Incentive Design of Conservation Voltage Reduction Planning for Industrial Loads in Ontario

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Electrical and Computer Engineering

Waterloo, Ontario, Canada, 2013

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In this thesis, a novel framework for planning and investment studies pertaining to the implementation of system-wide conservation voltage reduction (CVR) is presented. In the CVR paradigm, optimal voltage profiles at the load buses are determined so as to yield load reductions and hence energy conservation. The system modifications required for CVR is known to be capital intensive; therefore, the proposed model determines the system savings and the appropriate price incentives to offer industries such that a minimum acceptable rate-of-return (MARR) is accrued. In this model, the industrial facilities are represented by a combination of constant impedance, constant current, and constant power loads.

A detailed case study for Ontario, Canada, is carried out considering that industrial loads are investing in CVR implementation to reduce their energy costs. The optimal incentives that need be offered by the system planner, over a long-term horizon and across various zones of Ontario, are determined using the presented mathematical model. Furthermore, a comprehensive risk analysis, comprising sensitivity studies and Monte Carlo simulations, is carried out considering the variations in the most uncertain model parameters.

In this work, it is shown that savings from CVR are enough so that incentives are not required in Ontario. Sensitivity analysis shows that electricity price and project cost have the highest impact on the incentives, and that electricity price and industrial demand have the most effect on system savings. Monte Carlo simulations show that the expected energy cost savings result in expected incentive rates to be relatively low compared to the average electricity price in Ontario. CVR is shown in this thesis to be a low cost Demand Side Management program to implement from the perspective of the power system planner, and a worthwhile investment for the industrial load.

Acknowledgements

I would like to thank the Ontario Power Authority for funding this study. I would also like to thank Flakeboard Company Limited for providing useful inputs to this study.

I am grateful to have Professors Claudio Canizares and Kankar Bhattacharya as my supervisors for mentoring me on this research work. Their guidance has led me on an appropriate path to creating this thesis in which I am truly proud of. Their attention to detail, expertise, and vision has made this work possible and I thank them for that.

To my wonderful girlfriend of 8 years, Phybe Yang, thank you for always being there for me and helping me develop into a stronger individual. Having you by my side gave me motivation and determination to overcome any obstacles I had.

Finally, I want to thank my close friends from my undergraduate years. You have been a positive influence in my life and I am blessed to be among such driven individuals.

Dedication

I dedicate this to my parents, Phong Le and Hong Ho,
for their relentless support and believing in me.

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List of Acronyms

CVR	Conservation Voltage Reduction
DSM	Demand Side Management
EPRI	Electric Power Research Institute
HOEP	Hourly Ontario Electricity Price
IESO	Independent Electricity System Operator
IRR	Internal rate of return
MARR	Minimum Acceptable Rate-of-Return
MINLP	Mixed Integer Nonlinear Programming
NLP	Nonlinear Programming
NPV	Net Present Value
OPA	Ontario Power Authority
OPF	Optimal Power Flow
pdf	probability density function
PWF	present worth factor
RTP	Real-time-price
TOU	Time-of-use
VVC	Volt/Var control

Nomenclature

Indices

i, j	Index of bus
y	Index of year

Parameters

a, b, c	Constants associated with load model
d	Discount rate [%]
B_{ij}^{y}	Suceptance [pu]
G_{ij}^{y}	Conductance [pu]
$\overline{GC_i^y}$	Maximum generation capacity [MW]
$\underline{GC_i^y}$	Minimum generation limit [MW]
$\overline{P_{ij}^y}$	Maximum line limit [MW]
${P_{ind}}_i^y$	Nominal active power of industrial load [MW]
${P_L}_i^y$	Non-industrial load [MW]
N	Total number of buses
${V_o}_i^y$	Nominal voltage [pu]
Y	Total number of years

ρ	Electricity price [$/MWh]
β	Project cost [$/MW]

Variables

I_i	Investment amount [$]
IRR_i	Internal rate-of-return [%]
J	System savings [$]
P_{ij}^y	Active power line flow [MW]
$P_{G}{}_i^y$	Generator active power [MW]
$P_{ZIP}{}_i^y$	Effective active power [MW]
$Q_{G}{}_i^y$	Generator reactive power [MVAR]
$Q_{ZIP}{}_i^y$	Effective reactive power [MVAR]
R_i^y	Total incentive [$]
S_i^y	Energy cost savings [$]
V_i^y	Adjusted voltage [pu]
α	Incentive [$/MWh]
θ	Power factor angle [rad]
δ_{ij}^y	Angle between bus i and j [rad]

Chapter 1

Introduction

1.1 Motivation

Demand Side Management (DSM) has been a time-tested and effective mechanism to dampen growing energy demands, which may otherwise lead to increased carbon emissions and require the high cost of expanding the power system infrastructure. The common DSM strategies include peak clipping, load shifting, energy conservation, and energy efficiency. [1][2]. It benefits utilities when the DSM program is designed to reduce the peak demand in the long-run, since it alleviates investments in additional capacity, and although utilities decrease their revenue from energy conservation programs, they should still promote them because of their positive impacts for society and the environment.

An erstwhile but effective energy conservation technique called Conservation Voltage Reduction (CVR) is often used as part of DSM programs [3]. CVR relies on the concept that, since loads are voltage dependent, operating at a load voltage close to the lower acceptable limit can reduce energy consumption. However, operating at the lowest acceptable voltage is not always favored, for example, in display devices [4], or motors operating at higher than rated torque conditions [5]. Operating at the load voltage that results in the maximum reduction in demand, while respecting the operational constraints of the load, is referred to as voltage optimization. It is reported in [6] that using voltage optimization as opposed to CVR would yield higher energy cost savings.

Better efficiency and energy savings in the system can be achieved through CVR with appropriate system modifications, but this can be capital intensive and may not be desirable for an investor. The costs come from equipment such as the central core unit that sets the optimal voltages, voltage regulator controllers, and power monitors [6]. On the other hand, the costs accrued by a distribution system to accommodate for low operating voltages come from adding regulators or re-conductoring the feeders [7]. The benefits from CVR for the system planner can outweigh the costs if power system upgrades can be deferred and environmental improvements can be accrued. Therefore, if energy cost savings cannot recover the cost of a CVR implementation project, financial incentives may have to be offered by the system planner to help investors see an appropriate rate-of-return. To this effect, a system-wide mathematical model could be developed to determine the energy cost savings and the financial incentives.

Very little work has been reported in the literature on how an investor can recover their costs from a CVR program and to the best of the author's knowledge, there are no programs designed to incentivise wide-scale CVR. In fact, it is mentioned in [5] that CVR regulatory programs have not been implemented because of the large capital investment required.

1.2 Literature Review

1.2.1 Conservation Voltage Reduction

Energy conservation was widely considered in the 1970s due to events such as the oil crisis of 1973 and 1979. This transformed voltage reduction, a technique that was initially used as the last resort for load shedding, into an energy conservation scheme called CVR [5]. Since there have been mixed reviews on the effectiveness of CVR, field tests from several utilities and its technical and economical aspects are discussed in [5], where the impact of voltage reduction on active power, reactive power and energy reduction is examined considering measured data from 1941 to 1979 for various load mixes consisting of residential, commercial and industrial loads. In addition, experimental results for induction motors with lowered voltage show that there is a reduction in active power drawn associated with efficiency and power factor improvement. It is also noted in [5] that not all devices such as microwaves and heating elements show energy reduction even though there is load reduction.

Data from several field tests are analyzed using T-ratios in [8] to show that energy savings from voltage reductions are statistically significant. Generally, the energy savings are measured by applying voltage reduction on alternate days and comparing it with adjacent days without voltage reduction. Based on the combined results of the field tests, it is argued that 1% reduction in voltage would result in energy savings of 0.76%, 0.99%, and 0.41% for residential, commercial, and industrial loads, respectively. Furthermore, a functional representation to relate the energy savings to the load mix is proposed.

The effect of varying voltages on end-user devices in residential, commercial, and industrial loads are reported in [4, 9, 10]. In [9], power consumption is recorded while varying the voltage on devices such as air conditioner units, refrigerators, lights, etc; thereafter, using the aggregate mix of these devices in a distribution feeder, the net impact on load consumption from voltage variation is analyzed. In [10], the impact from CVR on devices that are typically found in industrial facilities are discussed; and it is reported that CVR reduces transformer no load and core losses, improves the efficiency in electronic power supplies, brings about reduction in incandescent lights while fluorescent lights improve on performance index, and improves the efficiency of ac motors operating at less than rated load conditions. In the more recent study [4], the US Department of Energy uses end-user devices to model 24 prototype distribution feeders; simulations of CVR on these feeders are extrapolated on a national level, noting that heavily loaded feeders which allow for the most voltage reduction are the best candidates for CVR.

Several utilities have conducted field tests on CVR followed by an economic analysis of the project. The San Diego Gas & Electric Company carried out voltage reduction and determined the energy and peak reduction for residential and commercial loads [11]; it is noted that in order for a voltage reduction program to be deemed cost effective, the costs from voltage reduction implementation must be recovered and the customers' energy bill must be reduced; a 0.1% to 0.2% electricity rate increase is recommended in order for the utility to maintain its minimum revenue requirements. The Northeast Utility carried out CVR on eight distribution circuits by compressing the voltage limits from +3% and -5% to 0% and -5% [12], observing energy savings in the range of 0.57% to 1.35% per 1% point reduction in voltage; one of the circuits, with predominantly resistive heating loads, did not experience energy savings. An economic analysis revealed that only one out of the eight feeders tested was cost effective, assuming a project lifetime of 25 years, which shows that CVR is capital intensive. A similar more recent study in [3] at the Snohomish County Public Utility District reports energy reduction from CVR, and proposes a scheme to add an additional fee to the customers' electricity bill in order to recover the costs of implementation. In [13], a functional relationship between the cost of CVR implementation and the associated energy savings in the Pacific Northwest system is presented. Also, quotes for different options to achieve voltage reduction are reported for over 30 utilities; each option allows for different voltage reductions and are feasible on a few of the distribution circuits, resulting in unique energy savings and costs for each option. Based on this information, a relationship between the potential energy savings from CVR and project implementation costs is formulated for the Pacific Northwest system.

It is evident that CVR is an effective method for energy reduction based on the review. Various studies have been carried out from the perspective of the utility implementing CVR, but not from the point of view of the customer. With the need for additional infrastructure to support the growing demand, power system planners must provide incentives to customers to participate in initiatives to reduce or shift their demand. Therefore, in this thesis, an incentive design for CVR is developed for the Ontario, Canada, considering both the customer and utility interests.

