rates at which each bill component is charged are sometimes defined by blocks, that is, one rate for a given initial usage level of energy/peak power, and a different rate for the remainder. This kind of block charge is generally applied to nonresidential customers on both energy and peak power. The alternative structure is a constant per-unit rate irrespective of consumption level. Here, while SC2 customers' energy component is charged with a block rate, SC1's is at a constant rate. The delivery component is charged with a block rate for both. For SC9 customers, energy and delivery components are charged using a block rate.

In Fig. 1, it can be seen that for SC1, the supply component (constant rate) varies directly in proportion with energy. Hence, for all energy values, there is an exact 1% reduction in supply component with a 1% reduction in energy and power. However, the delivery component (block rate) explains the discontinuity in the total-bill curve at 250 kWh. Figs. 2 and 3 show similar curves for SC2 and SC9 customers, respectively. From these curves, it can be stated that for networks with a higher proportion of SC1 customers (residential/religious) than nonresidential customers (SC2 or 9), the total reduction in supply charges for the network (the permanent impact) should be expected to be higher as a proportion of initial charges than in more nonresidential networks.

The relative proportions of each SC for the three modeled networks are given in Fig. 4. Historical data for 2010 for these three networks as well as for all of ConEd are shown in Table I; and the monthly energy, peak power, supply and delivery components, as well as the total bill for a "typical" customer of each SC are shown in Table II. This typical customer was defined as follows: the median monthly consumption, median monthly peak demand, the corresponding supply and delivery components, and total bill amount, among the customers of a same SC, were averaged across the 12 months of the year. Those numbers, averaged across the three networks under study, were taken as the typical values referenced in Table II.

IV. REACTIVE POWER BILLING

In present-day energy markets, a primary concern for utilities is the reactive power consumption on their system. The major sinks of reactive power in a distribution system are the large commercial and industrial loads. Also, distribution utilities are required to maintain their system power factor at or above 0.95 lagging, which helps in maintaining the efficiency of the transmission lines, as well as that of their own distribution system. Hence, many public service commissions have allowed the utility to charge their large customers for their reactive power consumption with a hope that it will encourage customers to improve their load power factors. ConEd has recently started to implement reactive power billing for its large customers. Since the implementation of CVR affects not only the loads' but also the distribution system's reactive power consumption, it is necessary to incorporate the economic impact of reactive power billing in the model. In our case, a customer is charged for reactive power if it meets both the following criteria:

- Its monthly peak power demand in any of the past 12 months is more than 500 kW,
- At the time of peak power demand, its power factor is lower than 0.95.

The billable reactive power amount is then the reactive power consumption (kvar) at the time of the monthly peak active power demand (kW) minus that peak demand in kW multiplied by 0.33. This quantity corresponds to the amount of reactive power that was delivered by the utility at the time of peak active power demand on top of the corresponding reactive power if the power factor had been 0.95. The reactive power Q can be expressed as a function of the power factor PF as

$$Q(\mathrm{PF}) = \sqrt{S^2 - P^2} = \sqrt{\left(\frac{P}{\mathrm{PF}}\right)^2 - P^2} = P\sqrt{\frac{1}{\mathrm{PF}^2} - 1} \tag{1}$$

with S being the apparent power and P being the active power. We then have

$$Q_{\text{bill}} = Q_{\text{peak}} - Q(0.95) \cong Q_{\text{peak}} - 0.33P_{\text{peak}}. \tag{2}$$

V. Economic Results for Three Networks

Having established the economic relationship for energy consumption and demand, the study turned its attention to the impact of voltage reduction. Taking into account the aforementioned facts of Sections II–IV., the following operations were performed in order to obtain the results subsequently presented.

