OPTIMAL CAPACITOR PLACEMENT FOR LINE-LOSS REDUCTION AND IMPORTANCE OF VOLTAGE REDUCTION DURING REACTIVE POWER COMPENSATION AND ITS EFFECTS ON LOAD, LINE LOSS, AND GENERATION

A Dissertation by

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Submitted to the Department of Electrical Engineering
and faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirement for the degree of
Doctor of Philosophy

December 2013

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DEDICATION

To my parents

ACKNOWLEDGEMENTS

My deepest appreciation goes to my advisor, Dr. Ward Jewell for his invaluable advice, guidance, and support throughout my doctoral studies. His scholarly direction led me to explore a new research area in electrical power systems, and his teaching instructions motivated me to learn a subject deeply. Dr. Jewell was my source of inspiration to pursue graduate degrees in the field of power system engineering.

I would also like to thank my dissertation committee members—Dr. John Watkins, Dr. Edwin Sawan, Dr. Visvakumar Aravinthan, and Dr. James Steck—for their precious time and valuable suggestions on my dissertation. Their classes helped me to enhance my knowledge on various subjects.

My sincere gratitude goes to managing editor Kristie Bixby for her precious time in reviewing my journal and conference papers and also editing this dissertation. She helped me to improve my technical writing skills.

I also thank my friends and colleagues whom I have worked with in the power quality research laboratory. They were always willing to discuss and share their technical knowledge and skills, and give me advice whenever I needed it. Their company also made my days enjoyable.

Finally, I thank my parents, brothers, and sisters for their love, encouragement, and continuous support, which allowed me to pursue my graduate studies.

ABSTRACT

A methodology to determine the optimal capacitor locations and sizes to minimize line loss on a radial distribution system was developed in this work. Both the power loss index (PLI)-based approach and the loss sensitivity coefficient-based approach were comparatively studied to determine the optimal capacitor location. The index-based approach combined with a genetic algorithm was used to determine the capacitor sizes.

After reactive power compensation voltage-dependent loads consume more power because of the increase in node voltage; therefore, customers pay more for their electricity while utilities experience savings from line-loss reduction. Therefore, a rationale for the necessity of reducing voltage for load demand reduction during reactive power compensation is presented, and the optimal voltage setting at the substation regulator is determined. The joint effect of ambient temperature, price, size, and phase kVAr of the capacitor on load, line loss, and generation is analyzed using a 2^4 factorial design.

How consumer energy consumption, line loss, and generation are affected by voltage reduction is also evaluated. Since bus voltage also depends on line resistance, which varies with ambient temperature, the impact of temperature on power consumption, line loss, and generation is discussed as well.

At reduced voltage, variations in line loss need to be analyzed, because losses affect the cost-benefit analysis. A model is derived that explains, at reduced voltage, how line loss varies with the type of load. Also analyzed is the effect of line resistance on line loss for various types of loads. The results of this work will improve the effectiveness and reliability of future voltage-reduction programs. Finally, analyses for negative line loss, higher voltage at the downstream node, and the active and reactive current components of a capacitor are presented in this work.

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LIST OF ABBREVIATIONS

CVR	Conservation Voltage Reduction/Regulation
DP	Dynamic Programming
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
GA	Genetic Algorithm
IEA	International Energy Agency
LTC	Load Tap Changer
MLV	Method of Local Variations
MSS	Maximum Sensitivity Selection
NSGA	Non-dominated Sorting Genetic Algorithm
OLTC	On-Load Tap Changer
PEV	Plug-in Electric Vehicle
PLI	Power Loss Index
RCGA	Real-number Coded Genetic Algorithm
RCLP	Resistive Component-based Loss Partitioning
SG	Simulated Annealing

CHAPTER 1

INTRODUCTION

Electric power is transmitted from generating stations through transmission and distribution lines to end customers. Power loss occurs in the transmission and distribution lines due to the resistance of those lines. This power loss, for one phase of a line, is given by

$$P_{Loss} = I^2R \qquad (1.1)$$

where P_{Loss} is the active power loss, I is the current magnitude, and R is the resistance of the transmission and distribution lines, which depends on the length and diameter of the lines and also on the property of the conductor material.

Nowadays, electric energy consumption across the world, especially in industrialized countries, has increased tremendously. Due to technological advancement and development, the applications of electrical machines and equipment in industry and commerce, and the usage of electrical and electronic appliances in households has risen day by day. Therefore, the continuing increase of power flow from generating stations through transmission and distribution lines to end customers has resulted in increasing power losses on those lines. By and large, the greater the increase in load demand, the greater the power loss on transmission and distribution lines.

Shunt capacitor banks are extensively used for reactive power compensation to reduce power loss and to control voltage in a distribution system. In 2006 alone, total energy losses and distribution losses were about 1,638 billion kWh and 655 billion kWh, respectively [1]. A modest 10 percent reduction in distribution losses, therefore, would save about 65 billion kWh of electricity [1]. Prior to the late 1950s, loss-reduction capacitors were placed at points where the substation connected to the distribution feeders [2]. The reactive power supplied locally provides several benefits, such as power-loss reduction, voltage-profile improvement, power-factor correction, and reactive-capacity release. Optimal capacitor placement and size play a significant role in minimizing the power-loss reduction and improving the voltage profile in the distribution system.

Reactive power compensation benefits utilities in several ways, but its impact on customer loads needs to be analyzed in a customer-side cost-benefit analysis. In a study on optimal capacitor placement, it was found that after reactive power compensation by a shunt capacitor, voltage-dependent loads consume more power because of an increase in node voltage, and consequently, customers pay more for their electricity while utilities save on electricity because of the line-loss reduction. A voltage-reduction program should be employed during reactive power compensation to reduce the power consumption by customer loads and minimize total power consumption.

Voltage reduction is becoming a common strategy in distribution to reduce peak demand and energy consumption. At reduced voltage, variations in line loss need to be analyzed, because losses affect the cost-benefit analysis. A number of utilities across the country have conducted field tests of distribution voltage reductions [3]. California utilities have concluded that voltage reductions lead to significant energy savings; in contrast, other state utilities have concluded that there is no significant relationship between distribution voltage and energy consumption [3]. Due to voltage reduction, some utilities have significant energy savings and others do not. Part of this difference can be attributed to the types of load served and their effects on line loss at reduced voltage. Therefore, the impact of load types on power consumption and line loss in a voltage-reduction program should be analyzed.

Utilities began studying the effect of voltage reduction on customer loads in the 1980s. In 1981, the Electric Power Research Institute (EPRI) commissioned the University of Texas at

Arlington to test and study the effects of reduced voltage on the efficiency of important power system loads [4, 5]. The voltage-reduction strategy is mainly stimulated by peak load reduction during normal daily operation. It has also been applied in the reduction of load demand during emergencies to meet insufficient generation or transmission capacity. Electric utilities typically employ three types of voltage-reduction programs [6]: conservation voltage reduction, emergency voltage reduction, and routine voltage reduction [6, 7]. Generally, voltage reduction is employed for a relatively short duration, after which voltage is returned to normal [7, 8, 9]. The impact of voltage reduction on load demand, line loss, and power generation should be analyzed when a voltage-reduction program is applied by the utilities. Since temperature causes variation in line resistance, which again results in changes in system voltages, the impact of temperature on load, line loss, and generation needs to be analyzed as well.

1.1 Load Model

The load model plays a significant role in customer-load energy consumption in reactive power compensation and in a voltage-reduction program. When shunt capacitors are connected to a feeder line to compensate the reactive power, current flowing through the line is reduced, and as a result, the line voltage drop (Z*I) decreases, resulting in an increase in node voltage ($V_J\uparrow = V_I - Z*I\downarrow$). Since the node voltage increases, voltage-dependent loads consume more power after the reactive power compensation. This energy consumption depends on the type of the load model. Also, in a conservation voltage reduction (CVR) program, how much load demand and energy can be conserved depends on the type of load model, which is explained below.

Dynamic Load Model: The active and reactive power of the dynamic load model at any instant of time can be represented by a function of the bus voltage magnitude and frequency at the past and present instant of time.

Static Load Model: The active and reactive power of a static load model at any instant of time can be represented by a function of the bus voltage magnitude and frequency at the same instant. This kind of load includes resistive and lighting loads. Three of the most common static load models are constant impedance, constant current, and constant power. These and two others are explained below:

Constant Impedance Load Model: The active and reactive power of this static load model are directly proportional to the square of the voltage magnitude:

$$P_{load} = \left(\frac{V}{V_\circ}\right)^2 * P^\circ_{load} \qquad Q_{load} = \left(\frac{V}{V_\circ}\right)^2 * Q^\circ_{load}$$

where P°_{load} and Q°_{load} are the rated load at voltage $V_\circ$, and P_{load} and Q_{load} are the load at voltage *V*. Incandescent lighting, resistive water heaters, electric stoves, and clothes dryers are examples of constant impedance loads.

Constant Current Load Model: The active and reactive power of this static load model are directly proportional to the voltage magnitude:

$$P_{load} = \left(\frac{V}{V_\circ}\right) * P^\circ_{load} \qquad Q_{load} = \left(\frac{V}{V_\circ}\right) * Q^\circ_{load}$$

Welding units and electroplating processes are constant current loads.

Constant Power Load Model: The active and reactive power of this static load model are constant, i.e., its power does not vary with voltage magnitude. An induction motor operating close to its rated voltage, fluorescent lighting, and washing machines are examples of constant power loads.

IEEE 13-node and 34-node test feeders [10] have three types of static load: constant power, constant impedance, and constant current. Two other load models can more accurately represent the complex loads on a distribution system:

Polynomial Load Model: The active and reactive power of this static load model are given by a polynomial that is a function of the voltage magnitude. This model contains a constant impedance term (Z), a constant current term (I), and a constant power term (P), therefore called the ZIP model:

$$P_{load} = P^{\circ}_{load}\left[a_1\left(\frac{V}{V_0}\right)^2 + a_2\left(\frac{V}{V_0}\right) + a_3\right] \qquad Q_{load} = Q^{\circ}_{load}\left[b_1\left(\frac{V}{V_0}\right)^2 + b_2\left(\frac{V}{V_0}\right) + b_3\right]$$

Exponential Load Model: The active and reactive power of this static load model can be expressed by an exponential function of voltage magnitude:

$$P_{load} = P^{\circ}_{load}\left(\frac{V}{V_0}\right)^{np} \qquad Q_{load} = Q^{\circ}_{load}\left(\frac{V}{V_0}\right)^{np}$$

1.2 Network Configurations

IEEE 13-Node Test Feeder*:* This feeder, shown in Figure 1.1, is very small and has the following characteristics [10]:

- Short and relatively highly loaded for a 4.16 kV feeder.
- One substation voltage regulator consisting of three single-phase units connected in wye.
- Overhead and underground lines with variety of phasing.
- Shunt capacitor banks.
- In-line transformer.
- Unbalanced spot and distributed loads.

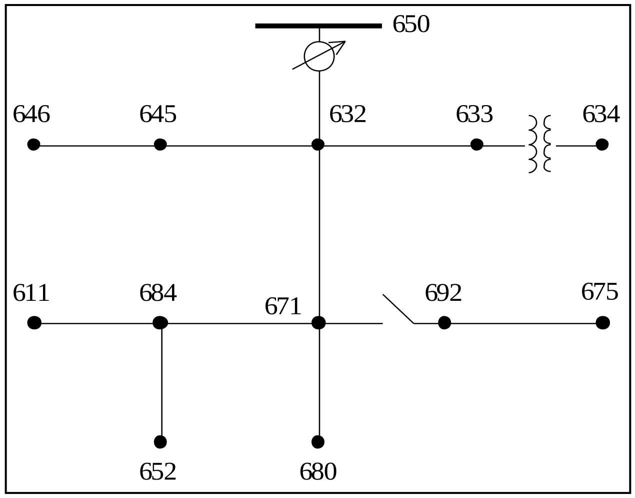


Figure 1.1: Single-line diagram of IEEE 13-node test feeder

IEEE 34-Node Test Feeder: This feeder, shown in Figure 1.2, is an actual feeder located in Arizona. The feeder's nominal voltage is 24.9 kV. It is characterized by the following [10]:

- Very long and lightly loaded.
- Two in-line regulators required to maintain a good voltage profile.
- An in-line transformer reducing the voltage to 4.16 kV for a short section of the feeder.
- Unbalanced loading with both spot and distributed loads.
- Shunt capacitors.

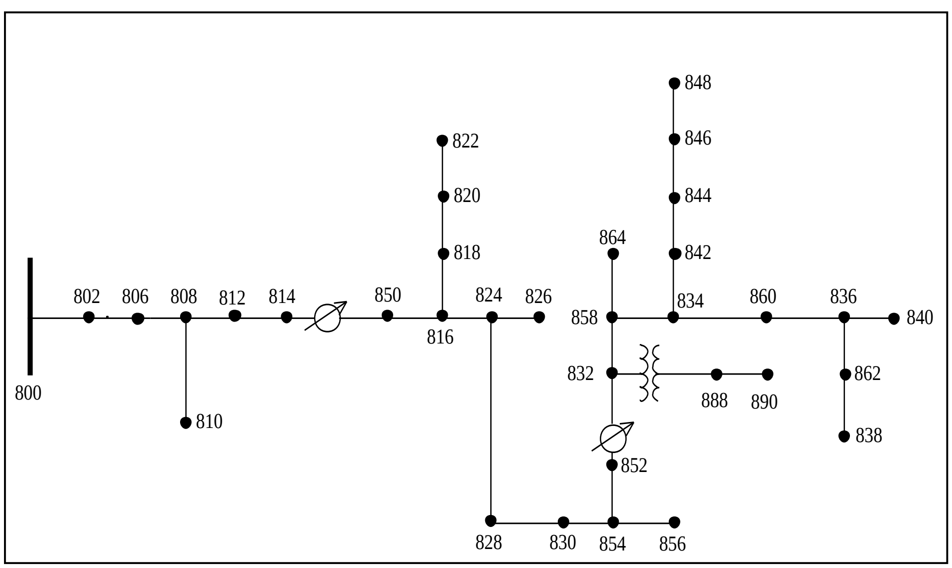


Figure 1.2: Single-line diagram of IEEE 34-node test feeder

1.3 Research Objective

The objective of this research was to design and develop a methodology to determine the optimal locations and sizes of capacitors for minimizing power loss by compensating the reactive power, to present a rationale for the necessity of reducing voltage during reactive power compensation, and to determine the optimal voltage setting at the substation regulator. The impact of voltage reduction and ambient temperature on load demand, line loss, and power generation was analyzed and a model of the impact of load type on power consumption and line loss was derived, which can be used as a guideline in conservation voltage-reduction/regulation (CVR) program.

1.4 Scope of This Work

In this research, the following issues were investigated:

- How different design techniques/methodologies, such as the power loss sensitivity factor-based technique and power loss index (PLI)-based technique, differ from each other relative to the optimal capacitor placement problem
- The impact of capacitor prices on the optimization problem, i.e., how sensitive the capacitor price is to the above cost function value. For that reason, two different capacitor prices—$1.25/kVAr and $2.00/kVAr—were considered.
- How reactive power compensation impacts load demand, line loss, and power generation/supply. For example, when reactive power is compensated, current flow through the line decreases, resulting in a reduction in line loss and an increase in energy consumption by voltage-dependent loads since the node voltage increases.
- The importance of voltage reduction and optimal voltage setting during reactive power compensation.

- The impact of load type on power consumption and line loss in voltage-reduction program.
- The impact of voltage reduction and ambient temperature on power consumption, line loss, and generation.
- The effect of ambient temperature, price, size, and phase kVAr of the capacitor on line loss, load demand and generation.
- Negative line loss in a single phase.
- Higher voltage at a downstream node
- Active and reactive components of the capacitor current with respect to the system reference.

In this research work, all analyses were tested on IEEE 13-node and 34-node test feeders. Various software were used in this research: WindMil for load-flow analysis, MATLAB for the optimization problem, and Design Expert for statistical analysis.

1.5 Beyond Scope of This Work

The following issues were considered to be beyond the scope of this research, but they are important and will be addressed in future work.

- The impact of distorted substation voltage on the optimal capacitor placement problem.
- Integration of distributed generations (solar, wind, geothermal, biomass) and shunt bank capacitors.
- Load variation caused by the plug-in electric vehicle (PEV).
- The transient effect caused by switched capacitors.

1.6 Summary and Organization of this Work

Line loss in transmission and distribution system is becoming of great concern as loads increase, and new transmission and distribution lines are being built day by day. Optimal placement of a shunt capacitor to reduce line loss through reactive power compensation has gained considerable attention. After reactive power compensation, voltage-dependent loads consume more power because of the increase in node voltage. Therefore, voltage reduction should be employed during reactive power compensation to reduce the load demand. The impact of voltage reduction and ambient temperature on load demand, line loss, and generation should also be analyzed because they affect the cost-benefit analysis in a voltage-reduction program.

Chapter 1 introduces this dissertation, and Chapter 2 reviews the previous work done on optimal capacitor placement and the impact of voltage reduction on load, line loss, and generation. Chapter 3 discusses the optimal capacitor placement and sizes for power loss reduction using a combined power loss index, loss sensitivity factor, and genetic algorithm. Chapter 4 presents the impact of load type on power consumption and line loss in a voltage-reduction program. Chapter 5 demonstrates the importance of voltage reduction and the optimal voltage setting during reactive power compensation. In Chapter 6, the joint effect of ambient temperature, price, size, and phase kVAr of the capacitor on line loss, load demand and generation is analyzed. Chapter 7 discusses the impact of voltage reduction and ambient temperature on power consumption, line loss, and generation. In Chapter 8, the joint effect of voltage reduction and ambient temperature on load, line loss, and generation is investigated. Chapter 9 presents an analogy for negative line loss, higher voltage at the downstream node, and active and reactive components of a capacitor current.

CHAPTER 2

LITERATURE REVIEW

2.1 Optimal Capacitor Placement and Sizes

Much research work on optimal capacitor placement, whereby several techniques are applied to capacitor placement and sizing, has been undertaken. Most of the work on capacitor placement occurred in the 1980s and is based on analytical analysis requiring cumbersome calculations. The early analytical methods for capacitor placement were mainly developed by Neagle and Samson [11] and Baran and Wu [12]. Their results suggest that maximum loss reduction occurs if the capacitor is placed at a point where its reactive power kVAr is equal to twice the load kVAr and is based on a simplified, voltage-independent system model obtained by the following: (a) considering only the main feeder with uniform load distribution and wire size, (b) taking into account only the loss reduction due to change in the reactive component of the branch currents, (c) ignoring the changes in node voltages, and (d) neglecting the cost of capacitors [11].

Grainger and Civanlar [13] used an analytical method for a radial distribution system with a voltage regulator to solve the capacitor-placement problem. To provide a smooth voltage profile along with a reduction in line loss, they proposed both capacitor and regulator placement along the feeder. It is very complicated to solve a capacitor-placement problem and regulator-placement problem simultaneously, due to the interdependency between line voltages and capacitor output. So they presented a decouple solution—one for capacitor placement and the other for regulator placement. Ponnavaikko and Rao [14] used a dynamic programming (DP) approach and the method of local variations (MLV) to solve this problem. In the cost function, they included cost savings due to a release in feeder capacity and other system capacities (transformers, transmission lines, and generation).

Since minimum line loss depends on optimal reactive power flow, controlling the switched capacitors plays a significant role. Grainger et al. [15] discussed the control strategy of the switched capacitors based on reactive load duration curves.

In the 1990s, most capacitor-placement problems were approached with a heuristic technique. Sundhararajan and Pahwa [16] proposed loss sensitivity and a genetic algorithm-based approach for optimal capacitor placement and sizes, and introduced a penalty factor in the objective function to minimize the search area. Ghose et al. [17] used a combined genetic algorithm and simulated annealing (GA-SA) technique to eliminate the premature convergence of the objective function, and considered voltage violation to be a penalty factor in the cost function. Reddy and Sydulu [18] presented a power loss index-based location and an index and genetic algorithm-based sizing in the capacitor-placement problem.

Milosevic and Begovic [19] used a multi-objective function in the capacitor-placement problem. They discussed load reduction as well. To solve the multi-objective problem, they applied a non-dominated sorting genetic algorithm (NSGA), based on the concept of pareto optimality. Chopade and Bikdash [20] did a comparative study of three types of distribution systems: radial, loop, and interconnected. Here they applied a genetic algorithm (GA) using ETAP software. Their results show that if all loads are considered to be linear, the interconnected and loop system configurations yield lower power losses and better operating conditions than the radial system configuration, but the radial system configuration generates the best annual benefits for capacitor placement. In distorted networks, the interconnected system configuration offers lower power losses, the best operating conditions, and the best annual benefits due to capacitor placement [20].

Marvasti et al. [21] proposed a model that accounts for both optimal capacitor placement and an optimal conductor selection method simultaneously to minimize line loss. In their cost function, the conductor cost is included along with capacitor cost. Prakash and Sydulu [22] used particle swarm optimization-based capacitor placement to improve the voltage profile and reduce active power loss.

Liu et al. [23] used a simplified dynamic programming to obtain the dispatch schedule for an on-load tap changer (OLTC), and switched capacitor banks at the substation and used a fuzzy logic control algorithm for capacitor banks on the feeder to deal with optimal reactive power and voltage control. Wu and Lo [24] applied the maximum sensitivity selection (MSS) method to the capacitor-sizing problem for a radial distribution system with distorted substation voltages. Their results suggest that harmonics in the substation voltage had an impact on the capacitance of optimal shunt capacitors.

2.2 Impact of Load Type on Power Consumption and Line Loss in Voltage-Reduction Program

Conventional loss analysis by applying detailed system modeling is difficult and impractical to be performed since voluminous data are involved [25]. During peak loading periods, the voltage along a feeder may drop significantly below the nominal value, and it becomes very important during these periods that load characteristics be accurately modeled for purposes of energy-loss analysis [26]. Chen et al. [25] proposed a simplified model for distribution system loss analysis based on loss sensitivity analysis with respect to the feeder loading, power factor, feeder length, and transformer capacity. Triplett and Kufel [27] presented results of the effect of voltage reduction on both energy consumption and line loss. Their numerical results show that voltage reduction causes not only a reduction in energy consumption but also a reduction in line loss.

2.3 Impact of Voltage Reduction and Ambient Temperature on Load, Line Loss, and Generation

Previous research work in this field has been on voltage reduction relative to peak load reduction during normal daily operation and load-demand reduction during emergencies to meet insufficient generation and transmission capacity. Chen et al. [5] have discussed how efficiency of electric loads relates to voltage variation. They conducted tests on a wide variety of loads at different voltages ranging from 100/200 to 126/252 volts for nominal voltages of 120 and 240 volts, respectively. Their results show that energy consumption decreases with voltage reduction for loads such as incandescent lamps, fluorescent lamps, and refrigerators. For central air conditioners, energy consumption decreases if voltage is reduced to 115 V, but energy consumption increases at voltages of 105 V or below. Warnock and Kirkpatrick [28] considered both a fixed 5% voltage reduction and a variable voltage reduction, and compared the seasonal energy savings. Their results show that a consistent energy savings occurs with residential and commercial loads during peak load periods—winter and summer—while industrial loads do not have a significant energy savings because their own regulations are in place.

CHAPTER 3

OPTIMAL CAPACITOR PLACEMENT AND SIZES FOR POWER LOSS REDUCTION USING COMBINED POWER LOSS INDEX, LOSS SENSITIVITY FACTOR, AND GENETIC ALGORITHM

In this chapter, a proposed methodology to determine the optimal capacitor locations and sizes for power-loss reduction in a radial distribution system is presented. The objective here is to minimize energy loss by considering capacitor cost. Both the power loss index (PLI)-based approach and the power loss sensitivity coefficient-based approach are comparatively studied to determine the optimal capacitor location. The index-based approach combined with a genetic algorithm is used to determine the capacitor sizes. How customer loads and costs change after reactive power compensation is discussed as well. The proposed method was tested on IEEE 13-bus and 34-bus test systems, and the results are comparatively analyzed and discussed.

The continuing increase of power flow from generating stations to end customers has resulted in increasing power losses on transmission and distribution lines. A feeder line between two nodes is shown in Figure 3.1. The relationship between power loss and load demand is given by equation (3.1):

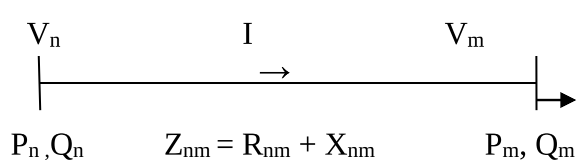


Figure 3.1: Feeder line between two nodes

$$
\begin{aligned}
P_{Loss} + jQ_{Loss} &= V_n I^* - V_m I^* \\
&= (V_n - V_m) I^* \\
&= (R_{nm} + j X_{nm}) I I^* \\
&= (R_{nm} + j X_{nm}) \frac{P_m^2 + Q_m^2}{V_m^2}, \text{ where } I I^* = |I|^2 = \frac{P_m^2 + Q_m^2}{V_m^2}
\end{aligned}
$$

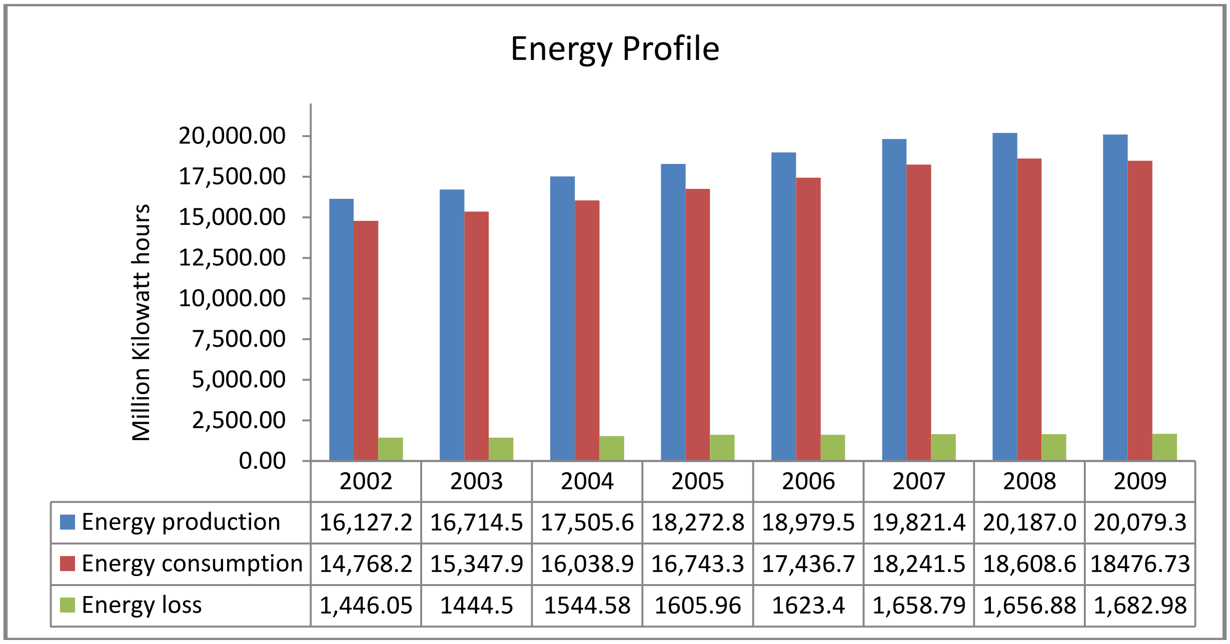
$$= \frac{P_m^2 + Q_m^2}{V_m^2} * R_{nm} + j \frac{P_m^2 + Q_m^2}{V_m^2} * X_{nm} \quad (3.1)$$

where P_n, Q_n are the active and reactive power, respectively, leaving from node n; P_m, Q_m are the active and reactive loads, respectively, at node m; P_{Loss}, Q_{Loss} are the active and reactive power losses, respectively, on the line between n and m; and I^* is the conjugate of the current I. From equation (3.1), it can be seen that active power loss can be reduced by controlling the reactive power, active power, voltage, and resistance. For an existing system, changing the resistance of the conductor would not be a good option; therefore, reducing the active and reactive power flow through the lines has received much more attention relative to solving the power-loss-reduction problem. Here active power loss will be reduced by decreasing the reactive power flow by optimally placing capacitors along the feeder line.

3.1 Energy Profiles

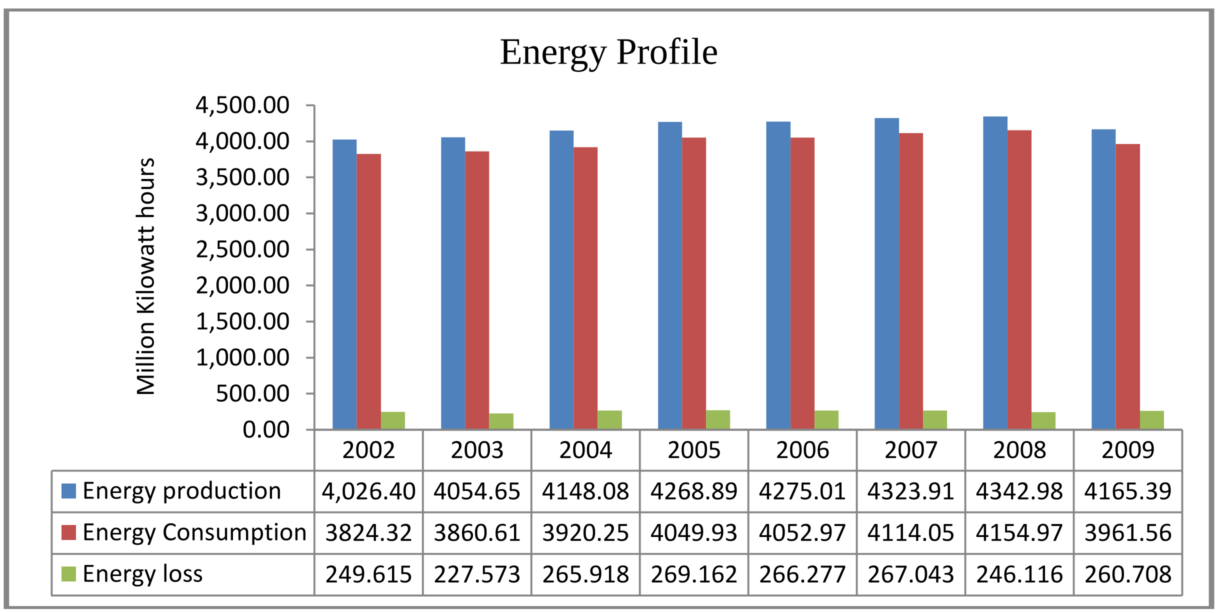
According to the International Energy Agency (IEA) of the U.S. Energy Information Administration (EIA), the world's total electricity consumption was 14.76 billion MWh in 2002 and 18.47 billion MWh in 2009. Energy lost in transmission and distribution systems was 1.44 billion MWh in 2002 and 1.68 billion MWh in 2009. The world's electric consumption increased by about 3.1 percent annually between 1980 and 2006, according to the 2006 IEA annual report, and is expected to grow to 33,300 billion kWh by 2030, according to World Net Electric Power Generation, 1990–2030, and also according to the IEA [1]. About 40 percent of this total loss occurs on the distribution network [1].

In the United States, total electricity consumption, according to the IEA, was 3.82 billion MWh in 2002 and 3.96 billion MWh in 2009, and energy lost in transmission and distribution systems was 249.6 billion kWh in 2002 and 260.7 billion kWh in 2009. That energy loss is 6.2 percent and 6.3 percent of total production of electricity in 2002 and 2009, respectively. The world's energy profile, including energy production, energy consumption, and energy loss (transmission and distribution losses) is shown in Figure 3.2, and the energy profile of the United States is shown in Figure 3.3 The statewise energy supply vs. energy loss in 2010 is shown in Figure 3.4.



	2002	2003	2004	2005	2006	2007	2008	2009
Energy production	16,127.2	16,714.5	17,505.6	18,272.8	18,979.5	19,821.4	20,187.0	20,079.3
Energy consumption	14,768.2	15,347.9	16,038.9	16,743.3	17,436.7	18,241.5	18,608.6	18476.73
Energy loss	1,446.05	1444.5	1544.58	1605.96	1623.4	1,658.79	1,656.88	1,682.98

Figure 3.2: World energy profile



	2002	2003	2004	2005	2006	2007	2008	2009
Energy production	4,026.40	4054.65	4148.08	4268.89	4275.01	4323.91	4342.98	4165.39
Energy Consumption	3824.32	3860.61	3920.25	4049.93	4052.97	4114.05	4154.97	3961.56
Energy loss	249.615	227.573	265.918	269.162	266.277	267.043	246.116	260.708

Figure 3.3: United States energy profile

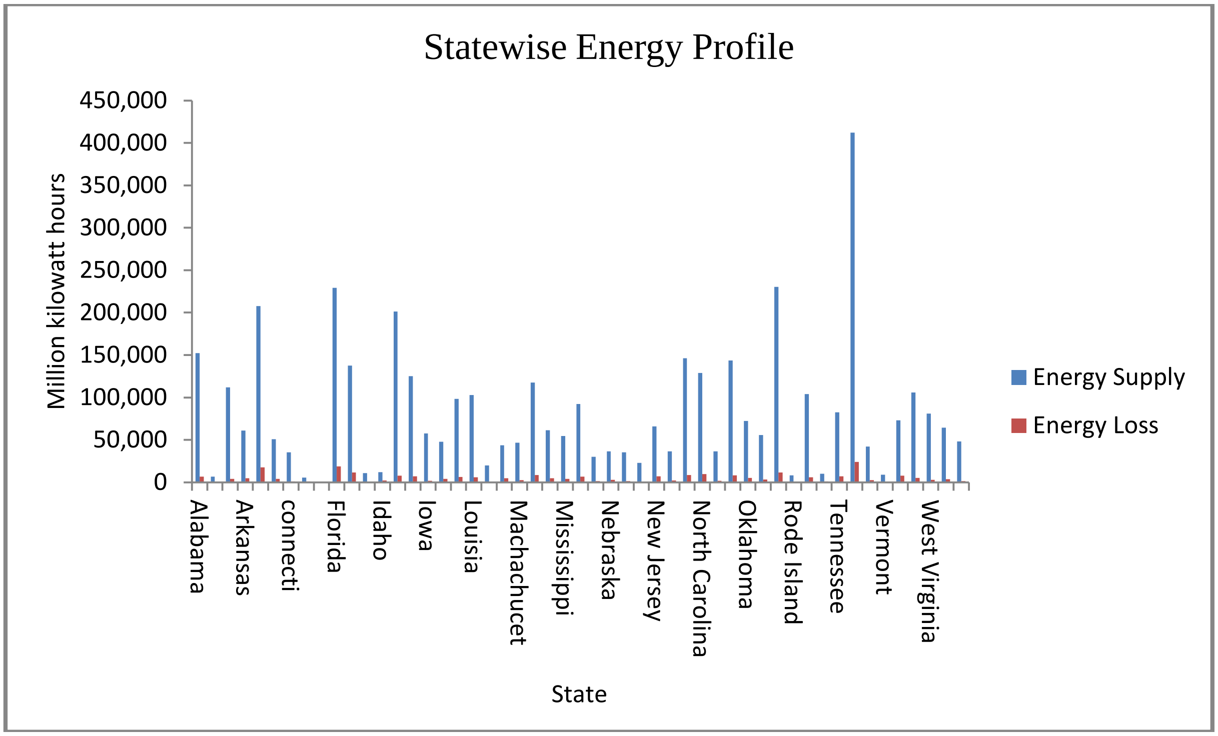


Figure 3.4: Statewise energy supply vs. energy loss in 2010

3.2 Proposed Methodology

The objective of this capacitor-placement problem is to design and develop a methodology to determine the optimal locations and sizes of capacitors for minimizing power loss by compensating reactive power. The cost function is comprised of the cost of the power lost in distribution lines and capacitor prices:

$$\min \quad K_e \sum_{i=1}^{m} T_i P_i + K_c \sum_{j=1}^{n} q_j \tag{3.2}$$

which is subject to the inequality constraint $V_{min} \leq V_j \leq V_{max}$, where K_e is the energy loss cost constant ($50/MWh [24, 29]), K_c is the capacitor cost constant ($/kVAr), P_i is the power loss at load level i for time period T_i, q_j is the capacitor size (kVAr) at node *j*, and V_j is the voltage magnitude at node *j*.

The power loss reduction problem is divided into two subproblems:

- Optimal location of capacitors on the feeder line.
- Optimal size of capacitors.

3.2.1 Optimal Location of Capacitors

To determine the optimal location of capacitors, a combination of the loss sensitivity-based approach [16] and the power loss index-based approach [17] is employed.

Loss Sensitivity Analysis

The loss sensitivity coefficient, which is a partial derivative of power loss with respect to reactive power, can be expressed by equations (3.3) and (3.4):

$$\frac{\partial P_L}{\partial Q_m} = \frac{2Q_m * R_{nm}}{V_m^2} \tag{3.3}$$

$$\frac{\partial Q_L}{\partial Q_m} = \frac{2Q_m * X_{nm}}{V_m^2} \tag{3.4}$$

where the active power loss sensitivity factor ($\frac{\partial P_L}{\partial Q_m}$) is used to determine the potential locations of the capacitors.

Previous work has been done using sensitivity indices related to steady-state stability, voltage control, and power losses to locate reactive power devices on the bulk power system [16]. Loss sensitivity coefficient factors become very powerful and useful in capacitor location or placement [30].

Power Loss Index

Power loss reduction is calculated by totally compensating the reactive power flow in the node and considering one node at a time. These values are normalized based on a scale of 1 to 0, with one being the highest loss reduction and zero being the lowest loss reduction. A priority list of capacitor locations is made by arranging the nodes in descending order of these indices: the higher the index value, the higher the probability of capacitor placement.

3.2.2 Optimal Size of Capacitors

Capacitor size is primarily determined by the index-based method [18], and then a genetic algorithm is used to derive the optimal capacitor size. An index of a node is derived by

$$Index[m] = \frac{1}{V_m^2} + \frac{I_q[j]}{I_p[j]} + \frac{Q_{load}[m]}{Q_{loadtotal}} \tag{3.5}$$

where *Index[m]* is the index of node *m*, V_m is the voltage at node *m*, $I_q[j]$ is the reactive current component in the j^th branch between n and m nodes, $I_p[j]$ is the real current component in the j^th branch between n and m nodes, $Q_{load}[m]$ is the reactive load beyond the node m including reactive load at node m, and $Q_{loadtotal}$ is the total reactive load of the system.

The capacitor size at node m is $Q_m = Index[m] * Q_{mload}$

Q_{mload} is the reactive load at node m.

3.2.3 Proposed Method for Capacitor Placement

The proposed method for capacitor placement is as follows:

- First, choose a minimum power loss index (PLI) value, that has a significant power loss reduction. PLI values below the chosen value do not have a significant power loss reduction. In this minimum PLI selection process, consider if the minimum PLI covers the search area containing nodes that have a significant amount of reactive load. Then select the nodes that have a PLI greater than or equal to the acceptable minimum PLI.
- Among the above-selected nodes, determine those that are also in the sensitivity-based priority list within the search area, which is determined by the rank corresponding to the

accepted minimum PLI value. These common nodes are the probable potential nodes for capacitor placement.