1.2.2 Volt/Var Control

Rather than operating at the lowest voltages as in CVR, there is a technique called Volt/Var control (VVC) where distribution automation is used to apply the optimal voltages that minimize system losses and energy consumption from loads. The objectives of VVC are usually similar to CVR, but the approach to finding the optimal system settings for voltages, tap settings and capacitor switching varies.

In [14], a quadratic programming based Optimal Power Flow (OPF) method is implemented, converting an inequality-constrained model to an equality-constrained one, where linear equations are solved directly. In [15], a VVC algorithm using an orient descent method useful for real-time applications, since it performs faster than Monte Carlo simulations is proposed. In [16], genetic algorithms are applied to VVC to determine the optimal dispatch schedule for on-load tap changer settings and capacitor switching using load forecast data; the algorithm is shown to outperform dynamic programming by reducing the search space. In [17], combinations of voltage regulator control with various capacitor switching control schemes are tested on different IEEE test systems. The combinations of voltage regulator and capacitor control is shown to be more effective at reducing losses than capacitor control, conventional control, and no control at all.

More recently, a distribution OPF model with a multi-objective function that minimizes energy and switching operations, similar to the objectives of VVC, is presented in [18]. It is reported that the computational burden is reduced, making it suitable for practical implementation, by converting a Mixed Integer Nonlinear Programming (MINLP) model to a Nonlinear Programming (NLP) model, and using an algorithm that finds the closest feasible integer solution in the search space.

Many studies on VVC have shown that optimization can be used to find the optimal voltages for energy and loss reduction. In the context of CVR, finding the optimal voltages yielding the lowest energy consumption is relevant to this research. Thus, an optimization model is developed here to ensure energy reduction from CVR, incorporating system operational constraints and an objective function that maximizes energy savings.

1.2.3 Demand Side Management

DSM is implemented through planning, implementation, and monitoring of a program that is designed to influence and manage demand profiles into a desired shape [1]. The more programs that are designed for DSM, the higher the need for evaluation to prove its cost-effectiveness [2]. A detailed discussion of the evaluation phases of DSM programs are presented in [2], using benefit/cost ratio, which in this context is the avoided increased capacity cost over the cost of the program. Typically, DSM programs offer special rates or incentives to induce load reduction; however, one of the difficulties of such programs is estimating the demand had there not been an incentive program in order to compensate the participant accordingly. In [19], a regression model is developed, based on interruptible and curtailable rate programs from over 100 utilities, to predict the demand before load reduction is implemented. Estimating the load reduction appropriately is necessary to evaluate the cost-effectiveness of the DSM program.

Interruptible load management is a common DSM technique to relieve peak demand. Utilities perform this by creating contracts with customers that allow them to reduce customer load by request. In return, customers receive incentives based on their reduction at a rate depending on the program they enter. An optimal selection of interruptible loads using an OPF framework is proposed in [20]; the model considers different rate schemes for participants depending on the power factor and advanced notification period and in addition to the system costs, which typically consists only of the generation costs in the conventional OPF method, the costs from optimally selecting interruptible loads are also considered; an example of the model using a 6 bus power system demonstrates that interrupible loads reduce the system costs and spot prices considerably compared to the conventional OPF technique. In [21], an optimal incentive contract design for load relief using game theory is developed. It is noted that the methodology is used specifically to provide load relief for voltage collapse, but could also be extended for other load reduction emergencies such as line overload and insufficient generation. Before the contract is created, an assessment of the load sensitivity is evaluated. Thus, the load reduction at a bus leading to the greatest system demand reduction would be considered the most valuable in the context of providing load relief. Game theory is used to determine the optimal contract containing details of the incentive offered and the load reduction required at each load bus.

An overview of DSM from a modern perspective is discussed in [22], including recent demonstrations of DSM in the context of smart grids and distribution automation, suggesting that energy efficiency can be detected at facilities through a data acquisition infrastructure with sensor networks, data loggers, gateways, databases, etc. The overall system should allow for measures to assess the effectiveness of the energy efficiency scheme.

The latest works in smart grid comprise two-way communication where the system operator can negotiate consumption patterns or request for emergency support from customers or businesses; with these developments, utilities and customers are able to interface in order to better manage demand. In [23], a DSM program is developed for a smart grid with an incentive that minimizes customers' cost by optimally scheduling appliances that have the flexibility of load shifting, so that costs are minimized for the customer and the peak to average load ratio is minimized. In [24], an optimization model that allows to schedule appliances in a residential energy hub is formulated while taking into account customer preferences; various objective functions are considered such as minimizing energy cost, energy consumption, CO_2 emissions, peak load, and a combination of the aforementioned objectives. Simulation results demonstrate that savings of 20% on energy costs and reduction of 50% on peak demand can be experienced depending on the objective function.

The main distinguishing feature between CVR and other DSM techniques is that CVR can be seamlessly integrated into system operations without causing inconvenient process modifications such as load shifting and interruptible load management. Therefore, an incentive program, such as those proposed and existing for DSM should be studied and implemented for users to adopt CVR as an energy savings scheme, as proposed in this thesis.

1.3 Objectives of this Research

The main objectives of this research are as follows:

- Develop a mathematical model that assists in the planning of wide-scale implementation of CVR, considering the associated equipment costs for loads. The proposed model is a planning tool that minimizes the system costs from the perspective of a power system planner, where costs are the net of the financial incentives and energy cost savings. The model ensures that the investor accrues a minimum rate-of-return from the CVR equipment, and it determines variables relevant to system planner such as the energy cost savings, the incentives to distribute, the IRR for the customer from the investment, and the optimal voltages at which to operate.

- Apply the proposed model to a realistic representation of the Ontario power grid in order to develop an appropriate incentive program that makes CVR an attractive option for energy conservation among planners, utilities, and customers.
- Perform a risk analysis based on sensitivity studies and Monte Carlo simulations in order to determine the impact of uncertainties in the outputs of the proposed mathematical model. This allows to study the robustness of the proposed incentive program.

1.4 Outline of the Thesis

The remainder of the thesis is organized as follows: Chapter 2 discusses the relevant background to this research such as load modeling, CVR and voltage optimization, DSM, and economic analysis methods. Chapter 3 describes the proposed voltage optimization model used for planning. Chapter 4 presents the application of the proposed model to a realistic representation of the Ontario, Canada, power grid, to evaluate the possible benefits and costs of a province-wide CVR/VVC program; sensitivity analysis and Monte Carlo simulation are also carried out to study the risks of the proposed CVR/VVC program. A summary of the presented work, the main contributions of this research and possible future work are discussed in Chapter 5.

Chapter 2

Background

This chapter first discusses load modeling and its application to evaluating load reduction from CVR. Then, a technical review of implementing CVR and voltage optimization is provided. Also, DSM is discussed to show where CVR fits as a load management strategy. Lastly, relevant economic evaluation methods that can be used to assess DSM programs are briefly discussed.

2.1 Load Modeling

The complex power drawn by a generic load at a node is given by:

$$S = VI^* \tag{2.1}$$

This yields real and imaginary components corresponding to the active and reactive power demand, respectively. Loads can be represented by a combination of constant impedance (Z), constant current (I), and constant power (P) loads, i.e., ZIP loads. This representation is illustrated in Figure 2.1 and mathematically corresponds to:

$$S_{ZIP} = S_Z + S_I + S_P \tag{2.2}$$

which comprises the following active and reactive components as given [4]:

$$P_{ZIP} = a\frac{|V_i|^2}{|V_o|^2}|V_o|^2|Y|\cos\theta_Z + b\frac{|V_i|}{|V_o|}|V_o||I|\cos(\theta_V - \theta_I) + cP_o \tag{2.3}$$

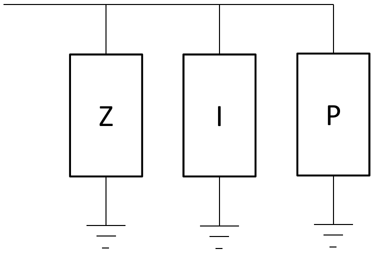

Figure 2.1: ZIP load model.

$$Q_{ZIP} = d\frac{|V_i|^2}{|V_o|^2}|V_o|^2|Y|\sin\theta_Z + e\frac{|V_i|}{|V_o|}|V_o||I|\sin(\theta_V - \theta_I) + fQ_o \tag{2.4}$$

Equations (2.3) and (2.4) can be simplified as follows:

$$P_{ZIP} = a\left(\frac{|V_i|}{|V_o|}\right)^2 P_o + b\left(\frac{|V_i|}{|V_o|}\right) P_o + cP_o \tag{2.5}$$

$$Q_{ZIP} = d\left(\frac{|V_i|}{|V_o|}\right)^2 Q_o + e\left(\frac{|V_i|}{|V_o|}\right) Q_o + fQ_o \tag{2.6}$$

In practice, the above ZIP load parameters a, b, and c (and d, e, and f) are determined experimentally by varying the node voltages while recording the active (and reactive) power drawn by the end-user device. The Electric Power Research Institute (EPRI) has completed a study considering the effect of voltage variation on the power drawn by various devices [25]. The US National Department of Energy has also conducted a study to find the ZIP model parameters for various types of loads [4]. For demonstration purposes in this chapter, the induction motor load characteristics reported in [25] from varying voltages are used to determine the ZIP model parameters. Thus, using a polynomial fitting curve as illustrated in Figure 2.2, the ZIP model parameters shown in Table 2.1 can be obtained. Therefore, if the voltage dependency of a load bus is known, the appropriate model can be found.

In [9], the impact of voltage variation on energy consumption of various devices is reported. It is observed from Figure 2.3 that the energy consumption in incandescent lamps, refrigerators, and fluorescent lamps monotonically decreases with decrease in voltage, while for air-conditioner (Figure 2.4) and 3-phase induction motors (Figure 2.5), the energy consumption decreases as the voltages are reduced, attaining a minimum and then increasing

Table 2.1: ZIP model parameters for 1 phase, 230 V and 0.5 HP induction motor of Figure 2.2.