1) Load-flow simulation of each network under study using OpenDSS of an entire year with a step of one hour (8760 steps), making use of the ZIP coefficients models developed for each customer class in [2]. The ZIP models have been validated using customer survey data as well as voltage-drop tests on at least six actual ConEd networks [2]. Each customer load was classified according to their service class (SC). The corresponding ZIP coefficients models were applied to the appropriate load, different for each hour, according to the historical data (see [2] for more details). The simulations were performed for a year at the original voltage level. Then, the whole set was run again several times, with a voltage schedule corresponding to each reduced voltage level.
2) The results were analyzed with the economic model previously described in this paper, that is, the exact bill structure used by ConEd was conserved and applied according to the SC of each customer. Thus, the 12 monthly bills of a year for each customer were calculated line by line.
3) In order to make sense of all the data, it was grouped following the main divisions of a bill. It is common to divide the bill in supply, delivery, reactive charge if any, and taxes.
4) The difference between the reference case (without reduction in voltage) and each reduction case was computed. Those differences are meaningful because the only parameter changing between a year without CVR and a year where CVR is applied is the voltage level at the substation, propagating differently to each load according to the topology of the network and the proper load considering the time of day and season for each customer with its individual load ZIP coefficients models.

The impact of voltage reduction is measured by three ratios called CVR factors defined below. The traditional "energy" CVR factor is the ratio of percentage of energy savings to percent voltage reduction

$$\mathrm{CVR}_E = \frac{\Delta E_{\%}}{\Delta V_{\%}}. \tag{3}$$

This notion is now extended for the purpose of our economic analysis: the "(peak) demand" CVR factor is the ratio of percent peak demand reduction to percent voltage reduction

$$\mathrm{CVR}_P = \frac{(\Delta \max P)_{\%}}{\Delta V_{\%}} \tag{4}$$

and the "economic" CVR factor is then the ratio of percent of money savings to percent voltage reduction

$$\mathrm{CVR}_{\$} = \frac{\Delta \$_{\%}}{\Delta V_{\%}}. \tag{5}$$

The energy factor does not consider the change in distribution losses, but only in power consumed by the loads. A detailed analysis of losses was presented in [2] for the same networks as in this paper. It was concluded that the overall losses reduce slightly in the majority of cases. The exception is for very heavy loading and large voltage reductions; see [2].

Note that voltage reductions beyond a certain level (2.25% in the case of the ConEd networks under study) may not be implementable in practice without installing voltage-supporting devices in some areas because it may cause violations of the limits set by the standards for the lowest voltage acceptable (see [2]). Such devices (voltage regulators, for example), by maintaining the voltage above the minimum for loads that already experience a lower voltage than the rest of the network without CVR, would effectively locally reduce the CVR factors, yet enable further voltage reductions at the network level. A balance needs to be found between the cost of installing and operating such devices and the benefits they bring.

The results of the analysis for the three networks under study are given in Figs. 5–10. For each network, first the impact of reducing the voltage from 2.25 to 8% on a typical customer of each SC is given (see Figs. 5, 7, and 9). Then, the aggregate impact at the network-wide level is given in Figs. 6, 8, and 10. The absolute values in GWh, MW and U.S.$ are given as well for the aggregate impact. The demand factors represent the reduction in yearly peak power demand; hence, the two peaks compared (that of the reduced-voltage case versus that of the regular-voltage case) are not coincidental in time.

Thus, the absolute values given for the change in total money collected (Figs. 6, 7, 9) equal those for the supply component since only that component is affected by CVR in the long run. Also, because of the fixed items in the bill (which do not depend on energy or demand), even the economic factor obtained before the effect of the RDM kicks in could never be as high as the energy (CVR) factor.

An important observation is that the network-wide economic factors are smaller than those of any typical customer. This can be explained by the influence of smaller customers (in terms of