- Then, place capacitor sizes, which are calculated by the index-based method, in these potential nodes, run the load flow analysis, and record the active power loss. Select different combinations of the probable potential locations to run the load-flow analysis, and record line loss at each simulation result. At the same time, examine the voltage violation limit (0.95–1.05 pu) at each node. For example, if the number of probable potential locations is n, then the total load flow runs are ${}^{n}C_{n} + {}^{n}C_{n-1} + {}^{n}C_{n-2} + \ldots\ldots + {}^{n}C_{1.}$ Keep in mind that the search area of potential locations n is already minimized by the combined PLI and loss sensitivity-based approach.
- Among those simulation results, consider the active power loss that generates the minimum cost function value to be the optimal solution for potential capacitor locations.
- Next, recalculate the optimal capacitor sizes by a genetic algorithm. A real-number-coded genetic algorithm (RCGA) is used in this research. Real number encoding has been confirmed to have better performance than either binary or gray encoding for constrained optimization problems [31, 32]. Derive an initial population of capacitor sizes by considering the values around those determined by the index-based method.
- Run the genetic algorithm to generate the population of next generations.
- Place the capacitors of that size at potential locations, run the load flows, record line loss, and calculate cost function values.
- Note that those capacitor sizes that give the minimum cost function value are the optimal solution for capacitor sizes.

3.3 Concept of Fixed and Switched Capacitors

Fixed and switched capacitors play a large role in line-loss reduction and voltage-profile improvement because they depend on the optimal reactive power flow that is controlled by fixed and switched capacitors. The use of fixed and on/off switched capacitors provides considerable reduction in power losses and improvement in the voltage profile when the capacitors are controlled to respond to daily, weekly, or seasonal changes in feeder reactive loads [13]. The power factor during off-peak hours is normally high; therefore, heavy capacitor compensation may lead to over-voltage problems during this time [14]. This situation poses certain limitations regarding capacitor compensation and hence leads to the concept of fixed and switched capacitor applications [14]. The minimum size of capacitors connected at all load levels can be considered as fixed capacitors, and others are considered as switched capacitors.

3.4 Test Design and Results for Optimal Capacitor Placement

Based on unbalanced systems and the availability of capacitor sizes, four different test cases are considered:

Case 1: Continuous capacitor sizes and phase kVAr of the capacitor are in the ratio of phase-reactive power flows into the node where the capacitor is connected.

Case 2: Continuous capacitor sizes and phase kVAr of the capacitor are equal.

Case 3: Discrete capacitor sizes and phase kVAr of the capacitor are in the ratio of phase reactive power flows into the node where the capacitor is connected.

Case 4: Discrete capacitor sizes and phase kVAr of the capacitor are equal.

Three load levels in a one-year time period are considered. Here, time duration in each load level, as shown in Table 3.1, is considered in such a way that the sensitivity of capacitor prices to cost function can be shown.

TABLE 3.1

LOAD DURATION DATA

Load Level (pu)	0.6	0.8	1
Duration (hours)	2760	3500	2500

The available three-phase capacitor sizes [33], shown in Table 3.2, are considered discrete sizes.

TABLE 3.2

AVAILABLE SIZES OF THREE-PHASE CAPACITORS [33]

150	300	450	600	900	1200

Loss sensitivity factors and power loss indices are calculated for the IEEE 13- and 34-bus system. Priority lists, based on both the loss sensitivity factor and the power loss index method, are provided in Tables 3.3 to 3.6.

TABLE 3.3

PRIORITY LIST BASED ON
LOSS SENSITIVITY FACTOR
FOR IEEE 13-BUS SYSTEM

Node No.	$\frac{\partial P_L}{\partial Q_L}$		
	Phase a	**Phase b**	**Phase c**
632	0.018851	0.013000	0.017670
671	0.015172	0.007006	0.012080
675	0.002672	0.000761	0.031454
634	0.002155	0.000182	0.001774
684	0.001919	-	0.001872
645	-	0.000035	0.004926
646	-	0.000021	0.001848
652	0.004378	-	-
611	-	-	0.001848

TABLE 3.4

PRIORITY LIST BASED ON
POWER LOSS INDEX (PLI)
FOR IEEE 13-BUS SYSTEM

Node No.	**Loss Reduction (KW)**	**PLI**
671	32	1.0000
632	22	0.6666
692	19	0.5666
675	18	0.5333
634	8	0.2000
684	7	0.1666
633	6	0.1333
645	6	0.1333
611	5	0.1000
646	4	0.0666
652	2	0.0000

TABLE 3.5

PRIORITY LIST BASED ON
LOSS SENSITIVITY FACTOR
FOR IEEE 34-BUS SYSTEM

Bus No.	$\frac{\partial P_L}{\partial Q_L}$		
	Phase a	**Phase b**	**Phase c**
890	0.063630	0.061812	0.063290
852	0.043458	0.039997	0.035145
812	0.040820	0.029796	0.024713
808	0.033536	0.025588	0.020648
814	0.033595	0.024044	0.020069
830	0.023658	0.021439	0.018879
824	0.011565	0.011098	0.009267
834	0.004075	0.003748	0.003160
858	0.003525	0.003153	0.002748
802	0.002585	0.002079	0.001679
806	0.001737	0.001346	0.001083
828	0.000950	0.000864	0.000759
844	0.000501	0.000590	0.000543
854	0.000582	0.000541	0.000476
816	0.000428	0.000332	0.000281
860	0.000264	0.000363	0.000235
846	0.000169	0.000285	0.000169
836	0.000054	0.000233	0.000148
842	0.000107	0.000122	0.000113
848	0.000024	0.000024	0.000024
840	0.000017	0.000017	0.000017
850	0.000013	0.000010	0.000009
820	0.015987	-	-
818	0.000688	-	-

TABLE 3.6

PRIORITY LIST BASED ON
POWER LOSS INDEX (PLI)
FOR IEEE 34-BUS SYSTEM

Bus No.	Loss Reduction (KW)	PLI
852	106	1.00000
832	106	1.00000
834	96	0.90566
858	95	0.89622
830	85	0.80188
854	83	0.783
828	71	0.6698
842	71	0.6698
844	71	0.6698
824	68	0.6415
814	65	0.613207
816	64	0.60377
850	64	0.60377
890	50	0.47169
860	47	0.443396
812	47	0.443396
808	24	0.2264
836	20	0.188679
846	17	0.160377
820	14	0.13207
818	13	0.12264
822	13	0.12264
848	13	0.12264
840	9	0.0849
826	3	0.0283
838	3	0.0283
862	3	0.0283
806	2	0.01886
802	2	0.01886
810	0	0
856	0	0
864	0	0

If power loss index-based and loss sensitivity-based priority lists are compared to each other, it can be seen that the rank of the same node in those priority lists is different. It should be noted that a significant difference in the priority lists can be seen in the IEEE 34-bus system. In previous work on capacitor placement, either one of the methods was followed. In this work, the two approaches are combined in order to have a better loss-reduction result than when either method is used alone. This proposed methodology has already been described in section 3.1.3

First, nodes that have a power loss index ≥ 0.1666 for a 13-bus system and PLI ≥ 0.443396 for a 34-bus system are selected. Nodes with a PLI < 0.1666 for a 13-bus system have a power loss reduction less than 4.52% of the total line loss, while the maximum loss reduction is 24.06% at the node where the PLI = 1. Similarly, in the 34-bus system case, those nodes with a PLI < 0.443396 have a power loss reduction less than 6.32% of total line loss, while the maximum power loss reduction is 27.89% at the node where the PLI = 1. Since the nodes that have a PLI < 0.1666 for a 13-bus system and a PLI < 0.443396 for a 34-bus system do not have a significant loss reduction, these nodes are not considered in the search area. Then, among these selected nodes, those nodes that are also in the sensitivity-based priority list within the rank determined by the accepted minimum PLI values of 0.1666 and 0.443396 for 13- and 34-bus systems, respectively, are determined.

3.4.1 Test Results for Optimal Capacitor Placement in IEEE 13-Bus System

Optimal locations and sizes are determined based on the proposed technique described in section 3.1.3, and the results are provided in Tables 3.7 to 3.10 for the IEEE 13-bus system.

TABLE 3.7

CAPACITOR LOCATIONS AND SIZES AT CAPACITOR PRICE OF $1.25/KVAR AND CONTINUOUS SIZES FOR IEEE 13-BUS SYSTEM

IEEE13-Bus System	**Capacitor Size (KVAr)**		
Load Level (pu)	**Bus No.**		
	671	**675**	**634**
0.6	325	225	75
0.8	575	425	125
1	875	560	250

TABLE 3.8

CAPACITOR LOCATIONS AND SIZES AT CAPACITOR PRICE OF $1.25/KVAR AND DISCRETE SIZES FOR IEEE 13-BUS SYSTEM

IEEE 13-Bus System	**Capacitor Size (KVAr)**		
Load Level (pu)	**Bus No.**		
	671	**675**	**634**
0.6	300	300	150
0.8	600	450	150
1	900	600	300

TABLE 3.9

CAPACITOR LOCATIONS AND SIZES AT CAPACITOR PRICE OF $2.00/KVAR AND CONTINUOUS SIZES FOR IEEE 13-BUS SYSTEM

IEEE 13-Bus System	**Capacitor Size (KVAr)**		
Load Level (pu)	**Bus No.**		
	671	**675**	**634**
0.6	-	320	-
0.8	550	400	-
1	875	560	-

TABLE 3.10

CAPACITOR LOCATIONS AND SIZES AT CAPACITOR PRICE OF $2.00/KVAR AND DISCRETE SIZES FOR IEEE 13-BUS SYSTEM

IEEE 13-Bus System	**Capacitor Size (kVAr)**		
Load Level	**Bus No.**		
(pu)	**671**	**675**	**634**
0.6	-	300	-
0.8	600	450	-
1	900	600	-

When the capacitor price is $1.25/kVAr, the potential capacitor locations are 671, 675, and 634 at all load levels, but when the capacitor price is $2.00/kVAr, those locations are 671 and 675 at 1 and 0.08 pu load levels, and 675 at 0.6 pu load level. These results imply that the optimal location is capacitor-price sensitive.

If the minimum size of the capacitor that is connected at all load levels is assumed to be a fixed capacitor, and others are considered to be switched capacitors, then in the case of a capacitor price of $1.25/kVAr and a continuous capacitor size, 325kVAr, 225kVAr, and 75kVAr are fixed capacitors located at nodes 671, 675, and 634, respectively. Two switched capacitors at node 671 are 250 kVAr {= (575-325)} and 300 kVAr {= (875-575)}. Similarly, two switched capacitors at node 675 are 200 kVAr {= (425-225)} and 135 kVAr {= (560-425)}. And two switched capacitors at node 634 are 50 kVAr {= (125-75)} and 125 kVAr {=(250-125)}. Table 3.11 shows line loss and utility savings after optimal capacitor placement.

A voltage violation occurs with Case 2 (V_{max} = 1.061 pu) and Case 4 (V_{max} = 1.064 pu) in phase b voltage. Therefore, Cases 2 and 4 are discarded. The maximum percentage reduction in energy loss is 27.13% for Case 3 and with a capacitor price of $1.25/kVAr. The maximum dollar savings is $8,062/year for Case 1 with a capacitor price of $1.25/kVAr.

TABLE 3.11

LINE LOSS AT BASE CASE AND AFTER OPTIMAL CAPACITOR PLACEMENT AND UTILITY SAVINGS FOR IEEE 13-BUS SYSTEM

Case		Line Loss (kwh/yr)		Savings ($/year)	
		$1.25/kVAr	**$2.00/kVAr**	**$1.25/kVAr**	**$2.00/kVAr**
Base Case		75,9720			
After Compensation	Case 1	556,360	581,900	8,062	6,021
	Case 2	-	-	-	-
	Case 3	553,600	581,160	8,056	5,928
	Case 4	-	-	-	-

3.4.2 Effect of Reactive Power Compensation on Customer Loads

When capacitors are placed at the buses, reactive power flow through the line is reduced, resulting in a current decrease that causes a reduction in the voltage drop along the feeder line, and eventually voltage at the node increases. This voltage increase causes customer loads that are voltage-dependent (constant impedance and constant current load) to consume more power. Power consumption depends on the type of the load. Since customers consume more power, they spend more money on electricity bills, while the utility has a dollar savings from power-loss reduction through reactive power compensation. Tables 3.12 and 3.13 show customer load energy consumption and costs for customers before and after optimal capacitor placement.

TABLE 3.12

ENERGY CONSUMPTION BY CUSTOMER LOADS AND COSTS WHEN CAPACITOR PRICE IS $1.25/KVAR FOR IEEE 13-BUS SYSTEM

Case		Energy Consumption (kWh/yr)	Cost ($/yr)	Incremental Cost ($/yr)
Base Case		24,066,040	1,903,623.76	
After Compensation	Case 1	24,218,140	1,915,654.87	12,031.11
	Case 2	-	-	-
	Case 3	24,227,640	1,916,406.32	12,782.56
	Case 4	-	-	-

TABLE 3.13

ENERGY CONSUMPTION BY CUSTOMERS' LOADS AND COSTS WHEN CAPACITOR PRICE IS $2.00/KVAR FOR IEEE 13-BUS SYSTEM

Case		**Energy Consumption (kWh/yr)**	**Cost ($/yr)**	**Incremental Cost ($/yr)**
Base Case		24,066,040	1,903,623.76	
After Compensation	Case 1	24,204,340	1,914,563	10,939.53
	Case 2	-	-	-
	Case 3	24,212,340	1,915,196	11,572.33
	Case 4	-	-	-

After reactive power compensation, the utility's savings are $8,062/year, while customers pay $12,031.11/year more in Case 1 with a capacitor price of $1.25. The net gain by the utility is ($8,062 + $12,031.11) = $20,093.11/year. When the capacitor price is $2.00/kVAr, as in Case 1, the utility's savings are $6,021/year, while customers' incremental costs are $10,939.53/year and the utility's net gain is ($6,021 + $10,939.53) = $16,960.53/year.

3.4.3 Test Results for Optimal Capacitor Placement in IEEE 34-Bus System

Optimal capacitor locations and sizes for the IEEE 34-bus system are shown in Tables 3.14 and 3.15. As can be seen, in the IEEE 34-bus system, optimal locations of capacitors do not change with two given capacitor prices, but they do change with the type of capacitor (continuous or discrete). For example, when capacitor sizes are continuous, there are three optimal locations—Buses 844, 890, and 860—and for discrete sizes, there are four optimal locations—Buses 844, 890, 860, and 830.

Table 3.16 shows line loss and the utility's savings after optimal capacitor placement. Since the optimal locations in a 34-bus system do not change with capacitor prices, line loss and consumption do not vary with given capacitor prices. The maximum percentage of energy loss reduction is 29.52%, and dollar savings are $29,717/year with Case 1. Maximum energy loss reduction occurs when phase kVArs of the capacitor are in the ratio of phase reactive power flows through the line.

TABLE 3.14

CAPACITOR LOCATIONS AND SIZES AT CAPACITOR PRICES OF $1.25/kVAr AND $2.00/kVAr AND CONTINUOUS SIZE FOR IEEE 34-BUS SYSTEM

Load Level (pu)	**Capacitor Size (kVAr)**		
	Bus No.		
	844	**890**	**860**
0.6	400	100	-
0.8	435	135	140
1	475	210	275

TABLE 3.15

CAPACITOR LOCATIONS AND SIZES AT CAPACITOR PRICES OF $1.25/KVAR AND $2.00/KVAR AND DISCRETE SIZE FOR IEEE 34-BUS SYSTEM

Load Level (pu)	**Capacitor Size (kVAr)**			
	Bus No.			
	844	**890**	**860**	**830**
0.6	450	150	-	-
0.8	450	150	150	-
0.6	300	300	300	150

TABLE 3.16

LINE LOSS AT BASE CASE AND AFTER OPTIMAL CAPACITOR PLACEMENT AND UTILITY SAVINGS FOR IEEE 34-BUS SYSTEM

Case		**Line Loss (kWh/yr)**		**Savings ($/year)**	
		$1.25/kVAr	2.00/kVAr	$1.25/kVAr	$2.00/kVAr
Base Case		2,094,480			
After Compensation	Case 1	1,476,140	1,476,140	29,717	28,997
	Case 2	1,484,640	1,484,640	29,292	28,572
	Case 3	1,481,140	1,481,140	29,167	28,267
	Case 4	1,487,140	1,487,140	28,867	27,967

Table 3.17 shows customers' load energy consumption and cost before and after optimal capacitor placement. In a 34-bus system, as in Case 1 with a capacitor price of $1.25, the utility's savings are $29,717/year, while customers pay more at $5,796.45/year, and the net gain of the utility company is ($29,717 + $5,796.45) = $35,513.45/year. If a capacitor price of $2.00/kVAr is considered, as in Case 1, then the utility savings are $28,997/year, while customers' incremental cost is $5,796.45/year, and the net gain by the utility is ($28,997 + $5,796.45) = $34,793.45/year).

TABLE 3.17

ENERGY CONSUMPTION BY CUSTOMER LOAD AND COST WHEN CAPACITOR PRICE IS $1.25/KVAR AND $2.00/KVAR FOR IEEE 34-BUS SYSTEM

Case		**Energy Consumption (kWh/yr)**	**Cost ($/yr)**	**Incremental Cost ($/yr)**
Base Case		12,401,000	980,919.1	
After Compensation	Case 1	12,474,280	98,6715.5	5,796.45
	Case 2	12,472,280	98,6557.3	5,638.25
	Case 3	12,526,320	99,0831.9	9,912.81
	Case 4	12,523,080	99,0575.6	9,656.53

In a 13-bus system, customers' incremental costs are higher than the utility's savings, but in a 34-bus system, customers' incremental costs are lower than the utility's savings. .

There should be a trade-off between the utility's savings and customers' incremental costs. This can be achieved by simultaneously lowering the voltage (changing the voltage set point of the substation transformer load tap changer (LTC) [34]) to reduce the energy consumption by voltage sensitive loads, when capacitors are placed along the feeder line. The importance of voltage reduction and optimal voltage setting during reactive power compensation is discussed in Chapter 5.

3.4.4 Voltage and Reactive Power Profiles after Reactive Power Compensation

13-Bus System: Optimal locations of capacitors for a 13-bus system change for two different capacitor prices—$1.25/kVAr and $2.00/KVAr. Voltage and reactive power profiles are shown in Figures 3.5 to 3.10 for 1 pu load and a capacitor price of $1.25/kVAr.

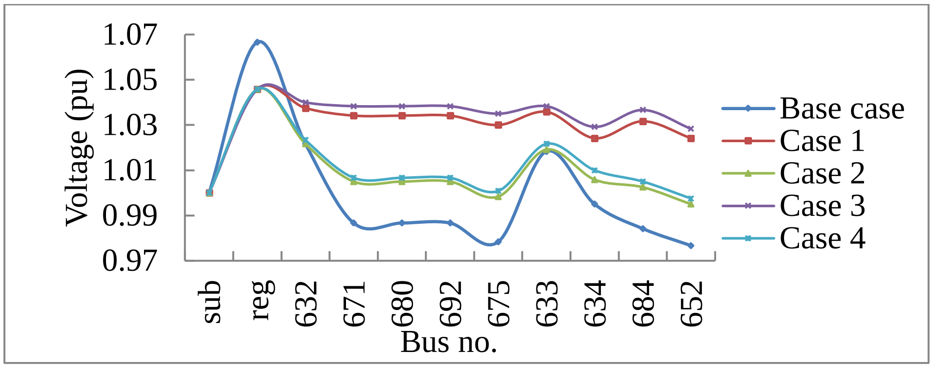


Figure 3.5: Phase a voltage before and after optimal capacitor placement for IEEE 13-bus system

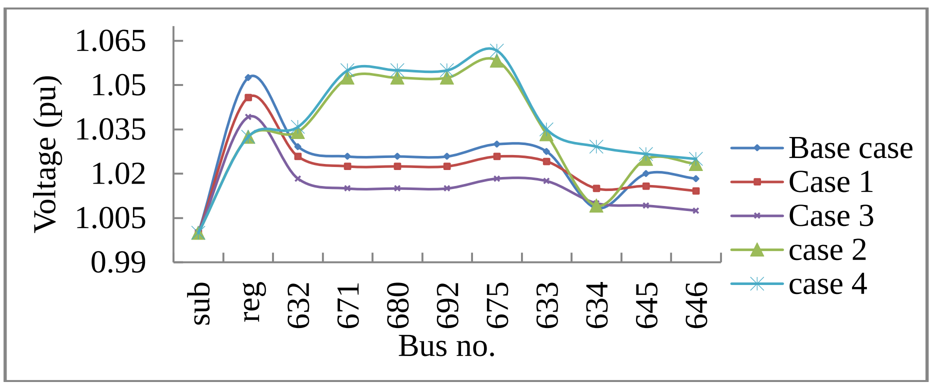


Figure 3.6: Phase b voltage before and after optimal capacitor placement for IEEE 13-bus system

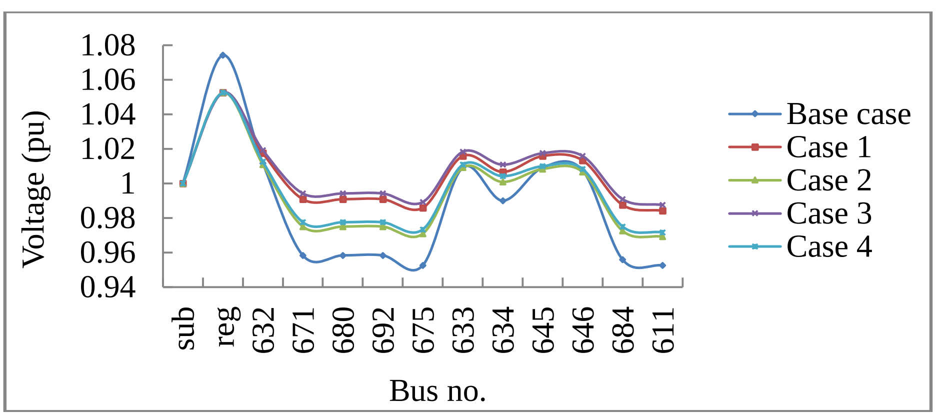


Figure 3.7: Phase c voltage before and after optimal capacitor placement for IEEE 13-bus system

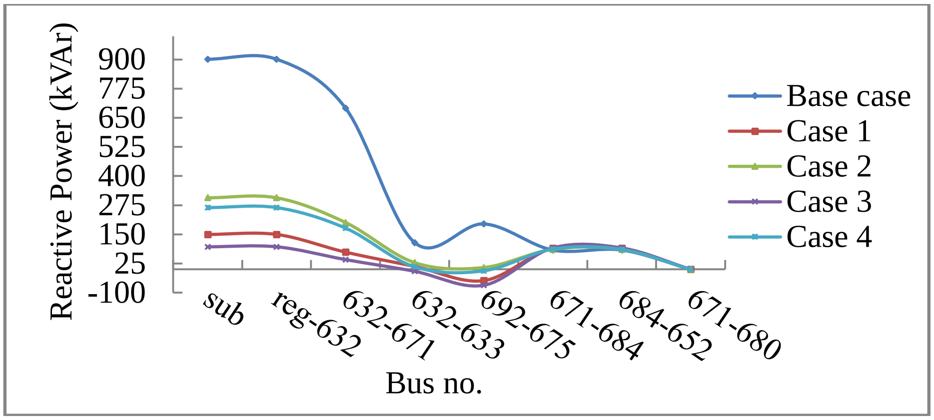


Figure 3.8: Phase a reactive power for IEEE 13-bus system

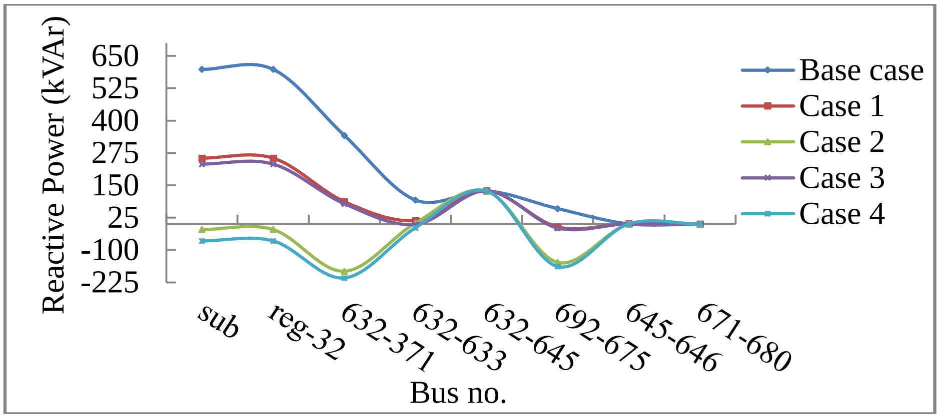


Figure 3.9: Phase b reactive power for IEEE 13-bus system

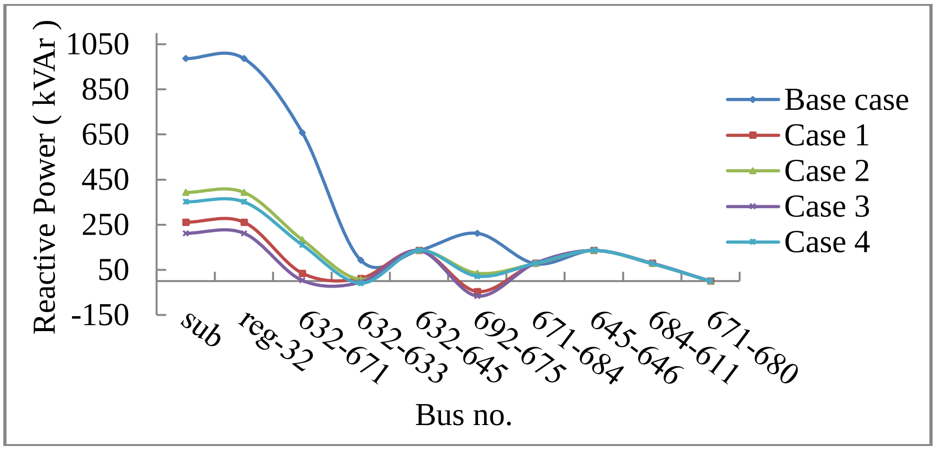


Figure 3.10: Phase c reactive power for IEEE 13-bus system

34-Bus System: Optimal locations of capacitors for the 34-bus system do not change with two different capacitor prices—$1.25/kVAr and $2.00/kVAr. Voltage and reactive power profiles for 1 pu load and capacitor prices of $1.25/kVAr and $2.00/kVAr are shown in Figures 3.11 to 3.16.

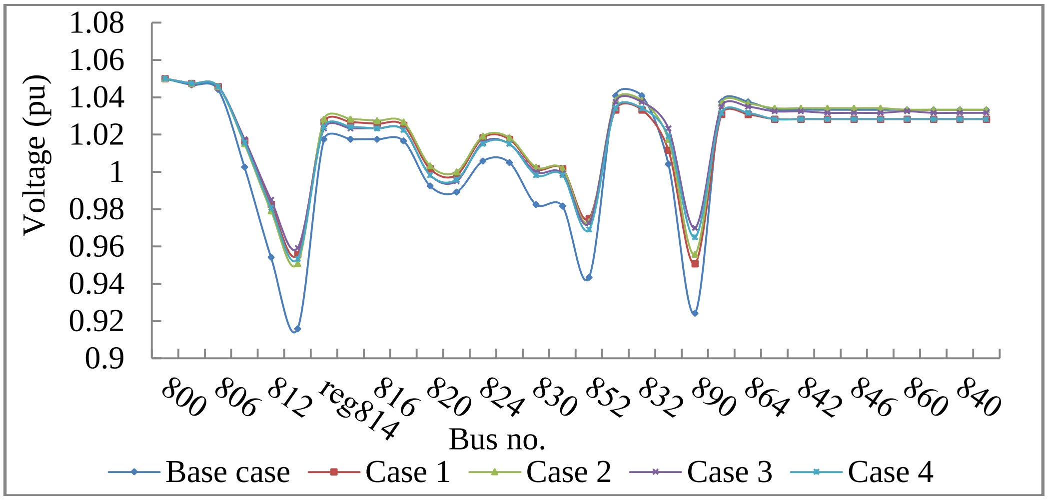


Figure 3.11: Phase a voltage before and after optimal capacitor placement for IEEE 34-bus system

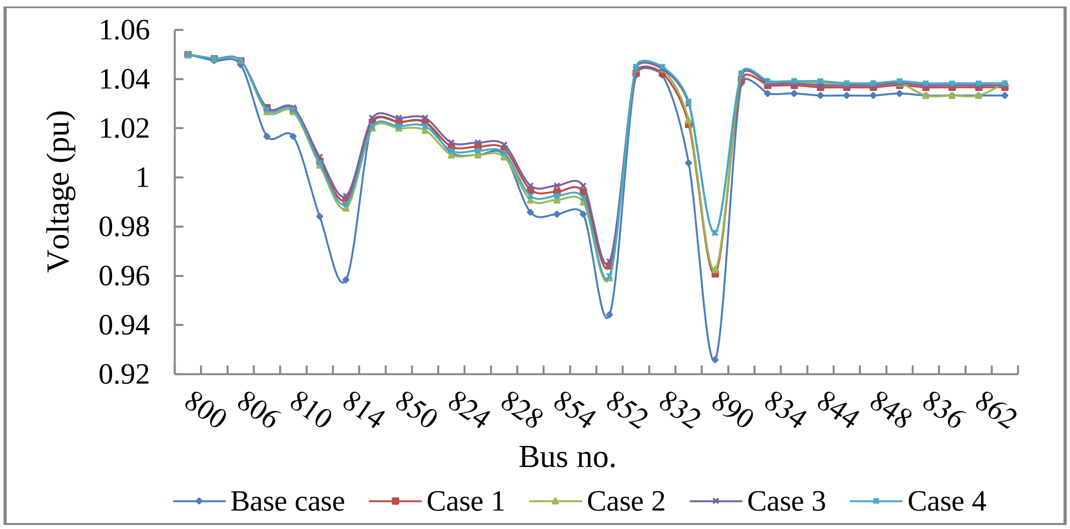


Figure 3.12: Phase b voltage before and after optimal capacitor placement for IEEE 34-bus system

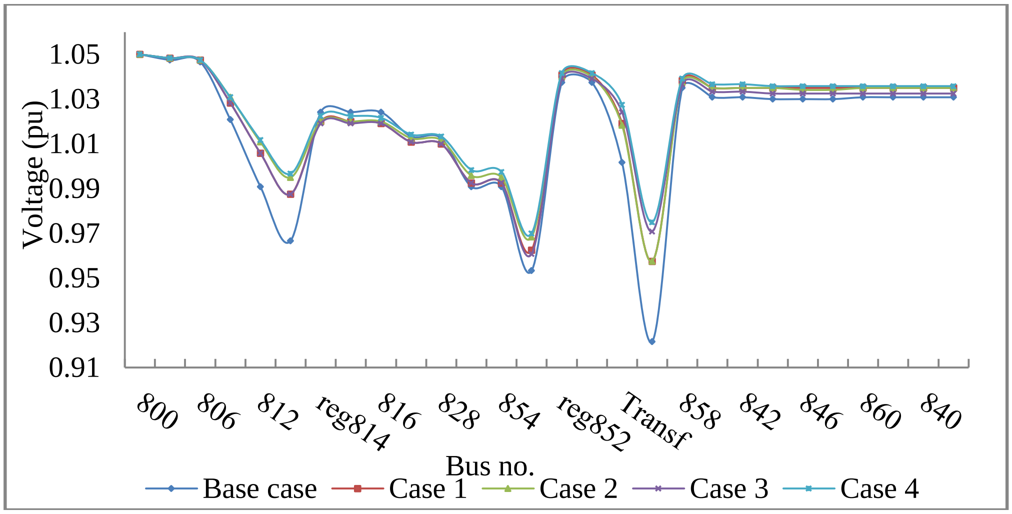


Figure 3.13: Phase c voltage before and after optimal capacitor placement for IEEE 34-bus system

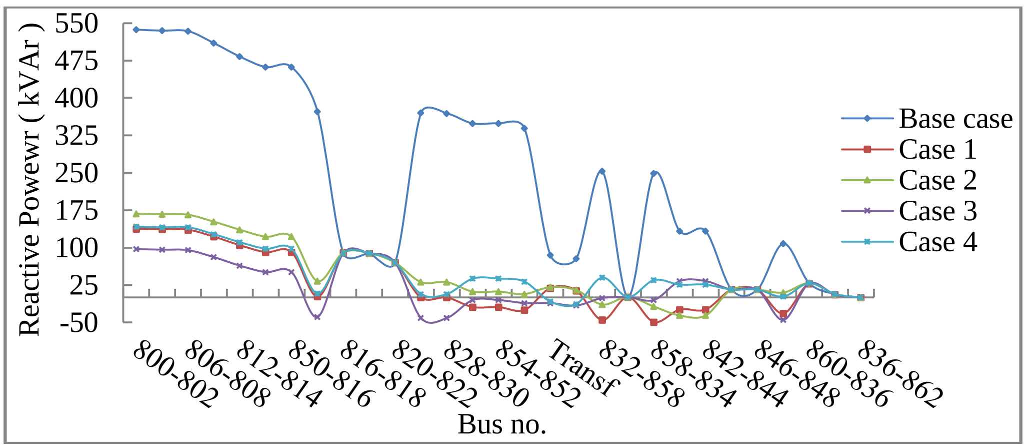


Figure 3.14: Phase a reactive power for 34-bus system

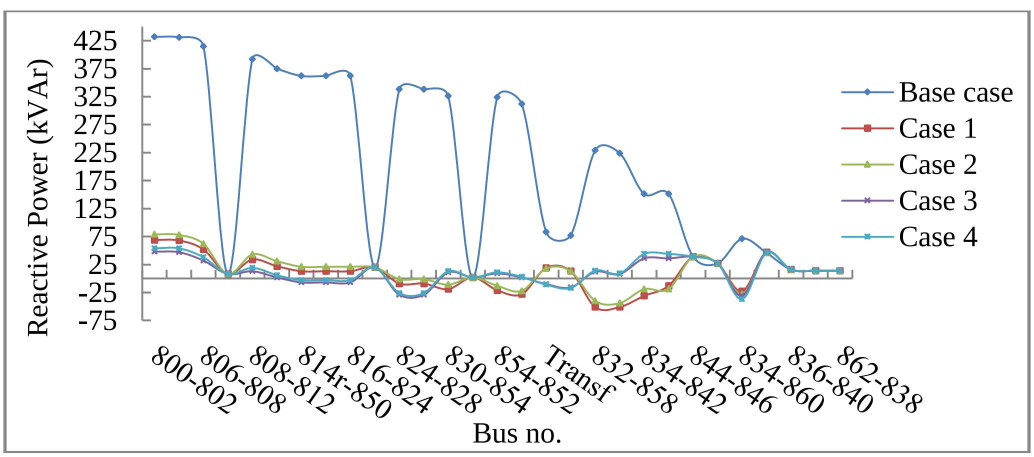


Figure 3.15: Phase b reactive power for IEEE 34-bus system

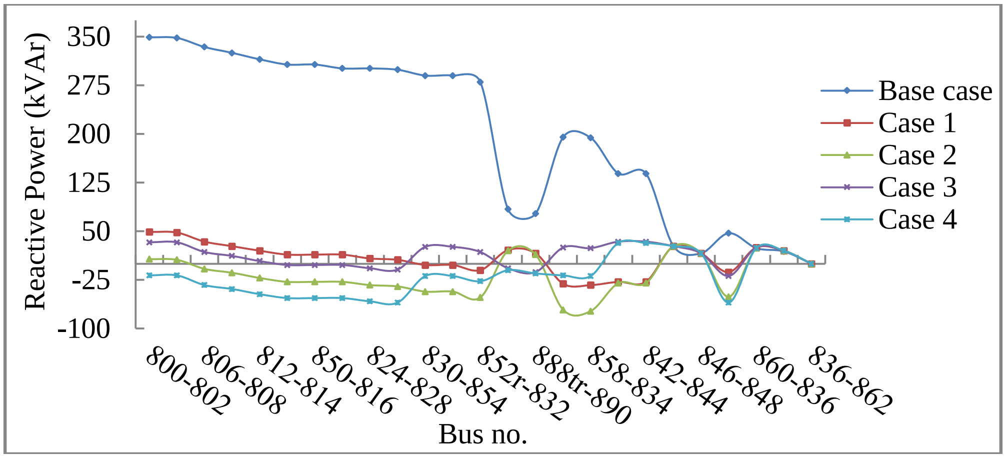


Figure 316: Phase c reactive power for IEEE 34-bus system

3.5 Conclusion

This chapter proposed a methodology for capacitor placement that considers both the power loss index and the loss sensitivity factor. Four case studies and two capacitor prices were considered to show how they affect the optimization problem, as well as system characteristics such as voltage profile and reactive power-flow profile, utility savings, and customer costs. This chapter also discussed how customers are impacted by reactive power compensation where the utility's goal is to have dollar savings from minimizing the active power loss.

CHAPTER 4

IMPACT OF LOAD TYPE ON POWER CONSUMPTION AND LINE LOSS IN VOLTAGE-REDUCTION PROGRAM

Voltage reduction is becoming a common strategy in distribution to reduce peak demand and energy consumption. At reduced voltage, variations in line loss need to be analyzed, because losses affect the cost-benefit analysis. Conventional loss analysis by applying detailed system modeling is difficult and impractical to perform since voluminous data are involved [25]. In this chapter, a model is derived that explains, at reduced voltage, how line loss varies with type of load. This model has been demonstrated on the IEEE 13-bus test system. Also analyzed is the effect of line resistance on line loss for various types of loads.

In this chapter, section 4.1 discusses the impact of load type on power consumption and line loss in a voltage-reduction program. Section 4.2 analyzes the effect of line resistance on the line loss analysis of section 4.1. Finally, section 4.3, presents the practical implementation of the concept of increasing and decreasing properties of current and line loss at a reduced voltage.

4.1 Impact of Load Type on Power Consumption and Line Loss at Reduced Voltage

The type of load served has a significant effect on demand and energy reductions obtained from voltage reduction. The accuracy of load models determines how well the effects of reduced voltage on a distribution system can be predicted. The three common load models explained in Chapter 1 are constant impedance, constant current, and constant power. Since the constant impedance load's power consumption is directly proportional to voltage squared, the reduction in power consumption in that load at reduced voltage is expected to be greater than the reduction in power consumption in an equivalent constant current load. Therefore, a system with dominant constant impedance load will have the greatest benefit from voltage reduction.

Voltage reduction not only reduces energy consumption but also causes variations in line loss and the power factor. Line loss also depends on load type and model, and may increase or decrease at reduced voltage. How line loss varies with voltage reduction is explained with the type of load, as follows:

Constant Power Load: P + jQ (*constant*) = $V\downarrow I^{*}\uparrow$, if voltage is decreased, current will increase proportionally, resulting in an increase in line loss ($|I|^2R$). There is no benefit in terms of energy conservation because load energy consumption remains constant and line loss increases after voltage reduction.

Constant Current Load: I(*constant*) = $\left(\frac{P+jQ\downarrow}{V\downarrow}\right)^{*}$, if voltage is decreased, the load will decrease but the current remains constant; therefore, there is no change in line loss.

Constant Impedance Load: Z(*constant*) = $\frac{|V\downarrow|^2}{P+jQ\downarrow}$, if voltage is reduced, the load will get reduced, again $I^{*}=\frac{P+jQ\downarrow}{V\downarrow}$. Since the reduction in load is greater than the reduction in voltage, current (I) will decrease, resulting in decrease in line loss.

Composite Load: For a composite load, the changes in energy consumption and line loss as voltage is reduced, depend on the percentages of the load of each type connected to the system. If constant power load dominates, its effect of increasing line loss at reduced voltage will exceed the decreased line loss of the constant impedance load, resulting in an increase in the system's overall line loss but a decrease in load power consumption. If constant impedance is the largest percentage of load, then its effect of decreasing line loss at reduced voltage will exceed the increasing effect of line loss from a constant power load, resulting in a decrease in the system’s overall line loss and a decrease in load power consumption. If constant current load is dominant, then line loss may increase or decrease at a reduced voltage, depending on the mix of the other load types. If there is more constant power load than constant impedance, losses will increase. If the constant impedance load is greater than the constant power load, then losses will decrease. These are summarized in the Tables 4.1 and 4.2.