Torque, pu	a	b	c	d	e	f	P_o, pu	Q_o, pu
1.2	7.50	-15.56	9.07	15.67	-30.16	15.49	1.22	0.83
1.0	4.30	-8.32	5.02	9.71	-17.13	8.42	1.01	0.77
0.70	2.41	-4.13	2.72	10.99	-18.57	8.58	0.75	0.76

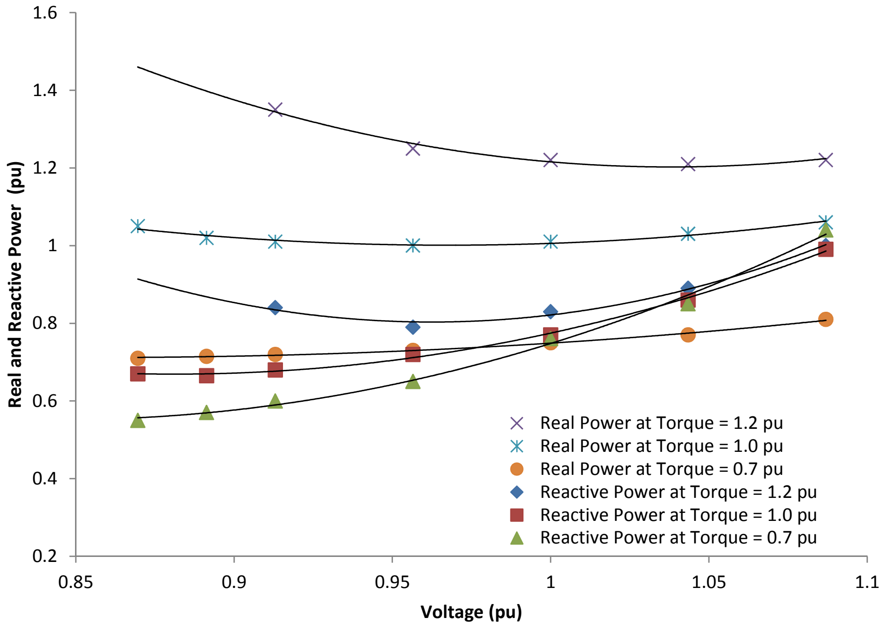

Figure 2.2: Power drawn by induction motor loads versus voltage variations [25].

with further decrease in voltage. Finally, it is noted that for resistive loads, there is no impact on energy consumption from varying the voltages (Figure 2.3), due to thermostatic effects, i.e. the resistive load stays on longer to reach the desired heat level.

2.2 Conservation Voltage Reduction

CVR as a method for energy conservation was very popular in the 1970s in the US [5]. It is shown in the previous section that operating at a voltage other than the rated voltage, results in energy reduction in certain devices. CVR operates on the macro level by adjusting

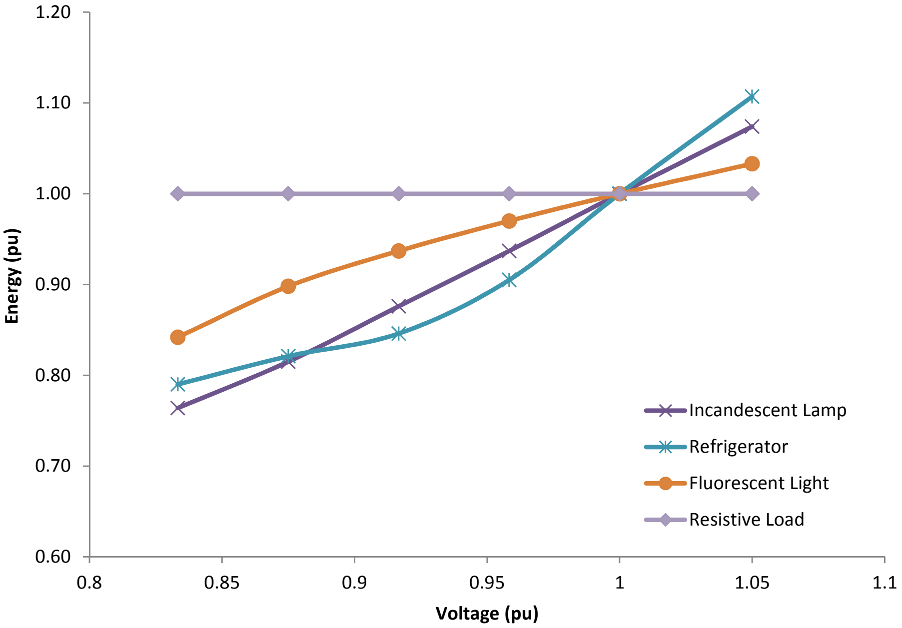

Figure 2.3: Energy consumption of various loads versus voltage variations [9].

the voltage at a substation, hence reducing the power drawn by multiple loads at once. Utilities participating in this scheme, operated their systems at voltages that would reduce the energy consumption; however, this meant less revenue from customers and thus was not very appealing. Recently, CVR has regained popularity, as evident from the study by the US Department of Energy [4], due to the potential for avoided costs of expanding the power system infrastructure, and probable incentives to be offered by power system planners.

With CVR, the feeder voltages are reduced to the lowest level within operating limits as specified by ANSI C84.1 standards [26]. Typically, the voltage may drop below the minimum acceptable value the further away it is from the substation [12]. Hence, to reduce the substation voltage further without the lowest voltage on the line dropping below the minimum, system modifications such as re-conductoring the feeders [7], or installing a regulator or capacitor [27] are needed. The node voltages after system modification and CVR implementation can be significantly improved [12].

Voltage optimization is a new concept that has evolved from CVR, and the difference is that there is an optimal operating voltage, not necessarily the lowest allowable voltage,

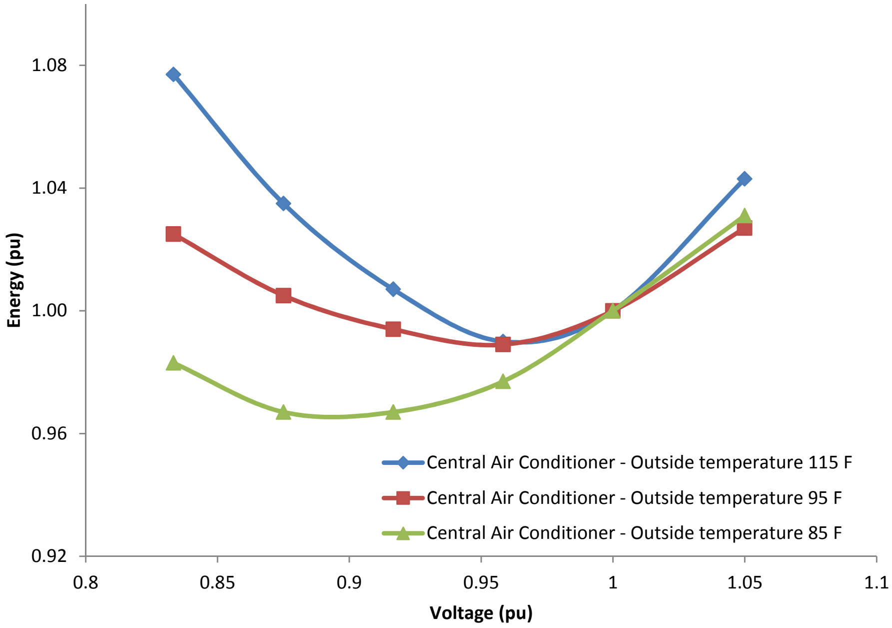

Figure 2.4: Energy consumption of central AC versus voltage variations [9].

that would yield the highest load reduction. This is applied by placing meters near the loads, where voltages would be the lowest. These meters send information back to a central control core unit that appropriately adjusts the voltage to ensure that it does not fall below a minimum acceptable level. The simplified single line diagram for voltage optimization is shown in Figure 2.6. There is no generic method to measure the cost of a voltage optimization project because it depends on the system; the costs accrue from meters, voltage regulators and a central control unit.

2.3 Demand Side Management

DSM programs are designed to manage load profiles by reducing the consumption or shifting the electricity consumption to low demand hours, so as to put less strain on the power system. In Figure 2.7 [1], various types of DSM strategies are shown. Peak clipping is the reduction of load during peak demand hours; an example would be the direct load control of appliances by the utility. Valley filling can be realized by increasing the off-peak

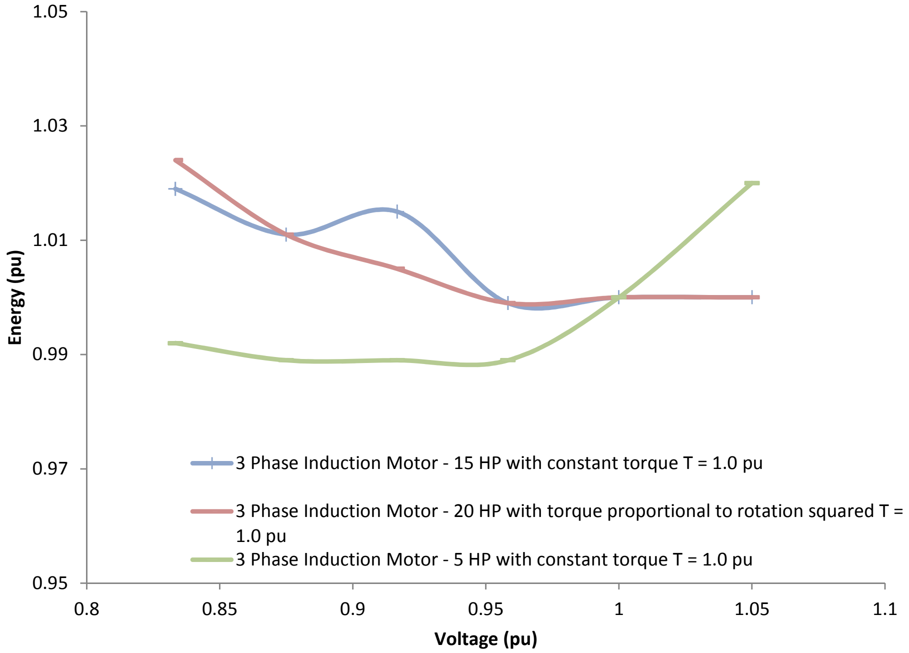

Figure 2.5: Energy consumption of induction motors as affected by voltage variation [9]

loads, by charging for example, energy storage devices during off-peak demand periods. Strategic conservation reduces the overall energy and induces efficiency improvement by, for example, investing in better insulation for a facility. Voltage optimization is considered an energy conservation strategy because it can reduce the demand for all hours of the day. Strategic load growth occurs when the utility increases its revenue for energy sales through increased demand brought about by certain policies; an example would be the promoting of automation in industrial facilities to produce more throughput and thereby increasing the energy demand. Flexible load shape is a reliability concept that allows the utility to change the load at anytime through interruptible loads and demand response programs. Lastly, load shifting is managing the electricity usage patterns from peak demand hours to low demand hours; this does not have a net reduction on energy consumption since the usage is shifted and not reduced, and facilities are offered incentives given the inconveniences for the facility associated with process changes.