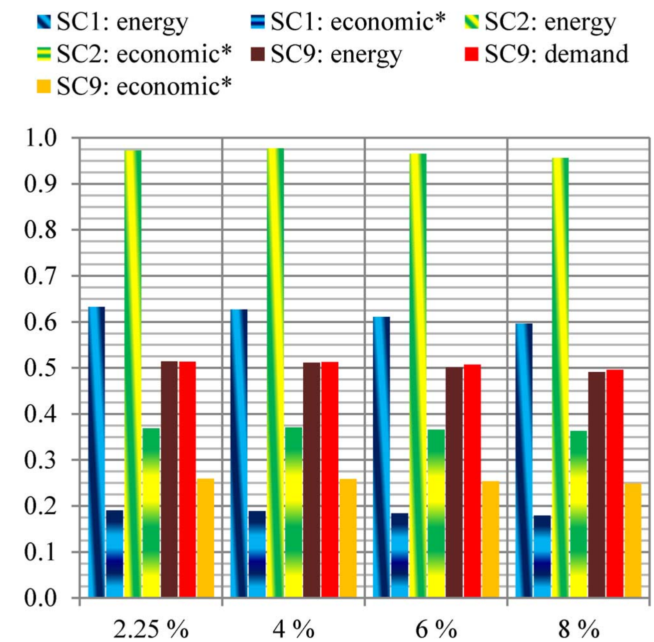

Fig. 5. CVR factors versus voltage reduction level for a typical customer in the Fulton network. (*) Values representative of the long-term effect. The values would be temporarily higher before the adjustment of rates due to decoupling.

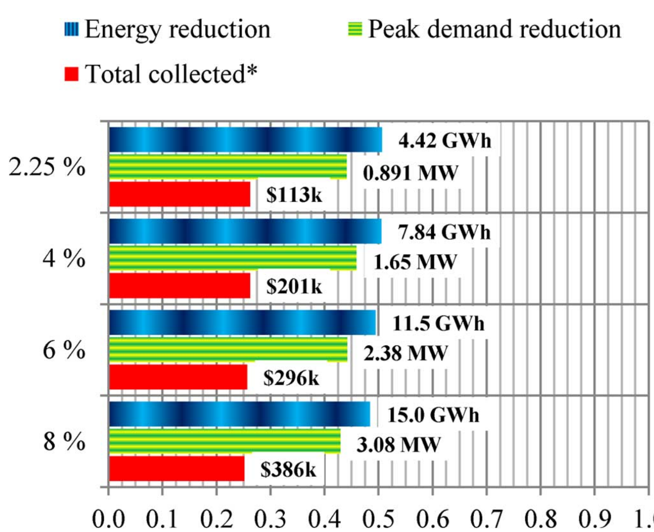

Fig. 6. CVR factors versus voltage reduction level for the aggregated results for the Fulton network; absolute values are given for reference as well. (*) NB: The absolute values given for the total U.S. dollars collected equal those for the supply component since that component is only affected by CVR in the long run.

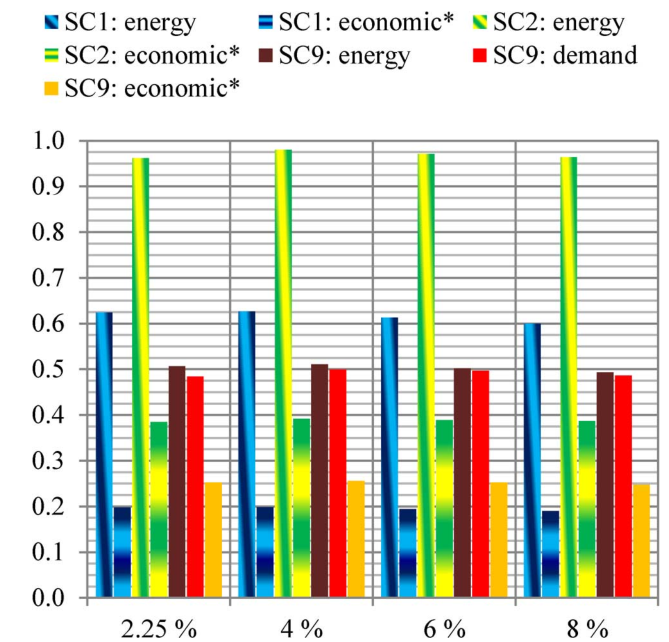

Fig. 7. CVR factors versus a voltage reduction level for a typical customer in the Yorkville network. (*) Values representative of the long-term effect. The values would be temporarily higher before the adjustment of rates due to decoupling.