TABLE 4.1

EFFECT OF REDUCED VOLTAGE ON LINE CURRENT

Load Model	**Line Current**
Constant Power	Increase
Constant Current	Constant
Constant Impedance	Decrease

TABLE 4.2

EFFECT OF REDUCED VOLTAGE ON POWER CONSUMPTION AND LINE LOSS

Load Model	**Load Power Consumption**	**Line Loss**
Constant Power	Constant	Increase
Constant Current	Decrease	Constant
Constant Impedance	Decrease	Decrease
Composite Load:		
Constant Power Load Dominant	Decrease (ΔP_{Load}^{P})	Increase
Constant Current Load Dominant	Decrease ($\Delta P_{Load}^{C_P}, \Delta P_{Load}^{C_Z}$) $\Delta P_{Load}^{P} < P_{Load}^{C_P} < P_{Load}^{C_Z}$	Increase (if % of constant power load > % of constant impedance load) or Decrease (if % of constant power load < % of constant impedance load)
Constant Impedance Load Dominant	Decrease (ΔP_{Load}^{Z}) $\Delta P_{Load}^{P} < P_{Load}^{C_P} < P_{Load}^{C_Z} < \Delta P_{Load}^{Z}$	Decrease

In Table 4.2, the term ΔP_{Load}^{P} is the reduction in real power consumption of the load at reduced voltage when the constant power load is dominant. The term $\Delta P_{Load}^{C_P}$ is the reduction in real power consumption when the constant current load is dominant, and there is more constant power load than constant impedance. The term ΔP_{Load}^{Cz} is the reduction in power consumption when the constant current load is dominant, and there is more constant impedance than constant power load. The term ΔP_{Load}^{Z} is the reduction in power consumption when the constant impedance load is dominant in the composite load model.

Example: IEEE 13-Bus System

The IEEE 13-bus distribution test feeder [10], which has three-phase, two-phase, and single-phase lines, is an unbalanced system. Based on the load data provided, this is a dominant constant power load system. For the analysis in this Chapter, in addition to the given load model [10], the load mix has been changed from that provided, with several combinations and percentages of load types considered to demonstrate the modeling presented previously in Table 4.2. First, the resulting load and loss changes for varying substation voltages are shown in Tables 4.3 to 4.5 for three different load mixes in which the constant power load dominates.

Constant Power Load Dominant in Composite Load Model

TABLE 4.3

LOAD MIX 1 WITH CONSTANT POWER LOAD DOMINANT

Constant Power Load: 2768 kW, 1653 kVAr Constant Impedance Load: 358 kW, 218 kVAr Constant Current Load: 340 kW, 231 kVAr Capacitor: 700 kVAr						
Substation Voltage	**Load**		**Line Loss**		**Power Supplied from Substation**	
(V)	**(kW)**	**(kVAr)**	**(kW)**	**(kVAr)**	**(kW)**	**(kVAr)**
122	3469	2104	111	324	3580	1726
121	3461	2099	112	328	3574	1736
120	3454	2094	114	332	3567	1745
119	3444	2088	115	337	3560	1758
118	3437	2084	117	341	3554	1767
117	3427	2077	119	347	3546	1779
116	3416	2071	121	353	3537	1793

TABLE 4.4

LOAD MIX 2 WITH CONSTANT POWER LOAD DOMINANT

Substation Voltage (V)	Load (kW)	Load (KVAr)	Line Loss (kW)	Line Loss (KVAr)	Power Supplied from Substation (kW)	Power Supplied from Substation (KVAr)
Constant Power load: 2023 kW, 1234 kVAr Constant Current Load: 843 kW, 462 kVAr Constant Impedance Load: 600 kW, 406 kVAr Capacitor: 700 kVAr						
122	3467	2104	110	322	3577	1724
121	3452	2094	111	324	3563	1727
120	3437	2085	112	327	3549	1731
119	3420	2074	113	330	3533	1736
118	3405	2065	114	333	3519	1739
117	3381	2050	115	337	3496	1745
116	3367	2042	116	340	3483	1748

TABLE 4.5

LOAD MIX 3 WITH CONSTANT POWER LOAD DOMINANT

Substation Voltage (V)	Load (kW)	Load (kVAr)	Line Loss (kW)	Line Loss (KVAr)	Power Supplied from Substation (kW)	Power Supplied from Substation kVAr)
Constant Power Load: 1325 kW, 785 kVAr Constant Current Load: 1183 kW, 693 kVAr Constant Impedance Load: 958 kW, 624 kVAr Capacitor: 700 kVAr						
122	3470	2106	110	322	3581	1725
121	3448	2092	111	322	3559	1722
120	3426	2078	111	323	3537	1719
119	3400	2062	111	325	3511	1717
118	3372	2044	111	326	3483	1712
117	3343	2026	112	327	3454	1709
116	3323	2013	112	328	3435	1706

In comparing Tables 4.3 and 4.5, the rate of change of load with voltage in Table 4.3 is smaller than that in Table 4.5, but the rate of change of line loss in Table 4.3 is greater than that in Table 4.5. This is because the percentage of dominant constant power load is much higher in Table 4.3 than in Table 4.5 and percentage of constant current load is much higher in Table 4.5

than in Table 4.3. Next, results are presented for load and loss changes as substation voltage varies for three different load mixes in which constant current load dominates, as shown in Tables 4.6 to 4.8.

Constant Current Load Dominant in Composite Load Model

TABLE 4.6

LOAD MIX 1 WITH CONSTANT CURRENT LOAD DOMINANT

Constant Current Load: 2768 kW, 1653 kVAr
Constant Power Load: 358 kW, 218 kVAr
Constant Impedance Load: 340 kW, 231 kVAr
Capacitor: 700 kVAr

Substation Voltage (V)	Load (kW)	Load (kVAr)	Line Loss (kW)	Line Loss (kVAr)	Power Supplied from Substation (kW)	Power Supplied from Substation (kVAr)
122	3467	2105	110	321	3577	1724
121	3443	2090	110	322	3553	1719
120	3418	2075	110	322	3529	1714
119	3389	2057	111	322	3500	1709
118	3348	2032	111	322	3459	1700
117	3325	2018	111	323	3436	1695
116	3303	2004	111	323	3413	1690

TABLE 4.7

LOAD MIX 2 WITH CONSTANT CURRENT LOAD DOMINANT

Constant Current Load: 2023 kW, 1234 kVAr
Constant Power Load: 843 kW, 462 kVAr
Constant Impedance Load: 600 kW, 406 kVAr
Capacitor: 700 kVAr

Substation Voltage (V)	Load (kW)	Load (kVAr)	Line Loss (kW)	Line Loss (kVAr)	Power Supplied from Substation (kW)	Power Supplied from Substation (kVAr)
122	3481	2112	112	323	3594	1732
121	3458	2097	113	324	3571	1729
120	3436	2083	113	325	3549	1726
119	3405	2064	113	326	3519	1720
118	3384	2050	114	327	3497	1717
117	3348	2028	115	330	3463	1713
116	3327	2014	115	331	3442	1710

TABLE 4.8

LOAD MIX 3 WITH CONSTANT CURRENT LOAD DOMINANT

Constant Current Load: 2023 kW, 1234 kVAr Constant Impedance Load: 843 kW, 462 kVAr Constant Power Load: 600 kW, 406 kVAr Capacitor: 700 kVAr						
Substation Voltage (V)	**Load**		**Line Loss**		**Power Supplied from Substation**	
	(kW)	**(kVAr)**	**(kW)**	**(kVAr)**	**(kW)**	**(kVAr)**
122	3464	2103	111	318	3574	1717
121	3438	2088	110	318	3548	1712
120	3412	2073	110	317	3522	1706
119	3381	2054	110	317	3491	1700
118	3338	2029	110	316	3448	1690
117	3314	2015	110	316	3424	1685
116	3290	2002	110	316	3400	1679

It needs to be mentioned here that WindMil load flow simulation provides the integer values in line loss; therefore, in Table 4.8, line loss for voltages 121 V to 116 V are seen as constant, but there are actually fractional changes in line loss. Comparing Tables 4.7 and 4.8, line loss increases in Table 4.7 and decreases in Table 4.8 as the substation voltage decreases. This is because although constant current load is dominant in both cases, constant power load is greater than constant impedance load in Table 4.7, and constant impedance load is greater than constant power load in Table 4.8. The results in Tables 4.7 and 4.8 agree with the conditions presented for line-loss increase or decrease for dominant constant current load in the composite load model in Table 4.2. Tables 4.9 and 4.10 present results for two other load mixes with constant current load dominant, and these results also agree with Table 4.2.

TABLE 4.9

LOAD MIX 4 WITH CONSTANT CURRENT LOAD DOMINANT

Constant Current Load: 1325 kW, 785 kVAr Constant Power Load: 1183 kW, 693 kVAr Constant Impedance Load: 958 kW, 624 kVAr Capacitors: 700 kVAr						
Substation Voltage	**Load**		**Line Loss**		**Power Supplied from Substation**	
(V)	**(kW)**	**(kVAr)**	**(kW)**	**(kVAr)**	**(kW)**	**(kVAr)**
122	3491	2118	112	327	3604	1743
121	3468	2103	113	328	3581	1741
120	3445	2089	113	330	3558	1738
119	3415	2070	113	331	3529	1733
118	3394	2056	114	333	3507	1730
117	3358	2034	115	336	3473	1728
116	3337	2021	116	338	3453	1725

TABLE 4.10

LOAD MIX 5 WITH CONSTANT CURRENT LOAD DOMINANT

Constant Current Load: 1325 kW, 785 kVAr Constant Impedance Load: 1183 kW, 693 kVAr Constant Power Load: 958 kW, 624 kVAr Capacitors: 700 kVAr						
Substation Voltage	**Load**		**Line Loss**		**Power Supplied from Substation**	
(V)	**(kW)**	**(kVAr)**	**(kW)**	**(kVAr)**	**(kW)**	**(kVAr)**
122	3458	2100	109	319	3568	1716
121	3433	2085	109	318	3542	1710
120	3407	2070	109	318	3516	1705
119	3378	2052	109	318	3487	1699
118	3334	2027	109	316	3443	1688
117	3310	2013	109	316	3419	1683
116	3287	1999	108	316	3396	1677

Finally, Tables 4.11 and 4.12 present results for the composite load model with constant impedance loads dominant.

Constant Impedance Load Dominant in Composite Load Model

TABLE 4.11

LOAD MIX 1 WITH CONSTANT IMPEDANCE LOAD DOMINANT

Constant Impedance Load: 2768 kW, 1653 kVAr Constant Power Load: 358 kW, 218 kVAr Constant Current Load: 340 kW, 231 kVAr Capacitors: 700 kVAr						
Substation Voltage (V)	**Load (kW)**	**Load (kVAr)**	**Line Loss (kW)**	**Line Loss (kVAr)**	**Power Supplied from Substation (kW)**	**Power Supplied from Substation (kVAr)**
122	3480	2113	110	322	3590	1733
121	3440	2089	109	319	3549	1716
120	3401	2066	108	316	3509	1699
119	3352	2036	107	313	3460	1677
118	3288	1998	106	308	3394	1649
117	3252	1976	105	305	3357	1633
116	3207	1949	104	302	3311	1614

TABLE 4.12

LOAD MIX 2 WITH CONSTANT IMPEDANCE LOAD DOMINANT

Constant Impedance Load: 2023 kW, 1234 kVAr Constant Current Load: 843 kW, 462 kVAr Constant Power Load: 600 kW, 406 kVAr Capacitors: 700 kVAr						
Substation Voltage (V)	**Load (kW)**	**Load (kVAr)**	**Line Loss (kW)**	**Line Loss (kVAr)**	**Power Supplied from Substation (kW)**	**Power Supplied from Substation (kVAr)**
122	3481	2113	111	323	3592	1735
121	3448	2093	110	322	3558	1722
120	3415	2073	110	320	3524	1710
119	3373	2048	109	318	3482	1695
118	3319	2016	108	316	3427	1676
117	3288	1997	108	314	3396	1165
116	3250	1974	107	312	3357	1651

Comparing Tables 4.11 and 4.12, it can be seen that the decreasing rate of line loss in Table 4.11 is greater than the decreasing rate of line loss in Table 4.12, because the percentage of impedance load in Table 4.11 is larger than the percentage of impedance load in Table 4.12.

4.2 Effect of Reactive Power Compensation on Line loss

The use of switched capacitors for voltage control must also be considered in this analysis. As line voltage decreases, usually with increasing load, capacitors are switched on in order to compensate. The resulting rise in voltage leads to increased line loss for systems with a dominant constant impedance load, but that increment in losses is less than the decrement in losses caused by the reduction in current flow due to reactive power compensation provided by the capacitor. For a system with a dominant constant power load, the voltage increase after reactive power compensation will reduce line loss; therefore, line loss will decrease to a greater degree in a system with a dominant constant power load than in a system with a dominant constant impedance load.

4.3 Impact of Line Resistance and Load Placement on Line Loss at Reduced Voltage

There are exceptions to the line loss analysis presented in section 4.1, because line resistance, which is a function of conductor size, length, and location of loads, also affects line loss. For example, in a system with dominant constant power loads, it can be shown that, in contrast to section 4.1, line loss may decrease if resistance of the line connected to the constant impedance load is high. This is explained by Systems 1 and 2 shown in Figures 4.1 and 4.2, respectively.

In these systems, the current I_p flowing to the constant power load at node 1 is I_{p1} when the substation voltage is V_1, and I_{p2} when the substation voltage is V_2, and $V_1 > V_2$. Similarly, I_{z1} and I_{z2} are currents I_z in the line connected to the constant impedance load at node 2 at substation voltages V_1 and V_2, respectively. The resistances of lines 1 and 2 are R_{Line1} and R_{Line2}, respectively. Note that I_p includes I_z in system 2, while the two are independent in system 1.

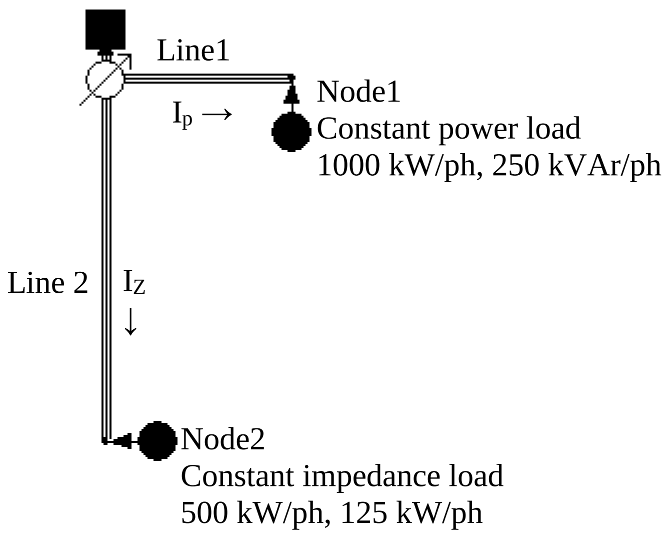


Figure 4.1: System 1

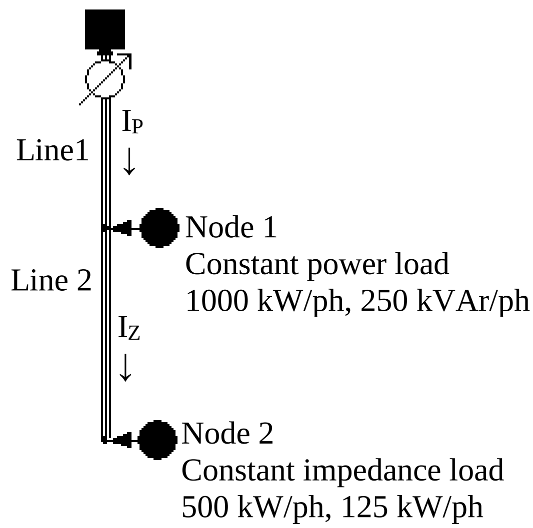


Figure 4.2: System 2

At voltage V_1, line loss is

$$P_{Loss1} = |I_{P1}|^2 R_{Line1} + |I_{Z1}|^2 R_{Line2} \tag{4.1}$$

At voltage V_2, line loss is

$$P_{Loss2} = |I_{P2}|^2 R_{Line1} + |I_{Z2}|^2 R_{Line2} \tag{4.2}$$

The difference in line loss at V_2 and V_1 is

$$\Delta P_{Loss} = P_{Loss2} - P_{Loss1}$$

$$= (|I_{P2}|^2 R_{Line1} + |I_{Z2}|^2 R_{Line2}) - (|I_{P1}|^2 R_{Line1} + |I_{Z1}|^2 R_{Line2})$$

$$= (|I_{p2}|^2 - |I_{p1}|^2) R_{Line1} + (|I_{z2}|^2 - |I_{z1}|^2) R_{Line2} \tag{4.3}$$

System 1

As explained in section 4.1, at reduced voltage, the current flowing to the constant power load will increase, and the current flowing to the constant impedance load will decrease. Therefore,

$$|I_{P1}| < |I_{P2}| \tag{4.4}$$

$$|I_{Z1}| > |I_{Z2}| \tag{4.5}$$

Also,

$$(|I_{p2}|^2 - |I_{p1}|^2) > 0, \text{since } |I_{p2}| > |I_{p1}| \tag{4.6}$$

$$(|I_{z2}|^2 - |I_{z1}|^2) < 0, \text{since } |I_{z2}| < |I_{z1}| \tag{4.7}$$

Hence, at reduced voltage, the increasing effect of line loss comes from the term $(|I_{p2}|^2 - |I_{p1}|^2)$, and the decreasing effect of line loss comes from the term $(|I_{z2}|^2 - |I_{z1}|^2)$. At reduced voltage, line loss will increase if

$$\left|\left(|I_{p2}|^2 - |I_{p1}|^2\right)\right| R_{Line1} > |(|I_{z2}|^2 - |I_{z1}|^2)| R_{Line2} \tag{4.8}$$

$$\Rightarrow \frac{R_{Line1}}{R_{Line2}} > \frac{|(|I_{z2}|^2 - |I_{z1}|^2)|}{\left|\left(|I_{p2}|^2 - |I_{p1}|^2\right)\right|} \tag{4.9}$$

or line loss will decrease if

$$\left|\left(|I_{p2}|^2 - |I_{p1}|^2\right)\right| R_{Line1} < |(|I_{z2}|^2 - |I_{z1}|^2)| R_{Line2} \tag{4.10}$$

$$\Rightarrow \frac{R_{Line1}}{R_{Line2}} < \frac{|(|I_{z2}|^2 - |I_{z1}|^2)|}{\left|\left(|I_{p2}|^2 - |I_{p1}|^2\right)\right|} \tag{4.11}$$

If constant power load is dominant, then

$$|(|I_{p2}|^2 - |I_{p1}|^2)| > |(|I_{z2}|^2 - |I_{z1}|^2)| \tag{4.12}$$

But there is no guarantee that for the system with a dominant constant power load, line loss will increase, i.e., $|(|I_{p2}|^2 - |I_{p1}|^2)| R_{Line1} > |(|I_{z2}|^2 - |I_{z1}|^2)| R_{Line2}$, because line loss also depends on line resistance. Therefore, a dominant constant power load in a composite load model does not guarantee that line loss will increase with voltage reduction.

Similarly, if a constant impedance load is dominant, then

$$|(|I_{p2}|^2 - |I_{p1}|^2)| < |(|I_{z2}|^2 - |I_{z1}|^2)| \tag{4.13}$$

Again, there is no guarantee that for the system with dominant constant impedance load, line loss will decrease, i.e., $|(|I_{p2}|^2 - |I_{p1}|^2)|R_{Line1} < |(|I_{z2}|^2 - |I_{z1}|^2)|R_{Line2}$, because line loss depends on line resistance as well. Therefore, a dominant constant impedance load in the composite load model does not guarantee that line loss will decrease with voltage reduction. The two examples that follow illustrate this effect. The first shows that line loss has increased with decreasing voltage, and the second shows that line loss has decreased with decreasing voltage, although in both cases, constant power load is dominant.

System 2

If current flowing into the constant power load at node 1 is I_p^{load}, then $I_p = I_p^{load} + I_z$. At voltage V_1, $I_{p1} = I_{p1}^{load} + I_{z1}$, and at voltage V_2, $I_{p2} = I_{p2}^{load} + I_{z2}$. From equation (4.3),

$$\Delta P_{Loss} = \left(\left|I_{p2}^{load} + I_{z2}\right|^2 - \left|I_{p1}^{load} + I_{z1}\right|^2\right) R_{Line1} + (|I_{z2}|^2 - |I_{z1}|^2) R_{Line2}$$

Line loss will increase if

$$\left(\left|I_{p2}^{load} + I_{z2}\right|^2 - \left|I_{p1}^{load} + I_{z1}\right|^2\right) R_{Line1} + (|I_{z2}|^2 - |I_{z1}|^2) R_{Line2} > 0$$

$$\Rightarrow \frac{R_{Line1}}{R_{Line2}} > \frac{(|I_{z1}|^2 - |I_{z2}|^2)}{\left(\left|I_{p2}^{load} + I_{z2}\right|^2 - \left|I_{p1}^{load} + I_{z1}\right|^2\right)} \tag{4.14}$$

Line loss will decrease if

$$\left(\left|I_{p2}^{load} + I_{z2}\right|^2 - \left|I_{p1}^{load} + I_{z1}\right|^2\right) R_{Line1} + (|I_{z2}|^2 - |I_{z1}|^2) R_{Line2} < 0$$

$$\Rightarrow \frac{R_{Line1}}{R_{Line2}} < \frac{(|I_{z1}|^2 - |I_{z2}|^2)}{\left(\left|I_{p2}^{load} + I_{z2}\right|^2 - \left|I_{p1}^{load} + I_{z1}\right|^2\right)} \tag{4.15}$$

It needs to be mentioned that conditions in equations (4.5) and (4.7) also hold for System 2.

Example 1

Dominant constant power loads at node 1 in System 1 are 1,000 kW/ph, 250 kVAr/ph, and constant impedance loads at node 2 are 500 kW/ph, 125 kVAr/ph; the length of line 1 = 1,650 ft, and the length of line 2 = 5,000 ft; resistance = 0.1859 Ω/mile.

At V_1 = 122v, currents are found in system 1 as

$|I_{p1}|$ = 414.78 A and, $|I_{z1}|$ = 219.62A

At V_2 = 118V, currents are found in system 1 as

$|I_{p2}|$ = 423.27A and $|I_{z2}|$= 215.36A.

Now, from equation (4.3),

$$\Delta P_{Loss} = (|I_{p2}|^2 - |I_{p1}|^2)R_{Line1} + (|I_{z2}|^2 - |I_{z1}|^2)R_{Line2}$$

= $(423.27^2 - 414.78^2)$*1650*0.000189*0.1859 + $(215.36^2 - 219.62^2)$*5000*0.000189*0.1859

= (7115.044)*0.058 + (–1853.01)*0.176

This positive value is for the constant power load's increasing current property at reduced voltage

This negative value is for the constant impedance load's decreasing current property at reduced voltage

= 412.67 + (–326.2)

= 86.47 watts

In Example 1, line loss increases by 86.47 watts/ph. It can be seen that the increasing effect of line loss comes from the term (7,115.044*0.058), and the decreasing effect of line loss comes from the term (–1,853.01*0.176). Here, the increasing effect of line loss (412.67 = 7,115.044*0.058 W) is greater than the decreasing effect of line loss (–326.2 = –1,853.01*0.176 W). Therefore, resultant line loss increases by 86.47 watts/ph.

Example 2

In example 2, the same loads are connected at nodes 1 and 2 in system 1, but the length of line 1 is now 900 ft, and the length of line 2 is the same as 5,000 ft.

At voltage V_1 = 122v, currents are found in system 1 as

$|I_{p1}|$ = 411.47A, $|I_{z1}|$ = 219.62A.

At voltage V_2 = 118V, currents are found in system 1 as

$|I_{p2}|$ = 419.75A, $|I_{z2}|$ = 215.36A.

Now,

$$\Delta P_{Loss} = (|I_{p2}|^2 - |I_{p1}|^2)R_{Line1} + (|I_{z2}|^2 - |I_{z1}|^2)R_{Line2}$$

$$= (419.75^2 - 411.47^2)*900*0.00018939*0.1859 + (215.36^2 - 219.62^2)*5000*0.00018939*0.185$$

$$= 6882.5*0.03168 \quad + \quad (-1853.01)*0.176$$

This positive value is for the constant power load's increasing current property at reduced voltage

This negative value is for the constant impedance load's decreasing current property at reduced voltage

$$= 218.0376 + (-326.1297)$$

$$= -108.092 \text{ watts}$$

In Example 2, line loss decreases by 108.092 watts/ph, even though constant power load is dominant. Here we can see that although the increasing effect (6882.5 A^2) of line loss contributed by the current of a dominant constant power load is greater than the decreasing effect (–1853.01 A^2) of line loss contributed by the current of constant impedance load, but the resistance (0.176 Ω) of the line carrying the current to a constant impedance load is a much larger value with respect to the resistance (0.03168 Ω) of the line connected to the constant power load, which makes the entire decreasing effect of line loss (–326.1297 = –1853.01*0.176 watts) greater than the entire increasing effect of line loss (218.03168 = 6,882.5*0.03168 watts).

Whether line loss will increase or decrease with a reduction in voltage can be determined by equations (4.9), (4.11), (4.14) and (4.15). Tables 4.13 to 4.20 show at a reduced voltage how line loss and current change with distance of the line for Systems 1 and 2 in Figures 4.1 and 4.2, respectively.

Assume that $\frac{R_{Line1}}{R_{Line2}} = \begin{cases} k_1, system\ 1 \\ k_2, system\ 2 \end{cases}$

TABLE 4.13

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.4$, $k_2 = 0.66$

System 1: Line 1 = 2,000 ft Line 2 = 5,000 ft					**System 2: Line 1 = 2,000 ft Line 2 = 3,000 ft**			
Substation Voltage (V)	**Current (A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**kW**	**kVAr**	**kW**	**kVAr**
122	416.39	219.62	636.32	214.86	62	199	100	322
118	424.99	215.37	640.68	210.51	63	201	101	324
114	439.34	208.63	648.37	203.61	64	205	102	327

TABLE 4.14

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.33$, $k_2 = 0.49$

System 1: Line 1 = 1,650 ft Line 2 = 5,000 ft					**System 2: Line 1 = 1,650 ft Line 2 = 3,350 ft**			
Substation Voltage (V)	**Current(A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**kW**	**kVAr**	**kW**	**kVAr**
122	414.78	219.62	633.26	217.24	55	178	87	278
118	423.27	215.36	638.88	211.42	56	179	87	279
114	437.47	208.64	646.37	204.55	56	181	88	281

TABLE 4.15

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.32$, $k_2 = 0.47$

System 1: Line 1 = 1,600 ft Line 2 = 5,000 ft					**System 2: Line 1 = 1,600 ft Line 2 = 3,400 ft**			
Substation Voltage (V)	**Current (A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**KW**	**KVAr**	**KW**	**kVAr**
122	414.56	219.62	634.40	215.88	55	175	85	272
118	423.03	215.37	638.63	211.55	55	176	85	273
114	437.19	208.63	646.08	204.69	55	178	86	275

TABLE 4.16

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.19$, $k_2 = 0.23$

System 1: Line 1 = 950 ft Line 2 = 5,000 ft					**System 2: Line 1 = 950 ft Line 2 = 4,050 ft**			
Substation Voltage (V)	**Current (A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**KW**	**KVAr**	**KW**	**kVAr**
122	411.69	219.62	631.38	217.47	42	136	60	193
118	419.98	215.36	635.42	213.16	42	135	60	193
114	433.82	208.63	642.54	206.36	42	134	60	192

TABLE 4.17

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.18$, $k_2 = 0.22$

System 1: Line 1 = 900 ft Line 2 = 5,000 ft					**System 2: Line 1 = 900 ft Line 2 = 4,100 ft**			
Substation Voltage (V)	**Current (A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**KW**	**KVAr**	**KW**	**KVAr**
122	411.47	219.62	631.14	217.58	42	133	58	187
118	419.75	215.36	635.18	213.28	41	132	58	186
114	433.56	208.63	642.27	206.48	41	131	58	185

TABLE 4.18

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.17$, $k_2 = 0.2$

System 1: Line 1 = 850 ft Line 2 = 5,000 ft					System 2: Line 1 = 850 ft Line 2 = 4,150 ft			
Substation Voltage (V)	**Current (A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**KW**	**KVAr**	**KW**	**kVAr**
122	411.26	219.62	630.93	217.71	41	131	57	181
118	419.52	215.36	634.94	213.40	40	129	56	180
114	433.31	208.63	642.01	206.61	40	128	56	179

TABLE 4.19

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.1$, $k_2 = 0.117$

System 1: Line 1 = 500 ft Line 2 = 5,000 ft					System 2: Line 1 = 500 ft Line 2 = 4,250 ft			
Substation Voltage (V)	**Current (A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**KW**	**KVAr**	**KW**	**KVAr**
122	409.77	219.62	629.36	218.51	34	110	44	140
118	417.94	215.36	633.28	214.23	34	108	43	138
114	434.31	207.35	640.19	207.46	33	105	42	135

TABLE 4.20

VARIATION IN CURRENT AND LINE LOSS WHEN $k_1 = 0.02$, $k_2 = 0.0204$

System 1: Line 1 = 100 ft Line 2 = 5,000 ft					System 2: Line 1 = 100 ft Line 2 = 4,900 ft			
Substation Voltage (V)	**Current (A)**				**Line Loss**			
	System 1		**System 2**		**System 1**		**System 2**	
	Line 1	**Line 2**	**Line 1**	**Line 2**	**KW**	**KVAr**	**KW**	**KVAr**
122	408.12	219.62	627.62	219.40	27	87	29	93
118	416.19	215.36	631.44	215.14	26	85	28	90
114	432.34	207.34	639.57	207.11	25	79	27	85

Note that when $k_1 \leq 0.18$ or $k_2 \leq 0.2$, line loss starts decreasing as voltage decreases for both systems where constant power load is dominant.

In a distribution system, loads are normally located within a distance with respect to a voltage regulator where the possibility of occurrence of the condition in equations (4.11) or (4.15) for a system with a dominant constant power load is low, and the condition in equations (4.9) or (4.14) for a system with a dominant constant impedance load is low. So, for line-loss analysis in a voltage-reduction program, Table 4.2 can be used as a guideline in a distribution system.

4.4 Practical Determination of Load Type

In section 4.1, it was found that if voltage is reduced, the line current decreases for a system with a dominant constant impedance load and increases for a system with a dominant constant power load. For a system with a dominant constant current load, an increase or decrease in current depends on the relative percentages of constant power and constant impedance load. These properties of increasing or decreasing current at reduced voltage can be used to determine the dominant load type of a system, a segment in a system, or an individual load. For example, for the IEEE 13-bus system, shown in Figure 4.3, to determine the dominant load type of the entire system, observe the variation of current with voltage in line 650-632, which is connected directly to the substation.

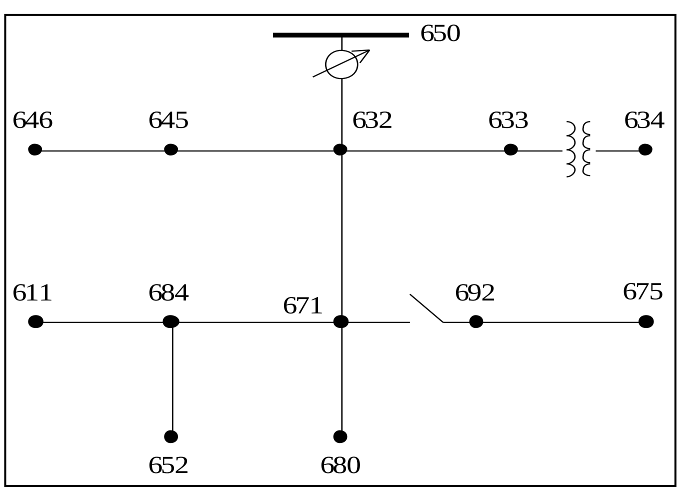


Figure 4.3: IEEE-13 bus System

Segment 1: all lines beyond node 632 toward node 645

Segment 2: all lines beyond node 632 toward node 633

Segment 3: all lines beyond node 632 toward node 671

Segment 4: all lines beyond node 671 toward node 684

Segment 5: all lines beyond node 671 toward node 692

To determine the dominant load type of the segment consisting of lines 632-645 and 645-646, observe the current in line 632-645. When the voltage reduction technique is applied to determine the dominant load type of a system or segment, capacitors should be switched off, because capacitors are constant impedance and will be seen as such as voltage is reduced. Tables 4.21 to 4.26 show the segment-wise load type determined using this technique. To show the impact of capacitors on determining the load type in this method, both systems—one with capacitors and one without capacitors—are considered. In the given IEEE 13-bus system, two shunt capacitors (one at node 675 and another at node 611) are connected.

TABLE 4.21

DETERMINATION OF LOAD TYPE FOR ENTIRE SYSTEM

Voltage (V)	Current Line 650-632 With Capacitor			Current Line 650-632 Without Capacitor			Dominant Load Type for Entire System
	Ph a	Ph b	Ph c	Ph a	Ph b	Ph c	
122	599.6	456.4	650.8	556.3	416.2	586.7	Constant P,Q (Ph a) Constant P,Q (Ph b) Constant P,Q (Ph c)
121	599.6	456.4	650.8	559.9	418.7	590.2	
120	602.9	458.9	654.1	563.4	421.3	593.8	
119	606.2	461.5	657.3	567.4	425.7	597.6	
118	610.1	465.8	660.9	571.1	428.3	601.2	

TABLE 4.22

DETERMINATION OF LOAD TYPE FOR SEGMENT 1

Voltage (V)	**Current Line 632-645**						**Dominant Load Type Segment 1**
	Without Capacitor			**With Capacitor**			
	Ph a	**Ph b**	**Ph c**	**Ph a**	**Ph b**	**Ph c**	
122	-	143.55	64.67	-	143.41	65.10	- (ph a) Constant P,Q (Ph b) Constant Z (Ph c)
121	-	143.55	64.67	-	143.55	64.64	
120	-	143.71	64.21	-	143.71	64.19	
119	-	143.87	63.76	-	144.21	63.51	
118	-	144.38	63.09	-	144.38	63.07	

TABLE 4.23

DETERMINATION OF LOAD TYPE FOR SEGMENT 2

Voltage (V)	**Current Line 632-633**						**Dominant Load Type Segment 2**
	Without Capacitor			**With Capacitor**			
	Ph a	**Ph b**	**Ph c**	**Ph a**	**Ph b**	**Ph c**	
122	81.27	61.92	63.08	80.67	61.50	62.63	Constant P,Q (Ph a) Constant P,Q (Ph b) Constant P,Q (Ph c)
121	81.27	61.92	63.08	81.29	61.94	63.11	
120	81.89	62.36	63.57	81.90	62.38	63.60	
119	82.51	62.81	64.06	82.52	63.28	64.08	
118	83.14	63.71	64.54	83.14	63.72	64.57	

TABLE 4.24

DETERMINATION OF LOAD TYPE FOR SEGMENT 3

Voltage (V)	**Current Line 632-671**						**Dominant Load Type Segment 3**
	Without Capacitor			**With Capacitor**			
	Ph a	**Ph b**	**Ph c**	**Ph a**	**Ph b**	**Ph c**	
122	518.3	253.6	530.5	476.8	215.5	475.6	Constant P,Q (Ph a) Constant P,Q (Ph b) Constant P,Q (Ph c)
121	518.3	253.6	530.5	479.8	217.4	478.9	
120	521.1	255.5	533.9	482.7	219.3	482.2	
119	523.8	257.4	536.9	486.1	222.1	485.9	
118	526.9	260.2	540.5	489.1	224.0	489.2	

TABLE 4.25

DETERMINATION OF LOAD TYPE FOR SEGMENT 4

Voltage (V)	Current Line 671-684 Without Capacitor Ph a	Ph b	Ph c	With Capacitor Ph a	Ph b	Ph c	Dominant Load Type Segment 4
122	62.72	-	78.23	63.62	-	71.16	Constant Z (Ph a) - (Ph b) Constant I (Ph c) (without capacitor) Constant Z (Ph c) (with capacitor)
121	62.72	-	78.23	63.14	-	71.13	
120	62.24	-	78.23	62.66	-	71.09	
119	61.78	-	78.23	62.20	-	71.07	
118	61.31	-	78.23	61.73	-	71.04	

TABLE 4.26

DETERMINATION OF LOAD TYPE FOR SEGMENT 5

Voltage (V)	Current Line 671-692 Without Capacitor Ph a	Ph b	Ph c	With Capacitor Ph a	Ph b	Ph c	Dominant Load Type Segment 5
122	261.22	36.65	208.21	227.05	68.71	178.42	Constant P,Q (ph a) Constant P.Q (ph b) Constant P,Q (ph c)
121	261.23	36.65	208.22	228.88	68.09	179.61	
120	262.94	36.91	209.52	230.72	67.47	180.80	
119	264.64	37.16	210.81	232.54	66.25	182.00	
118	266.38	37.68	212.11	234.40	65.66	183.22	

Table 4.25 shows that, when the capacitor is turned off at node 611, the phase c current in line 671-684 is constant at a reduced voltage, because of the constant current load at node 611 in phase c. If the capacitor is turned on at node 611, then the phase c current in line 671-684 decreases at a reduced voltage, even though a constant current load is connected at node 611 in phase c. This is because the capacitor is a constant impedance load, and therefore, the constant current load’s constant current property cannot be detected if the capacitor is on when the voltage reduction method is applied to determine the type of load. Therefore, when the voltage reduction method is employed to determine load type, capacitors should be turned off.

In a large distribution system, it can be seen that different segments of the system have different dominant load types. Therefore, the general practice of reducing voltage at the substation regulator, for power-loss reduction cannot be an optimal application of the voltage-reduction program. Instead of reducing voltage from the substation regulator, voltage should be reduced at those segments where the constant impedance load is dominant. For segments that have a dominant constant power load, voltage can be raised to reduce line loss. Therefore, the method discussed above to determine the dominant load type of a segment can be used to determine the location of voltage regulators, the decrease or increase in voltage at the corresponding voltage regulator as well for line-loss reduction.

4.5 Conclusion

In a demand reduction or energy conservation program through voltage reduction, line loss should be considered, because of its effect on utility revenue. This chapter explained how line loss varies with voltage reduction. First, a general model of line loss was developed for different types of loads, considering only line current. Here, line loss will increase for the system with dominant constant power load and decrease for the system with constant impedance load. For the system with dominant constant current load, line loss will increase, if the percentage of constant power load is greater than the percentage of constant impedance load, or decrease, if the percentage of constant impedance load is greater than the percentage of constant power load. This analysis is verified with test results from the IEEE 13-bus system. A technique was also demonstrated using the model to determine the dominant load type in a system or part of a system. Exceptions to the general model were shown in cases where resistance of some lines is significantly higher than others. Line resistance is determined by conductor type, line length, and load placement.

CHAPTER 5

IMPORTANCE OF VOLTAGE REDUCTION AND OPTIMAL VOLTAGE SETTING DURING REACTIVE POWER COMPENSATION

After reactive power compensation, voltage-dependent loads, such as constant impedance and constant current loads, consume more power because of the increase in node voltage; therefore, customers pay more for their electricity while utilities experience savings from line-loss reduction. Here, a voltage-reduction strategy plays an important role in reducing total energy consumption during reactive power compensation. This chapter presents a rationale for the necessity of reducing voltage during reactive power compensation and determining the optimal voltage setting at the substation regulator.