The evaluation of a DSM program is a continuous process [2]. The initial phase is a simple assessment of the DSM program involving a benefit/cost analysis. The benefit is the avoided cost of having to pay for extra energy generation or infrastructure expansion, and

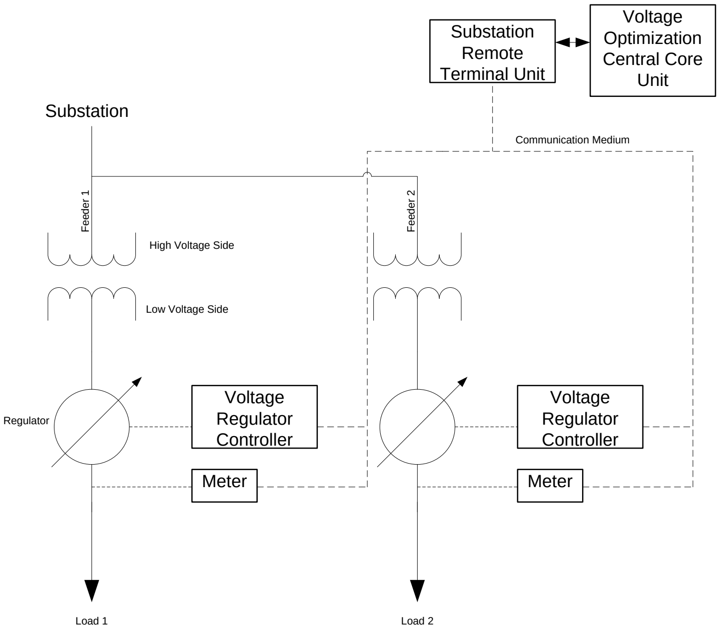

Figure 2.6: System modifications for voltage optimization [6].

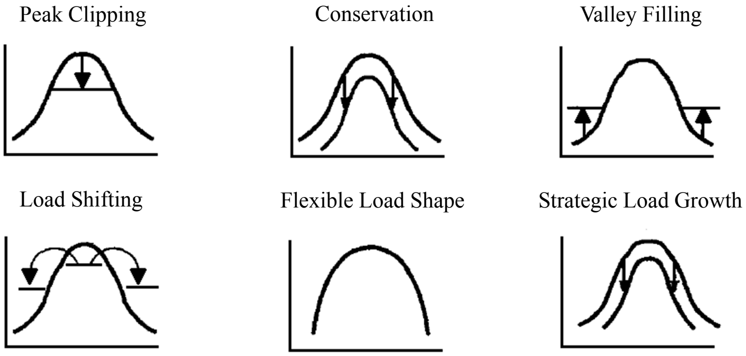

Figure 2.7: Various DSM techniques [1]

the cost that accrues from the implementation of the DSM program. In the intermediate phase, field data is available to support the benefit/cost ratio such as program costs, customer participation, and the effects on the load shape by comparing the before and after consumption. In the intensive phase, an assessment of DSM programs are carried out for long-term power system planning; in this stage, DSM alternatives are compared, project costs are calculated, the impact of the DSM program is estimated, followed by market research to observe the acceptance of the program, and finally, associated generation planning is carried out.

2.4 Economic Analysis

One important aspect of economic evaluation is the time value of money. Since money cannot be summed directly for different time periods, the present worth factor (PWF) is used to evaluate the worth of money in future years to a present value considering a certain discount rate, as given by:

$$PWF_y = \frac{1}{(1+d)^y} \tag{2.7}$$

In order to evaluate a project, the income and expenses must be known or evaluated for the project lifetime. The sum of the yearly cash flow converted to present value is called the Net Present Value (NPV), which is given by,

$$NPV = \sum_{y=1}^{Y} (Income_y - Expenses_y) PWF_y \tag{2.8}$$

The NPV is used to assess the worth of the project in present terms or to compare with NPVs of other projects. An example is illustrated in Figure 2.8 where a cash flow diagram is converted to an NPV.

IRR is the interest rate at which the NPV equals zero, which is also considered as the break-even point for the project since the income equals the expenses. In practice, it measures the profitability of a project and is calculated using the following equation:

$$\sum_{y=1}^{Y} \frac{Income_y - Expenses_y}{(1+IRR)^y} = 0 \tag{2.9}$$

The Minimum Acceptable Rate-of-Return (MARR) is the lowest rate of IRR at which the investors are willing to invest in a project. A positive IRR indicates that the project is earning money. If the IRR is less then the MARR, it would be more practical to invest in another project that allows for a higher return. The IRR in (2.9) can be calculated using spreadsheets based on a trial and error approach.

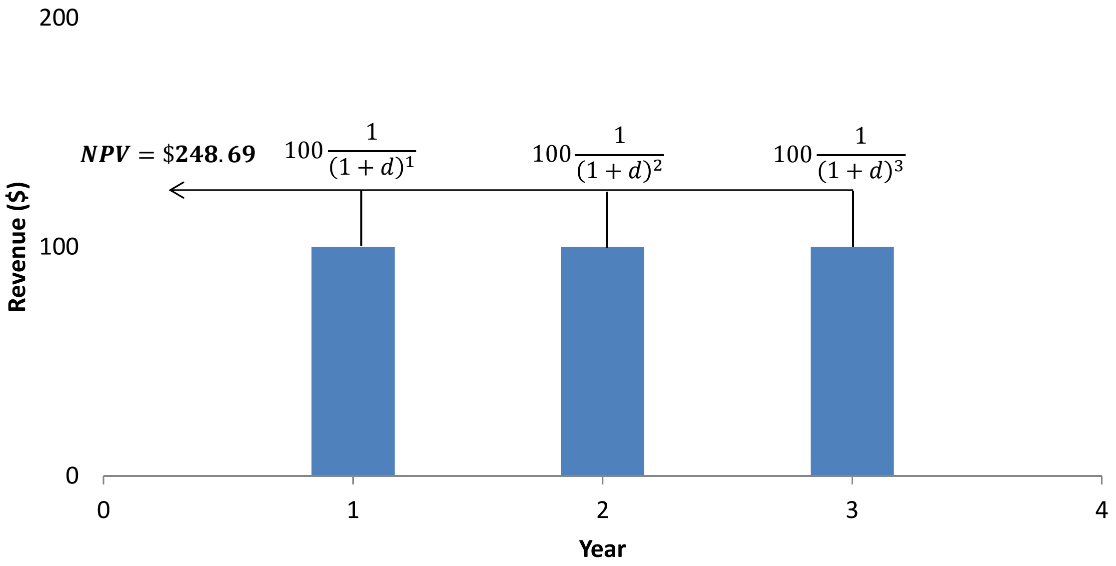

Figure 2.8: Converting cash flow to an NPV for $d = 10\%$.

Economic evaluation is generally used to compare different projects and can also be used to assess a project if there are uncertainties in the input parameters. In power systems, variation can come from operation costs, fuel, profit, etc. The economic risks can be analyzed using sensitivity analysis and Monte Carlo simulations as explained next.

2.4.1 Uncertainty and Risk Analysis

For incentive programs that consider a long-time horizon, several input parameters are uncertain; therefore, risk analysis is required to take into account scenarios that may occur when the inputs vary. Uncertainties in an input parameter can be represented by a random variable, which is the outcome of an experiment with a certain probability that can either be discrete or continuous [28]. With discrete random variables, the possibility of an outcome's value are countable numbers; an example would be the outcome of rolling a six sided dice, which only has the possibility of landing on one of the six sides. Continuous random variables, which can take on any number within a defined range, have a probability given by:

$$P\{X \in A\} = \int_A f(x)dx \tag{2.10}$$

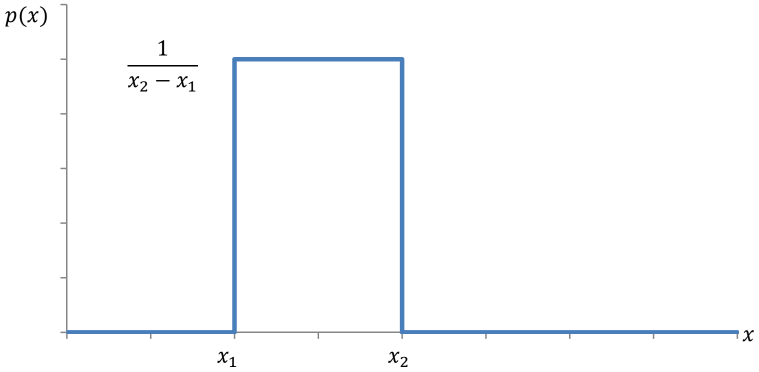

Figure 2.9: Uniform probability distribution function.

where X is the random variable, A is the range of possible values, and $f(x)$ is the probability density function (pdf) of the random variable X.

The area under the pdf must satisfy the condition following:

$$P\{X \in (-\infty \leq x \leq \infty)\} = \int_{-\infty}^{\infty} f(x)dx = 1 \tag{2.11}$$

This ensures the probability of the experiment is 100% when integrating over the entire range of the pdf. Uniform pdf and normal pdf are relevant in this research, hence, only these pdfs are discussed next.

Uniform Probability Distribution Function

A random variable that has the same probability for its entire range is considered to have a uniform pdf, which is given by:

$$f(x) = \begin{cases} \dfrac{1}{x_2 - x_1} & \text{if } x_1 \leq x \leq x_2 \\ 0 & \text{otherwise} \end{cases} \tag{2.12}$$

The associated pdf is illustrated in Figure 2.9.

Normal Probability Distribution Function

The normal pdf is a bell shaped curve that describes the probability of many phenomenon. Some examples are academic grades, the error made when measuring a quantity and the

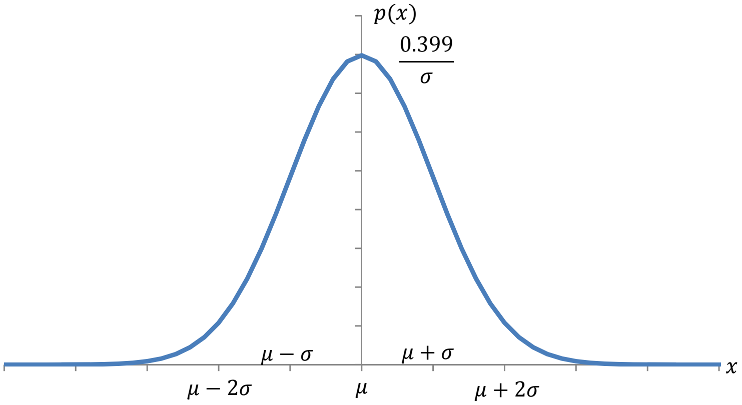

Figure 2.10: Normal probability distribution function.

direction of a molecule in a gas. This pdf is given by the following equation:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(x-\mu)^2/2\sigma^2} \tag{2.13}$$

which has two main parameters: the mean μ, and the standard deviation σ. A normal pdf is depicted in Figure 2.10.

2.4.2 Sensitivity Analysis and Monte Carlo Simulation

In sensitivity analysis, the impact of uncertain parameters in a model are analyzed by perturbing one parameter at a time while leaving other parameters unchanged. These results are plotted on a scatter plot in order to study how sensitive the results of an experiment are to the parameter being varied. This allows to determine the most sensitive parameters in a mathematical model.