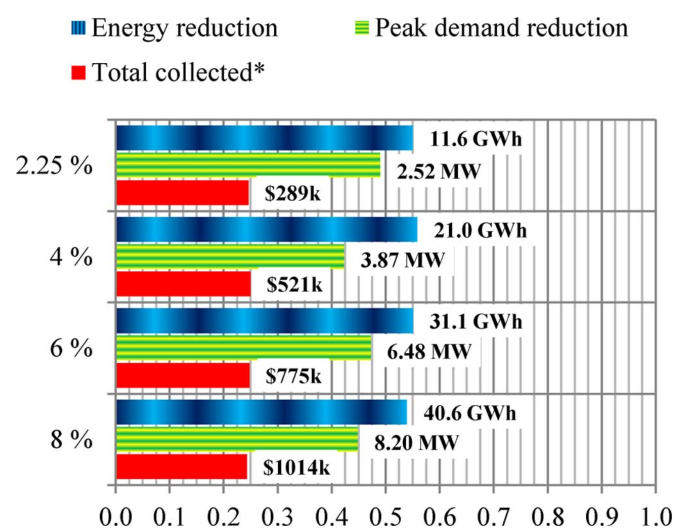

Fig. 8. CVR factors versus voltage reduction level for the aggregated results for the Yorkville network; absolute values are given for reference as well. (*) NB: The absolute values given for the total U.S. dollars collected equal those for the supply component since that component is only affected by CVR in the long run.

consumption: below the median), whose supply component is a smaller proportion of the total bill than for the typical customer, as has been shown in Figs. 1–3. The larger customers (above the median) cannot counterbalance the smaller ones since those curves tend to flatten with increasing consumption.

The ranges for all CVR factors considered in this study are given in Table III as a summary of the results. The demand factors are the most volatile. This can be explained by the noncoincidence of the CVR and non-CVR peaks. With SC9 corresponding to the bulk of the load in terms of energy and SC1/SC2 representing the majority in terms of number (many small loads), one can expect the network values to be energetically closer to those of SC9 and economically to SC1 and SC2s. This is indeed confirmed by the data presented. One can notice also that the average SC9 customer has noticeably higher factors than the average SC2 customer which, in turn, has slightly higher factors than the average SC1 customer.

At the network-wide level, it is worth noting that Yorkville and Madison Square's peak demand factors do not decrease uniformly with voltage reduction, the factors are higher for 6 and 8% voltage reduction than for 2.25%. Their energy factor slightly decreases with voltage reduction. This is explained by

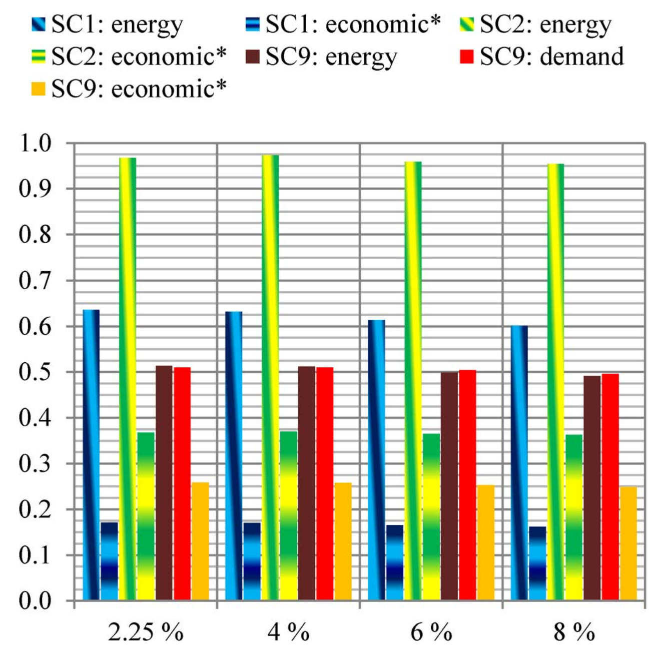

Fig. 9. CVR factors versus the voltage reduction level for a typical customer in the Madison Square network. (*) Values representative of the long-term effect. The values would be temporarily higher before the adjustment of rates due to decoupling.