A voltage-reduction program is usually used to reduce the peak load demand during normal daily operation. Voltage reduction also plays an important role in mitigating insufficient generation or transmission capacity during emergencies. Electric utilities typically employ three types of voltage-reduction programs [6]: conservation voltage reduction, emergency voltage reduction, and routine voltage reduction [6, 7]. In addition to these programs, reducing voltage should also be considered during reactive power compensation so that customers with voltage-dependent loads do not consume and thus pay more for electricity.

5.1 Impact of Load Model on Power Consumption during Reactive Power Compensation

When shunt capacitors are connected to a distribution line to compensate reactive power, current flowing through the line is reduced, and as a result, the line voltage drop (ZI) decreases, resulting in an increase in node voltage ($V_1\uparrow = V_0 - Z*I\downarrow$). Since the node voltage increases, voltage-dependent loads, such as constant current and constant impedance loads, consume more power after the reactive power compensation. The percent change in power consumption depends on the type of load model. Among the three static load models discussed in Chapter 1, constant impedance loads will increase the most, due to a voltage rise after reactive power compensation, because its power consumption is directly proportional to the voltage squared. Therefore, customers who have a significant number of constant impedance loads will consume more energy and thus pay more for their electricity. A comparison of the increment in power consumption after reactive power compensation is given as

$$\Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{P}} < \Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{C}} < \Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{Z}} \tag{5.1}$$

where $\Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{P}}$ is the increment in power consumption at increased voltage after reactive power compensation when the constant power load is dominant, $\Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{C}}$ is the increment in power consumption when the constant current load is dominant, and $\Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{Z}}$ is the increment in power consumption when the constant impedance load is dominant in the composite load model, given the same amount of initial load in each system.

5.2 Optimal Voltage Setting during Reactive Power Compensation

As mentioned previously, the voltage rise after reactive power compensation causes voltage-dependent loads to consume more power, and consequently, customers will pay more for their electricity, while utilities will have a savings due to line-loss reduction. There should be a trade-off between the utility's savings and the customers' additional costs. This can be achieved by simultaneously lowering the voltage (changing the voltage set point of the substation transformer load tap changer (LTC) [34]) to reduce the energy consumption by voltage-sensitive loads when capacitors are placed along the feeder line. In this chapter, it is shown that if voltage at the substation is lowered to the minimum permissible level during reactive power compensation, then the load demand decreases and customers pay less for their electricity. However, the utility's savings will be reduced with respect to the case of reactive power compensation without a voltage-reduction program because of the increase in line loss at the minimum permissible voltage at the substation for a system where a constant power load is dominant. That triggers the finding of the optimal voltage set point at the substation voltage regulator during reactive power compensation. Here it needs to be mentioned that the technique for the optimal voltage set point during reactive power compensation depends on the characteristic of a system's line loss at reduced voltage. In the analysis of impact of load type on line loss in Chapter 4, it was found that at reduced voltage, line loss increases for the system with a dominant constant power load and decreases for the system with a dominant constant impedance load. For the system with a dominant constant current load, line loss will increase if the percentage of constant power load is greater than the percentage of constant impedance load, or decrease if the percentage of constant impedance load is greater than the percentage of constant power load.

5.2.1 Optimal Voltage Set Point for System with Dominant Constant Power Load

Now, for a system with a dominant constant power load, the optimal voltage at the substation would be that voltage during reactive power compensation where the energy consumption of customer loads lies between the energy they consume at the minimum permissible voltage at the substation during reactive power compensation and the energy they consume before reactive power compensation. At the same time, line loss lies between the loss during reactive power compensation without the voltage-reduction program and the loss at minimum permissible voltage at the substation during reactive power compensation.

Within these constraints, the optimal voltage at the substation during reactive power compensation can be defined as the voltage where the utility has maximum savings due to line-loss reduction without any increase in total energy consumption with respect to the base case (the case before reactive power compensation).

The objective of the optimal voltage setting is to maximize the dollar savings due to line-loss reduction from reactive power compensation with a voltage-reduction program for energy conservation. The objective function for the system with a dominant constant power load is defined as

$$\max \sum_{i=1}^{m} K_e \left(T_i P_{iLoss(base)} - T_i P_{iLoss(comp+vol\_reduc)} \right) \tag{5.2}$$

subject to the inequality constraints,

$$\sum_i T_i P_{iLoss(comp)} \le \sum_i T_i P_{iLoss(comp+vol\_reduc)} \le \sum_i T_i P_{iLoss(comp+\max vol\_reduc)} \tag{5.3}$$

$$\sum_i T_i P_{iLoad(comp+\max vol\_reduc)} \le \sum_i T_i P_{iLoad(comp+vol\_reduc)} \le \sum_i T_i P_{iLoad(base)} \tag{5.4}$$

where K_e is the energy loss cost constant ($50/MWh [24, 29]), $P_{iLoss(base)}$ is line loss at the base case at load level i for time period T_i, $P_{iLoss(comp+vol\_reduc)}$ is line loss after reactive power compensation with voltage reduction at load level *i* for time period T_i, $P_{iLoss(comp)}$ is line loss after reactive power compensation without voltage reduction at load level *i*, $P_{iLoss(comp+\max vol\_reduc)}$ is line loss after reactive power compensation with maximum permissible voltage reduction at load level *i*, $P_{iLoad(comp+\max vol\_reduc)}$ is load after reactive power compensation with maximum permissible voltage reduction at load level *i*, $P_{iLoad(comp+vol\_reduc)}$ is load after reactive power compensation with voltage reduction at load level *i*, and $P_{iLoad(base)}$ is load at the base case at load level *i* for the time period T_i.

5.2.2 Optimal Voltage Set Point for System with Dominant Constant Impedance Load

Since line loss decreases at a reduced voltage for the system with a dominant constant impedance load, the optimal voltage set point technique for this system would be different than for the system with a dominant constant power load. Here, the optimal voltage set point at the substation regulator for the system with a dominant constant impedance load would be the minimum permissible voltage, where the system's minimum voltage is at the lower range of ANSI or CAN standard acceptable levels (0.95 pu). The objective function can be defined as

$$\sum_{i=1}^{m} K_e \left(T_i P_{iLoss(base)} - T_i P_{iLoss(comp+\max vol\_reduc)} \right) \tag{5.5}$$

subject to the equality constraint

$$V_i = V_{\min} \tag{5.6}$$

where V_i is the system voltage at load level *i*, and $V_{\min}$ is the minimum permissible voltage (0.95 pu).

5.2.3 Optimal Voltage Set Point for System with Dominant Constant Current Load

For a system with a dominant constant current load, whether the line loss will increase or decrease at a reduced voltage depends on the percentages of the constant power load and constant impedance load connected to the system. Therefore, the technique for determining the optimal voltage set point for the system with a dominant constant current load will follow either one of the methods derived above, depending on the percentages of constant power and constant impedance load.

5.2.3 Test Results for IEEE 13-Bus System

In this unbalanced system, a constant power load is dominant. Two different capacitor prices and four test cases are considered, because they affect optimization in the capacitor placement problem in a reactive power compensation program for line-loss reduction, as shown in Chapter 3. Again, the four test cases are as follows:

Case 1: Continuous capacitor sizes and phase kVAr of the capacitor are in the ratio of phase-reactive power flows into the node where the capacitor is connected.

Case 2: Continuous capacitor sizes and phase kVAr of the capacitor are equal.

Case 3: Discrete capacitor sizes and phase kVAr of the capacitor are in the ratio of phase reactive power flows into the node where the capacitor is connected.

Case 4: Discrete capacitor sizes and phase kVAr of the capacitor are equal.

The available three-phase capacitor sizes are considered discrete sizes. Since, the system is unbalanced, phase kVArs of the capacitor are considered in the ratio of phase-reactive power flows into the node. Two capacitor prices, \$1.25/kVAr and \$2.00/kVAr, and two different temperatures, 25^0C and 50^0C, are considered to show the changes in the optimal voltage set points and corresponding line loss, energy consumption, utility savings, and customer electricity bills. Three load levels in a one-year time period are considered. Load duration data for testing the IEEE 13-bus system are shown in Table 5.1. Test results are shown in Tables 5.2 to 5.5, where,

a = after compensation

b = after compensation + minimum permissible voltage at substation

c = after compensation + optimal voltage at substation.

TABLE 5.1

LOAD DURATION DATA

Load Level (Pu)	0.6	0.8	1
Duration (hours)	2760	3500	2500

TABLE 5.2

CAPACITOR PRICE: \$1.25/kVAr, TEMPERATURE: 25^0C

IEEE 13-Bus System		Substation Voltage (V) Load Level 1 pu	0.8 pu	0.6 pu	Line Loss (MWh/year)	Reduction in Line Loss (MWh/year)	Load (MWh/year)	Increment (inc)/ Decrement (dec) in Load (MWh/year)	Utility Savings (\$/year)	Customer Incremental (inc)/ Decremental (dec) Cost (\$/year)
Base Case		122	122	122	681.92		24086.06			
Case 1	a	122	122	122	502.08	179.84	24232.64	146.58 (inc)	6885.75	11594.48 (inc)
	b	118	117.5	117	534.10	147.82	23953.14	133.46 (dec)	5284.75	10513.97 (dec)
	c	119.1	119.6	120	518.34	163.58	24085.04	1.02 (dec)	6072.75	80.68 (dec)
Case 2	a	122	122	122	527.84	154.08	24170.38	84.32 (inc)	5597.75	6669.71 (inc)
	b	119	118.3	117.5	551.36	130.56	23972.40	113.66 (dec)	4421.75	8990.51 (dec)
	c	120.2	120	120	536.60	145.32	24079.02	7.04 (dec)	5159.75	556.86 (dec)
Case 3	a	122	122	122	495.82	186.10	24250.16	164.10 (inc)	7055	12980.31 (inc)
	b	118	117.5	117	525.34	156.58	23962.38	123.68 (dec)	5579	9783.09 (dec)
	c	119	119.7	120	513.08	168.84	24075.54	10.52 (dec)	6192	832.13 (dec)
Case 4	a	122	122	122	525.08	156.84	24178.14	92.08 (inc)	5592	7283.53 (inc)
	b	119	118	117	551.36	130.56	23949.12	136.94 (dec)	4278	10831.95 (dec)
	c	120.5	119.5	120	533.84	148.08	24075.54	10.52 (dec)	5154	832.13 (dec)

TABLE 5.3

CAPACITOR PRICE: \$2.00/kVAr, TEMPERATURE: 25^0C

IEEE 13-Bus System		Substation Voltage (V) Load Level 1 pu	0.8 pu	0.6 pu	Line Loss (MWh/year)	Reduction in Line Loss (MWh/year)	Load (MWh/year)	Increment (inc)/ Decrement (dec) in Load (MWh/year)	Utility Savings (\$/year)	Customer Incremental (inc)/ Decremental (dec) Cost (\$/year)
Base Case		122	122	122	6819.20		24086.06			
Case 1	a	122.0	122.0	122.0	524.86	157.06	24229.62	143.56 (inc)	4983	11355.60 (inc)
	b	118	117	117.5	556.88	125.04	23956.40	129.66 (dec)	3382	10256.11 (dec)
	c	119	119.5	120.5	544.62	137.30	24080.06	6.00 (dec)	3995	474.60 (dec)
Case 2	a	122	122	122	555.88	126.04	24164.60	78.54 (inc)	3432	6212.51 (inc)
	b	119	118	118	574.14	107.78	23972.42	113.64 (dec)	2519	8988.92 (dec)
	c	120	119.5	120.5	565.38	116.54	24064.80	21.26 (dec)	2957	1681.66 (dec)
Case 3	a	122	122	122	524.12	157.80	24232.36	146.30 (inc)	4890	11572.33 (inc)
	b	118	117.5	117.5	556.14	125.78	23960.90	125.16 (dec)	3289	9900.15 (dec)
	c	119	119.5	120	538.62	143.30	24081.02	5.04 (dec)	4165	398.66 (dec)
Case 4	a	122	122	122	549.88	132.04	24191.10	105.04(inc)	3602	8308.66 (inc)
	b	119	118.5	118	573.40	108.52	23981.66	104.40 (dec)	2426	8258.04 (dec)
	c	120	120.5	120	558.38	123.54	24084.78	1.28 (dec)	3177	101.25 (dec)

TABLE 5.4

CAPACITOR PRICE: \$1.25/kVAr, TEMPERATURE: 50^0C

IEEE 13-Bus System		Substation Voltage (V) Load Level 1pu	0.8 pu	0.6 pu	Line Loss (MWh/year)	Reduction in Line Loss (MWh/year)	Load (MWh/year)	Increment (inc)/ Decrement (dec) in Load (MWh/year)	Utility Savings (\$/year)	Customers' Incremental (inc)/ Decremental (dec) Cost (\$/year)
Base Case		122	122	122	759.72		24066			
Case 1	a	122	122	122	556.36	203.36	24218.1	152.1 (inc)	8062	12031.10 (inc)
	b	119	118	117	588.64	171.08	23971.6	94.4 (dec)	6448	7468.62 (dec)
	c	119	120	120	583.12	176.60	24057.0	9.0 (dec)	7074	711.90 (dec)
Case 2	a	122	122	122	590.88	168.84	24147.9	81.9 (inc)	6336	6471.96 (inc)
	b	120	119	118	608.40	151.32	23987.4	78.6 (dec)	5460	6220.42 (dec)
	c	120.3	120	120	599.64	160.08	24059.3	6.7 (dec)	5898	536.29 (dec)
Case 3	a	122	122	122	553.60	206.12	24227.6	161.6 (inc)	8056	12782.60 (inc)
	b	119	118	118	579.62	180.10	23989.7	76.3 (dec)	6755	6040.08 (dec)
	c	119.3	119.5	120	570.86	188.86	24062.3	3.7 (dec)	7193	297.42 (dec)
Case 4	a	122	122	122	582.12	177.60	24157.4	91.4 (inc)	6630	7224.99 (inc)
	b	120	119	118	599.64	160.08	23997.2	68.8 (dec)	5754	5448.41 (dec)
	c	120	120.3	120	593.38	166.34	24055.5	10.5 (dec)	6067	832.13 (dec)

TABLE 5.5

CAPACITOR PRICE: \$2.00/kVAr, TEMPERATURE: 50^0C

IEEE 13-Bus System		Substation Voltage (V) Load Level 1 pu	0.8 pu	0.6 pu	Line Loss (MWh/year)	Reduction in Line Loss (MWh/year)	Load (MWh/year)	Increment (inc)/ Decrement (dec) in Load (MWh/year)	Utility Savings (\$/year)	Customer Incremental (inc)/ Decremental (dec) Cost (\$/year)
Base Case		122	122	122	759.72		24066			
Case 1	a	122	122	122	581.90	177.82	24204.30	138.30 (inc)	6021	10939.50 (inc)
	b	118	118	118	616.42	143.30	23964.90	101.10 (dec)	4295	7998.59 (dec)
	c	119	119.7	120	601.66	158.06	24056.26	9.74 (dec)	5033	773.59 (dec)
Case 2	a	122	122	122	616.42	143.30	24142.10	76.10 (inc)	4295	6014.76 (inc)
	b	120	118	118	637.44	122.28	23974.90	91.10 (dec)	3244	7209.17 (dec)
	c	120	120	120.5	624.92	134.80	24052.78	13.22 (dec)	3870	1048.86 (dec)
Case 3	a	122	122	122	581.16	178.56	24212.30	146.30 (inc)	5928	11572.30 (inc)
	b	119	118	118	610.68	149.04	23991.70	74.30 (dec)	4452	5883.46 (dec)
	c	119.5	119.3	120	599.16	160.56	24063.26	2.74 (dec)	5028	219.89 (dec)
Case 4	a	122	122	122	612.92	146.80	24151.60	85.60 (inc)	4340	6766.21(inc)
	b	119	119	118	632.94	126.78	23982.90	83.10 (dec)	3339	6576.37(dec)
	c	120	119	120.5	624.92	134.80	24038.78	7.22 (dec)	3740	2156.26 (dec)

In Table 5.2, it can be seen that with respect to the base case, at 25^{0}C in Case 1 with a capacitor price of $1.25/kVAr, after reactive power compensation without voltage reduction, line loss is reduced by 179.84 MWh/year and energy consumption is increased by 146.58 MWh/year; consequently the utility saves $6,885.75/year for line-loss reduction, while customers pay $11,594.48/year more for increase in energy consumption. When voltage is lowered to the minimum permissible level at the substation during reactive power compensation, both line loss and energy consumption are reduced by 147.82 MWh/year and 133.46 MWh/year, respectively, with respect to base case. Consequently, the utility saves $5,284.75/year which is less than the savings ($6,885.75/year) in the previous case, because at the reduced voltage, line loss increases for the system with a dominant constant power load, and customers pay $10,513.97 less, due to the reduction in energy consumption at reduced voltage. Now, if voltages are set to the optimal level during reactive power compensation, reductions in line loss and energy consumption are 163.58 MWh/year and 1.02 MWh/year, respectively. In this case, the utility saves $6,072.75/year, which is greater than the savings ($5,284.75/year) in the case of reactive power compensation with minimum permissible voltage at the substation, and customers pay $80.68/year less with respect to the base case. By and large, when reactive power is compensated with simultaneously lowering the substation voltage at the optimal level, or minimum permissible level, both the utility and customers benefit, but in the case of reactive power compensation without a voltage-reduction program at the substation, only the utility benefits and customers pay more. By comparing Tables 5.2 to 5.5, it can be seen that, at a lower capacitor price and a higher temperature, reductions in line loss for reactive power compensation are greater, and consequently the dollar savings from line-loss reduction are greater at a lower capacitor price and higher ambient temperature. Due to the variation in ambient temperature and capacitor price, the optimal voltage set points also change.

5.3 Conclusion

The importance of voltage reduction and an optimal voltage setting at the substation during distribution reactive power compensation are presented in this chapter. A voltage-reduction program should be considered during reactive power compensation so that energy consumption by the voltage-dependent loads does not increase after reactive power compensation. Without a voltage-reduction program, a utility's savings is increased, but customers pay more for electricity due to the increase in energy consumption by voltage-dependent loads. With a voltage-reduction program and a minimum permissible voltage setting at the substation, during reactive power compensation, customers' energy savings are increased and the utility's savings from line-loss reduction are reduced. With a voltage-reduction program having an optimal voltage setting at the substation, during reactive power compensation, the utility's saving is optimized, and customers also benefit because energy consumption stays below the base case.

CHAPTER 6

STUDY OF JOINT EFFECT OF AMBIENT TEMPERATURE, PRICE, SIZE, AND PHASE KVAR OF CAPACITOR ON LINE LOSS, LOAD AND GENERATION

Previously in Chapter 5, several factors were considered to show the variation in line loss, load demand, and consequent variation in a utility's savings and customers' electric bills. Factorial designs are widely used in experiments involving several factors where it is necessary to study the joint effect of factors on a response [35]. This factorial design would be beneficial to engineers in order to understand what combination of factors to operate a system would offer the best response. Here in Chapter 6, the 2^4 factorial design was used to determine the joint effect of four factors—ambient temperature, capacitor price, capacitor size, and capacitor phase kVArs—on line loss, load, and generation. Each of these factors has two levels, "low" and "high," denoted by "–" and "+," respectively, as shown in Table 6.1.

TABLE 6.1

FACTORS AND THEIR LEVELS

Ambient Temperature	A	–	25^0C
		+	50^0C
Capacitor Price	B	–	$1.25/kVAr
		+	$2.00/kVAr
Capacitor Size	C	–	Continuous
		+	Discrete
Capacitor Phase kVAr	D	–	Capacitor phase kVArs are in ratio of reactive power flow into line
		+	Capacitor Phase kVArs are evenly distributed

The effect of these factors on line loss, load, and generation are considered for three cases: (a) line loss, load, and generation after reactive power compensation; (b) line loss, load, and generation after reactive power compensation with minimum permissible voltage at substation; and (c) line loss, load, and generation after reactive power compensation with optimal voltage at the substation.

6.1 2^4 Factorial Design for Line Loss, Load, and Generation after Reactive Power Compensation

Table 6.2 shows line loss, load, and generation after reactive power compensation for 16 different combinations of four factors, where each factor has two levels.

TABLE 6.2

LINE LOSS, LOAD, AND GENERATION AFTER REACTIVE POWER COMPENSATION

Temperature	**Capacitor Price**	**Capacitor Size**	**Capacitor Phase kVAr**	**Line Loss (MWh)**	**Load (MWh)**	**Energy Generation (MWh)**	**Run Label**
A	B	C	D	Responses			
–	–	–	–	502.08	24232.64	24734.72	(1)
+	–	–	–	556.36	24218.10	24774.46	a
–	+	–	–	524.86	24229.62	24754.48	b
+	+	–	–	581.90	24204.30	24786.2	ab
–	–	+	–	495.82	24250.16	24745.98	c
+	–	+	–	553.60	24227.60	24781.2	ac
–	+	+	–	524.12	24232.36	24756.48	bc
+	+	+	–	581.16	24212.30	24793.46	abc
–	–	–	+	527.84	24170.38	24698.22	d
+	–	–	+	590.88	24147.90	24738.78	ad
–	+	–	+	555.88	24164.60	24720.48	bd
+	+	–	+	616.42	24142.10	24758.52	abd
–	–	+	+	525.08	24178.14	24703.22	cd
+	–	+	+	582.12	24157.40	24739.52	acd
–	+	+	+	549.80	24191.10	24740.98	bcd
+	+	+	+	612.92	24151.60	24764.52	abcd

6.1.1 2^4 Factorial Design for Line Loss after Reactive Power Compensation

The software Design-Expert v8 [36] was used for statistical analysis of the line loss response. Results for factor effect estimates and sums of squares for 2^4 factorial design for line loss after reactive power compensation are presented in Table 6.3, and the reduced ANOVA is shown in Table 6.4. The important effects from this analysis are the main effects of A, B, and D, where A, ambient temperature, has the most significant effect on line loss, contributing 67.66%. Factor C, capacitor size, does not have a significant effect on line loss.

TABLE 6.3

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN FOR LINE LOSS AFTER REACTIVE POWER COMPENSATION

Factors	**Effect Estimate**	**Sum of Squares**	**% Contribution**
A-Temperature	58.73	13794.50	67.6653
B-Capacitor Price	26.67	2845.16	13.9562
C-Capacitor Size	–3.94	62.09	0.3046
D-Capacitor Phase kVAr	30.14	3633.68	17.8241
AB	0.69	1.90	0.0093
AC	0.00	0.00	0.0000
AD	2.19	19.18	0.0941
BC	1.19	5.71	0.0280
BD	0.62	1.56	0.0077
CD	–1.32	6.92	0.0339
ABC	0.63	1.56	0.0077
ABD	0.19	0.14	0.0007
ACD	–0.87	3.06	0.0150
BCD	–0.69	1.90	0.0093
ABCD	1.50	9.00	0.0442

TABLE 6.4

ANOVA FOR SELECTED FACTORIAL MODEL FOR LINE LOSS AFTER REACTIVE POWER COMPENSATION

Source	**Sum of Squares**	**df**	**Mean Squares**	**F Value**	**P-Value Prob > F**
Model	20335.43	4	5083.86	1097.67	< 0.0001
A-Temperature	*13794.50*	*1*	*13794.50*	*2978.40*	*<0.0001*
B-Capacitor Price	*2845.16*	*1*	*2845.16*	*614.30*	*< 0.0001*
C-Capacitor Size	*62.09*	*1*	*62.09*	*13.41*	*0.0037*
D-Capacitor Phase kVAr	*3633.68*	*1*	*3633.68*	*784.56*	*< 0.0001*
Residuals	50.95	11	4.63		
Cor Total	20386.38	15			

In reduced ANOVA, a model is selected in such a way that residuals, which are the differences between the observed and fitted values of line loss, lie between –3 MWh/year and +3 MWh/year. The fitted regression model for line loss is represented by equation (6.1) in terms of coded factors that assume the value of +1 (for high level) or –1 (for low level).

$$P_{Loss} = 555.06 + 29.36*A + 13.33*B - 1.97*C + 15.07*D \quad (6.1)$$

where A, B, C, and D are the coded variables (+1 or –1) representing ambient temperature, price, size, and phase kVAr of capacitor, respectively. The relationship between coded variables and actual variables is

$$A = \frac{T-(T_{low}+T_{high})/2}{(T_{high}-T_{low})/2}, \qquad B = \frac{C_p-(C_{low}+C_{high})/2}{(C_{high}-C_{low})/2}$$

where T and C_p are the actual values of ambient temperature and capacitor price, respectively; T_{low} and T_{high} represent low and high level of actual temperature, respectively; and C_{low} and C_{high} represent low and high levels of the actual capacitor price, respectively. In terms of actual factors, line loss can be given by equations (6.1.1) to (6.1.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Loss} = 396.1211 + 2.3488*T + 35.5457*C_p \quad (6.1.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Loss} = 392.1811 + 2.3488*T + 35.5457*C_p \quad (6.1.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Loss} = 426.2611 + 2.3488*T + 35.5457*C_p \quad (6.1.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Loss} = 422.3211 + 2.3488*T + 35.5457*C_p \quad (6.1.4)$$

Model Adequacy and Hypotheses Test

R^2 is a statistic that tells the adequacy of the multiple regression model, i.e., how the model fits the data. It can be used to make inferences about the statistical utility of models for predicting line loss, load, and energy generation.

$$R^2 = \frac{Model\ sum\ of\ squares}{Total\ sum\ of\ squares} = \frac{SS_{Model}}{SS_{Total}}$$

Hypothesis Test: For the linear model $P = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4$, the following would test the utility of the overall model:

H_0: $\beta_0 = \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$

H_a: At least one of the above β parameters is nonzero

The test statistic used to test this null hypothesis is

$$F = \frac{Mean\ square\ for\ model}{Mean\ square\ for\ error} = \frac{R^2/k}{(1-R^2)/[n-(k+1)]}$$

At a given significance level of α, the rejection region, shown in Figure 6.1, is $F > F_{\alpha,v_1,v_2}$, where k is the number of parameters in the model (not including β_0), n is the number of data, $v_1 = k$, and $v_2 = [n-(k+1)]$.

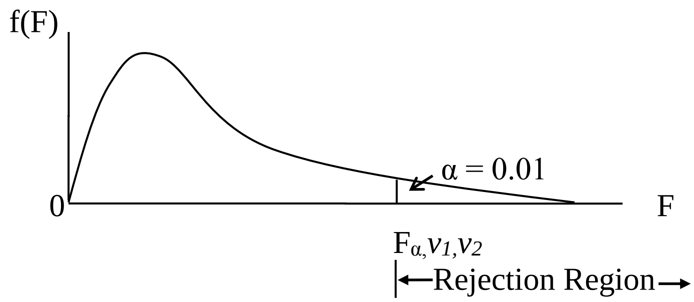


Figure 6.1: Rejection region for F statistic

Model Adequacy, Hypotheses Test, and Residuals for Line Loss after Reactive Power Compensation

For line loss, $R^2 = \frac{SS_{Model}}{SS_{Total}} = \frac{20335.43}{20386.38} = 0.9975$, which implies 99.75% variability in line loss can be explained by equation (6.1), where $F = \frac{0.9975/4}{(1-0.9975)/[16-(4+1)]} = 1097.25$ and $F_{\alpha,v_1,v_2} = F_{0.01,4,11} = 5.67$. Since $F > F_{\alpha,v_1,v_2}$, the null hypothesis H_0 can be rejected, and it can be concluded that at least one of the model coefficients in equation (6.1) is nonzero. Hence, this F test indicates that the multiple regression model represented by equation (6.1) can be used for predicting line loss after reactive power compensation. A normal probability plot of residuals is shown in Figure

6.2. The predicted versus actual plot for line loss is shown in Figure 6.3. Residuals versus factor effects are plotted in Figures 6.4 to 6.7.

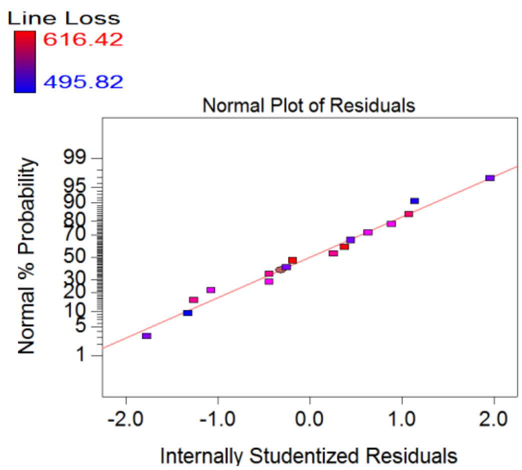


Figure 6.2: Normal probability plot of residuals for line loss after compensation

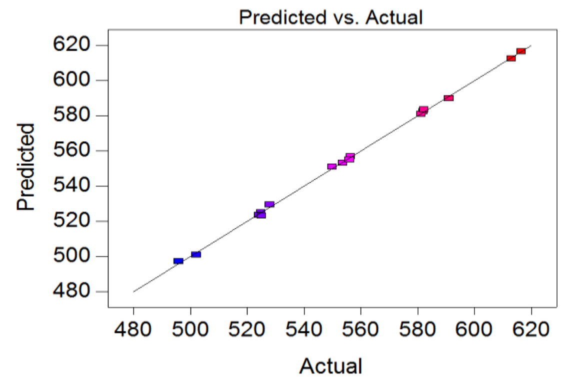


Figure 6.3: Predicted vs. actual plot for line loss after compensation

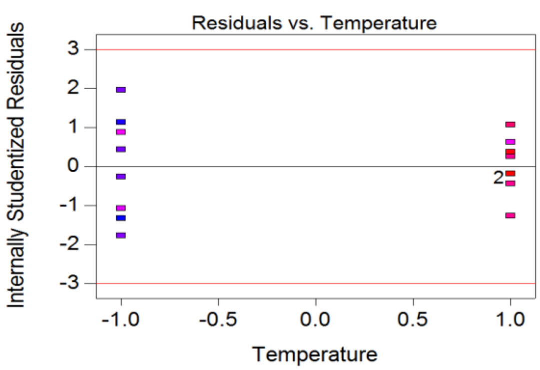


Figure 6.4: Residuals vs. temperature plot for line loss after compensation

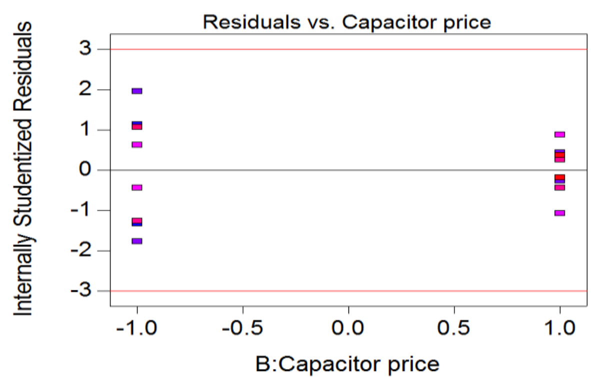


Figure 6.5: Residuals vs. capacitor price plot for line loss after compensation

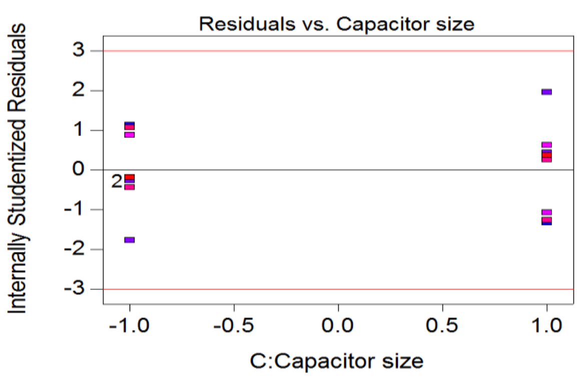


Figure 6.6: Residuals vs. capacitor size plot for line loss after compensation

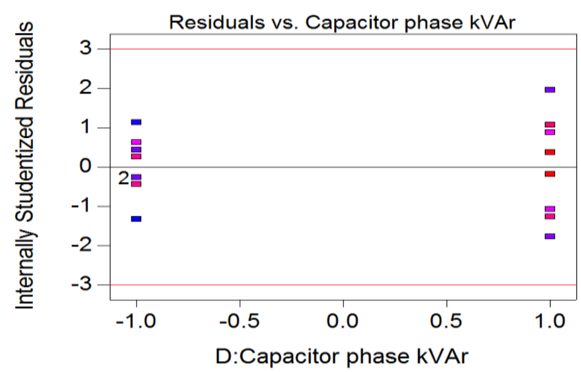


Figure 6.7: Residuals vs. capacitor phase kVAr plot for line loss after compensation

From the residuals versus temperature plot shown in Figure 6.4, it can be seen that at a higher level of temperature, the residuals of line loss after reactive power compensation are greater than the residuals at a lower level of temperature. The residuals versus capacitor size plot shown in Figure 6.6 indicates that residuals with discrete capacitor sizes are less than the residuals with continuous capacitor sizes. The half normal and normal probability of the factor effects are shown in Figures 6.8 and 6.9, respectively. As shown, the effects that lie along the line are negligible, where the larger effects are far from the line. The effects of A, B, C, and D are plotted in Figures 6.10 to 6.13.

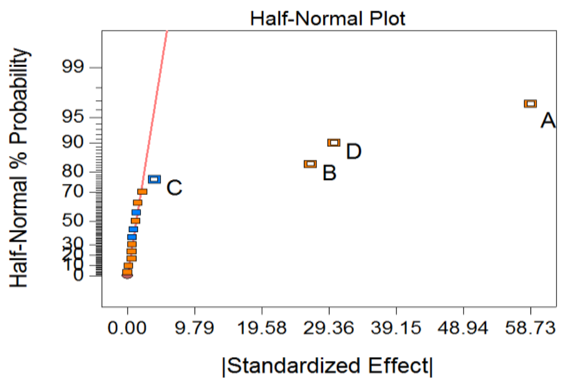


Figure 6.8: Half-normal plot of factor effects on line loss after reactive power compensation

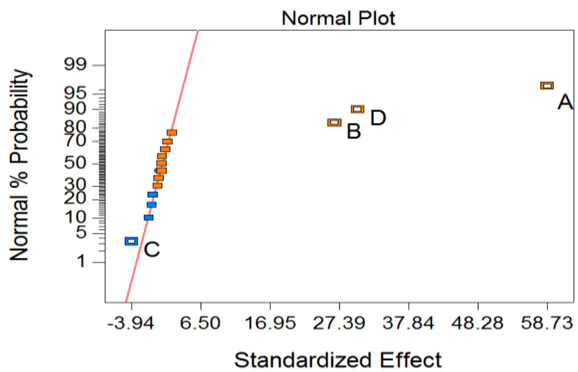


Figure 6.9: Normal plot of factor effects on line loss after reactive power compensation

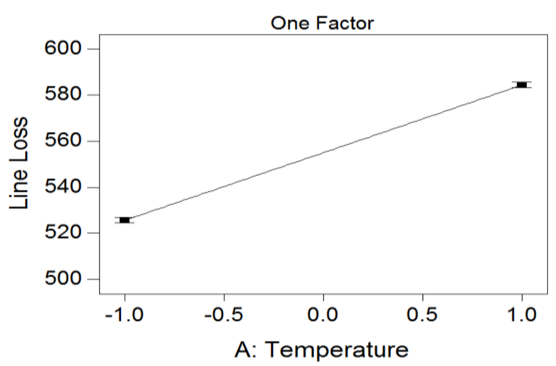


Figure 6.10: Line loss vs. temperature after reactive power compensation

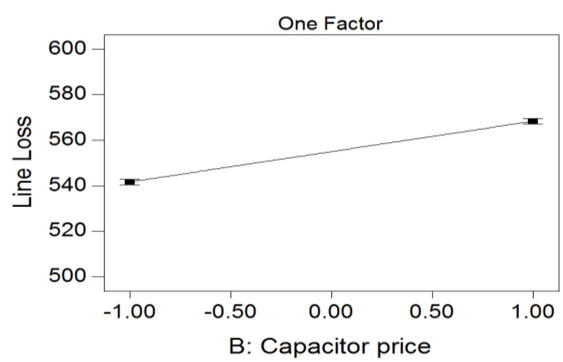


Figure 6.11: Line loss vs. capacitor price after reactive power compensation

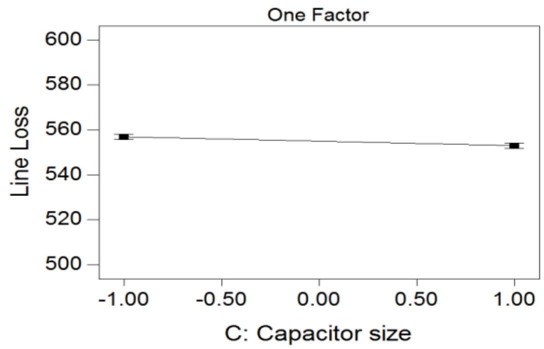


Figure 6.12: Line loss vs. capacitor size after reactive power compensation

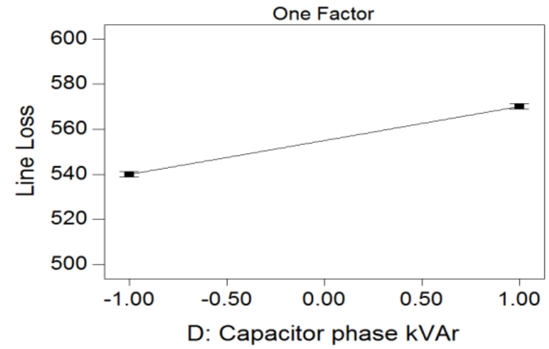


Figure 6.13: Line loss vs. capacitor phase kVAr after reactive power compensation

The interaction effects on line loss after reactive power compensation are not significant. Only the AD interaction effect, which is comparatively greater than the other five two-factor interaction effects is shown in Figure 6.14.

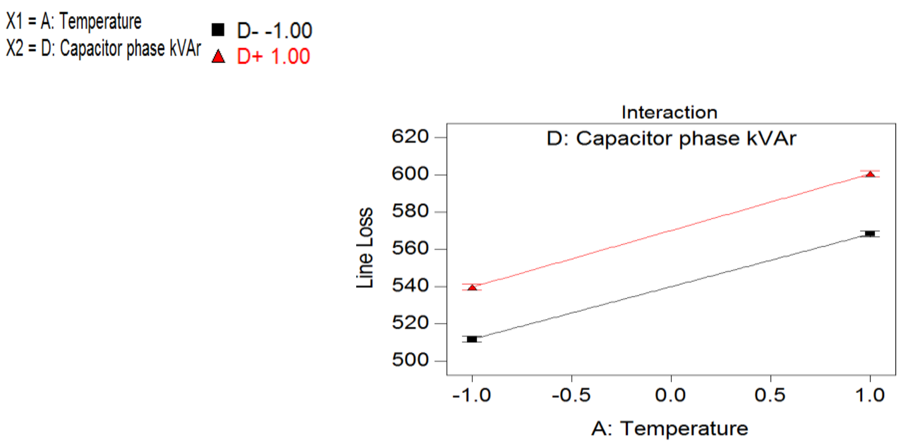
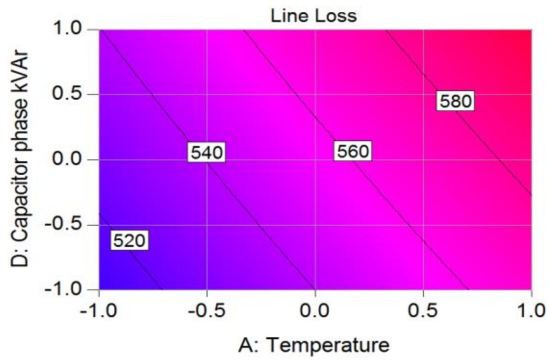


Figure 6.14: Line loss vs. temperature and capacitor phase kVAr after reactive power compensation

The red and blue lines shown in Figure 6.14 are approximately parallel, the contours shown in Figure 6.15 are straight lines, and the response surface shown in Figure 6.16 is not twisted, indicating a lack of interaction between temperature and capacitor phase kVAr; i.e., irrespective of temperature, line loss for the system with evenly distributed capacitor phase kVArs is more than line loss for the system where capacitor phase kVArs are in the ratio of reactive power flow through the line.