The purpose of Monte Carlo simulation is to find the probability and the expected value of the outcome from an experiment. In Monte Carlo analysis, multiple parameters are adjusted simultaneously while recording the variables of interest in the model. The input parameters are random variables with a defined pdf. The simulations run for a defined number of sample periods until there is convergence in the cumulative expected value, and the results are plotted on a histogram to analyze the probability as well as the frequency of occurrence, which indicate the likelihood of ranges in outputs that may occur. Monte Carlo simulations are typically used to evaluate the impact of uncertainties in relevant input parameters, identified through sensitivity analysis, on the outputs of the mathematical model when several parameters are likely to change at once.

2.5 Summary

This chapter presents various discussions on CVR, voltage optimization, DSM, and economic analysis, which form the background of the research work presented in thesis. Applying voltage optimization by operating optimal voltages has been shown to yield energy reductions in end-user devices; it can also be applied at the “macro” level by reducing the substation voltage as done by many utilities. There are various DSM strategies, with CVR and voltage optimization being considered an energy conservation scheme by reducing demand for all hours. In order to evaluate the energy cost savings and the rate-of-return accrued to investors from CVR and voltage optimization, the various economic analysis fundamentals discussed here can be used.

Chapter 3

CVR Incentive Design

3.1 Introduction

This chapter presents the mathematical model for the planning of wide-scale CVR. First, the voltage dependent load model and the corresponding power savings equation are introduced. Then, the equations relating the load model to financial variables for the system planner and the investors are presented. Power flow equations are included in the model to ensure that the physical limitations of the system, such as system voltage and power transfer limits, are respected while maximizing the system savings for the planner from CVR.

3.2 Mathematical Modeling Framework

3.2.1 Load Representation

A generic industrial load can be represented as a combination of different voltage dependent loads that are constant impedance (Z), constant current (I) and constant power (P) [7]. Such a ZIP load can be mathematically expressed as:

$$P_{ZIP}{}_i^y = P_{ind}{}_i^y \left[a + b\left(\frac{V_i^y}{V_{oi}^y}\right) + c\left(\frac{V_i^y}{V_{oi}^y}\right)^2 \right] \tag{3.1}$$

$$Q_{ZIP}{}_i^y = P_{ZIP}{}_i^y \tan\theta \tag{3.2}$$

where $a+b+c=1$ and $P_{ind}{}_i^y$ represents the nominal power consumed by the load at the nominal voltage V_{oi}^y. The effective power of the load after voltage adjustment is given by $P_{ZIP}{}_i^y$, where V_i^y is the voltage that varies the active power of the industrial load. $Q_{ZIP}{}_i^y$ can be calculated from (3.2) using the power factor angle θ, assuming it is constant. In this study, a variety of weights for a, b and c are used to represent industrial loads. Each set of weights, is assumed to be uniform throughout the power system at each bus.

The reduction in power consumption for a ZIP load, vis-à-vis a constant power industrial load, is given by:

$$Load\ Reduction = \frac{P_{ind}{}_i^y - P_{ZIP}{}_i^y}{P_{ind}{}_i^y}\% \tag{3.3}$$

3.2.2 Conservation Voltage Reduction Planning Model

The savings accrued to the power system planner is the energy cost savings minus the distributed incentives. In the proposed CVR planning model, the NPV of the planner's savings, referred to as the system savings, is considered as the objective function for maximization, as follows:

$$J = \sum_{y=1}^{Y}\sum_{i=1}^{N}(S_i^y - R_i^y)\frac{1}{(1+d)^y} \tag{3.4}$$

Here, the system planner benefits when CVR customers maximize their energy cost savings and the incentive is minimized.

It is assumed that the implementation cost depends on the size of the load. Hence, the investment from industries is given by:

$$I_i = \beta\ P_{L}{}_i^1 \tag{3.5}$$

where the industrial demand at bus i in year 1 $P_{L}{}_i^1$ is multiplied by the project cost β in order to determine the cost of the investment.

The total energy cost savings from industrial loads at bus i, over a year (8760 hours), is given by:

$$S_i^y = 8760(P_{ind}{}_i^y - P_{ZIP}{}_i^y)\rho \tag{3.6}$$

and the total incentive offered by the system planner to industrial customers at a bus, over a year is given by:

$$R_i^y = 8760({P_{ind}}_i^y - {P_{ZIP}}_i^y)\alpha \tag{3.7}$$

A benchmark that investors (or CVR customers in this case) use to determine whether a project is worth pursuing is the IRR. The IRR of investors in CVR at bus i is obtained by equating the NPV of both the energy cost savings and the incentive amount to the investment as follows:

$$I_i = \sum_{y=1}^{Y} (S_i^y + R_i^y) \frac{1}{(1 + IRR_i)^y} \tag{3.8}$$

By finding the IRR, the system planner has a better insight into the zone (or bus) where investments made would yield the most benefit to industrial customers. The IRR for industrial customers at bus i is constrained by the MARR as follows:

$$MARR \leq IRR_i \tag{3.9}$$

This ensures that the IRR in each zone experiences at least the MARR, in order to recover the investment in CVR implementation.

The impact on the power system must be considered when many facilities optimize their voltage by incorporating the following power flow equations:

$$ {P_G}_i^y - ({P_L}_i^y + {P_{ZIP}}_i^y) = \sum_{j=1}^{N} V_i^y V_j^y (G_{ij}^y cos(\theta_{ij}^y) + B_{ij}^y sin(\theta_{ij}^y)) \tag{3.10}$$

$$ {Q_G}_i^y - ({Q_L}_i^y + {Q_{ZIP}}_i^y) = \sum_{j=1}^{N} V_i^y V_j^y (G_{ij}^y sin(\theta_{ij}^y) - B_{ij}^y cos(\theta_{ij}^y)) \tag{3.11}$$

In these equations, the aggregate load at every bus in the power system comprises both non-industrial and industrial customers. The non-industrial loads ${P_L}_i^y$ and ${Q_L}_i^y$ are represented simply by constant power loads, while the industrial loads ${P_{ZIP}}_i^y$ and ${Q_{ZIP}}_i^y$ are represented by voltage dependent loads as per (3.1) and (3.2).

Equation 3.10 and 3.11 allow ensuring that line flows do not go beyond limits, as per the the following constraint:

$$|P_{ij}^y| \leq \overline{P_{ij}^y} \tag{3.12}$$

Furthermore, voltage limits given by:

$$0.95 \leq V_i^y \leq 1.05 \tag{3.13}$$

and generation limits given by:

$$\underline{GC_i^y} \leq {P_G}_i^y \leq \overline{GC_i^y} \tag{3.14}$$

are needed to assure the feasibility of serving the required load.

The proposed CVR planning model given by (3.1)-(3.14) is a non-linear programming (NLP) model that is coded in GAMS, a high-level modeling platform, and solved using the solver MINOS [29].

3.3 Summary

A mathematical model for the planning of wide-scale CVR in a power system is formulated here. The objective is to maximize the system savings by maximizing the energy cost savings in the system while minimizing the incentive, which must ensure that investors on CVR see a return above the MARR. While adjusting the voltages for the maximum system savings, power flow equations are considered to ensure that the system is operating within limits and hence feasible. The loads in this case are represented using a ZIP model.

Chapter 4

Results and Analysis

4.1 Introduction

The optimization model presented in the previous chapter is used here to plan a wide-scale CVR implementation in Ontario, Canada. The case study is carried out from the perspective of the power system planner with the objective of promoting industrial customers to adopt this technology. Thus, the first part of this chapter discusses the system parameters and the demand characteristics of the Ontario system, which are used as inputs to the optimization model. Different ZIP model parameters are considered, and the following studies and detailed results are presented.

- Calculation of the system savings from the implementation of CVR across the province of Ontario, of the incentives required to drive such investments, and of the rate-of-return accrued to investors.
- Sensitivity analysis considering the variation of electricity price, industrial demand, discount rate, and project cost, one at a time.
- Application of Monte Carlo simulations, to determine the expected values of the system savings and incentive for varying multiple parameters simultaneously.

4.1.1 Case Study Description

The power grid system of Ontario, which is the system of interest for this study, comprises 10 zones: Bruce, West, Southwest (SW), Niagara, Toronto, East, Ottawa, Essa, Northeast

(NE), and Northwest (NW) [30]. A simplified power system model of Ontario, adequate for long-term planning purposes and represented by 10-buses, is illustrated in Figure 4.1, where the numbers correspond to the zone/bus number that is used in the simulation. The line data, line limits, and generation limits are obtained from [31].

For this study, the zonal demand and the long-term demand forecast data obtained from [32] is adjusted to closely reflect the actual average demand reported in [30]. Figure 4.2 shows the zonal-wise demand for Ontario, covering the period from 2011 to 2020. The share of industrial load per zone, provided in [32], is used to find the zonal industrial demand as illustrated in Figure 4.3, where the industrial demand of Bruce zone is lumped with SW [32], Observe that Toronto has the highest industrial growth followed by SW, while East and NW are zones with the lowest industrial growth.

The nominal values for the optimization model used here are summarized in Table 4.1. The average of the Hourly Ontario Electricity Price (HOEP) for all hours from 2002 to 2012 is obtained from [33], and is used here as the base electricity price for the studies. It should be mentioned that in practice, these are just part of the electricity costs for industrial customers, with global adjustment and peak demand charges not considered here, which would otherwise increase (double or more) the actual energy costs; therefore, the savings assumed in these studies can be considered here “pessimistic”. The project cost is an estimate based on results presented by a CVR/voltage optimization equipment vendor, which would include the central core unit that sets the optimal voltages, voltage regulator controllers, and power monitors [6]; the discount rate is based on the recommended value by the Treasury Board of Canada Secretariat [34]; the MARR for the investor is assumed to be 10%; and the project lifetime is assumed as 10 years.

Since the ZIP load parameters in (3.1) are not known for the Ontario system, the following weights are considered: 1 for high, 2/3 for medium and 1/3 for low. All the specific combinations of weights, as well as the corresponding load reductions calculated using (3.3), considering load voltage of 0.95 pu, are shown in Table 4.2.

4.1.2 Base Cases

The ten base-case results corresponding to the ten ZIP models, including the system savings and average zonal IRRs, are presented in Table 4.3. The energy cost savings from the ZIP models result in IRRs that are higher than the MARR; hence, the system planner does not have to offer any incentives. The bus voltages at all zones, except Bruce, are at the minimum allowable of 0.95 pu, since it yields the maximum load reduction, as expected

Table 4.1: Base Values.

Parameter	Base Value
Electricity Price	44 \$/MWh
Project Cost	35,000 \$/MW
Discount Rate	8%
MARR	10%
Project Lifetime	10 years

Table 4.2: ZIP parameters used for simulations.