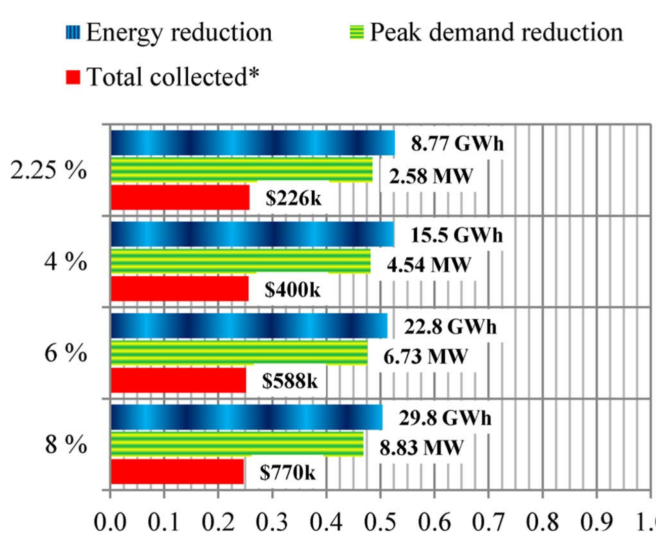

Fig. 10. CVR factors versus voltage reduction level for the aggregated results for the Madison Square network; absolute values are given for reference as well. (*) NB: The absolute values given for the total U.S. dollars collected equal those for the supply component since that component is only affected by CVR in the long run.

the fact that the ZIP curves used to model the loads (see [2]) make the power (and, hence, energy) a slightly convex function of the voltage.

In most cases, the CVR factors are very similar across all voltage reduction levels. Voltage reduction seems to affect the parameters of the network (electrical or economical) in a mostly linear manner. Therefore, the effects of further voltage reduction can be accurately estimated by multiplying the savings in proportion by the CVR factor provided that one does not cross the lower limit of acceptable low voltages at the load points.

TABLE III
SUMMARY OF RESULTS (FIGS. 5–16): CVR FACTORS RANGE

	Energy	Peak Demand	Economic
Typical SC1 customer	0.54-0.73	Not a bill input	0.16-0.22
Typical SC2 customer	0.81-0.99		0.31-0.39
Typical SC9 customer	0.43-0.59	0.37-0.51	0.24-0.28
Network-wide level	0.45-0.63	0.41-0.69	0.20-0.27
Taking a "figure of merit" of:	0.54	0.55	0.24
…corresponds, for a 2.25-% voltage reduction, to a drop of:	1.2%	1.2%	0.5%

Taking an average energy factor of 0.54, a savings of approximately 1.2% of all the energy consumed across ConEd's system would be expected by implementing a voltage reduction of 2.25%. Since this voltage level would most probably not cause any or a few voltage violations, these savings are attainable at virtually no cost to the utility or the customer and could start immediately.

Similarly, taking an average peak demand reduction factor of 0.55, the yearly peak, which defines one of the most important design criteria for the power system, could be immediately shaved by 1.2%. Let us remember that the power system, from generation to distribution, must be designed in order to seamlessly serve the yearly peak, so any mechanism that can reduce it is advantageous. At the same rate, by reducing the voltage by 4%, the peak could be reduced by 2%. Under extreme stress, most utilities would rather have their system go through a temporary period of low voltage beyond the standardized limits, rather than having to go into selective load shedding.

Considering a 2.25% voltage reduction and an economic factor of 0.24, the long-term total collected revenues from customers would drop by 0.5%. Note that this would not be a loss of profit for the utility because of the decoupling mechanism. Instead, this would correspond to a lowering of customer bills, directly linked to the amount of energy effortlessly saved, which utilities would not have to competitively buy on the power market. Knowing that power prices skyrocket in times of peak demand, it is another reason to emphasize the importance of peak shaving, which would benefit the utility and the customers. Indeed, even though the price of power is a pass-through cost that is eventually recovered by the utility when it charges its customers, it still has to advance the money on their behalf.