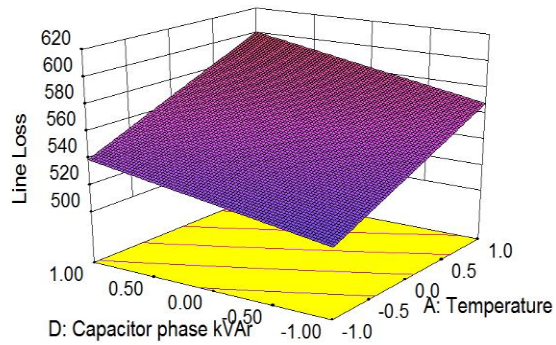


Figure 6.15: Contour plot of temperature vs. capacitor phase kVAr for line loss after reactive power compensation

Figure 6.16: Response surface for line loss vs. temperature vs. capacitor phase kVAr after reactive power compensation

Cube Plots of Line Loss after Reactive Power Compensation

In Figure 6.17, it can be seen that with three variables—temperature, capacitor price, and capacitor size—line loss is minimized (510.137 MWh/year) at a lower temperature, lower capacitor price, and discrete capacitor size. Figure 6.18 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—line loss is minimized (499.043 MWh/year) at a lower temperature, lower capacitor price, and when capacitor phase kVArs are in the ratio of reactive power flow through the line. In Figure 6.19, it can be seen that with three variables—temperature, capacitor size, and capacitor phase kVAr—line loss is minimized (510.408 MWh/year) at a lower temperature, discrete capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line. Figure 6.20 shows that with three variables—capacitor price, capacitor size, and capacitor phase kVAr—minimum line loss (525.055 MWh/year) occurs at a lower capacitor price, discrete capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line.

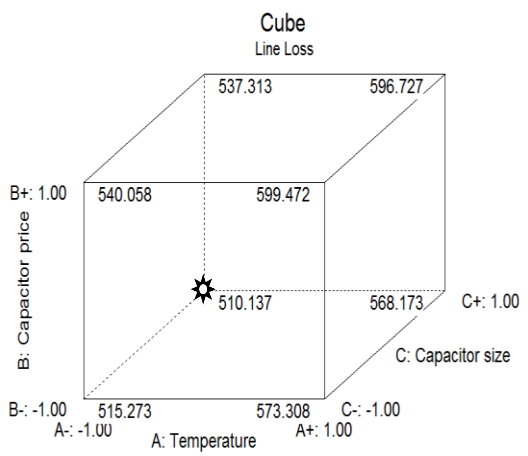


Figure 6.17: Cube plot of line loss vs. temperature, capacitor price, and capacitor size after reactive power compensation

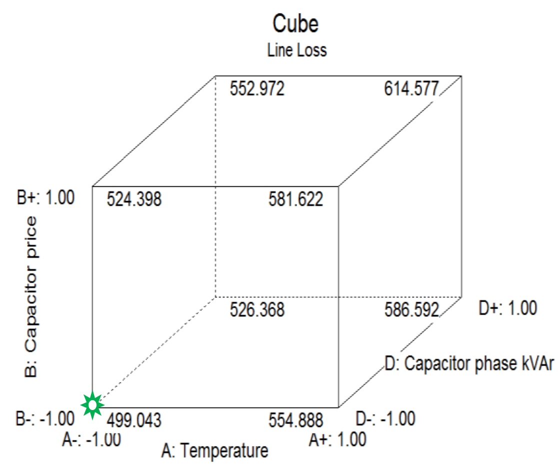


Figure 6.18: Cube plot of line loss vs. temperature, capacitor price, and capacitor phase kVAr after reactive power compensation

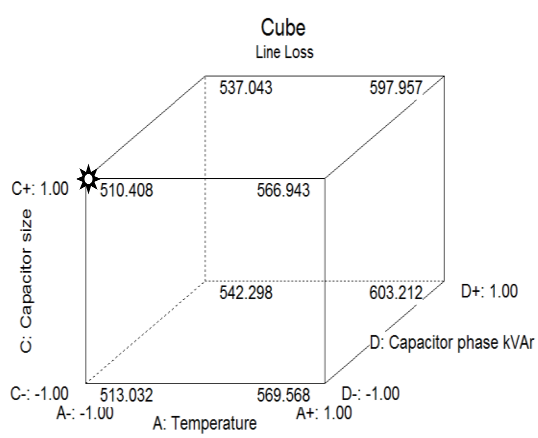


Figure 6.19: Cube plot of line loss vs. temperature, capacitor size, and capacitor phase kVAr after compensation

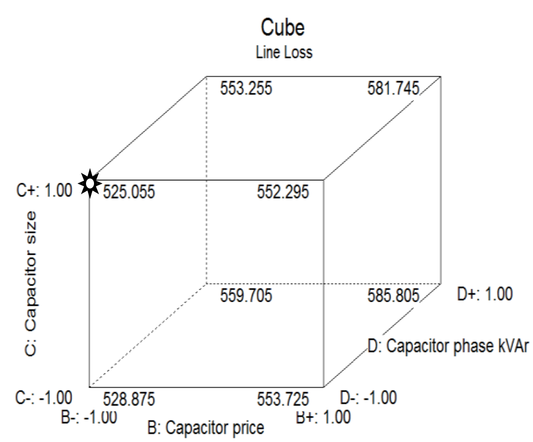


Figure 6.20: Cube plot of line loss vs. capacitor price, capacitor size, and capacitor phase kVAr after compensation

Factor level combinations that minimize line loss for three-factor combinations out of four factors are shown by black star marks in the cube plots. The minimum (499.043 MWh/year) of all minimum line losses (510.137 MWh/year, 499.043 MWh/year, 510.408 MWh/year, 525.055 MWh/year) occurs at a lower temperature, lower capacitor price, and when capacitor phase kVArs are in the ratio of reactive power flow through the line; this combination of factor levels is indicated by a green star in Figure 6.18.

6.1.2 2^4 Factorial Design for Load Demand after Reactive Power Compensation

The factor effect estimates, sums of squares, and percentage contribution are shown in Table 6.5. From this analysis, it can be seen that, among the four factors, Factor D, capacitor phase kVAr, has the greatest effect on load demand, and its contribution to variability in load demand is 82.75%. The effect of capacitor price on load demand is negligible. ANOVA for selected factorial model is shown in Table 6.6.

TABLE 6.5

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN ON LOAD DEMAND AFTER REACTIVE POWER COMPENSATION

Factor	Effect Estimate	Sum of Squares	% Contribution
A-Temperature	–23.46	2201.96	11.4841
B-Capacitor Price	–6.79	184.55	0.9625
C-Capacitor Size	11.38	517.79	2.7005
D-Capacitor Phase kVAr	–62.98	15867.20	82.7541
AB	–3.38	45.77	0.2386
AC	–2.25	20.30	0.1058
AD	–2.84	32.32	0.1685
BC	0.31	0.38	0.0019
BD	5.69	129.39	0.6748
CD	1.94	15.02	0.0783
ABC	– 0.68	1.86	0.0097
ABD	–1.31	6.89	0.0359
ACD	–1.56	9.77	0.0509
BCD	4.38	76.65	0.3998
ABCD	–4.00	64.08	0.3342

TABLE 6.6

ANOVA FOR SELECTED FACTORIAL MODEL FOR LOAD DEMAND AFTER REACTIVE POWER COMPENSATION

Source	Sum of Squares	df	Mean Squares	F Value	P-Value Prob > F
Model	19139.98	10	1914.00	282.19	< 0.0001
A-Temperature	*2201.96*	*1*	*221.96*	*324.64*	*< 0.0001*
B-Capacitor price	*184.55*	*1*	*184.55*	*27.21*	*0.0034*
C-Capacitor size	*517.79*	*1*	*517.79*	*76.34*	*0.0003*
D-Capacitor phase kVAr	*15867.18*	*1*	*15867.18*	*2339.37*	*< 0.0001*
AB	*45.77*	*1*	*45.77*	*6.75*	*0.0484*
AC	*20.30*	*1*	*20.30*	*2.99*	*0.1442*
AD	*32.32*	*1*	*32.32*	*4.76*	*0.0808*
BD	*129.39*	*1*	*129.39*	*19.08*	*0.0072*
BCD	*76.65*	*1*	*76.65*	*11.30*	*0.0201*
ABCD	*64.08*	*1*	*64.08*	*9.45*	*0.0277*
Residuals	33.91	5	6.78		
Cor Total	19173.89	15			

In reduced ANOVA, the model is selected in such a way that residuals lie between –3 MWh/year and +3 MWh/year. The regression model for load demand, in terms of coded factor, can be represented by equation (6.2).

$$P_{Load} = 24194.39 - 11.73*A - 3.4*B + 5.69*C - 31.49*D - 1.69*A*B - 1.13*A*C$$
$$-1.42*A*D + 2.84*B*D + 2.19*B*C*D - 2*A*B*C*D \quad (6.2)$$

In terms of actual factors, load demand can be given by equation (6.2.1) to (6.2.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Load} = 24217.3100 + 0.5448*T + 18.7200*C_p - 0.7872*T*C_p \quad (6.2.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Load} = 24306.4500 - 1.0226*T - 24.9599*C_p + 0.0661*T*C_p \quad (6.2.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Load} = 24209.2166 - 1.0691*T - 9.8133*C_p + 0.0661*T*C_p \quad (6.2.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Load} = 24156.3967 + 0.1368*T + 33.8667*C_p - 0.7872*T*C_p \qquad (6.2.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Load Demand after Reactive Power Compensation

For load demand, $R^2 = \frac{SS_{Model}}{SS_{Total}} = \frac{19139.38}{19173.89} = 0.9982$, which implies that 99.82% variability in load demand can be explained by equation (6.2), where F = 277.3, $F_{\alpha,v_1,v_2} = F_{0.01,10,5} = 5.67$. Since $F > F_{\alpha,v_1,v_2}$, H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.2) is nonzero. Hence, this F test indicates that the overall multiple regression model presented by equation (6.2) can be used for predicting load demand after reactive power compensation.

A normal probability plot of residuals is shown in Figure 6.21. The predicted versus actual plot for load demand is shown in Figure 6.22. Residuals versus factor effects are plotted in Figures 6.23 to 6.26. From the residuals versus temperature plot shown in Figure 6.23, it can be seen that at a lower level of temperature, residuals of load demand after reactive power compensation are greater than residuals at a higher level of temperature.

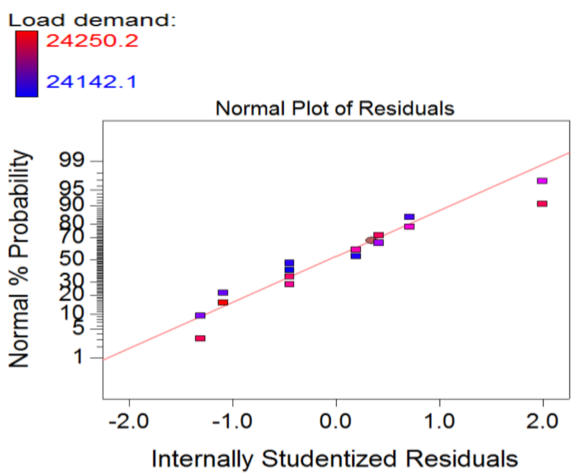


Figure 6.21: Normal probability plot of residuals for load demand after compensation

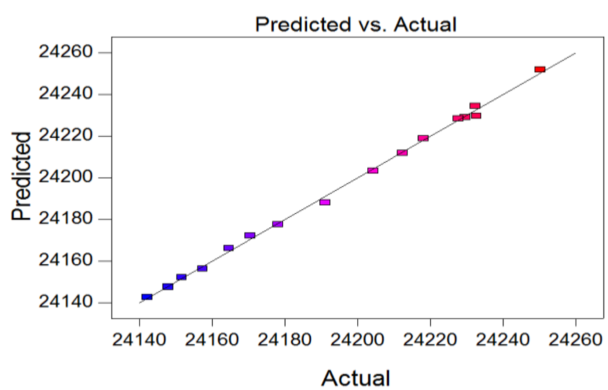


Figure 6.22: Predicted vs. actual plot for load demand after compensation

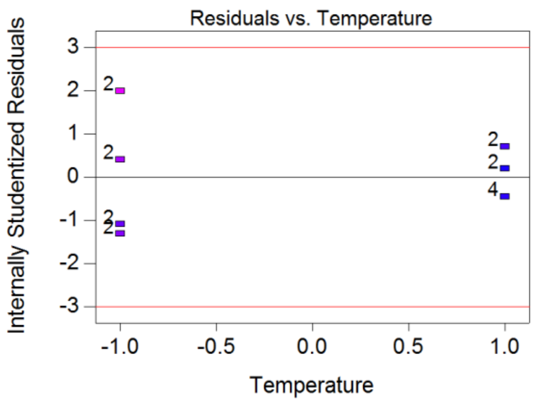


Figure 6.23: Residuals vs. temperature plot for load demand after compensation

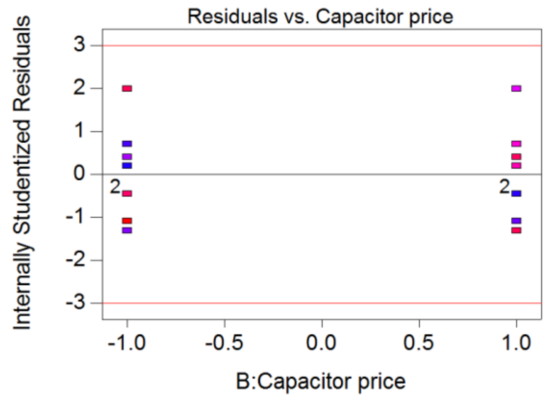


Figure 6.24: Residuals vs. capacitor price plot for load demand after compensation

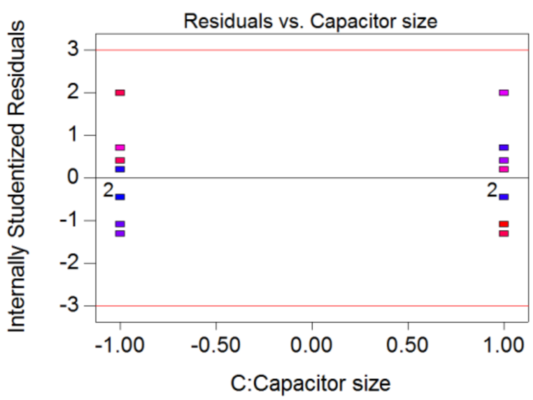


Figure 6.25: Residuals vs. capacitor size plot for load demand after compensation

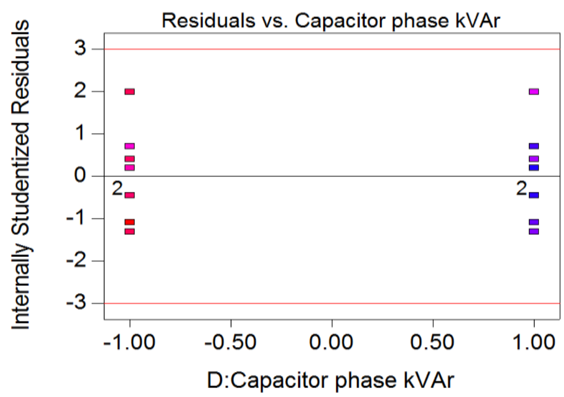


Figure 6.26: Residuals vs. capacitor phase kVAr plot for load demand after compensation

The half-normal and normal probability of the factor effects are shown in Figure 6.27 and 6.28, respectively. The main effects of A, B, C, and D are plotted in Figures 6.29 to 6.32.

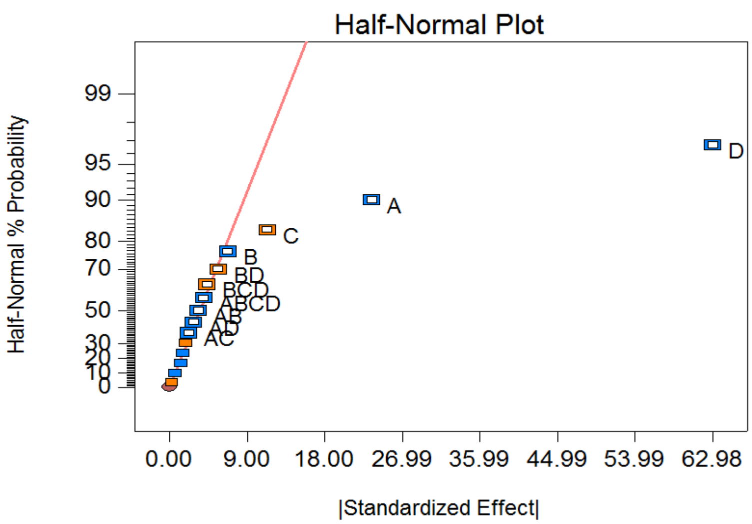


Figure 6.27: Half-normal plot of factor effects on load demand after reactive power compensation

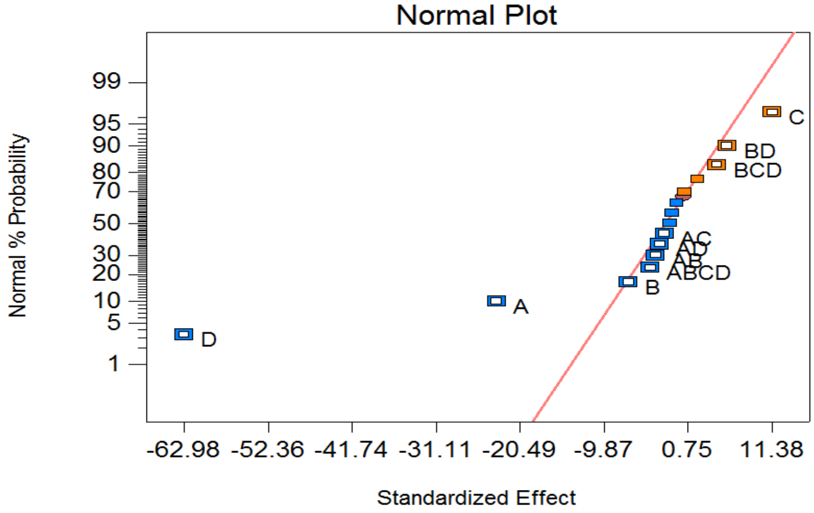


Figure 6.28: Normal plot of factor effects on load demand after reactive power compensation

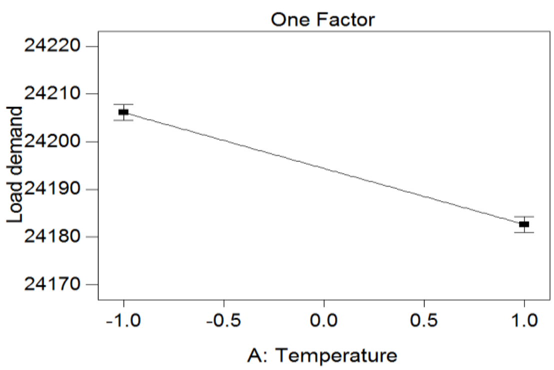


Figure 6.29: Load vs. temperature after reactive power compensation

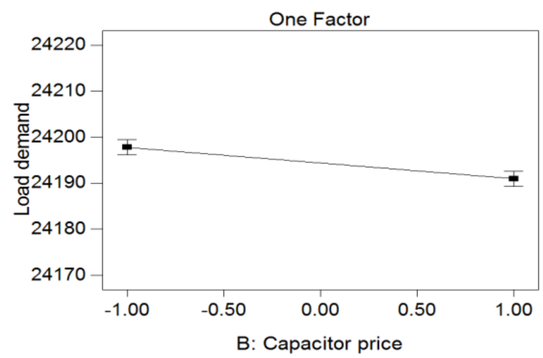


Figure 6.30: Load vs. capacitor price after reactive power compensation

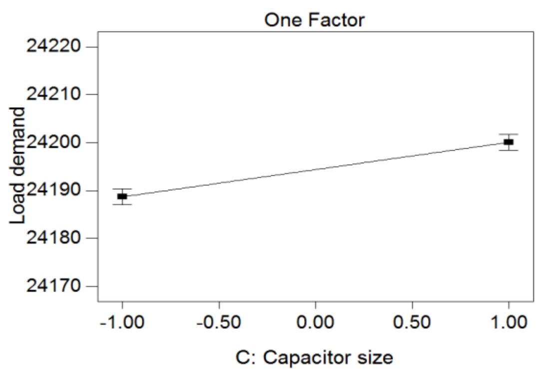


Figure 6.31: Load vs. capacitor size after reactive power compensation

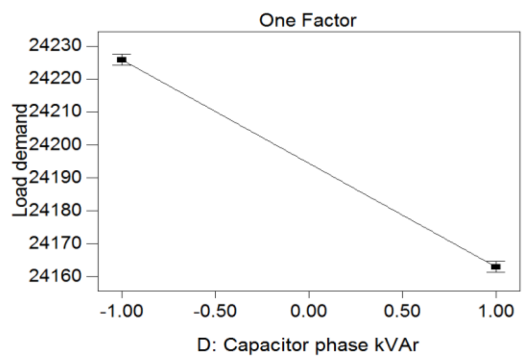


Figure 6.32: Load vs. capacitor phase kVAr after reactive power compensation

The effect of interaction, contour, and response surface plots for load demand after reactive power compensation are shown in Figures 6.33 to 6.35.

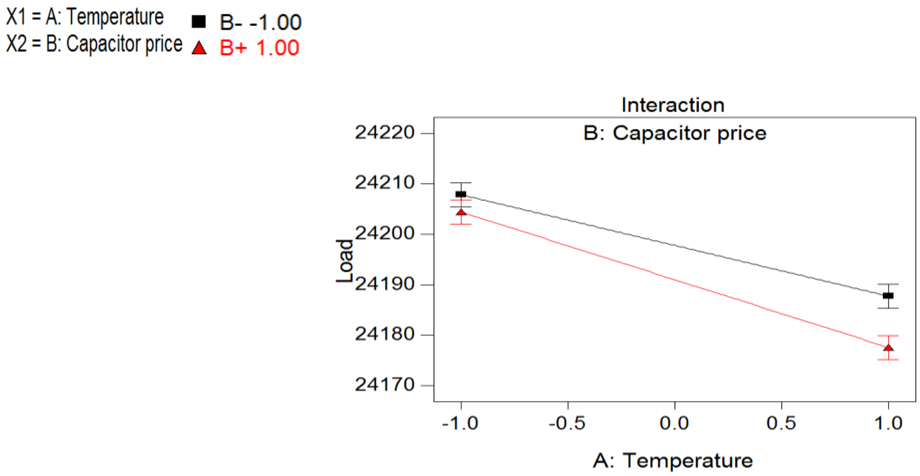


Figure 6.33: Load vs. temperature and capacitor price after reactive power compensation

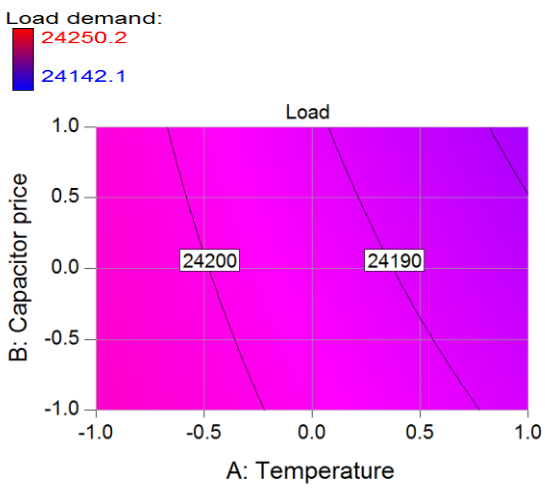


Figure 6.34: Contour plot of temperature vs. capacitor price for load after reactive power compensation

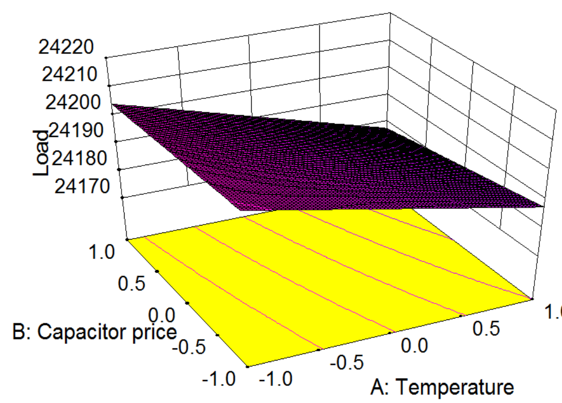


Figure 6.35: Response surface for load vs. temperature vs. capacitor price after reactive power compensation

The red and blue lines are not parallel in Figure 6.33, the contours in Figure 6.34 are curves, and the response surface in Figure 6.35 is twisted, indicating an effect of interaction between temperature and capacitor price on load demand. Figure 6.33 shows, within two given capacitor prices, that load demand is lower at a higher capacitor price. The slope of the red line is greater than the slop of blue line, implying that variations in load due to the change in ambient temperature are greater with a higher capacitor price. Similarly, Figures 6.36 to 6.38 indicate that there is an effect of interaction between temperature and capacitor size on load demand after reactive power compensation.

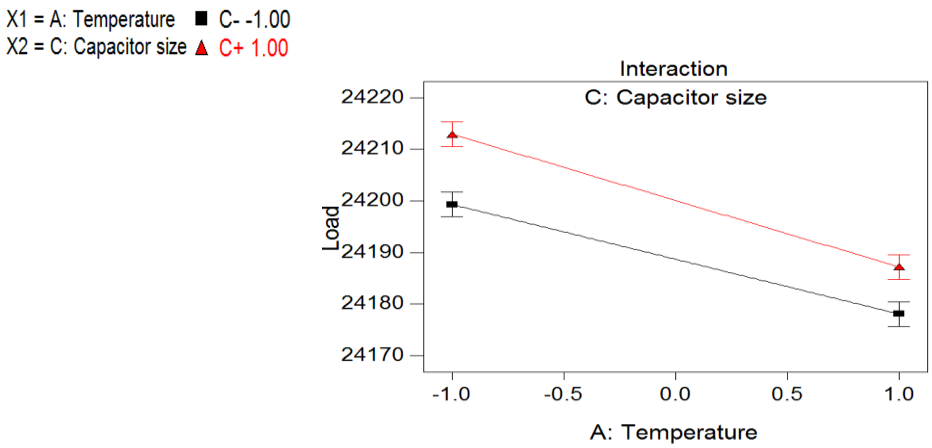


Figure 6.36: Load vs. temperature and capacitor size after reactive power compensation

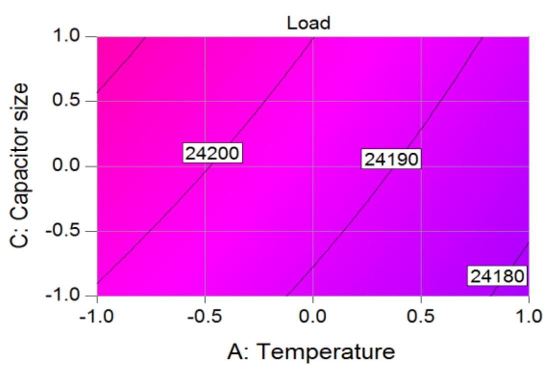


Figure 6.37: Contour plot of temperature vs. capacitor size for load after reactive power compensation

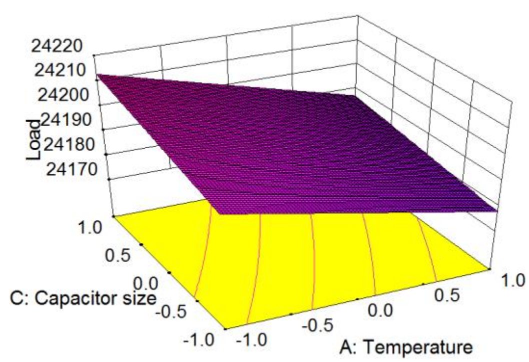


Figure 6.38: Response surface for load vs. temperature vs. capacitor size after reactive power compensation

Figures 6.39 to 6.41 show that the effect of interaction between temperature and capacitor phase kVAr is not significant. Irrespective of the temperature level, load demand for the system with evenly distributed capacitor phase kVArs is less than the load demand for the system where capacitor phase kVArs are in the ratio of reactive power flow through the line. Comparing Figures 6.14 and 6.39, it can be seen that, when capacitor phase kVArs are in the ratio of reactive power flow through the line, line loss is lower but load demand is higher than load demand with evenly distributed capacitor phase kVArs. It can also be seen that line loss increases with the increase in temperature, whereas load demand decreases.

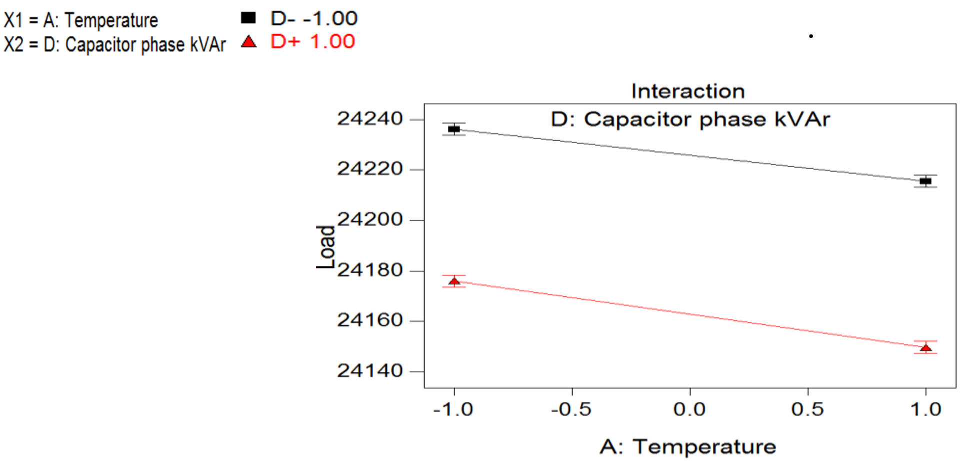


Figure 6.39: Load vs. temperature and capacitor phase kVAr after compensation

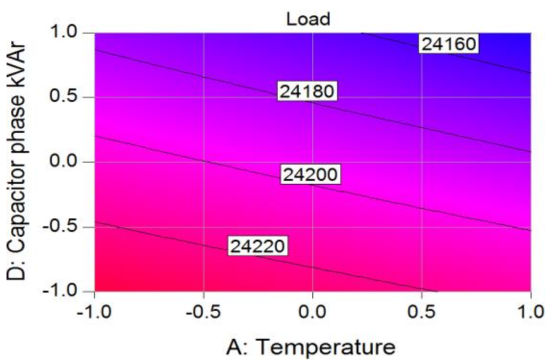


Figure 6.40: Contour plot of temperature vs. capacitor phase kVAr for load after reactive power compensation

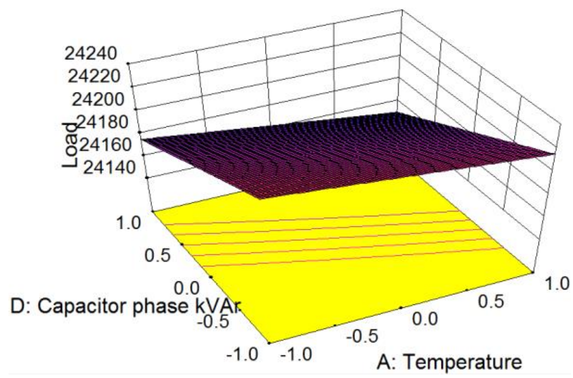


Figure 6.41: Response surface for load vs. temperature vs. capacitor phase kVAr after reactive power compensation

Figures 6.42 to 6.44 show that load does not change with capacitor price when capacitor phase kVArs are evenly distributed, but it does change when capacitor phase kVArs are in the ratio of reactive power flow through the line.

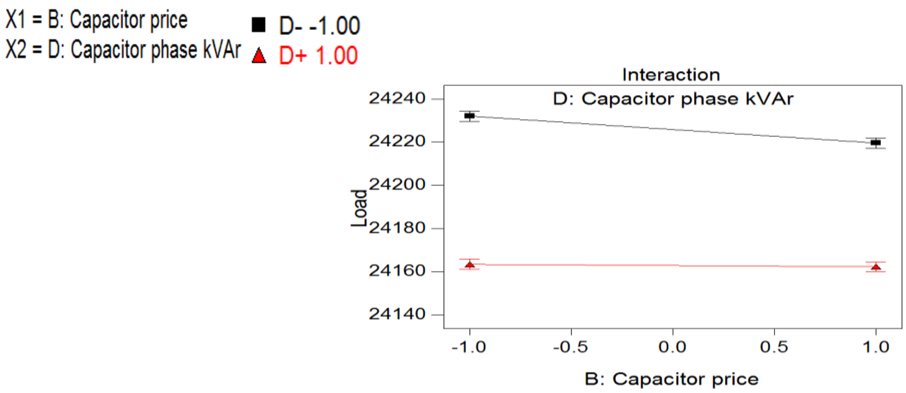


Figure 6.42: Load vs. capacitor price and capacitor phase kVAr after reactive power compensation

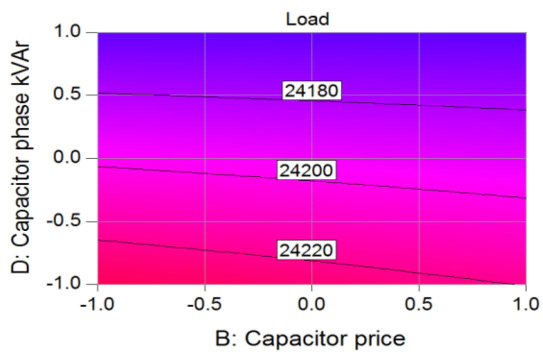


Figure 6.43: Contour plot of capacitor price vs. capacitor phase kVAr for load after reactive power compensation

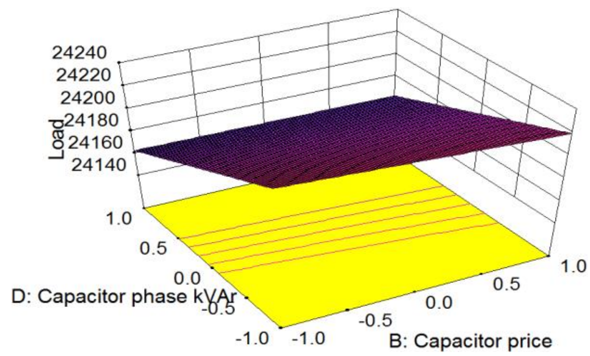


Figure 6.44: Response surface for load vs. capacitor price vs. capacitor phase kVAr after reactive power compensation

Cube Plots of Load Demand after Reactive Power Compensation

In Figure 6.45, it can be seen that with three variables—temperature, capacitor price, and capacitor size—load demand is minimized (24,172.86 MWh/year) at higher temperature, higher capacitor price, and continuous capacitor size. Figure 6.46 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—load demand is minimized (24,147.51MWh/year) at higher temperature, higher capacitor price, and evenly distributed capacitor phase kVArs.

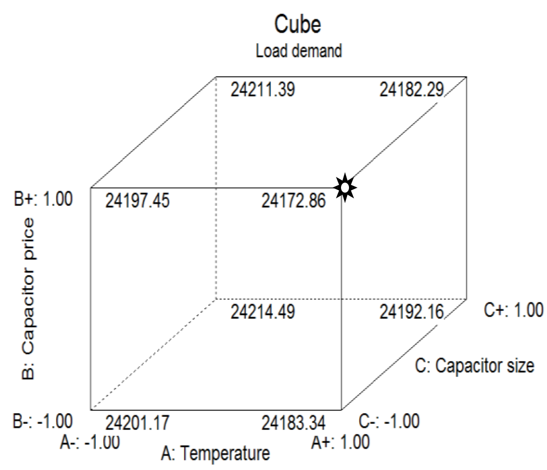


Figure 6.45: Cube plot of load vs. temperature, capacitor price, and capacitor size after compensation

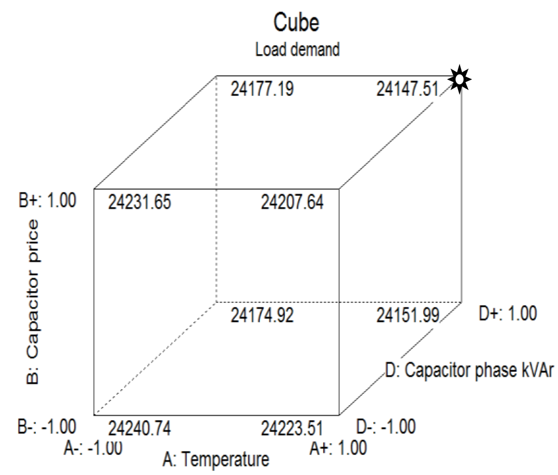


Figure 6.46: Cube plot of load vs. temperature, capacitor price, and capacitor phase kVAr after compensation

In Figure 6.47, it can be seen that with three variables—temperature, capacitor size, and capacitor phase kVAr—load demand is minimized (24,144.22 MWh/year) at higher temperature, continuous capacitor size, and evenly distributed capacitor phase kVArs. Figure 6.48 shows that with three variables—capacitor price, capacitor size, and capacitor phase kVAr—line loss is minimized (24,155.54 MWh/year) at higher capacitor price, continuous capacitor size, and evenly distributed capacitor phase kVArs.

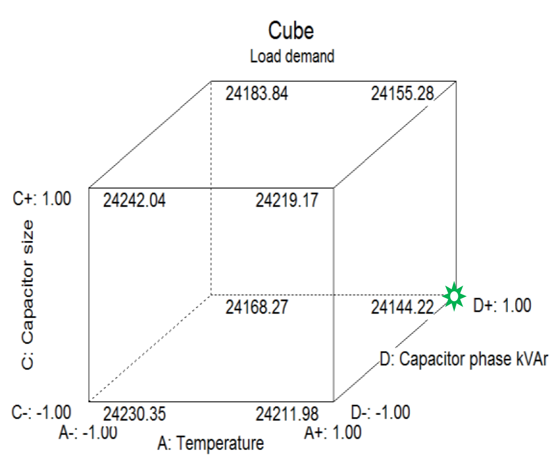


Figure 6.47: Cube plot of load vs. temperature, capacitor size, and capacitor kVAr after reactive power compensation

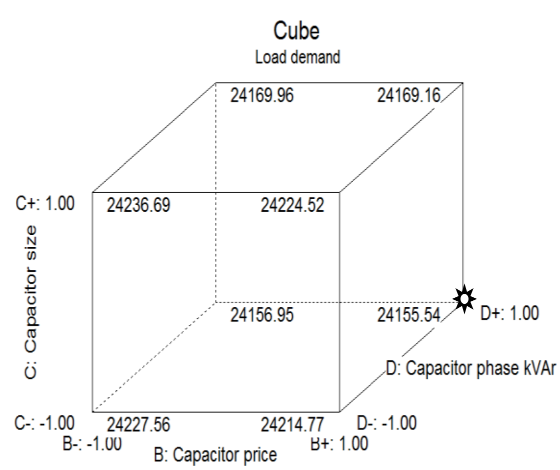


Figure 6.48: Cube plot of load vs. capacitor price, capacitor size, and capacitor phase kVAr after reactive power compensation

Factor level combinations that minimize the loads for three-factor combinations out of four factors, are shown by star marks in the cube plots. The minimum (24,144.22 MWh/year) of all minimum loads (24,172.86 MWh/year, 24,147.51MWh/year, 24,144.22 MWh/year, and 24,155.54 MWh/year) occurs at a higher temperature, continuous capacitor size, and evenly distributed capacitor phase kVArs; this combination of factor levels is indicated by a green star in Figure 6.47.