ZIP Model	a	b	c	Load Reduction (%)
1	1	0	0	0.00
2	2/3	1/3	0	1.67
3	2/3	0	1/3	3.25
4	1/3	2/3	0	3.33
5	1/3	1/3	1/3	4.92
6	0	1	0	5.00
7	1/3	0	2/3	6.50
8	0	2/3	1/3	6.58
9	0	1/3	2/3	8.17
10	0	0	1	9.75

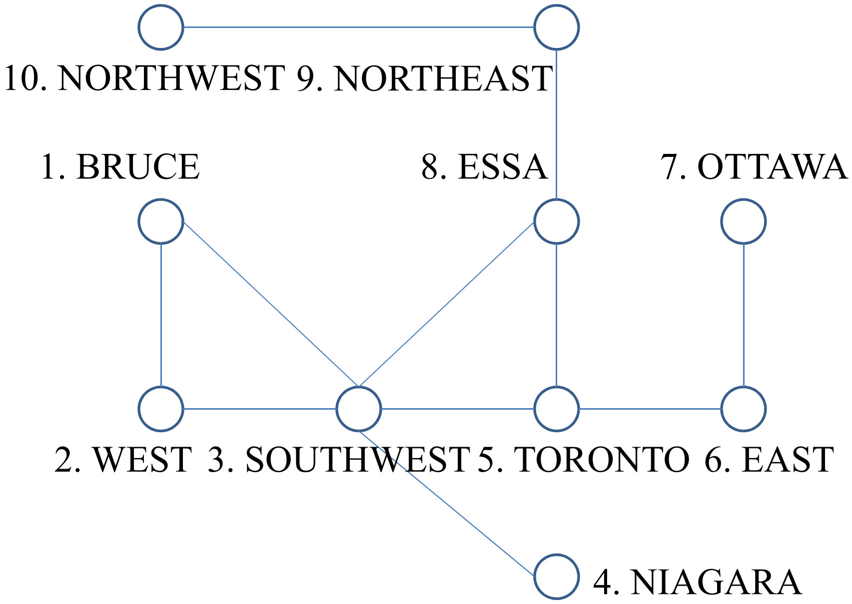

Figure 4.1: Ontario 10-zone (bus) system model.

based on the ZIP load model assumed. The voltage at Bruce is not affected because there is no CVR investment in this zone.

The case with ZIP Model 2 is analyzed in detail by considering the cash flow of the system planner illustrated in Figure 4.4. This model is used here as a reference, since it reflects the savings observed in actual CVR deployments [5]. In this figure, the system savings increase over the years as industrial demand increases. The NPV of the system savings is \$146 million in this case, and the average IRR for all zones excluding Bruce, since there is no investment in this zone, is 13.79%.

The IRR for all zones and ZIP models considered are plotted in Figure 4.5. They are higher for those ZIP models which have higher load reduction; therefore, the highest IRRs are accrued from CVR investments in Toronto, SW, and West, while the lowest correspond to Ottawa, East, and NW zones. Note that the order of zonal IRRs are directly correlated to the growth in industrial demand of the zone, i.e., the higher the growth, the higher the energy cost savings, and hence the higher IRRs from the investment. This is consistent for all ZIP models.

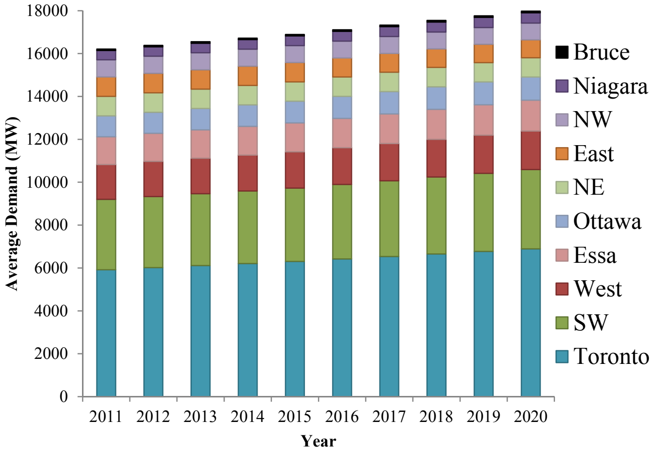

Figure 4.2: Average demand estimate in Ontario for 2011 to 2020.

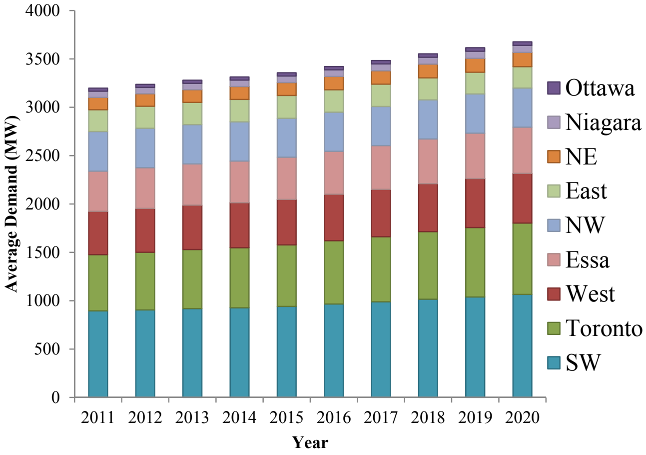

Figure 4.3: Average industrial demand estimate in Ontario for 2011 to 2020.

4.1.3 Risk Analysis using Parameter Sensitivities

A single set of results is inadequate to formulate long-term policies on incentive designs for a system planner, since parameters such as electricity price, project cost, industrial demand and discount rate are volatile. Therefore, a risk analysis is carried out considering

Table 4.3: Base-case results for various ZIP models.

ZIP Model	System Savings ($ in millions)	Average IRR (%)
1	-	-
2	146	13.79
3	284	34.66
4	291	35.67
5	430	54.09
6	437	55.59
7	568	71.80
8	575	72.00
9	714	90.17
10	852	106.48

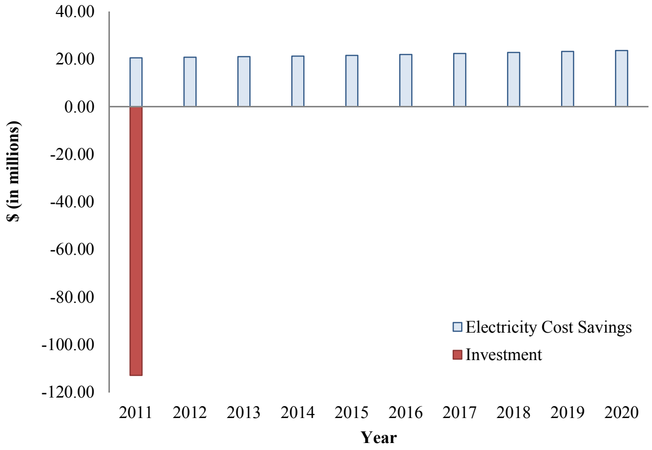

Figure 4.4: Cash flow for ZIP model 2.

parameter sensitivities to understand the volatility of the outcomes with respect to the parameter variations.

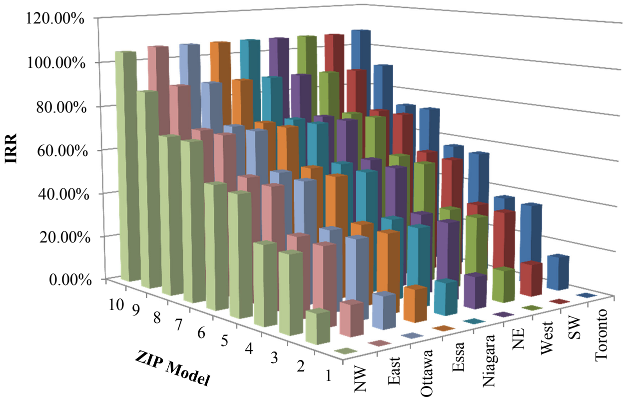

Figure 4.5: Zonal IRR for each ZIP model.

Although there are ten ZIP models, only ZIP model 2 is analyzed further since it is the only model that requires an incentive when parameters are varied, and is the more "realistic". Sensitivity analysis is performed by perturbing one parameter at a time while keeping other parameters unchanged, and analyzing the impact on the variable of interest. The variables studied are the system savings, incentive, and the IRR. Electricity price, project cost, industrial demand, and discount rate, which are the most volatile parameters, are varied by ±25% from their respective nominal values (Table 4.1), while the output is plotted on a scatter plot. The sensitivity of the system savings and the incentive when each parameter is perturbed is illustrated in Figure 4.6 and Figure 4.7, respectively. The following observations can be made from the studies:

- As the electricity price increases, the system savings increase, as shown in Figure 4.6, which is understandable, since for the same megawatt-hour reduction in energy consumption, energy cost savings are greater with a higher electricity price. When the electricity price ranges between -25% to -10% of the nominal in Figure 4.6, the system savings increase at a faster rate because the corresponding incentive decreases, as shown in Figure 4.7. For electricity price variation beyond -10%, the savings increase at a slower rate because the incentives are no longer offered.
- The project cost does not impact the system savings from -25% to 10%, as seen in Figure 4.6. Beyond 10% variation of the project cost, the system savings decrease

because of the introduction of incentives, as shown in Figure 4.7. This is an expected result since as the cost of the system increases, incentives are required.

- As the industrial demand increases, the system savings increase proportionately, as shown in Figure 4.6. The more participation in CVR, the higher the system savings, which is a desirable result for the system planner.
- As the discount rate increases, the system savings decrease because the later year savings are discounted more. The incentive is unaffected by changes in the industrial demand and the discount rate; hence, they are not shown in Figure 4.7.

Instead of showing the IRR for every zone as obtained from the optimization model, the average IRR is used to carry out the sensitivity analysis, as shown in Figure 4.8. From this figure, the following can be noted:

- For variations of the electricity price in the range of -25% to -10%, the IRR remains at 10% because of constraint (3.9), which prevents the IRR to dip below the MARR. Beyond that, the IRR increases with increasing electricity price because of the corresponding increase in system savings, as noted in Figure 4.6. This is due to the high return on investment accrued when the electricity price increases.
- From a -25% to 10% variation of the project cost, the IRR decreases; beyond 10%, the IRR saturates close to 10% because of constraint (3.9). As the project cost increases, the IRR decreases because it is more difficult for the investors to recover their costs with higher project costs.
- The IRR is independent of the industrial demand and the discount rate.

4.1.4 Risk Analysis using Monte Carlo Simulation

Monte Carlo simulation is performed by perturbing multiple parameters simultaneously, thereby capturing more realistic scenarios than the sensitivity analysis. Each parameter is represented by a random variable with a certain pdf and different samples are generated iteratively until the expected values converge. The objective of Monte Carlo simulation is to find the pdf as well as the mean of the system savings and incentive.