After having drawn some common features, let us now compare the networks under study. Yorkville has an average SC9 customer demand factor noticeably lower than that of the other two networks. Yorkville is the largest both in number of loads and energy consumption. Its network-wide CVR factors are all lower, especially its economic factor: about half that of Fulton or Madison Square. This is reasonable, since Yorkville has the highest number of relatively smaller loads (highest proportion of residential/religious loads: SC1, smallest proportion of large commercial/industrial loads: SC9), and we have seen previously that small loads have a relatively small supply component. A

TABLE IV
CHRONOLOGY OF CVR PROGRAMS IN NORTH AMERICA

Year, reference	Organization or company	Voltage reduction [%]	Energy [GWh]	CVR factor (energy)	Average power [MW]	Comments
1973 [5]	Public Service Commission of NY State	3-5				Cause: oil embargo; stopped when embargo lifted
1973 [6]	America Electric Power	5, every other day	4%			1-yr study; investment not justifiable
1976 [7]	Pacific Gas and Electric	3.2-4.8	2686			
1979 [6]	American Electric Power	5, for 24 h	3.55%	0.71	4%	
1984 [8]	Northeast Utilities	Min.: -3 to -5; max.: +5 to +3		1 (non-heating)		Conclusion: use LDC instead of changing limits
1984 [9]	Commonwealth Edison		1%	0.46 (residential) 0.99 (commercial) 0.41 (industrial)		Cost of implementation not justified
1987 [10]	Bonneville Power Administration				168-270	Cost: 5 ¢/kWh (average) < 1 ¢ for most loads
1988 [11]	Snohomish Co. PUD	2.1	281 kWh/yr /customer	0.621 0.33 (heating) 1.1 (commercial)		Pilot study on 3 substations Savings: $6.28/yr/customer
1996 [12]	BC Hydro		1.3/yr	0.7	1.6 (peak)	Pilot study; VVO method
2002 [13]	Inland Power and Light			0.621		"Adaptive Voltage Control"; 1 yr
2004 [14]	Northwest Energy Efficiency Alliance	Down to 115.5 V, every other day	346 kWh /yr/house	0.3-0.86 0.57 (residential)	200-270	2.5 yr; cost: 2-2.5 ¢/kWh
2005 [15]	Hydro-Québec		1,500	0.4		Pilot study
2007 [12]	BC Hydro		7/yr			VVO method
2009 [16]	NWPCC				400	
2010 [17]	US Department of Energy		3.04%			Simulation; loss reduction not significant

rule of thumb would be: networks with a higher proportion of small commercial loads yield the highest energy and economical savings and largest peak shaving as well.

The reader will note the absence of analysis regarding the potential deferred investment benefit of CVR. This reflects the fact that ConEd already uses voltage reduction during peak periods to meet demand. It is during these peak periods that excess capacity is required and when equipment life is shortened. As such, reduced maximum demand during non-peak periods does not have a substantial technical or economic impact on the system.

VI. CONCLUSION

This paper introduces an economic model, based on a field-validated load model, for the assessment of the impact of CVR. The model evaluates the impact on individual customers and utility, taking into account the utility revenue model and the different billing structures, including service class, monthly rates, and the presence of reactive power billing. The results presented here for voltage reductions of 2.25, 4, 6, and 8% indicate that for individual customers, the larger the original bill, the higher the savings in percent. For the utility, the main advantages are the reduction in aggregated energy consumption and peak demand shaving.

Overall, the savings are significant, especially considering the possibility of utility-wide implementation of CVR. The money saved from this program could most effectively be used to install voltage regulators or capacitors that would prevent voltage limits violations and, thus, enable further lowering the voltage, which would lead to more energy and economic savings, until the flattest and lowest but yet acceptable voltage profile possible is reached.

APPENDIX
CHRONOLOGY OF CVR PROGRAMS

The chronology of CVR programs in North America is given in Table IV.

In the table, LDC stands for line drop compensation, VSR stands for voltage-sensitive relay, and VVO stands for voltage-var optimization.

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