6.1.3 2^4 Factorial Design for Energy Generation after Reactive Power Compensation

Factor effect estimates, sums of squares, and percentage contributions for the 2^4 factorial design for energy generation after reactive power compensation are shown in Table 6.7.

TABLE 6.7

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN FOR ENERGY GENERATION AFTER REACTIVE POWER COMPENSATION

Factor	Effect Estimate	Sum of Squares	% Contribution
A-Temperature	35.2625	4973.78	43.5559
B-Capacitor Price	19.8775	1580.46	13.8403
C-Capacitor Size	7.4375	221.26	1.9376
D-Capacitor Phase kVAr	–32.8425	4314.52	37.7827
AB	–2.6925	28.99	0.2539
AC	–2.2525	20.29	0.1777
AD	–0.6525	1.70	0.0149
BC	1.5025	9.03	0.0790
BD	6.3125	159.39	1.3958
CD	0.6225	1.55	0.0135
ABC	–0.0575	0.01	0.0001
ABD	–1.1275	5.08	0.0445
ACD	–2.4375	23.76	0.2081
BCD	3.6875	54.39	0.4763
ABCD	–2.5025	25.05	0.2194

The important effects that are seen from this analysis are the main effects of A, B, and D, where A, ambient temperature, and D, capacitor phase kVAr, are the dominant effects on energy generation and their contributions are 43.55% and 37.78%, respectively, of the total effect.

Factor C, capacitor size, does not have a significant effect on line loss. The results of reduced ANOVA are shown in Table 6.8.

TABLE 6.8

ANOVA FOR SELECTED FACTORIAL MODEL FOR GENERATION AFTER REACTIVE POWER COMPENSATION

Source	**Sum of Squares**	**df**	**Mean Squares**	**F Value**	**P-Value Prob > F**
Model	11332.80	7	1618.97	149.75	< 0.0001
A-Temperature	*4973.78*	*1*	*4973.78*	*460.04*	*< 0.0001*
B-Capacitor Price	*1580.46*	*1*	*1580.46*	*146.18*	*< 0.0001*
C-Capacitor Size	*221.27*	*1*	*221.27*	*20.47*	*0.0019*
D-Capacitor Phase kVAr	*4314.52*	*1*	*4314.52*	*399.07*	*< 0.0001*
AB	*29.00*	*1*	*29.00*	*2.68*	*0.1401*
BD	*159.39*	*1*	*159.39*	*14.74*	*0.0049*
BCD	*54.39*	*1*	*54.39*	*5.03*	*0.0552*
Residuals	86.49	8	10.81		
Cor Total	11419.29	15			

In reduced ANOVA, the model is selected in such a way that residuals lie between –5.60 MWh/year and +5.60 MWh/year. The regression model in terms of coded factors for energy generation is given by equation (6.3).

$$P_{Gen} = 24749.45 + 17.63*A + 9.94*B + 3.72*C - 16.42*D - 1.35*A*B + 3.16*B*D + 1.84*B*C*D \quad (6.3)$$

In terms of actual factors, energy generation can be given by equations (6.3.1) to (6.3.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Gen} = 24654.3567 + 1.8784*T + 33.7866*C_p - 0.288*T* C_p \quad (6.3.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Gen} = 24677.7433 + 1.8784*T + 23.9733*C_p - 0.288*T* C_p \quad (6.3.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Gen} = 24610.0766 + 1.8784*T + 40.8266*C_p - 0.288*T* C_p \quad (6.3.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Gen} = 24601.57 + 1.8784*T + 50.64*C_p – 0.288*T* C_p \quad (6.3.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Energy Generation after Reactive Power Compensation

For energy generation, $R^2 = \frac{11332.8}{11419.29} = 0.9924$, which implies 99.24% variability in generation, can be explained by equation (6.3). $F = \frac{0.9924/7}{(1-0.9924)/[16-(7+1)]} = 149.75$; $F_{\alpha,v_1,v_2} = F_{0.01,7,8} = 6.18$. Since $F > F_{\alpha,v_1,v_2}$, the null hypothesis H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.3) is nonzero. Hence, this F test indicates that the multiple regression model presented by equation (6.3) can be used for predicting generation after reactive power compensation. A normal probability plot of residuals is shown in Figure 6.49. The predicted versus actual plot for line loss is shown in Figure 6.50. Residuals versus factor effects are plotted in Figure 6.51 to 6.54.

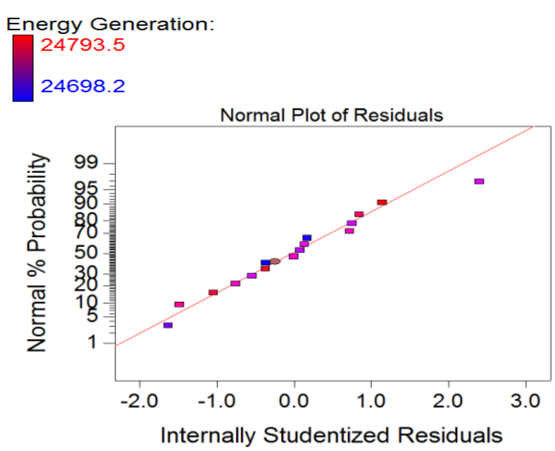


Figure 6.49: Normal probability plot of residuals for energy generation after compensation

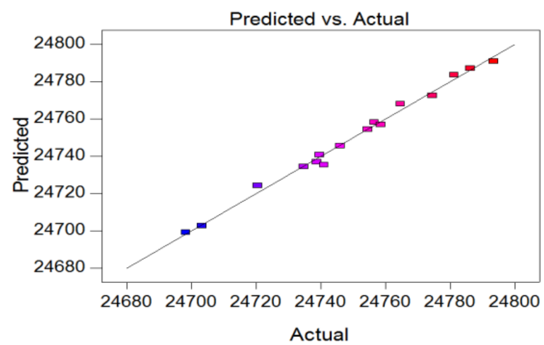


Figure 6.50: Predicted vs. actual plot for energy generation after compensation

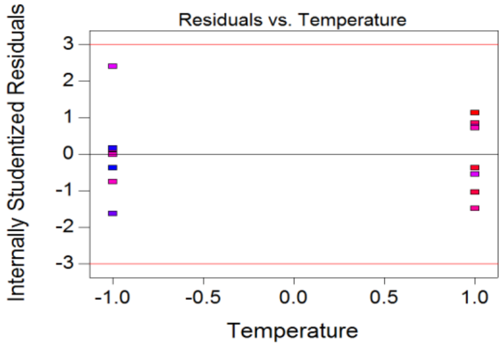


Figure 6.51: Residuals vs. temperature plot for energy generation after compensation

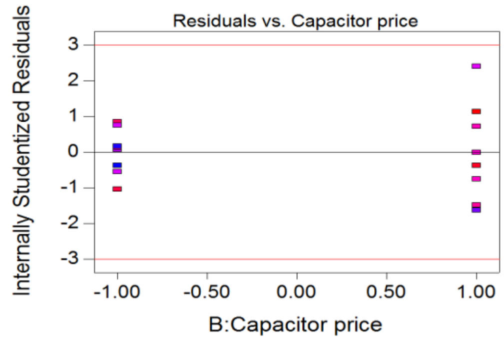


Figure 6.52: Residuals vs. capacitor price plot for energy generation after compensation

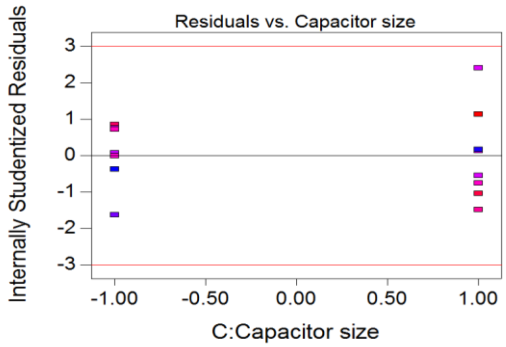


Figure 6.53: Residuals vs. capacitor size plot for energy generation after compensation

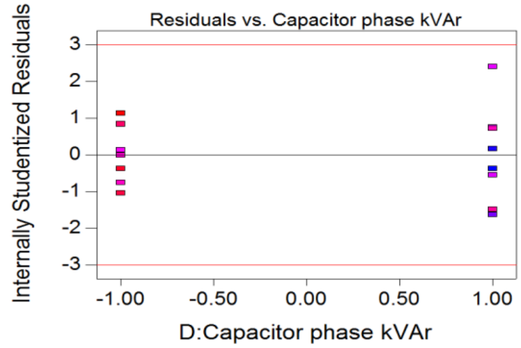


Figure 6.54: Residuals vs. capacitor phase kVAr plot for energy generation after compensation

From residuals versus capacitor price and capacitor size plots shown in Figures 6.52 and 6.53, respectively, it can be seen that residuals are larger at a higher capacitor price and discrete capacitor size. Figure 6.54 shows that residuals are larger at evenly distributed capacitor phase kVArs.

The half-normal and normal probability of the factor effects are shown in Figures 6.55 and 6.56, respectively. The main effects of A, B, C, and D are plotted in Figures 6.57 to 6.60.

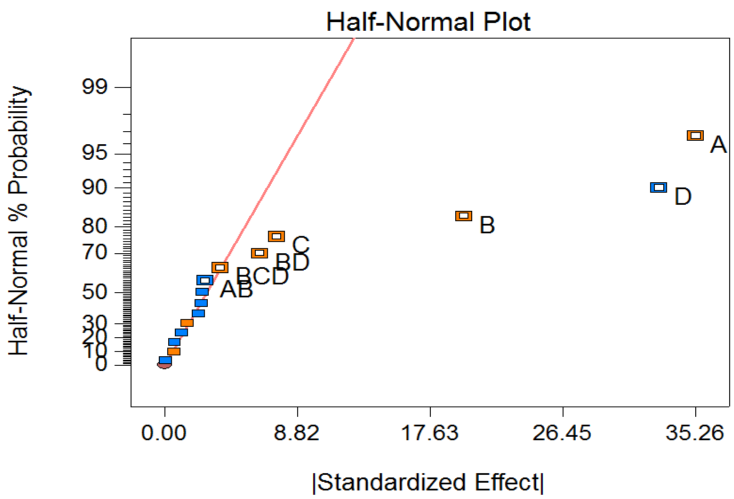


Figure 6.55: Half-normal plot of factor effects on energy generation after reactive power compensation

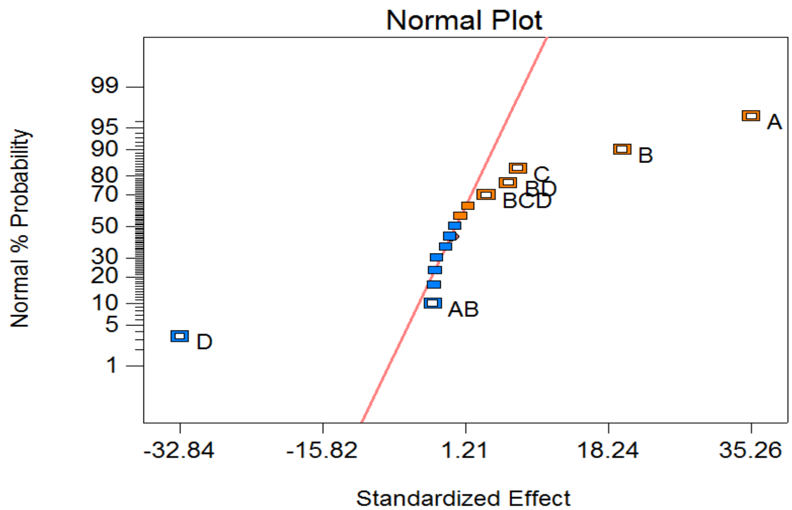


Figure 6.56: Normal plot of factor effects on energy generation after compensation

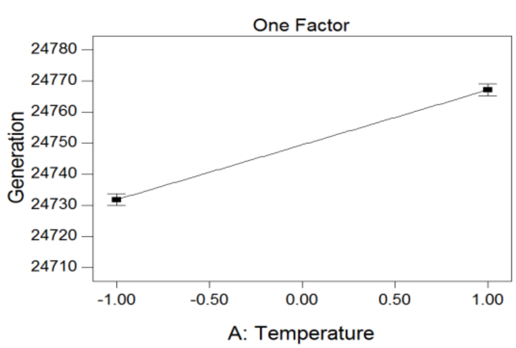


Figure 6.57: Energy generation vs. temperature after reactive power compensation

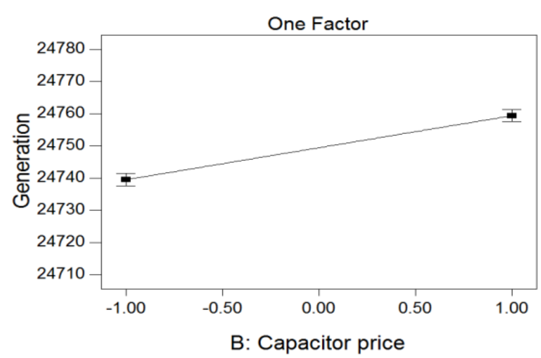


Figure 6.58: Energy generation vs. capacitor price after reactive power compensation

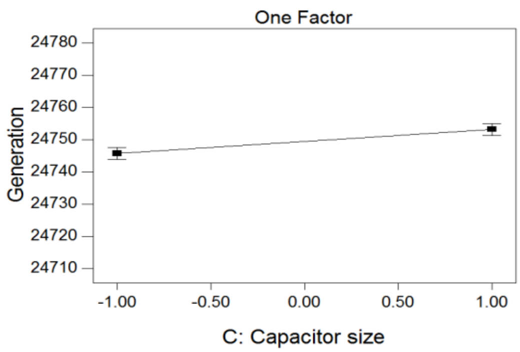


Figure 6.59: Generation vs. capacitor size after reactive power compensation

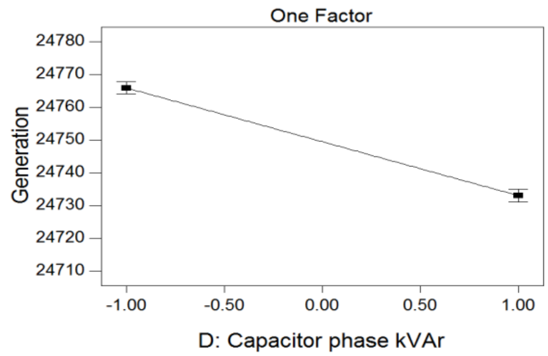


Figure 6.60: Generation vs. capacitor phase kVAr after reactive power compensation

Two-factor interactions that are important are shown in Figures 6.61 to 6.70. From the AB interaction effect shown in Figure 6.61, it can be seen that regardless of temperature level, generation is larger at a higher capacitor price than it is at a lower capacitor price. Contour and surface plot for the AB interaction are shown in Figures 6.62 and 6.63, respectively.

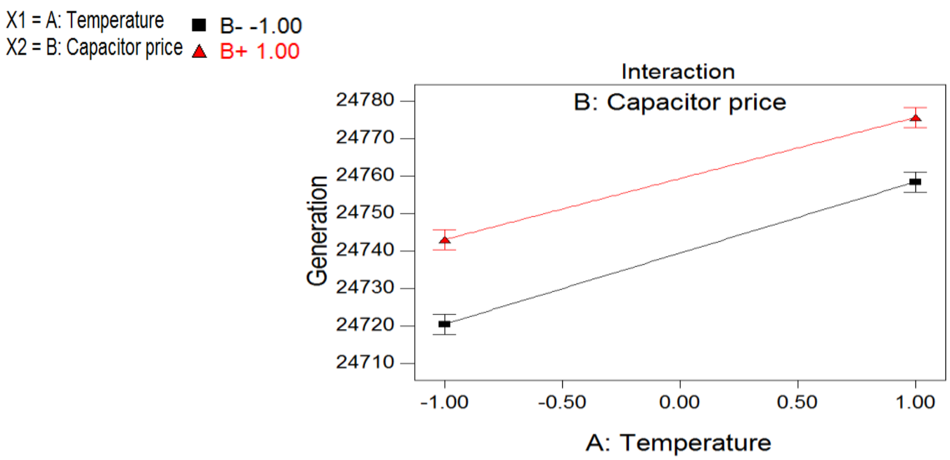


Figure 6.61: Generation vs. temperature and capacitor price after reactive power compensation

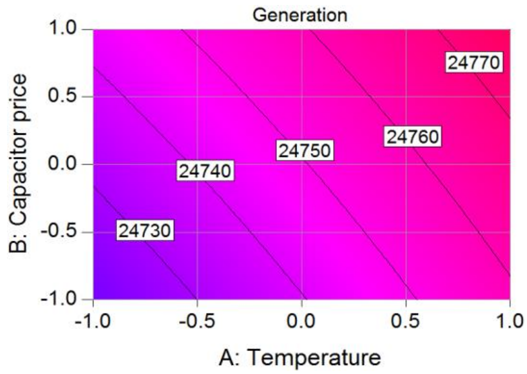


Figure 6.62: Contour plot of temperature vs. capacitor price for generation after reactive power compensation

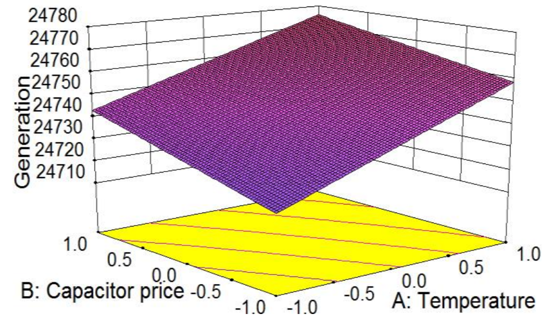


Figure 6.63: Response surface for generation vs. temperature vs. capacitor price after reactive power compensation

The red and blue lines in Figure 6.64 are not parallel, the contours in Figure 6.65 are curved lines, and the response surface in Figure 6.66 is twisted, thus indicating the interaction effect between capacitor price and capacitor phase kVAr.

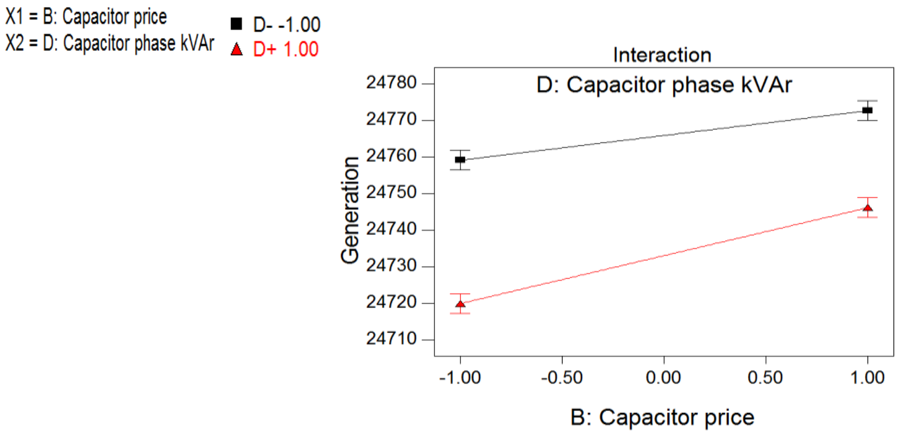


Figure 6.64: Generation vs. capacitor price and capacitor phase kVAr after reactive power compensation

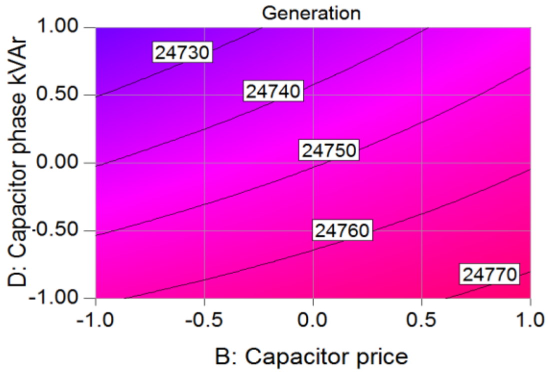


Figure 6.65: Contour plot of capacitor price vs. capacitor phase kVAr for generation after reactive power compensation

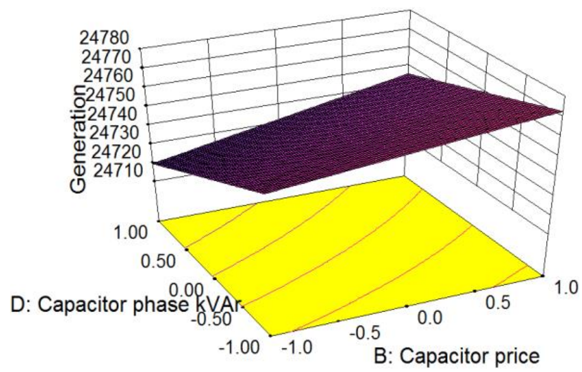


Figure 6.66: Response surface for generation vs. capacitor price vs. capacitor phase kVAr after reactive power compensation

Cube Plots of Energy Generation after Reactive Power Compensation

In Figure 6.67, it can be seen that with three variables—temperature, capacitor price, and capacitor size—energy generation is minimized (24,716.8 MWh/year) at a lower temperature, lower capacitor price, and continuous capacitor size. Figure 6.68 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—energy generation is minimized (24,701 MWh/year) at a lower temperature, lower capacitor price, and evenly distributed capacitor phase kVArs.

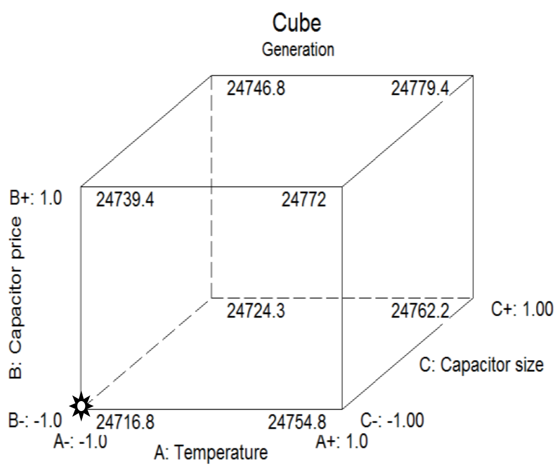


Figure 6.67: Cube plot of generation vs. temperature, capacitor price, and capacitor size after compensation

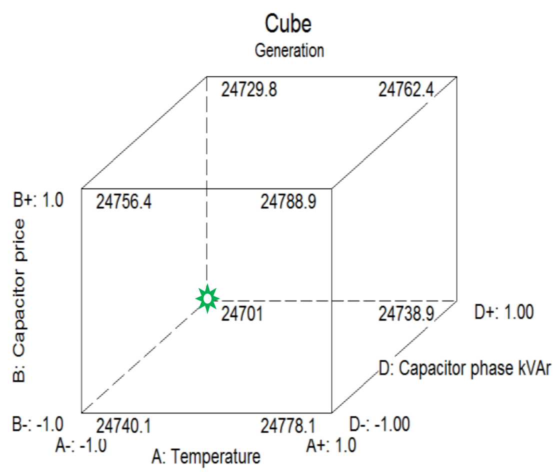


Figure 6.68: Cube plot of generation vs. temperature, capacitor price, and capacitor phase kVAr after compensation

In Figure 6.69, it can be seen that with three variables—temperature, capacitor size, and capacitor phase kVArs—energy generation is minimized (24,711.7 MWh/year) at a lower temperature, continuous capacitor size, and evenly distributed capacitor phase kVAr. Figure 6.70 shows that with three variables—capacitor price, capacitor size, and capacitor phase kVAr—energy generation is minimized (24,718.1 MWh/year) at a lower capacitor price, continuous capacitor size, and evenly distributed capacitor phase kVArs.

Factor level combinations that minimize energy generation for a three-factor combination out of four factors are shown by star marks in the cube plots. The minimum (24,701 MWh/year) of all minimum energy generation (24,716.8 MWh/year, 24,701 MWh/year, 24,711.7 MWh/year, 24,718.1 MWh/year) occurs at a lower temperature, lower capacitor price, and evenly distributed capacitor phase kVArs; this combination of factor levels is indicated by a green star in Figure 6.68.

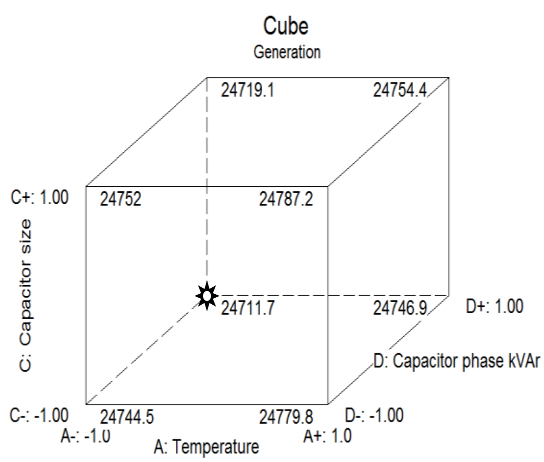


Figure 6.69: Cube plot of generation vs. temperature, capacitor size, and capacitor phase kVAr after compensation

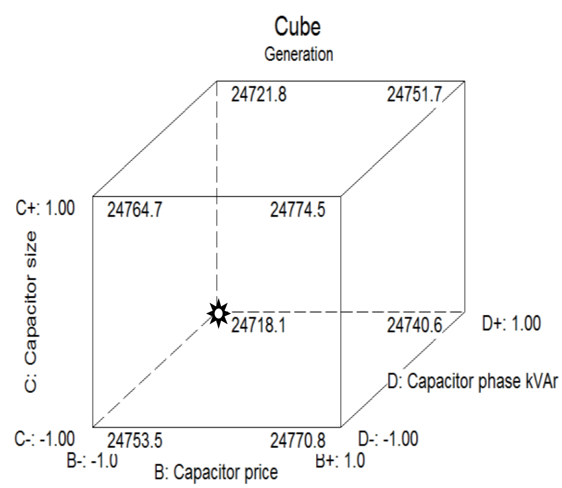


Figure 6.70: Cube plot of generation vs. capacitor price, capacitor size, and capacitor phase kVAr after compensation

6.2 2^4 Factorial Design for Line Loss, Load, and Generation after Reactive Power Compensation with Minimum Permissible Voltage Setting at Substation Regulator

Table 6.9 shows line loss, load, and generation after reactive power compensation with the minimum permissible voltage setting at the substation.

TABLE 6.9

LINE LOSS, LOAD, AND ENERGY GENERATION AFTER REACTIVE POWER COMPENSATION WITH MINIMUM PERMISSIBLE VOLTAGE AT SUBSTATION

Temperature	**Capacitor Price**	**Capacitor Size**	**Capacitor Phase kVAr**	**Line Loss (MWh)**	**Load (MWh)**	**Energy Generation (MWh)**	**Response Level**
A	**B**	**C**	**D**	**Responses**			
–	–	–	–	534.10	23953.10	24487.24	(1)
+	–	–	–	588.64	23971.60	24560.24	a
–	+	–	–	556.88	23956.40	24513.28	b
+	+	–	–	616.42	23964.90	24581.32	ab
–	–	+	–	525.34	23962.38	24487.72	c
+	–	+	–	579.62	23989.70	24569.32	ac
–	+	+	–	556.14	23960.90	24517.04	bc
+	+	+	–	610.68	23991.70	24602.38	abc
–	–	–	+	551.36	23972.40	24523.76	d
+	–	–	+	608.40	23987.40	24595.8	ad
–	+	–	+	574.14	23972.42	24546.56	bd
+	+	–	+	637.44	23974.90	24612.34	abd
–	–	+	+	551.36	23949.12	24500.48	cd
+	–	+	+	599.64	23997.20	24596.84	acd
–	+	+	+	573.40	23981.66	24555.06	bcd
+	+	+	+	632.94	23982.90	24615.84	abcd

6.2.1 2^4 Factorial Design for Line Loss after Reactive Power Compensation with Minimum Permissible Voltage Setting at Substation Regulator

Factor effect estimates, sums of squares, and percentage contribution for 2^4 factorial design for line loss after reactive power compensation with minimum permissible voltage setting at substation regulator are shown in Table 6.10.

TABLE 6.10

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN FOR LINE LOSS AFTER REACTIVE POWER COMPENSATION WITH MINIMUM PERMISSIBLE VOLTAGE SETTING AT SUBSTATION

Factors	**Effect Estimate**	**Sum of Squares**	**% Contribution**
A-Temperature	56.3825	12715.90	72.5113
B-Capacitor Price	27.4475	3013.46	17.1839
C-Capacitor Size	–4.7825	91.49	0.5217
D-Capacitor Phase kVAr	20.1075	1617.25	9.2221
AB	2.8475	32.43	0.1849
AC	–2.2225	19.76	0.1127
AD	0.6575	1.73	0.0098
BC	1.8525	13.73	0.0783
BD	–0.6575	1.73	0.0098
CD	1.2825	6.58	0.0375
ABC	0.0325	0.004	2.4092E-005
ABD	1.5325	9.39	0.0535
ACD	–0.9075	3.29	0.0188
BCD	–0.9725	3.78	0.0216
ABCD	1.2175	5.93	0.0338

Significant effects that emerge from this analysis are the main effects A, B, and D, where temperature, A, has the most significant effect on line loss, with a percentage contribution of 72.51%. Capacitor size, C, has the least significant effect with a percentage contribution of 0.52%. ANOVA for the selected model is shown in Table 6.11. In reduced ANOVA, the model is selected in such a way that residuals lie between –5 MWh/year and +5 MWh/year.

TABLE 6.11

ANOVA FOR SELECTED FACTORIAL MODEL FOR LINE LOSS AFTER REACTIVE POWER COMPENSATION WITH MINIMUM PERMISSIBLE VOLTAGE SETTING AT SUBSTATION

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**P-Value Prob > F**
Model	17438.14	4	4359.54	487.54	< 0.0001
A-Temperature	*12715.95*	*1*	*12715.95*	*1422.07*	*< 0.0001*
B-Capacitor Price	*3013.46*	*1*	*3013.46*	*337.01*	*< 0.0001*
C-Capacitor Size	*91.49*	*1*	*91.49*	*10.23*	*0.0085*
D-Capacitor Phase kVAr	*1617.25*	*1*	*1617.25*	*180.86*	*< 0.0001*
Residual	98.36	11	8.94		
Cor Total	17536.50	15			

The regression model for line loss after reactive power compensation with minimum permissible voltage setting at the substation can be given in terms of coded factor by equation (6.4).

$$P_{Loss} = 581.03 + 28.19* A + 13.72* B -2.39* C + 10.05* D \quad (6.4)$$

In terms of actual factor, the equation for line loss can be given by equations (6.4.1) to (6.4.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Loss} = 429.3466 + 2.2552*T + 36.5866*C_p \quad (6.4.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Loss} = 424.5666 + 2.2552*T + 36.5866*C_p \quad (6.4.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Loss} = 449.4466 + 2.2552*T + 36.6866*C_p \quad (6.4.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Loss} = 444.6666 + 2.2552*T + 36.6866*C_p \quad (6.4.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Line Loss after Reactive Power Compensation with Minimum Permissible Voltage Setting at Substation

For line loss, $R^2 = \frac{17438.14}{17536.5}$ = 0.99439, which implies that 99.439% variability in line loss can be explained by equation (6.4). F = 487.44, $F_{\alpha,v_1,v_2} = F_{0.01,4,11}$ = 5.67. Since $F > F_{\alpha,v_1,v_2}$, the null hypothesis H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.4) is nonzero. Hence, this F test indicates that the multiple regression model presented by equation (6.4) can be used for predicting line loss after reactive power compensation with the minimun permissible voltage setting at the subsation. A normal probability plot of residuals is shown in Figure 6.71. A predicted versus actual plot for line loss is shown in Figure 6.72. Residuals versus factor effects are plotted in Figures 6.73 to 6.76.

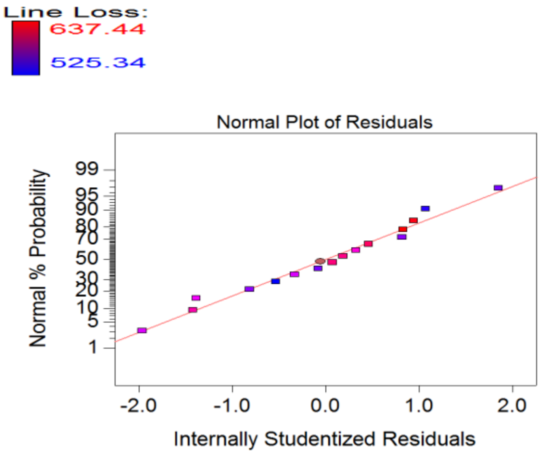


Figure 6.71: Normal probability plot of residuals for line loss after compensation with minimum permissible voltage

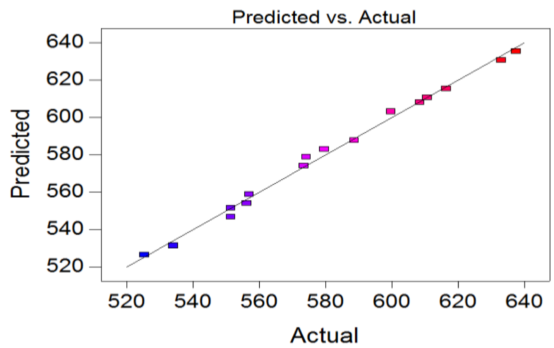


Figure 6.72: Predicted vs. actual plot for line loss after compensation with minimum permissible voltage

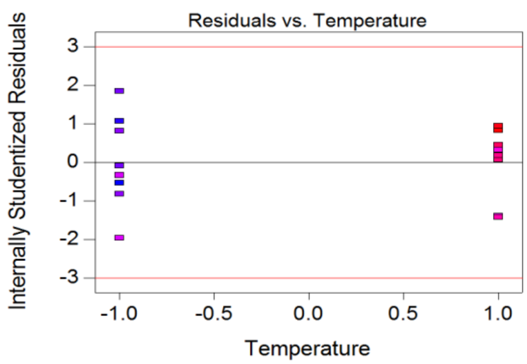


Figure 6.73: Residuals vs. temperature plot for line loss after compensation with minimum permissible voltage

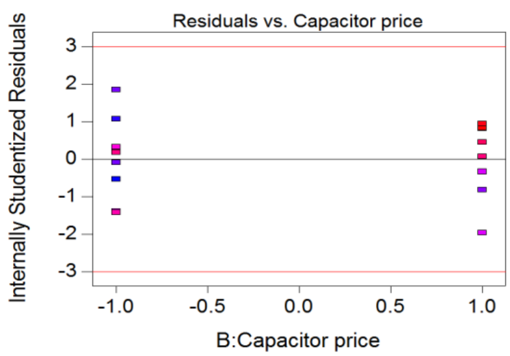


Figure 6.74: Residuals vs. capacitor price plot for line loss after compensation with minimum permissible voltage

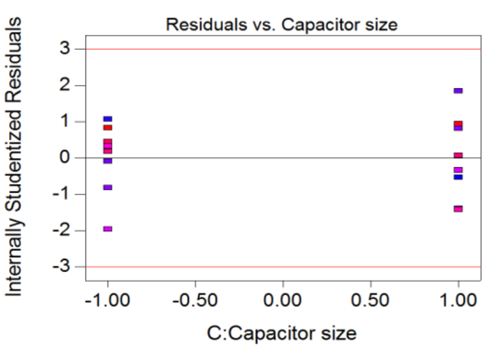


Figure 6.75: Residuals vs. capacitor size plot for line loss after compensation with minimum permissible voltage

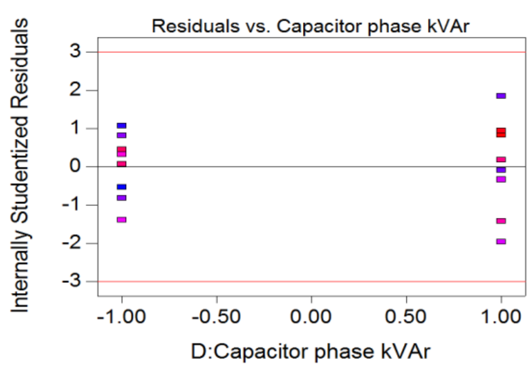


Figure 6.76: Residuals vs. capacitor phase kVAr plot for line loss after compensation with minimum permissible voltage

From the residuals versus temperature plot shown in Figure 6.73, it is shown that at lower temperature levels, the residuals of line loss after reactive power compensation with minimum permissible voltage at the substation are greater than the residuals at higher temperature levels, while at lower temperature levels, the residuals of line loss after reactive power compensation without a voltage reduction, as shown in Figure 6.4, are smaller than the residuals at higher temperature levels. The residuals versus capacitor phase kVAr plot shown in Figure 6.76 indicates that residuals are larger when the capacitor phase kVArs are evenly distributed. The half-normal and normal probability plots of the factor effects are shown in Figure 6.77 and 6.78, respectively.

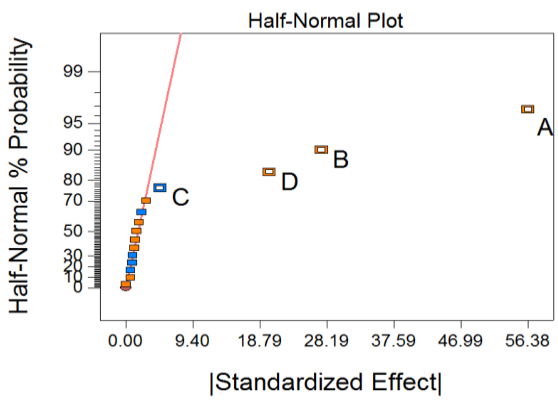


Figure 6.77: Half-normal plot of factor effects on line loss after reactive power compensation with minimum permissible voltage

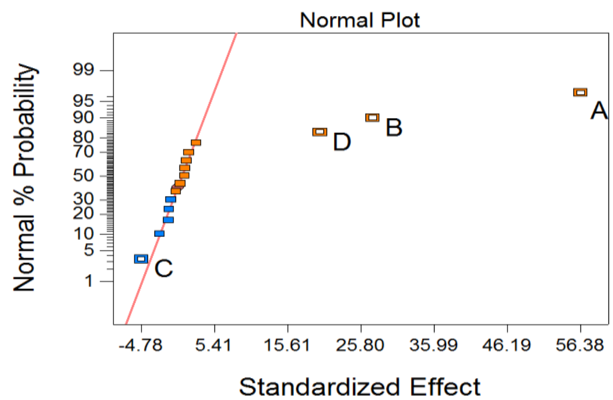


Figure 6.78: Normal plot of factor effects on line loss after reactive power compensation with minimum permissible voltage

The significant effects that emerge from the half-normal and normal probability plots are the main effects of A, B, C, and D, where temperature, A, has the most significant effect on line loss, and capacitor size, C, has the least significant effect on line loss. The main effects of A, B, C, and D are plotted in Figures 6.79 to 6.82.