The variables adjusted for Monte Carlo simulation are the ZIP models, the industrial demand, project costs, and the electricity price. Since the ZIP model that accurately

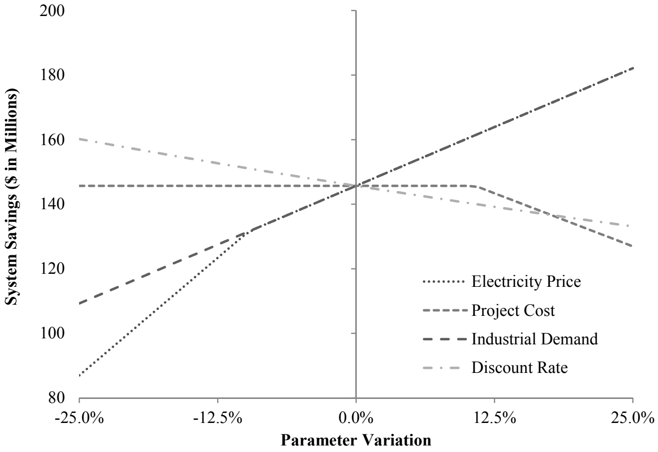

Figure 4.6: Sensitivity analysis for system savings with ZIP model 2.

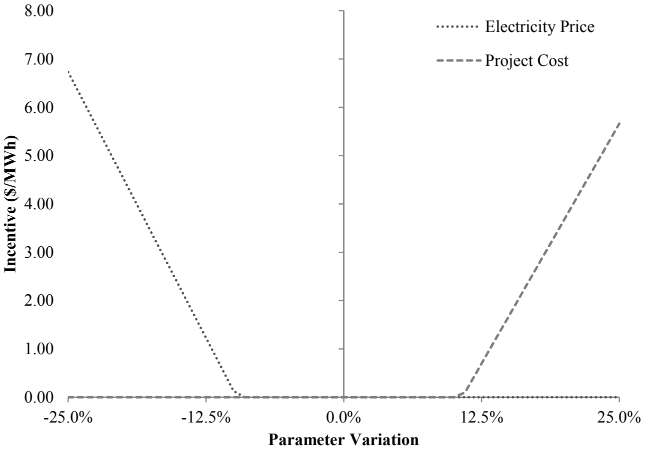

Figure 4.7: Sensitivity analysis for incentive with ZIP model 2.

represents the Ontario system is not known, it is considered a random variable with uniform pdf, for models 2 to 10. It is to be noted that ZIP model 1, which represents only constant power loads, always yields an infeasible solution because there are no energy savings from CVR. The industrial demand is also a volatile parameter since deviations can occur from forecast values; therefore, it is modeled considering a uniform pdf with its range varying

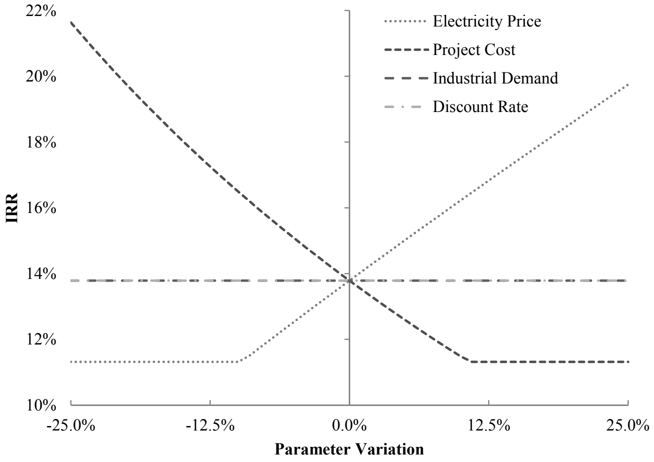

Figure 4.8: Sensitivity analysis for IRR with ZIP model 2.

over ±15% of its nominal value. Project costs are also assumed to vary ±15% around the nominal values, with a uniform pdf. Finally, the electricity price is represented by a normal pdf with a mean of 43.99 \$/MWh and a standard deviation of 31.74 \$/MWh. To justify the use of a normal pdf, the electricity prices from 2002 to 2012 were plotted on a histogram where a normal curve is found to be the most accurate fit, as shown in Figure 4.9.

Monte Carlo simulation is carried out and the convergence of the expected system savings and expected incentive is shown in Figure 4.10 and Figure 4.11, respectively. Observe that the Monte Carlo simulation converges for a sample size of 10,000; certain variations in the parameters lead to infeasible solutions that are discarded.

The expected system savings is obtained to be \$427 million, where the highest savings frequency is in the range of \$125 million to \$250 million, having a probability of 20%, as shown in the histogram in Figure 4.12. The expected system savings of \$427 million is comparable to the savings obtained in the base-case with ZIP Model 5 (Table 4.3). The expected incentive is calculated as 1.66 \$/MWh, where the highest incentive frequency occurs at 0 \$/MWh, having a probability of 84%, as shown in the histogram in Figure 4.13; the MARR constraint (3.9) does not allow the rate to go below 0 \$/MWh. It is evident from Monte Carlo simulation that most of the cases do not require an incentive, implying that energy cost savings accrued from CVR are sufficient.

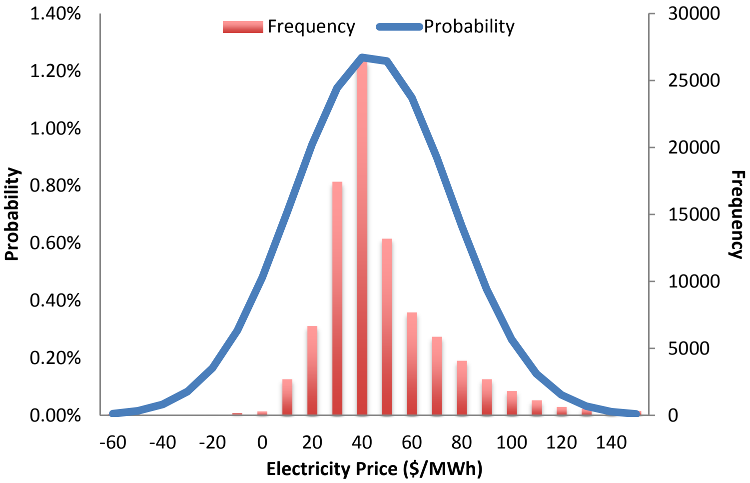

Figure 4.9: Histogram of electricity prices in Ontario with a normal distribution function.

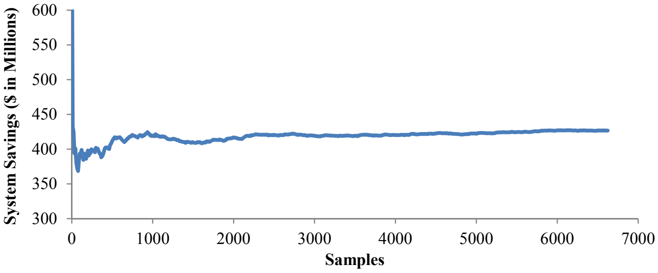

Figure 4.10: Variation of the expected system savings in Monte Carlo simulation.

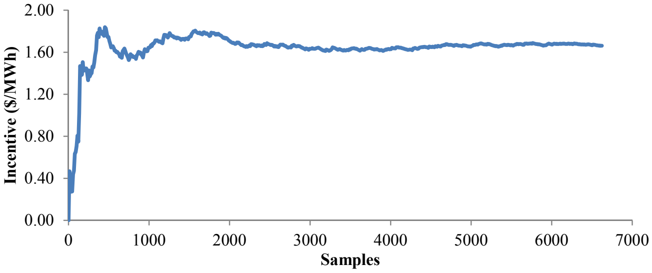

Figure 4.11: Variation of the expected incentive in Monte Carlo simulation.

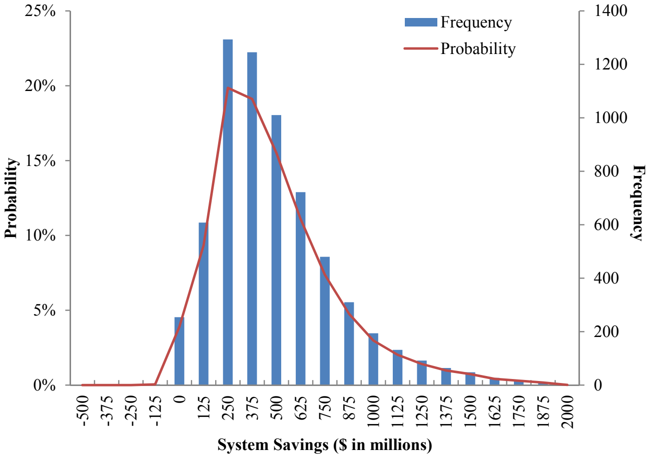

Figure 4.12: Monte Carlo simulation output for system savings.

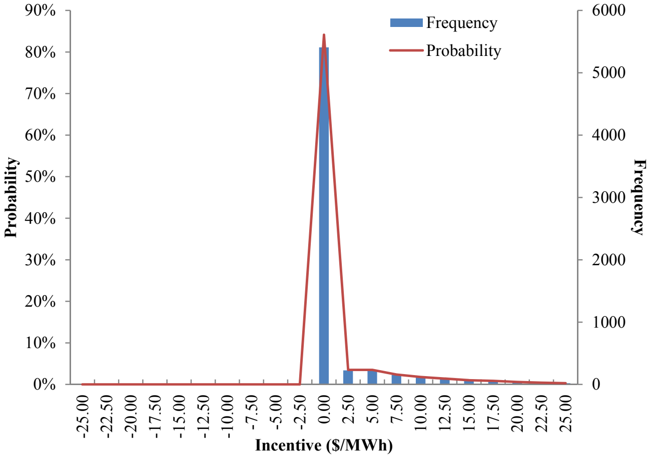

Figure 4.13: Monte Carlo simulation output for the incentive.

4.1.5 Summary

The optimization model was used here for the planning of wide-scale CVR in Ontario. A 10-bus system and demand estimates of Ontario were used for this study. Parameters such as the electricity price, project costs, discount rate, and industrial demand are gathered as inputs into the optimization model. There were 10 ZIP models that are developed with different weights for the parameters. The variables of interest that were solved using GAMs are the system savings, incentive, IRR and voltages. There are 3 studies that were carried out: Base-case analysis using nominal values of the parameters, sensitivity studies, and Monte Carlo simulations.

From solving the base-case, it was found that incentives are not required with any of the ZIP models considered, and that the ZIP model with higher load reduction yields higher system savings as well as higher IRR. The sensitivity studies showed that the system savings are most sensitive to electricity price and industrial demand; the incentive is most sensitive to electricity price and project cost; and lastly, the IRR is most sensitive to electricity price and project costs. The findings from Monte Carlo simulations determined that the expected energy cost savings are such that expected incentives are relatively low compared to the average electricity price. Overall, the results demonstrate that savings from CVR are likely to payoff the investment, and that the incentive required is likely to be low in Ontario.

Chapter 5

Summary, Contributions and Future Work

5.1 Summary

Wide-scale implementation of CVR can play a significant role in energy conservation if applied on a system with high voltage dependence. Through many papers in the literature review, it has been shown to be an effective method for energy demand reduction. However, it is important to study, beforehand, how much savings and what incentive to offer, in order to help facilities recover the cost of a CVR implementation project while ensuring an IRR above the MARR.

In this thesis, a new framework for planning CVR at the system-level is formulated. The optimization model proposed considers the system power flows, models the industrial loads as voltage dependent, and determines the optimal incentive offered for such investments.

This model has many volatile parameters such as the electricity price, industrial demand, project cost and discount rate. Sensitivity analysis is performed to observe the impact on the system savings when varying these parameters. It is determined that increasing the electricity price and industrial demand increases the system savings, whereas it decreases when increasing the discount rate and project cost. In addition, increasing the electricity price reduces the incentive whereas, increasing the cost of the system increases the incentive. For the last part of the sensitivity analysis, it is observed that increasing the electricity price increases the IRR whereas, increasing the cost of the system decreases the IRR.

Since variables do not change one-by-one in reality, Monte Carlo simulation is performed varying simultaneously the ZIP model, industrial demand and electricity price. The results obtained show that the expected system savings is comparable to the base-case with ZIP Model 5. Moreover, it shows that most of the cases do not require an incentive.

Based on the Ontario system case study, it is concluded that CVR energy savings require little incentive from the system planner in order for investors to meet the MARR. This model is to be used by a system planner to determine system savings from CVR projects as well as the incentive to offer to industrial companies in order to receive an IRR higher than MARR.

5.2 Contributions of the Thesis

The main contributions of this thesis are the following:

- A general optimization model that determines the energy cost savings and the required incentive for system wide implementation of CVR is developed, considering that the customer requires an acceptable return from the investment. This model can help power system planners develop incentive programs to make CVR an attractive option for DSM.
- The optimization model is applied to study the possible implementation of CVR in Ontario, Canada. The results of base-case studies show that incentives are not required to ensure that customers investing in CVR accrue an acceptable rate-of-return.
- Risk analysis using sensitivity studies and Monte Carlo simulations are carried out for the Ontario, Canada, system model, to analyze the impact of variations in input parameters such as electricity price, industrial demand, discount rate, and project costs. This shows that CVR is likely to pay off the investment with little incentive required from the power system planner.

5.3 Future Work

There are several areas in which this research work can be further developed on, such as the ZIP load modeling, load forecasting and the methodology to finding the energy cost savings:

- It is stated in the model that the ZIP load models are uniform throughout the entire system. For future work, ZIP load parameters can be developed more accurately with unique load parameters for each bus.
- The load forecast uses the average daily demand. Capturing the hourly demand will be useful to determine on-peak savings as well as off-peak savings.
- In the optimization model, it is assumed that energy cost savings occur for all hours of the year (8760) using CVR. The energy cost savings can be more accurate if it is divided into on-peak energy cost savings and off-peak energy cost savings.

These improvements can lead to more accurate findings for the system savings, incentive, IRR and voltages.

References

[1] C. W. Gellings, "The concept of demand-side management for electric utilities," *Proceedings of the IEEE*, vol. 73, no. 10, pp. 1468–1470, Oct. 1985.

[2] J. E. Runnels and M. D. Whyte, "Evaluation of demand-side management," *Proceedings of the IEEE*, vol. 73, no. 10, pp. 1489–1495, Oct. 1985.

[3] B. Kennedy and R. Fletcher, "Conservation voltage reduction (CVR) at Snohomish County PUD," *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 986–998, Aug. 1991.

[4] K. Schneider, F. Tuffner, J. Fuller, and R. Singh, "Evaluation of conservation voltage reduction (CVR) on a national level," Pacific Northwest National Laboratory, Richland, WA, Tech. Rep. PNNL-19596, Jul. 2010.

[5] B. R. Scalley and D. G. Kasten, "The effects of distribution voltage reduction on power and energy consumption," *IEEE Trans. Power Syst.*, vol. 24, no. 3, pp. 210–216, Aug. 1981.

[6] T. Wilson, K. Benson, and D. Bell, "Saving megawatts with voltage optimization," White Paper, Utilidata, May 2010. [Online]. Available: http://utilidata.com/assets/docs/white_papers/Industrial_Voltage_Optimization.pdf

[7] H. L. Willis, *Power Distribution Planning Reference Book*, 2nd ed. New York: Marcel Dekker, Inc., 2004.

[8] D. Kirshner and P. Giorsetto, "Statistical tests of energy savings due to voltage reduction," *IEEE Trans. Power App. Syst.*, vol. PAS-103, no. 6, pp. 1205–1210, Jun. 1984.

[9] M. S. Chen, R. Shoults, J. Fitzer, and H. Songster, "The effects of reduced voltages on the efficiency of electric loads," *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 7, pp. 2158–2166, Jul. 1982.

[10] T. Wilson, “Adaptivolt based CVR in industrial applications technical synopsis,” White Paper, Utilidata, May 2003. [Online]. Available: http://utilidata.com/assets/docs/white_papers/UtiliData_Technical_Synopsis_Industry_.pdf

[11] J. C. Erickson and S. R. Gilligan, “The effects of voltage reduction on distribution circuit loads,” *IEEE Trans. Power App. Syst.*, vol. PAS-101, no. 7, pp. 2014–2018, Jul. 1982.

[12] D. M. Lauria, “Conservation voltage reduction (CVR) at Northeast Utilities,” *IEEE Trans. Power Del.*, vol. 2, no. 4, pp. 1186–1191, Oct. 1987.

[13] J. D. Steese, S. Merrick, and B. Kennedy, “Estimating methodology for a large regional application of conservation voltage reduction,” *IEEE Trans. Power Syst.*, vol. 5, no. 3, pp. 862–870, Aug. 1990.

[14] M. El-Kady, B. Bell, V. Carvalho, R. Burchett, H. Happ, and D. Vierath, “Assessment of real-time optimal voltage control,” *IEEE Trans. Power Syst.*, vol. 1, no. 2, pp. 98–105, May 1986.

[15] I. Roytelman, B. K. Wee, and R. L. Lugtu, “Volt/var control algorithm for modern distribution management system,” *IEEE Trans. Power Syst.*, vol. 10, no. 3, pp. 1454–1460, Aug. 1995.

[16] Z. Hu, X. Wang, H. Chen, and G. A. Taylor, “Volt/var control in distribution systems using a time-interval based approach,” *IEEE Proceedings Generation, Transmission and Distribution*, vol. 150, no. 5, pp. 548–554, Sep. 2001.

[17] V. Borozan, M. E. Baran, and D. Novosel, “Integrated volt/var control in distribution systems,” in *Power Engineering Society Winter Meeting*, vol. 3, 2001, pp. 1485–1490.

[18] S. Paudyal, C. A. Canizares, and K. Bhattacharya, “Optimal operation of distribution feeders in smart grids,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4495–4503, Oct. 2011.

[19] D. W. Caves, P. Hanser, J. A. Herriges, and R. J. Windle, “Load impact of interruptible and curtailable rate programs: Evidence from ten utilities,” *IEEE Trans. Power Syst.*, vol. 3, no. 4, pp. 1757–1763, Nov. 1988.

[20] S. Majumdar, D. Chattopadhyay, and J. Parikh, “Interruptible load management using optimal power flow analysis,” *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 715–720, May 1996.

[21] F. L. Alvarado and M. Fahrioglu, "Designing incentive compatible contracts for effective demand management," *IEEE Trans. Power Syst.*, vol. 15, no. 4, pp. 1255–1260, Nov. 2000.

[22] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE Trans. Ind. Informat.*, vol. 7, no. 3, pp. 381–388, Aug. 2011.

[23] A.-H. Mohsenian-Rad, V. W. W. Wong, J. Jatskevich, R. Schober, and A. Leon-Garcia, "Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid," *IEEE Trans. Smart Grid*, vol. 1, no. 3, pp. 320–331, Dec. 2010.

[24] M. C. Bozchalu, S. A. Hashmi, H. Hassen, C. A. Canizares, and K. Bhatthacharya, "Optimal operation of residential energy hubs in smart," *IEEE Trans. Smart Grid*, vol. 3, no. 4, pp. 1755–1766, Dec. 2012.

[25] "Effects of reduced voltage on the operation and efficiency of eletric loads," EPRI, Arlington, TX, Tech. Rep. EPRI EL-2036, Sep. 1981.

[26] "Voltage tolerance boundary," Pacific Gas and Electric Company, 1999. [Online]. Available: http://www.pge.com/includes/docs/pdfs/mybusiness/customerservice/energystatus/powerquality/voltage_tolerance.pdf

[27] C. A. McCarthy and J. Josken, "Applying capacitors to maximize benefits of conservation voltage reduction," in *Rural Electric Power Conference, 2003*, Oct. 2003, pp. C4–1–C4–5.

[28] S. Ross, *A first course in probability*, 8th ed. New Jersey: Pearson Education, Inc., 2008.

[29] B. A. Murtagh, M. A. Saunders, and P. E. Gill, *GAMS - The Solver Manuals*, GAMS Development Corporation, Washington, DC, 2012. [Online]. Available: http://www.gams.com/dd/docs/solvers/allsolvers.pdf

[30] "Zonal demands," IESO, 2013. [Online]. Available: http://www.ieso.ca/imoweb/marketdata/ZonalDemands.asp

[31] A. Hajimiragha, "Sustainable convergence of electricity and transport sectors in the context of integrated energy systems," PhD thesis, University of Waterloo, Waterloo, Ontario, 2010.

[32] “Ontario’s integrated power system plan supplemental load forecast,” Ontario Power Authority, Toronto, Ontario, Tech. Rep., Dec. 2006. [Online]. Available: http://www.ontla.on.ca/library/repository/mon/16000/269050.pdf

[33] “Market data,” IESO, 2013. [Online]. Available: http://www.ieso.ca/imoweb/marketdata/marketData.asp

[34] “Canadian cost-benefit analysis guide,” Treasury Board of Canada Secretariat, Ottawa, Ontario, Tech. Rep., 2007. [Online]. Available: www.tbs-sct.gc.ca/rtrap-parfa/analys/analys-eng.pdf