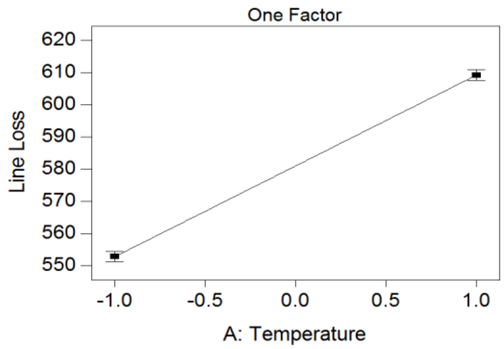


Figure 6.79: Line loss vs. temperature after reactive power compensation with minimum permissible voltage

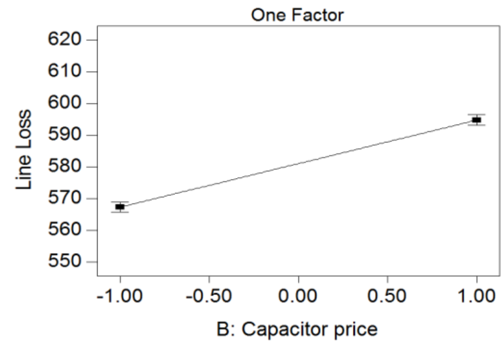


Figure 6.80: Line loss vs. capacitor price after reactive power compensation with minimum permissible voltage

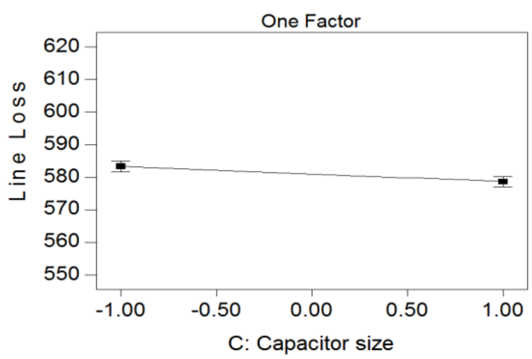


Figure 6.81: Line loss vs. capacitor size after reactive power compensation with minimum permissible voltage

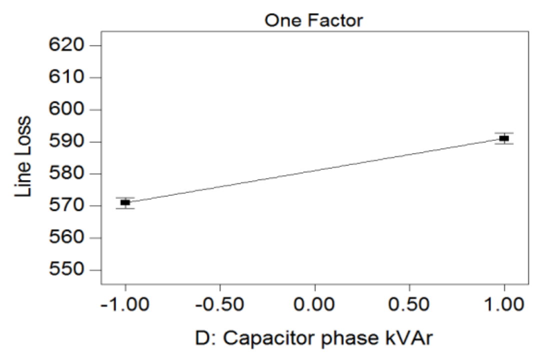


Figure 6.82: Line loss vs. capacitor phase kVAr after reactive power compensation with minimum permissible voltage

The AB interaction effect, which is comparatively greater than other five two-factor interaction effects, is shown in Figures 6.83 to 6.85.

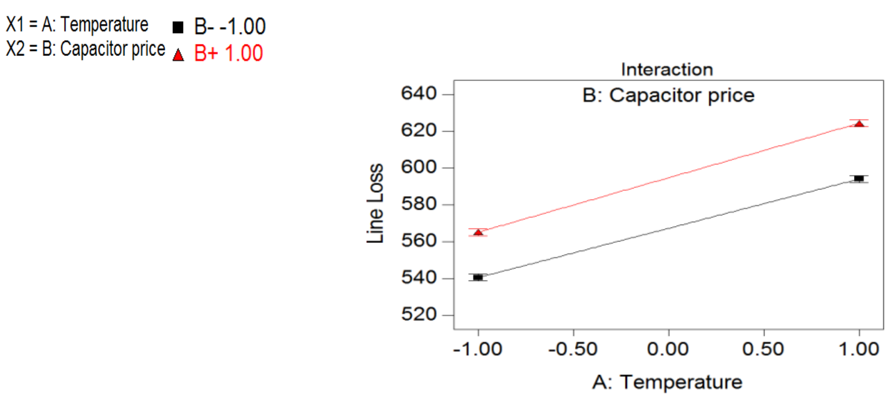


Figure 6.83: Line loss vs. temperature and capacitor price after reactive power compensation with minimum permissible voltage at substation

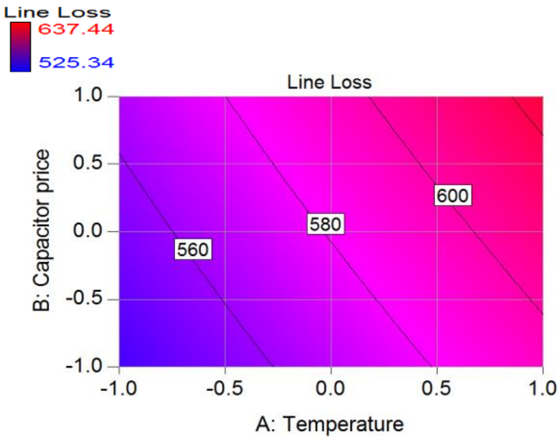


Figure 6.84: Contour plot of temperature vs. capacitor price for line loss after compensation with minimum permissible voltage

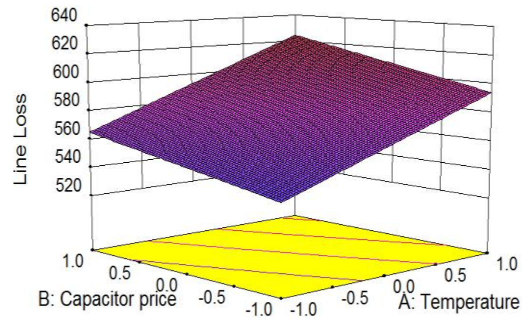


Figure 6.85: Response surface for line loss vs. temperature vs. capacitor price after compensation with minimum permissible voltage

The red and blue lines shown in Figure 6.83 are approximately parallel, the contours in Figure 6.84 are straight lines, and the response surface shown in Figure 6.85 is not twisted, thus indicating a lack of interaction between temperature and capacitor price. Irrespective of temperature, line loss for the system with a higher capacitor price is greater than line loss for the system with a lower capacitor price.

Cube Plots of Line Loss after Reactive Power Compensation with Minimum Permissible Voltage at Substation Regulator

In Figure 6.86, it can be seen that with three variables – temperature, capacitor size and capacitor price - line loss is minimized (536.7 MWh/year) at lower temperature, lower capacitor price and discrete capacitor size. Figure 6.87 shows that with three variables – temperature, capacitor price and capacitor phase kVAr – line loss is minimized (529.1 MWh/year) at lower temperature, lower capacitor price and when capacitor phase kVArs are in the ratio of reactive power flow through the line.

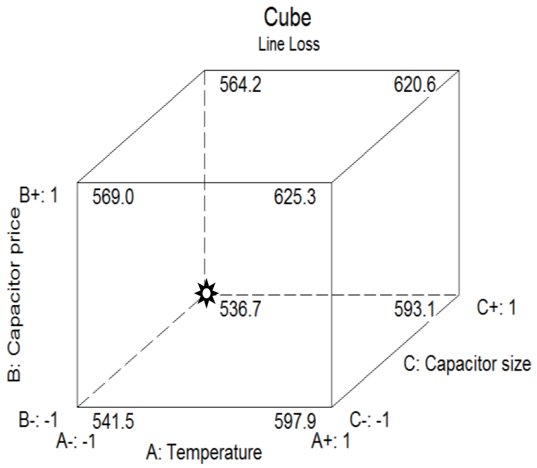


Figure 6.86: Cube plot of line loss vs. temperature, capacitor price, and capacitor size after reactive power compensation with minimum permissible voltage

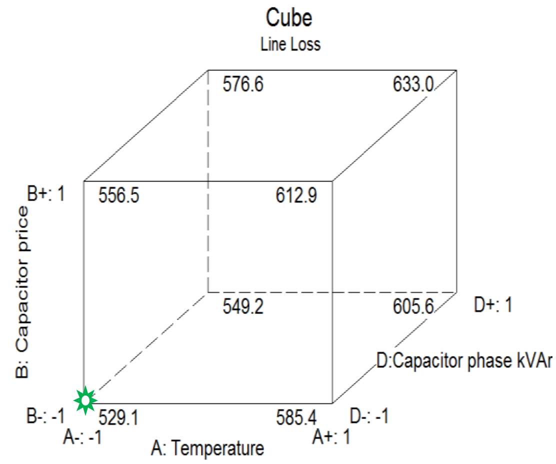


Figure 6.87: Cube plot of line loss vs. temperature, capacitor price, and capacitor phase kVAr after reactive power compensation with minimum permissible voltage

In Figure 6.88, it can be seen that with three variables—temperature, capacitor size, and capacitor phase kVAr—line loss is minimized (540.4 MWh/year) at a lower temperature, discrete capacitor size, and when the capacitor phase kVArs are in the ratio of reactive power flow through the line. With three variables—capacitor price, capacitor size, and capacitor phase kVAr—line loss is minimized (554.9 MWh/year) at a lower capacitor price, discrete capacitor size, and when the capacitor phase kVArs are in the ratio of reactive power flow through the line, as shown in Figure 6.89.

Factor level combinations that minimize line loss for the three-factor combination out of four factors are shown by star marks in the cube plots. The minimum (529.1 MWh/year) of all minimum line losses (536.7 MWh/year, 529.1 MWh/year, 540.4 MWh/year, 554.9 MWh/year) occurs at a lower temperature, lower capacitor price, and when the capacitor phase kVArs are in the ratio of reactive power flow through the line; this combination of factors' levels is indicated by a green star in Figure 6.87.

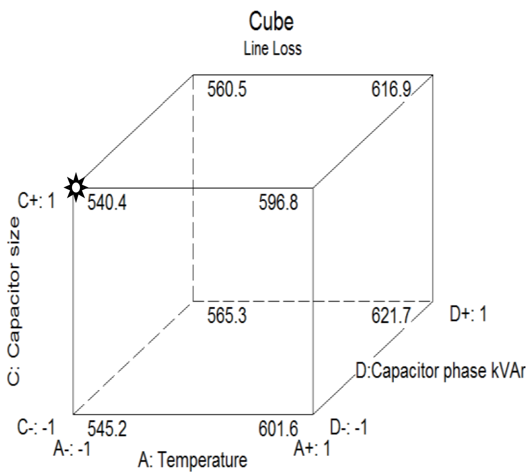


Figure 6.88: Cube plot of line loss vs. temperature, capacitor size, and capacitor phase kVAr after reactive power compensation with minimum permissible voltage

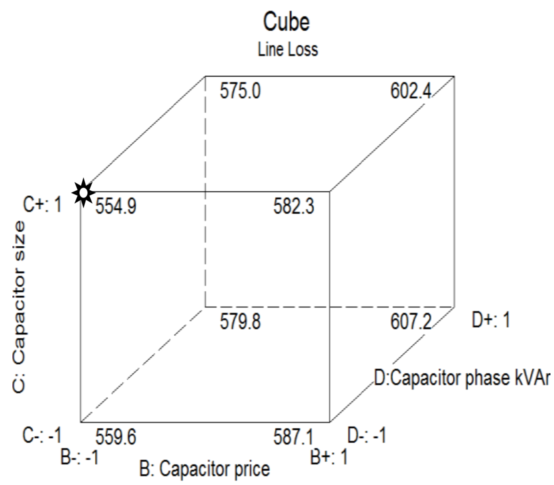


Figure 6.89: Cube plot of line loss vs. capacitor price, capacitor size, and capacitor phase kVAr after reactive power compensation with minimum permissible voltage

6.2.2 2^4 Factorial Design for Load Demand after Reactive Power Compensation with Minimum Permissible Voltage Setting at Substation Regulator

Factor effects estimates, sums of squares, and percentage contribution are shown in Table 6.12. The important effects that emerge in this analysis are the main effects of A, C, and D and the AB, AC, BC, CD, ABD, BCD, and ABCD interaction effects. ANOVA for selected factorial model is shown in Table 6.13. In reduced ANOVA, the model for load after reactive power compensation with minimum permissible voltage at the substation, is selected in such a way that the residuals lie between –3.25 MWh/year and +3.25 MWh/year.

TABLE 6.12

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN ON LOAD DEMAND AFTER REACTIVE POWER COMPENSATION WITH MINIMUM PERMISSIBLE VOLTAGE SETTING AT SUBSTATION

Factors	**Effect Estimate**	**Sum of Square**	**% Contribution**
A-Temperature	18.985	1441.72	45.5397
B-Capacitor Price	0.355	0.50	0.0159
C-Capacitor Size	7.800	243.36	7.6870
D-Capacitor Phase kVAr	8.410	282.91	8.9363
AB	-8.230	270.93	8.5579
AC	7.875	248.06	7.8355
AD	-2.285	20.88	0.6597
BC	4.335	75.17	2.3744
BD	1.085	4.71	0.1487
CD	-6.860	188.24	5.9500
ABC	-2.610	27.25	0.8607
ABD	-6.610	174.77	5.5204
ACD	0.085	0.03	0.0009
BCD	3.345	44.76	1.4137
ABCD	-5.970	142.56	4.5032

TABLE 6.13

ANOVA FOR SELECTED FACTORIAL MODEL FOR LOAD DEMAND AFTER REACTIVE POWER COMPENSATION WITH MINIMUM PERMISSIBLE VOLTAGE SETTING AT SUBSTATION

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**P-Value Prob > F**
Model	3112.48	10	311.25	29.16	0.0008
A-Temperature	*1441.72*	*1*	*1441.72*	*135.06*	*< 0.0001*
C-Capacitor Size	*243.36*	*1*	*243.36*	*22.80*	*0.0050*
D-Capacitor Phase kVAr	*282.91*	*1*	*282.91*	*26.50*	*0.0036*
AB	*270.93*	*1*	*270.93*	*25.38*	*0.0040*
AC	*248.06*	*1*	*248.06*	*23.24*	*0.0048*
BC	*75.17*	*1*	*75.17*	*7.04*	*0.0452*
CD	*188.24*	*1*	*188.24*	*17.63*	*0.0085*
ABD	*174.77*	*1*	*174.77*	*16.37*	*0.0099*
BCD	*44.76*	*1*	*44.76*	*4.19*	*0.0959*
ABCD	*142.56*	*1*	*142.56*	*13.35*	*0.0147*
Residuals	53.38	5	10.68		
Cor Total	3165.86	15			

The regression model for load demand after reactive power compensation with minimum permissible voltage setting at the substation can be given in terms of coded factor by equation (6.5).

$$P_{Load} = 23973.05 + 9.49*A + 3.90*C + 4.20*D - 4.11*A*B + 3.94*A*C + 2.17*B*C - 3.43*C*D - 3.31*A*B*D + 1.67*B*C*D - 2.98*A*B*C*D \quad (6.5)$$

In terms of actual factors, load demand can be given by equations (6.5.1) to (6.5.4)

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Load} = 23897.8967 + 1.7544*T + 28.9066*Cp - 0.8064*T*Cp \quad (6.5.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Load} = 23962.0833 + 0.31867*T - 16.1067*Cp + 0.4651*T*Cp \quad (6.5.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Load} = 23919.05 + 1.9832*T + 25.28*Cp - 0.9472*T*Cp \quad (6.5.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Load} = 23785.59 + 4.67973333*T + 93.44*Cp - 2.218666*T*Cp \quad (6.5.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Load Demand after Reactive Power Compensation with Minimum Permissible Voltage setting at Substation:

For line loss, $R^2 = \frac{3112.48}{3165.86} = 0.983$ which implies 98.3% variability in load demand can be explained by equation (6.5). $F = \frac{0.983/10}{(1-0.983)/[16-(10+1)]} = 28.91$, $F_{\alpha,v_1,v_2} = F_{0.01,10,5} = 10.05$. Since $F > F_{\alpha,v_1,v_2}$, null hypothesis H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.5) is nonzero. Hence, this F test indicates that multiple regression model presented by equation (6.5), can be used for predicting load demand after reactive power compensation with minimun permissible voltage setting at subsation. Normal probability plot of residuals is shown in Figure 6.90. Predicted versus actual plot for load demand is shown in Figure 6.91. Residuals versus factor effects are plotted in Figure 6.92 to 6.95.

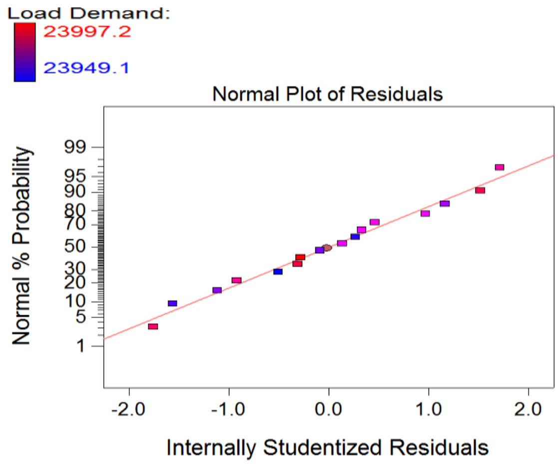


Figure 6.90: Normal probability plot of residuals for load demand after compensation with minimum permissible voltage setting

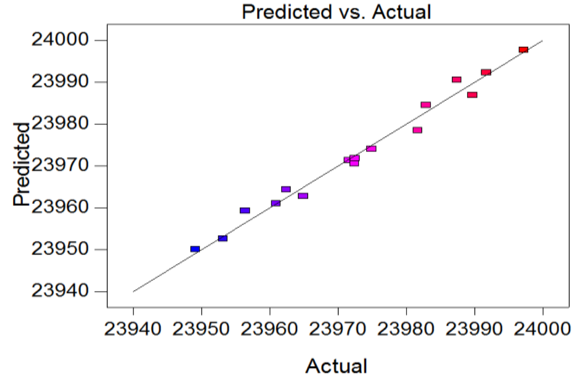


Figure 6.91: Predicted vs. actual plot for load demand after compensation with minimum permissible voltage setting

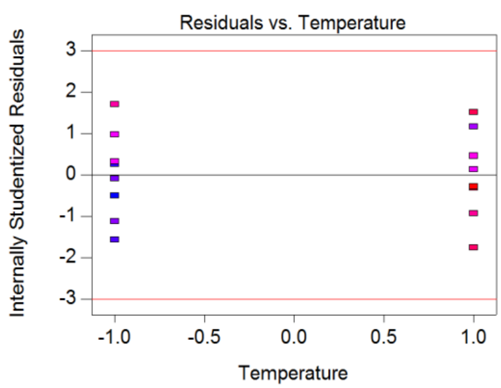


Figure 6.92: Residuals vs. temperature plot for load demand after compensation with minimum permissible voltage

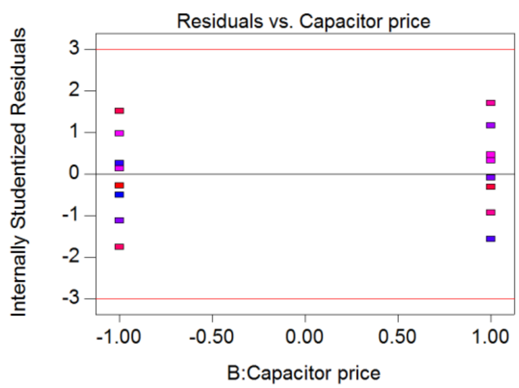


Figure 6.93: Residuals vs. capacitor price plot for load demand after compensation with minimum permissible voltage

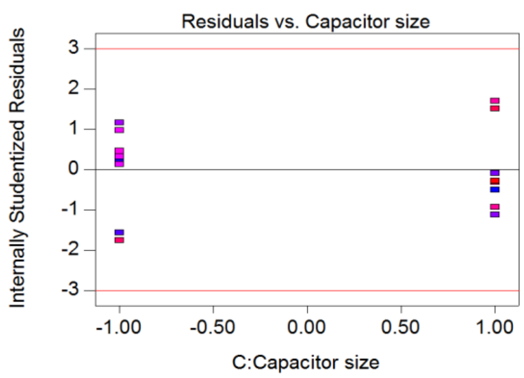


Figure 6.94: Residuals vs. capacitor size plot for load demand after compensation with minimum permissible voltage

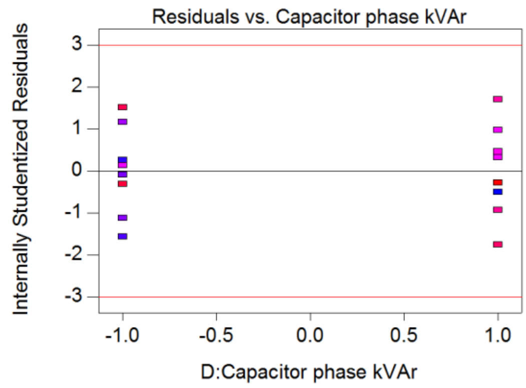


Figure 6.95: Residuals vs. capacitor phase kVAr plot for load demand after compensation with minimum permissible voltage

Figures 6.92 to 6.95 indicate that there are no significant changes in residuals with the variation in factor levels. The half-normal and normal probability plots of factor effects are shown in Figures 6.96 and 6.97, respectively. The effects of A, B, C, and D are plotted in Figures 6.98 to 6.101.

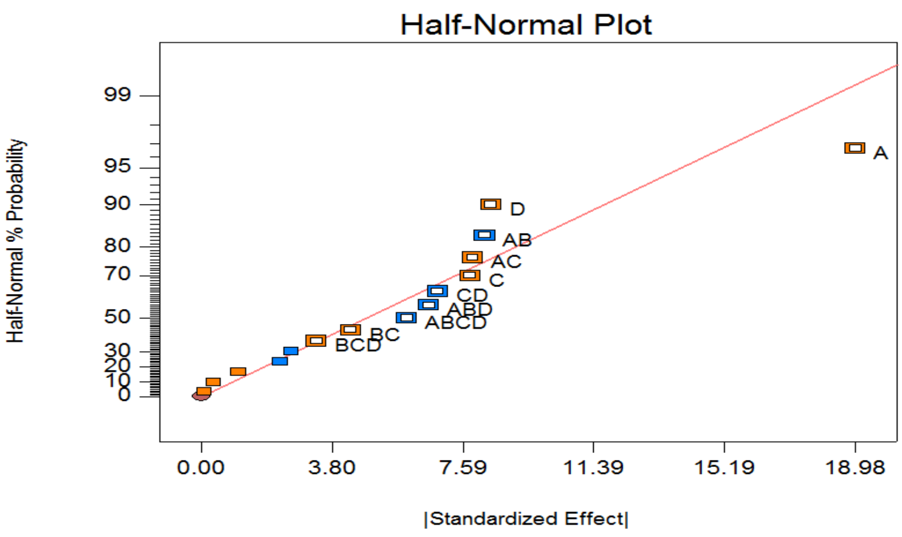


Figure 6.96: Half-normal plot of factor effects on load after reactive power compensation with minimum permissible voltage

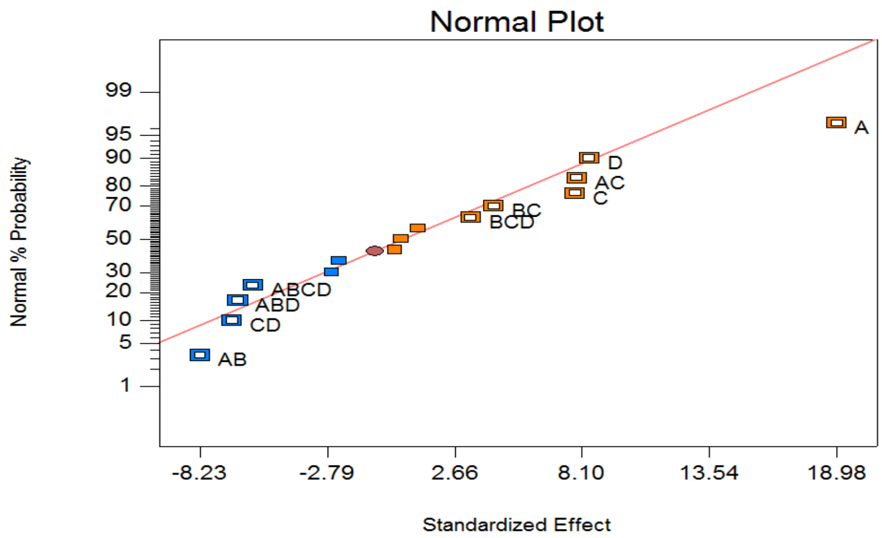


Figure 6.97: Normal plot of factor effect on load after reactive power compensation with minimum permissible voltage

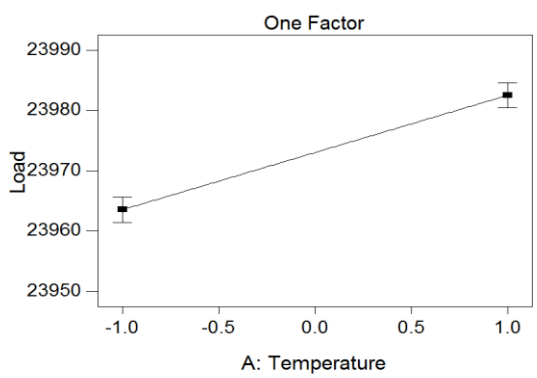


Figure 6.98: Load vs. temperature after reactive power compensation with minimum permissible voltage

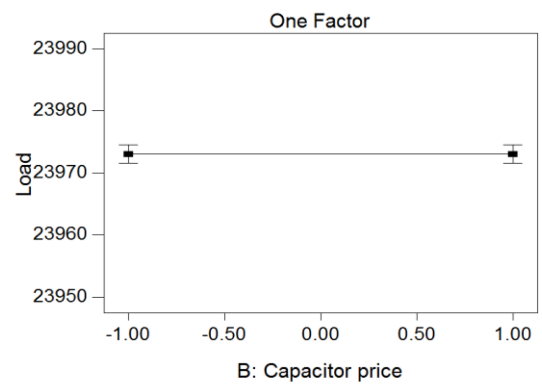


Figure 6.99: Load vs. capacitor price after reactive power compensation with minimum permissible voltage

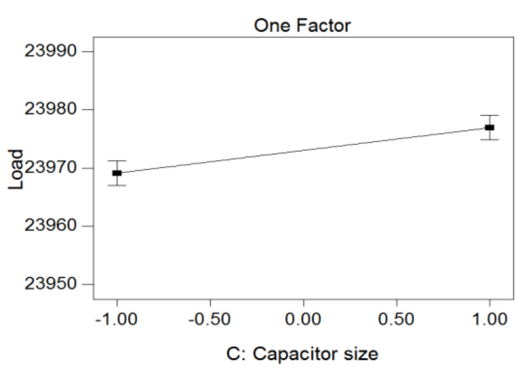


Figure 6.100: Load vs. capacitor size after reactive power compensation with minimum permissible voltage

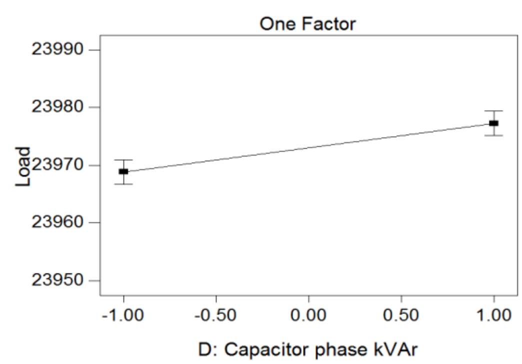


Figure 6.101: Load vs. capacitor phase kVAr after reactive power compensation with minimum permissible voltage

Important interaction effects AB, AC, BC, and CD are shown in Figures 6.102 to 6.113.

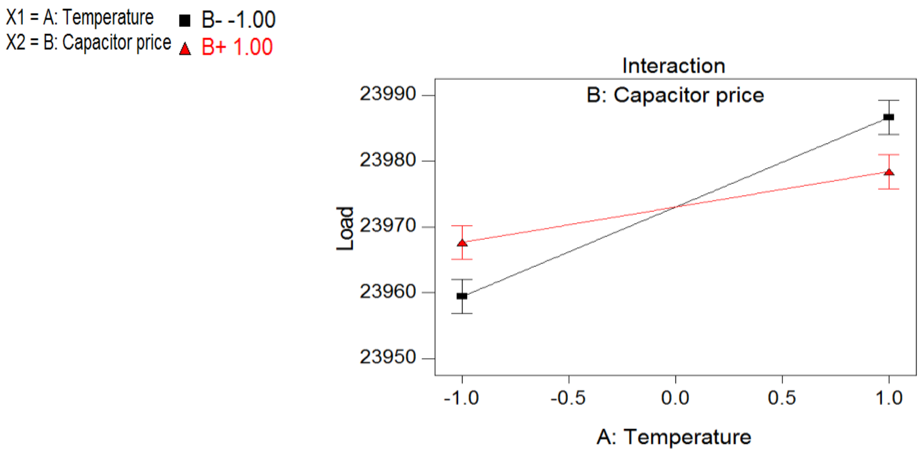


Figure 6.102: Load vs. temperature and capacitor price after reactive power compensation with minimum permissible voltage at substation

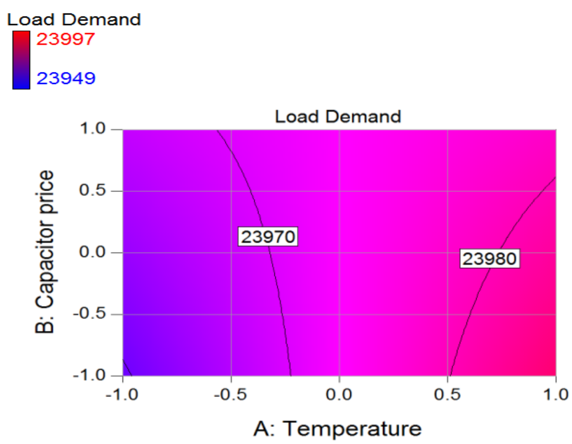


Figure 6.103: Contour plot of temperature vs. capacitor price for load after compensation with minimum permissible voltage

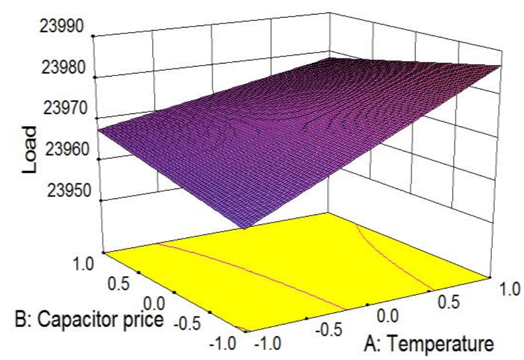


Figure 6.104: Response surface for load vs. temperature vs. capacitor price after compensation with minimum permissible voltage

The red and blue lines in Figure 6.102 intersect each other, the contours in Figure 6.103 are curved lines, and the response surface shown in Figure 6.104 is twisted, thus indicating a significant interaction effect of temperature and capacitor price on load demand after reactive power compensation with minimum permissible voltage at the substation. It can also be seen in Figure 6.102 that at a lower temperature level, load demand with a lower capacitor price is less than load demand with a higher capacitor price, but at a higher temperature level, load demand with a lower capacitor price is greater than load demand with a higher capacitor price. Figure 6.105 indicates that capacitor size has a very small effect at low temperature but a large effect at high temperature.

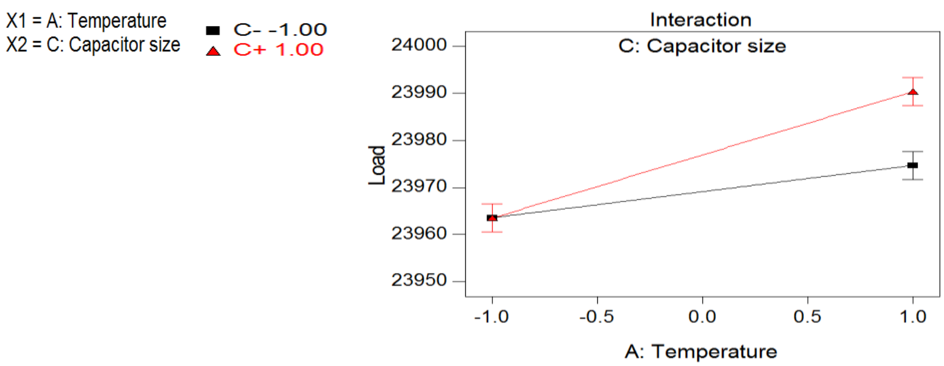
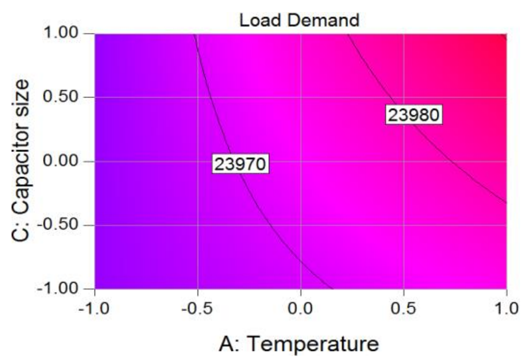


Figure 6.105: Load vs. temperature and capacitor size after reactive power compensation with minimum permissible voltage



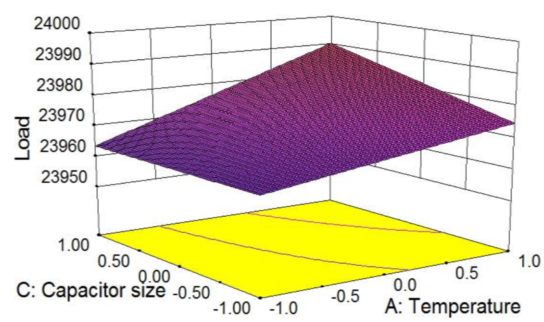


Figure 6.106: Contour plot of temperature vs. capacitor size for load after compensation with minimum permissible voltage

Figure 6.107: Response surface for load vs. temperature vs. capacitor size after compensation with minimum permissible voltage

The BC interaction shown in Figure 6.108 indicates that capacitor size has little effect on load at lower capacitor price but a large effect at a higher capacitor price. It also shows that capacitor price has a negative effect on continuous capacitor size but a positive effect on discrete capacitor size, i.e., load decreases with the increase in capacitor price at a continuous capacitor size and increases with the increase in capacitor price at a discrete capacitor size.

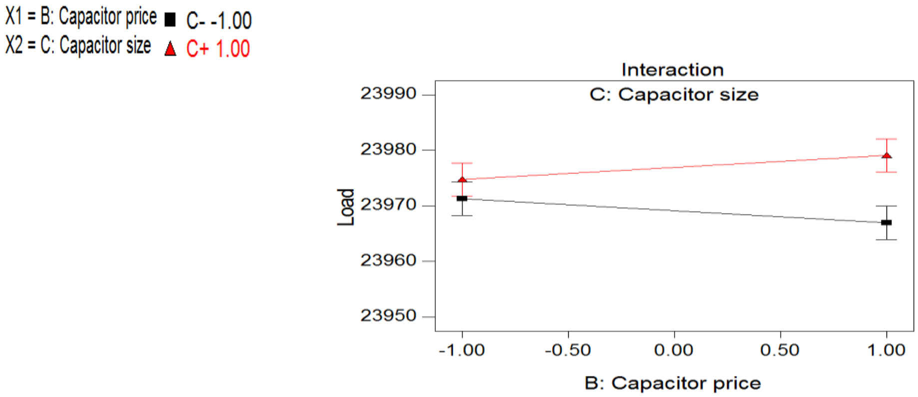
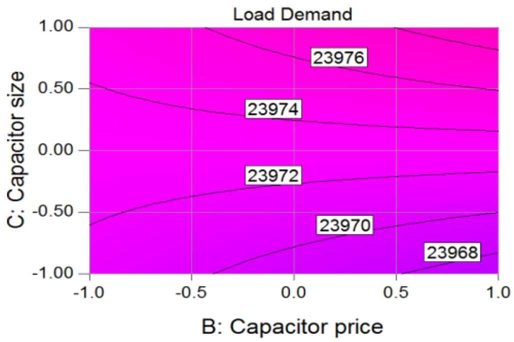


Figure 6.108: Load vs. capacitor price and capacitor size after reactive power compensation with minimum permissible voltage



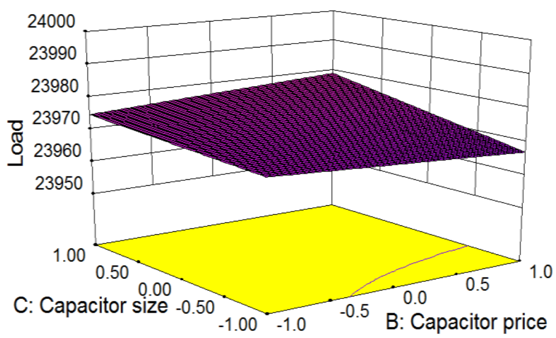


Figure 6.109: Contour plot of capacitor price vs. capacitor size for load after compensation with minimum permissible voltage

Figure 6.110: Response surface for load vs. capacitor price vs. capacitor size after compensation with minimum permissible voltage

The CD interaction shown in Figure 6.111 indicates that capacitor size has a very small effect on load when capacitor phase kVArs are evenly distributed and a very large effect when capacitor phase kVArs are in the ratio of reactive power flow through the line. The AB interaction effect is the largest (8.55% contribution) among two-factor interaction effects, where percentage contributions of AC, BC, and CD are 7.83%, 2.37%, and 5.95%, respectively, as shown in Table 6.12.

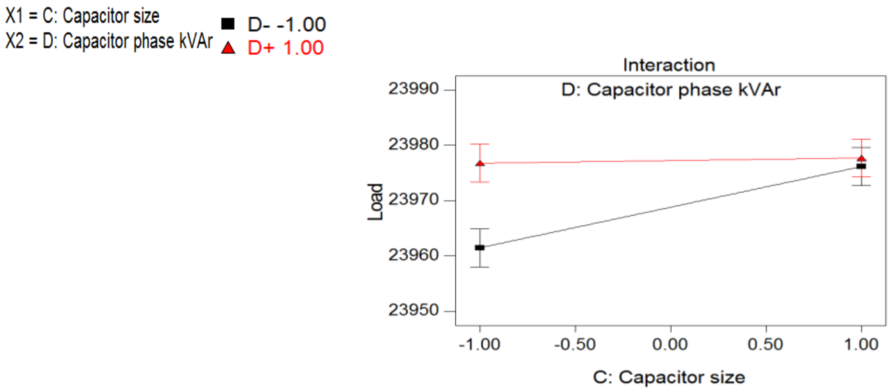


Figure 6.111: Load vs. capacitor size and capacitor phase kVAr after reactive power compensation with minimum permissible voltage

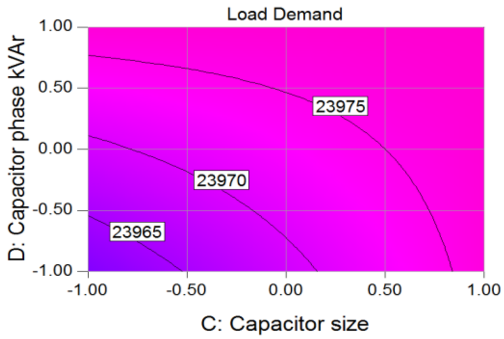


Figure 6.112: Contour plot of capacitor size vs. capacitor phase kVAr for load after compensation with minimum permissible voltage

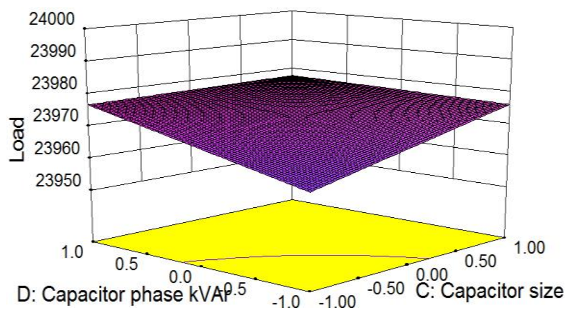


Figure 6.113: Response surface for load vs. capacitor size vs. capacitor phase kVAr after compensation with minimum permissible voltage

Cube Plots of Load after Compensation with Minimum Permissible Voltage at Substation

In Figure 6.114, it is shown that with three variables—temperature, capacitor price, and capacitor size—load demand is minimized (23,957.2 MWh/year) at a lower temperature, lower capacitor price, and discrete capacitor size. Figure 6.115 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—load demand is minimized (23,958.5 MWh/year) at a lower temperature, lower capacitor price, and when capacitor phase kVArs are in the ratio of reactive power flow through the line.

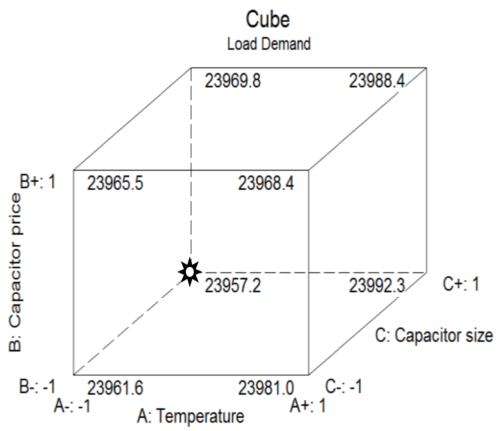


Figure 6.114: Load vs. temperature, capacitor price, and capacitor size after compensation and minimum permissible voltage

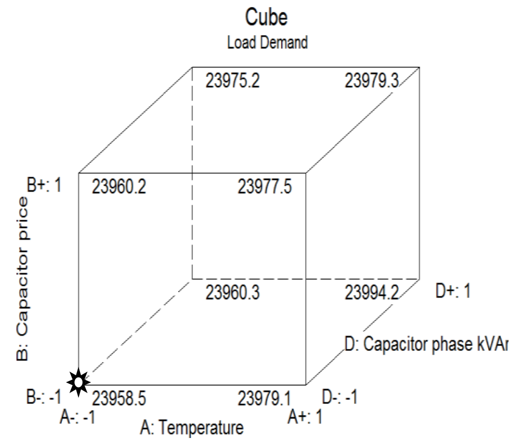


Figure 6.115: Load vs. temperature, capacitor price and capacitor phase kVAr after compensation and minimum permissible voltage

Figure 6.116 shows that with three variables—temperature, capacitor size, and capacitor phase kVAr—load is minimized (23,956 MWh/year) at a lower temperature, continuous capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line. With three variables—capacitor price, capacitor size, and capacitor phase kVAr—load is minimized (23,961 MWh/year) at a higher capacitor price, continuous capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line, as shown in Figure 6.117.

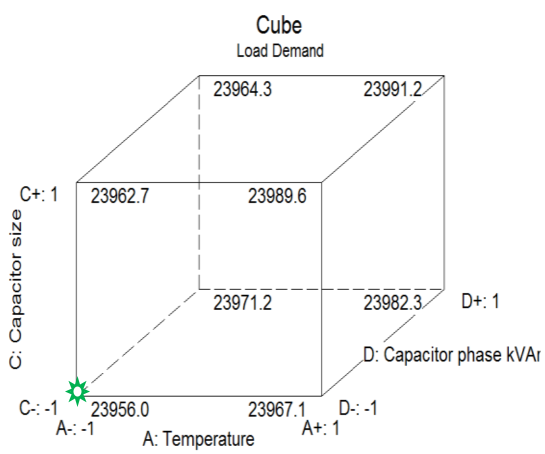


Figure 6.116: Load vs. temperature, capacitor size, and capacitor phase kVAr after compensation and minimum permissible voltage

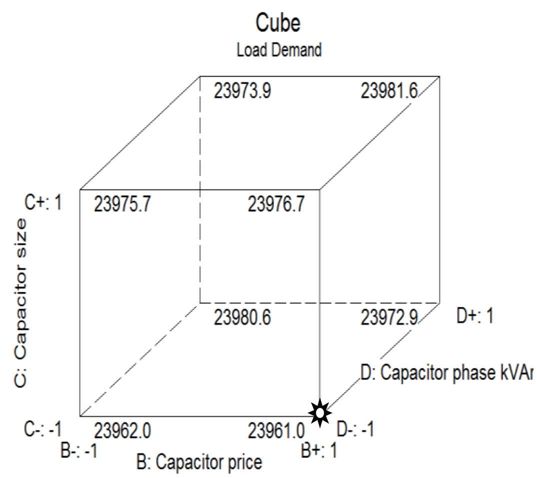


Figure 6.117: Load vs. capacitor price, capacitor size, and capacitor kVAr after compensation and minimum permissible voltage

Factor level combinations that minimize loads for three-factor combinations out of four factors are shown by star marks in the cube plots. The minimum (23,956 MWh/year) of all minimum loads (23,957.2 MWh/year, 23,958.5 MWh/year, 23,956 MWh/year, 23,961 MWh/year) occurs at a lower temperature, continuous capacitor size, and when the capacitor phase kVArs are in the ratio of reactive power flow through the line; this combination of factor levels is indicated by a green star in Figure 6.116.

6.2.3 2^4 Factorial Design for Energy Generation after Reactive Power Compensation with Minimum Permissible Voltage Setting at Substation Regulator

Factor effect estimates, sums of squares, and percentage contribution are shown in Table 6.14. The important effects that emerge from this analysis are the main effects of A, B, and D where temperature, A, has the most significant effect on generation and its percentage contribution is 76.04%. ANOVA for selected factorial model are shown in Table 6.15. In reduced ANOVA, the model is selected in such a way that the residuals lie between –5.5 MWh/year and +5.5 MWh/year.

TABLE 6.14

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN FOR ENERGY GENERATION AFTER REACTIVE POWER COMPENSATION WITH MINIMUM PERMISSIBLE VOLTAGE AT SUBSTATION

Factors	**Effect Estimate**	**Sum of Squares**	**% Contribution**
A-Temperature	75.3675	22721.00	76.0404
B-Capacitor Price	27.8025	3091.92	10.3477
C-Capacitor Size	3.0175	36.42	0.1219
D-Capacitor Phase kVAr	28.5175	3252.99	10.8868
AB	–5.3825	115.89	0.3878
AC	5.6525	127.80	0.4277
AD	–1.6275	10.59	0.0354
BC	6.1875	153.14	0.5125
BD	0.4275	0.73	0.0024
CD	–5.5775	124.43	0.4164
ABC	–2.5775	26.57	0.0889
ABD	–5.0775	103.12	0.3451
ACD	–0.8225	2.71	0.0091
BCD	2.3725	22.52	0.0754
ABCD	–4.7525	90.35	0.3024

TABLE 6.15

ANOVA FOR SELECTED FACTORIAL MODEL FOR ENERGY GENERATION AFTER REACTIVE POWER COMPENSATION WITH MINIMUM PERMISSIBLE VOLTAGE AT SUBSTATION

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**P-Value Prob > F**
Model	29780.68	9	3308.96	199.45	< 0.0001
A-Temperature	*22721.04*	*1*	*22721.04*	*1369.53*	*< 0.0001*
B-Capacitor price	*3091.92*	*1*	*3091.92*	*186.37*	*< 0.0001*
D-Capacitor phase kVAr	*3252.99*	*1*	*3252.99*	*196.08*	*< 0.0001*
AB	*115.89*	*1*	*115.89*	*6.99*	*0.0384*
AC	*127.80*	*1*	*127.80*	*7.70*	*0.0322*
BC	*153.14*	*1*	*153.14*	*9.23*	*0.0229*
CD	*124.43*	*1*	*124.43*	*7.50*	*0.0338*
ABD	*103.12*	*1*	*103.12*	*6.22*	*0.0470*
ABCD	*90.35*	*1*	*90.35*	*5.45*	*0.0584*
Residual	99.54	6	16.59		
Cor Total	29880.22	15			

The regression model for energy generation after reactive power compensation with optimal voltage at the substation can be given in terms of a coded factor using equation (6.6).

$$P_{Gen} = 24554.08 + 37.68*A+13.90*B + 14.26*D – 2.69*A*B + 2.83*A*C + 3.09*B*C – 2.79*C*D – 2.54*A*B*D – 2.38*A*B*C*D \quad (6.6)$$

In terms of actual factors, energy generation can be given by equations (6.6.1) to (6.6.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Gen} = 24352.7467 + 3.6651*T + 49.0667*Cp – 0.5397*T*Cp \quad (6.6.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Gen} = 24376.45 + 2.4677*T + 27.4667*Cp + 0.4757*T*Cp \quad (6.6.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Gen} = 24382.69 + 3.776*T + 51.62*Cp – 0.608*T*Cp \quad (6.6.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Gen} = 24271.47 + 5.8789*T + 106.1867*Cp – 1.6235*T*Cp \quad (6.6.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Energy Generation after Reactive Power Compensation with Minimum Permissible Voltage Setting at Substation

For line loss, $R^2 = \frac{SS_{Model}}{SS_{Total}} = \frac{29780.68}{29880.22} = 0.9966$, which implies 99.66% variability in energy generation can be explained by equation (6.6). $F = \frac{R^2/k}{(1-R^2)/[n-(k+1)]} = \frac{0.9966/9}{(1-0.9966)/[16-(9+1)]} = 195.41$. $F_{\alpha,v_1,v_2} = F_{0.01,9,10} = 4.94$. Since $F > F_{\alpha,v_1,v_2}$, the null hypothesis H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.6) is nonzero. Hence, this F test indicates that the multiple regression model presented by equation (6.6), can be used for predicting energy generation after reactive power compensation with minimum permissible voltage at substation. The normal probability plot of residuals is shown in Figure 6.118. The predicted versus actual plot for energy generation is shown in Figure 6.119. Residuals versus factor effects are plotted in Figure 6.120 to 6.123.

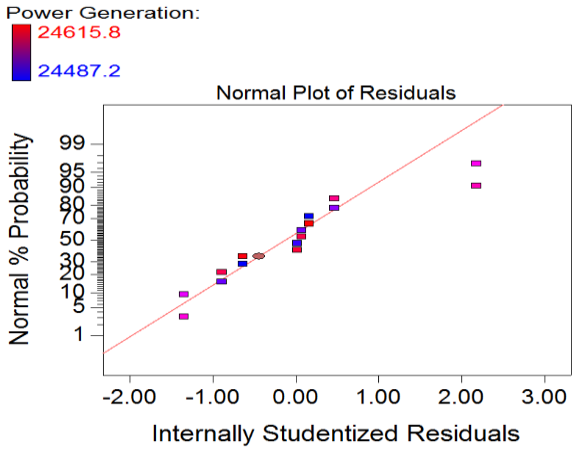


Figure 6.118: Normal probability plot of residuals for generation after compensation with minimum permissible voltage

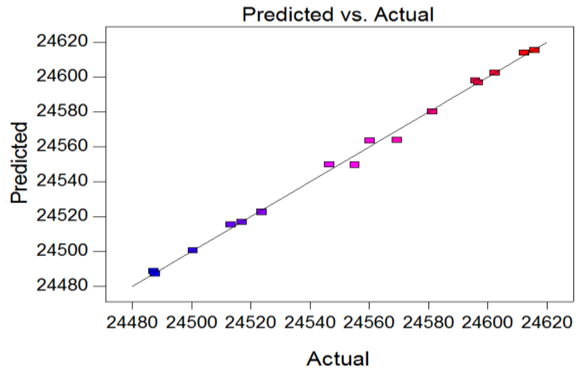


Figure 6.119: Predicted vs. actual plot for generation after compensation with minimum permissible voltage

Figures 6.120, 6.121, and 6.123 show that there are no significant variations in residuals if levels of temperature, capacitor price, and capacitor phase kVAr change, but in Figure 6.122, it can be seen that residuals vary significantly with the variation of capacitor size. Residuals with the capacitor size factor are smaller than residuals with the other three factors.

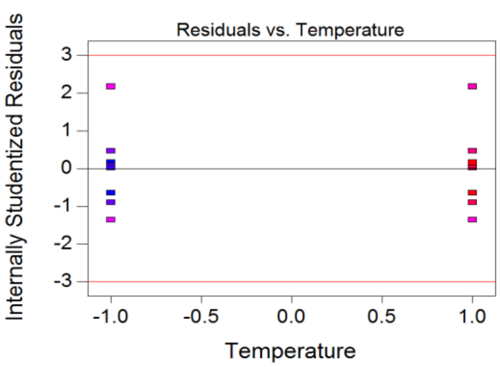


Figure 6.120: Residuals vs. temperature plot for generation after compensation with minimum permissible voltage

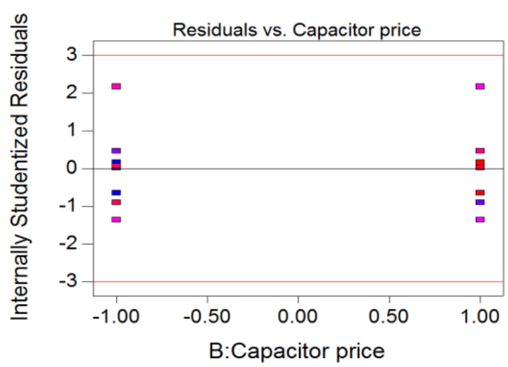


Figure 6.121: residuals vs. capacitor price plot for generation after compensation with minimum permissible voltage

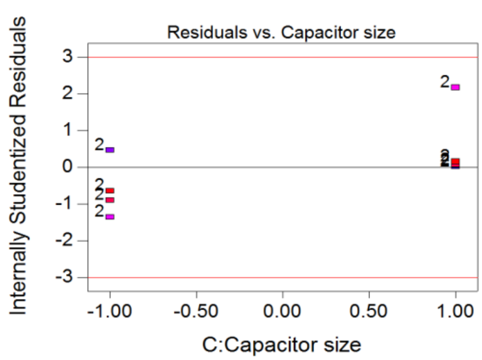


Figure 6.122: Residuals vs. capacitor size plot for generation after compensation with minimum permissible voltage

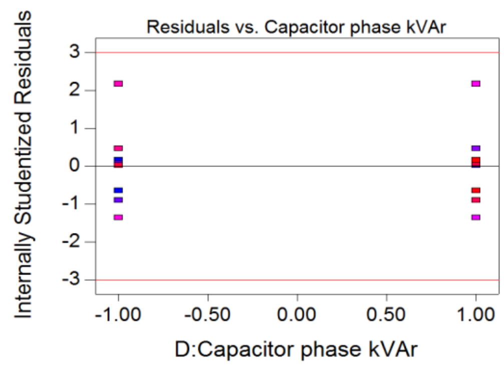


Figure 6.123: Residuals vs. capacitor phase kVAr plot for generation after compensation with minimum permissible voltage

The half-normal and normal probability plots of the factor effects are shown in Figures 6.124 and 6.125, respectively. The effects of A, B, C, and D are plotted in Figures 6.126 to 6.129.

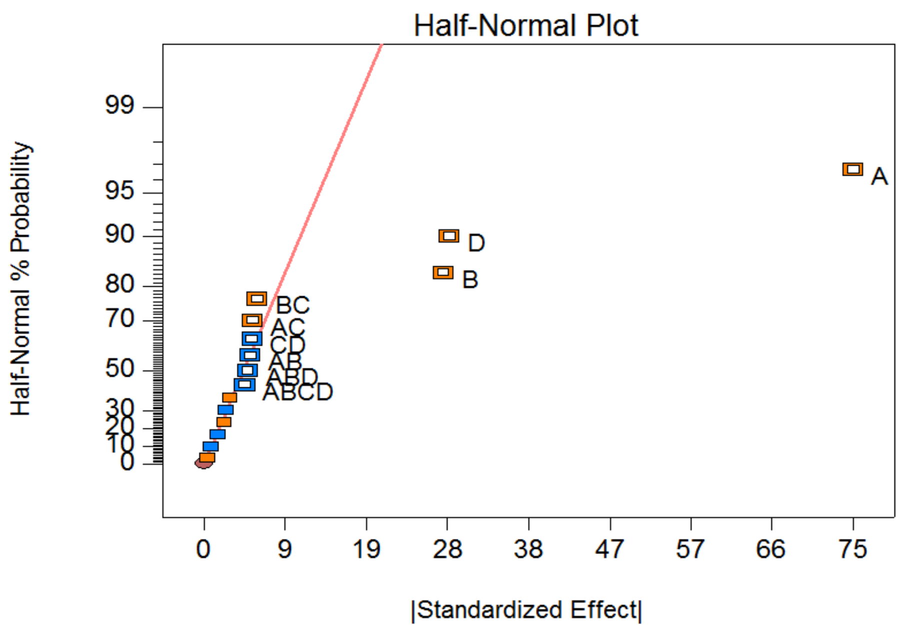


Figure 6.124: Half-normal plot of factor effects on generation after reactive power compensation with minimum permissible voltage

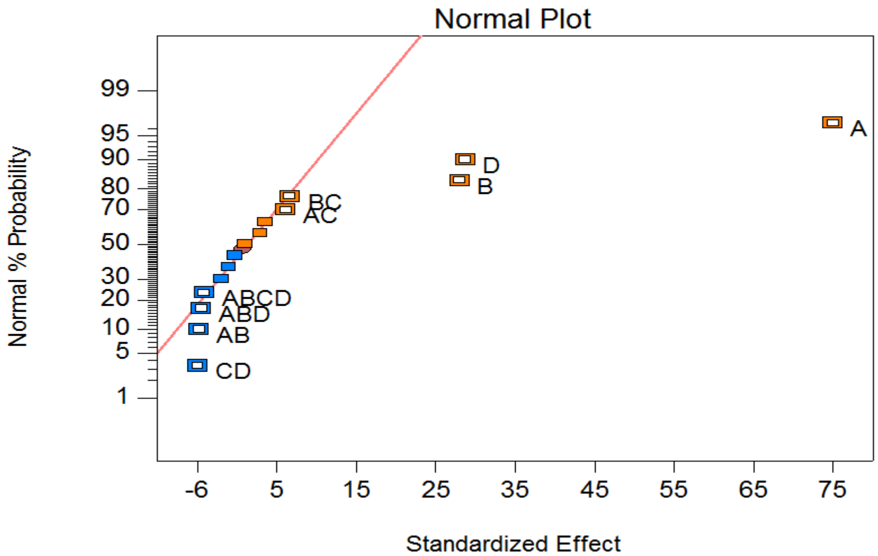


Figure 6.125: Normal plot of factor effects on generation after reactive power compensation with minimum permissible voltage

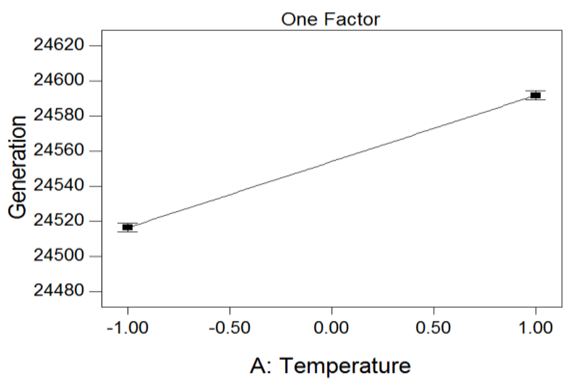


Figure 6.126: Generation vs. temperature after reactive power compensation with minimum permissible voltage

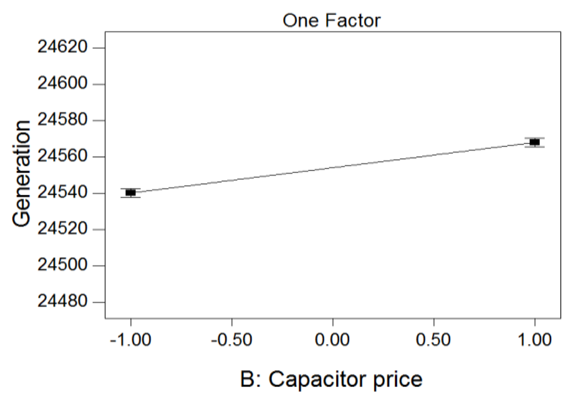


Figure 6.127: Generation vs. capacitor price after reactive power compensation with minimum permissible voltage

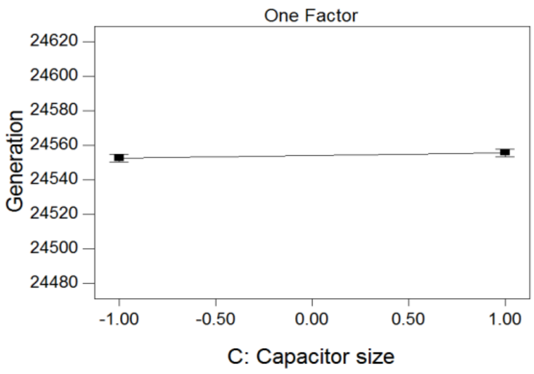


Figure 6.128: Generation vs. capacitor size after reactive power compensation with minimum permissible voltage

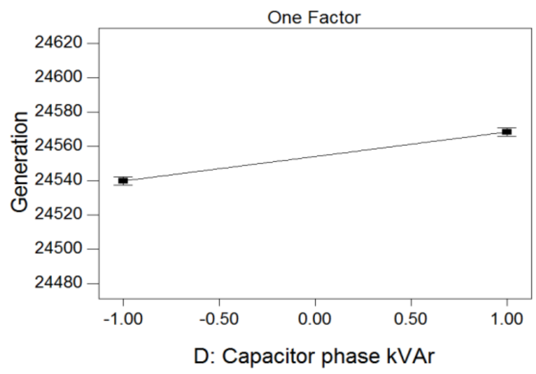


Figure 6.129: Generation vs. capacitor phase kVAr after reactive power compensation with minimum permissible voltage

Interaction effects AB, AC, BC, and CD, which are considered in equation (6.6), are shown in Figures 6.130 to 6.141. Figure 6.130 shows that irrespective of temperature level, generation after reactive power compensation with minimum permissible voltage at substation is greater with a higher capacitor price.

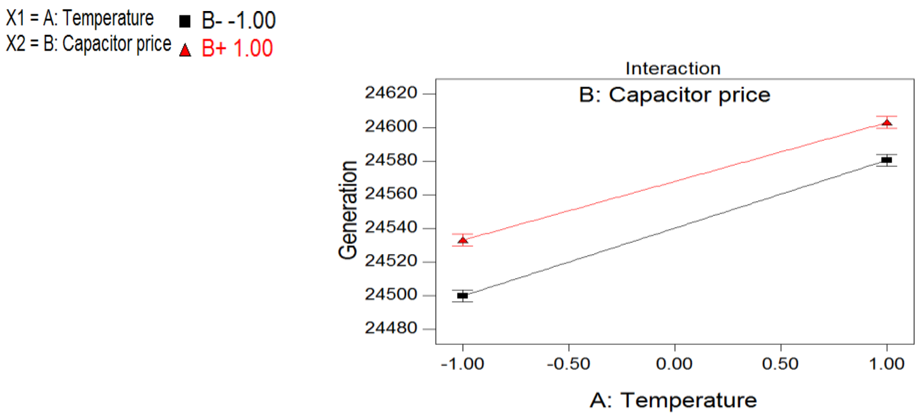


Figure 6.130: Generation vs. temperature and capacitor price after reactive power compensation with minimum permissible voltage at substation

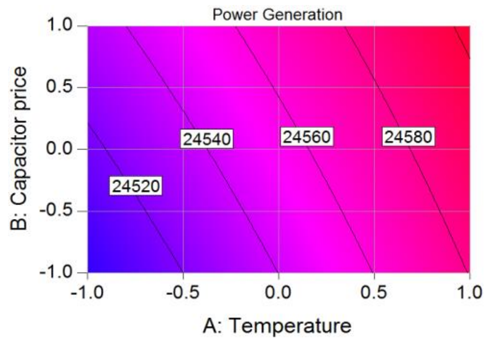


Figure 6.131: Contour plot of temperature vs. capacitor price for generation after compensation with minimum permissible voltage

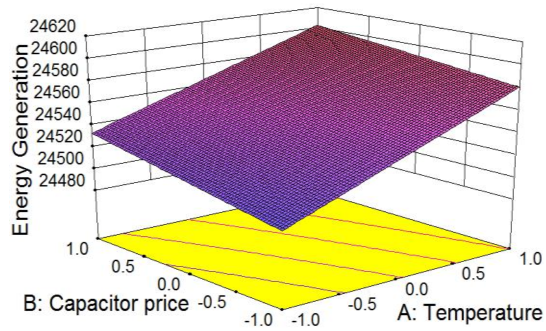


Figure 6.132: Response surface for generation vs. temperature vs. capacitor price after compensation with minimum permissible voltage

Figure 6.133 indicates that although capacitor size, C does not have significant effect on generation, but it has interaction with temperature i.e. at lower temperature generation is smaller for discrete capacitor size with respect to generation with continuous capacitor size where at high temperature generation is larger for discrete capacitor size with respect to generation for continuous capacitor size.

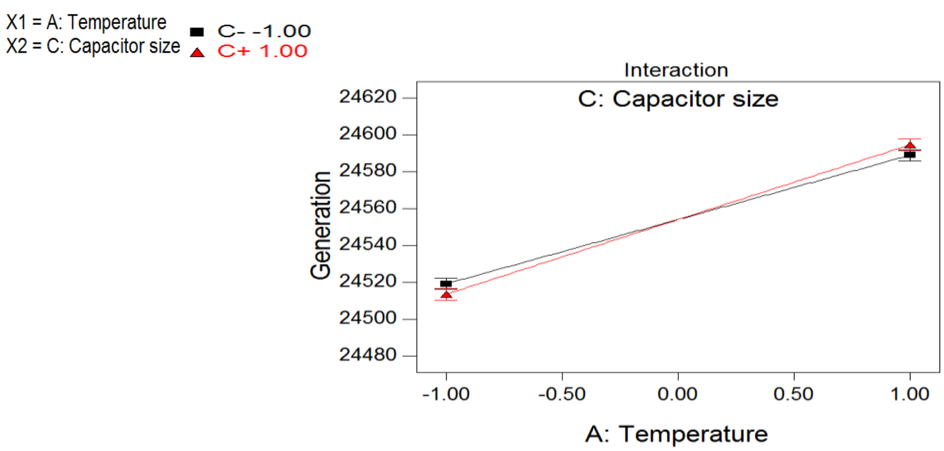


Figure 6.133: Generation vs. temperature and capacitor size after reactive power compensation with minimum permissible voltage

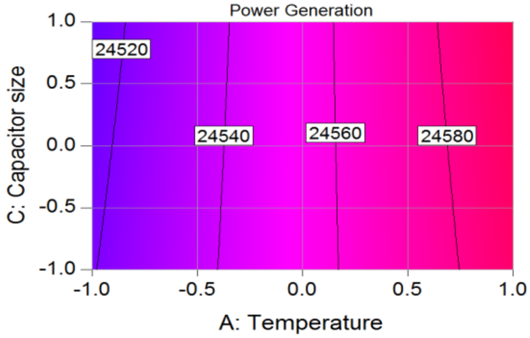


Figure 6.134: Contour plot of temperature vs. capacitor size for generation after compensation with minimum permissible voltage

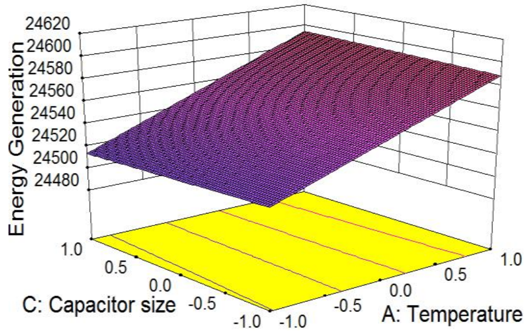


Figure 6.135: Response surface for generation vs. temperature vs. capacitor size after compensation with minimum permissible voltage

Similarly, Figure 6.136 indicates that capacitor size, C, has an interaction with capacitor price, i.e., at a lower capacitor price, generation is smaller for a discrete capacitor size with respect to generation for a continuous capacitor size, where at a higher capacitor price, generation is larger for a discrete capacitor size with respect to generation for a continuous capacitor size.

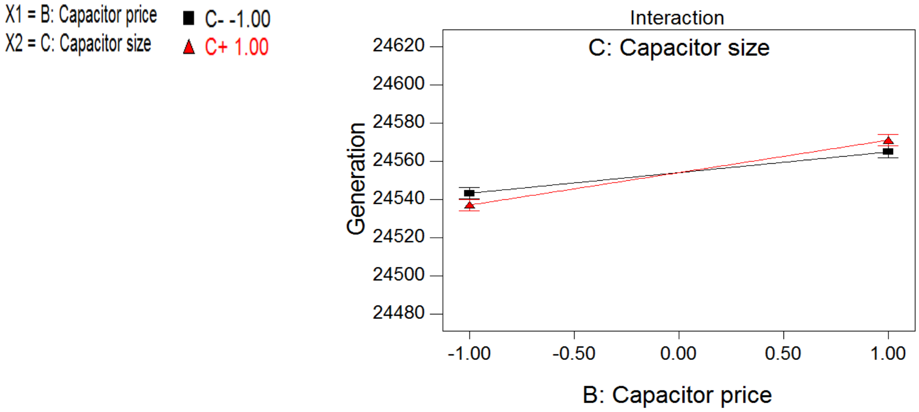


Figure 6.136: Generation vs. capacitor price and capacitor size after reactive power compensation with minimum permissible voltage

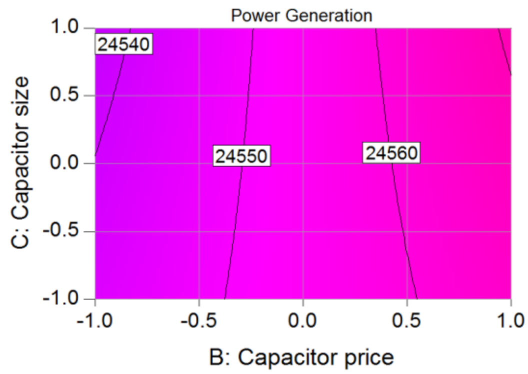


Figure 6.137: Contour plot of capacitor price vs. capacitor size for generation after compensation with minimum permissible voltage

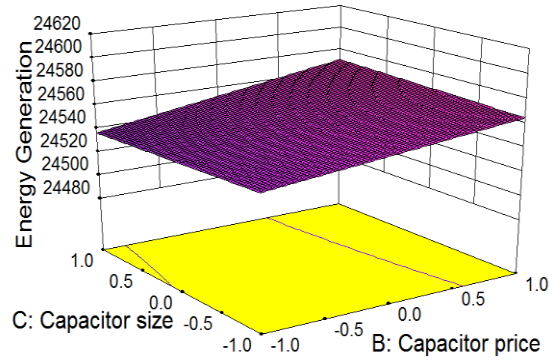


Figure 6.138: Response surface for generation vs. capacitor price vs. capacitor size after compensation with minimum permissible voltage

Figure 6.139 indicates that irrespective of capacitor size, when capacitor phase kVArs are in the ratio of reactive power flow through the line, energy generation is less than the generation with evenly distributed capacitor phase kVArs.

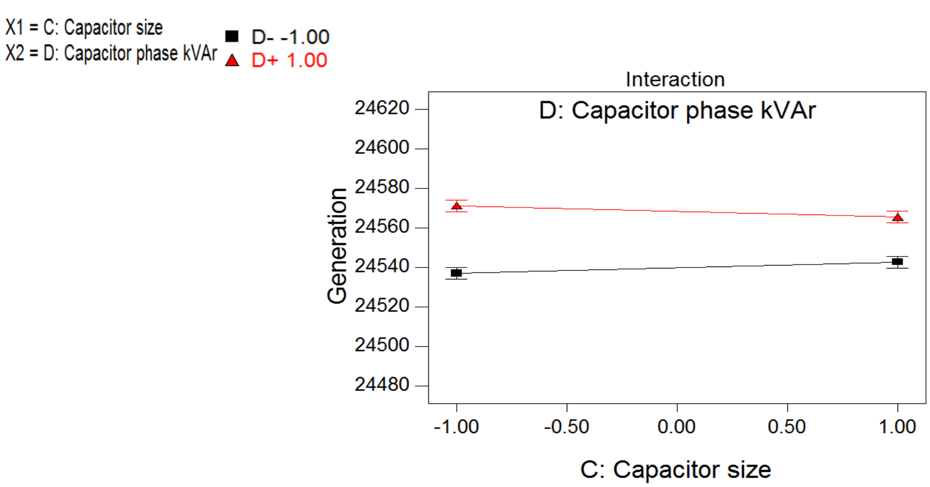


Figure 6.139: Generation vs. capacitor size and capacitor phase kVAr after reactive power compensation with minimum permissible voltage

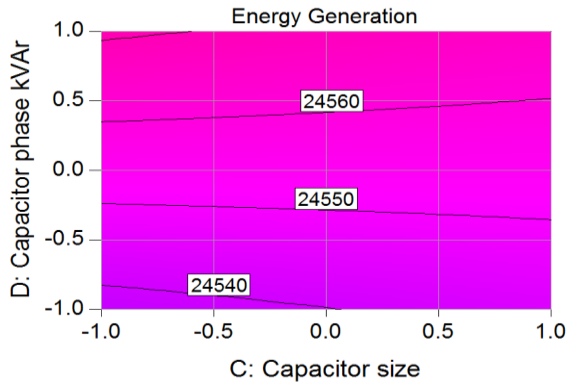


Figure 6.140: Contour plot of capacitor size vs. capacitor phase kVAr for generation after compensation with minimum permissible voltage

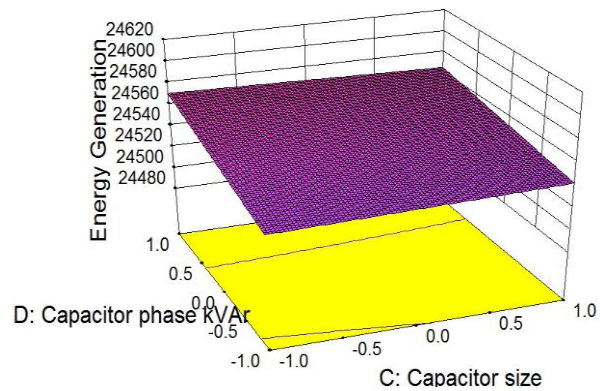


Figure 6.141: Response surface for generation vs. capacitor size vs. capacitor phase kVAr after compensation with minimum permissible voltage

Cube plots of Generation after Compensation with Minimum Permissible Voltage at Substation

In Figure 6.142, it can be seen that with three variables—temperature, capacitor size, and capacitor price—generation is minimized (24,493.9 MWh/year) at a lower temperature, lower capacitor price, and discrete capacitor size. Figure 6.143 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—generation is minimized (24,488.1 MWh/year) at a lower temperature, lower capacitor price, and when capacitor phase kVArs are in the ratio of reactive power flow through the line.

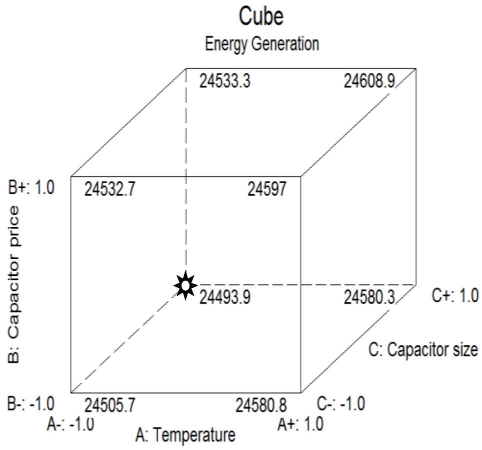


Figure 6.142: Generation vs. temperature, capacitor price, and capacitor size after compensation with minimum permissible voltage

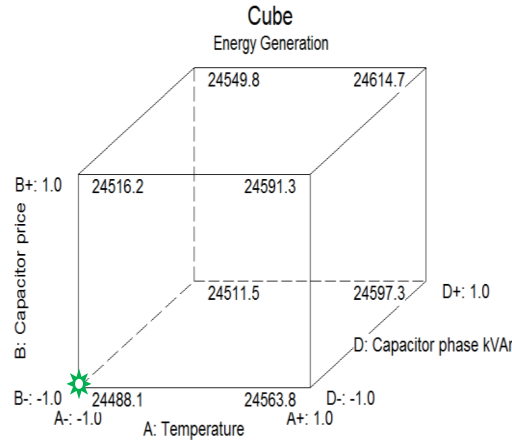


Figure 6.143: Generation vs. temperature, capacitor price, and capacitor phase kVAr after compensation with minimum permissible voltage

Figure 6.144 shows that with three variables—temperature, capacitor size, and capacitor phase kVAr—generation is minimized (24,502.1 MWh/year) at a lower temperature, discrete capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line. With three variables—capacitor price, capacitor size, and capacitor phase kVAr—generation is minimized (24,525.6 MWh/year) at a lower capacitor price, discrete capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line, as shown in Figure 6.145.

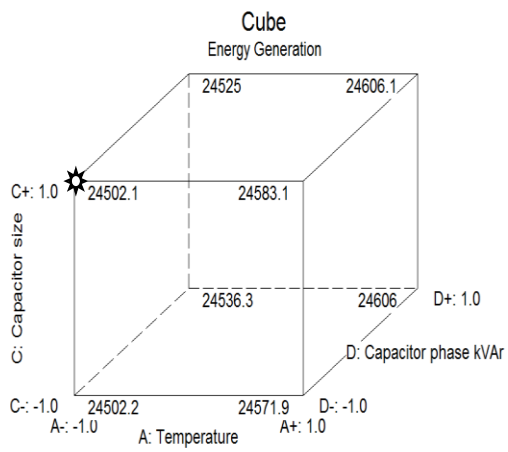


Figure 6.144: Generation vs. temperature, capacitor size, and capacitor phase kVAr after compensation and minimum permissible voltage

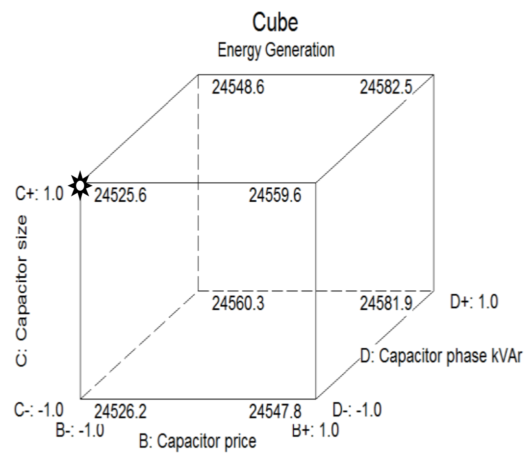


Figure 6.145: Generation vs. capacitor price, capacitor size, and capacitor phase kVAr after compensation and minimum permissible voltage

Factor level combinations that minimize generations for three-factor combinations out of four factors are shown by star marks in cube plots. The minimum (24,488.1 MWh/year) of all minimum generations (24,493.9 MWh/year, 24,488.1 MWh/year, 24,502.1 MWh/year, 24,525.6 MWh/year) occurs at a lower temperature, lower capacitor price, and when capacitor phase kVArs are in the ratio of reactive power flow through the line; this combination of factor levels is indicated by a green star in Figure 6.143.

6.3 2^4 Factorial Design for Line Loss, Load Demand, and Generation after Reactive Power Compensation with Optimal Voltage at Substation Regulator

Table 6.16 shows line loss, load, and generation after reactive power compensation with optimal voltage at the substation.

TABLE 6.16

LINE LOSS. LOAD, AND GENERATION AFTER REACTIVE POWER COMPENSATION WITH OPTIMAL VOLTAGE AT SUBSTATION

Temperature	Capacitor Price	Capacitor Size	Capacitor Phase kVAr	Line Loss (MWh)	Load Demand (MWh)	Energy Generation (MWh)	Response Level
A	**B**	**C**	**D**	**Responses**			
–	–	–	–	518.34	24085.04	24603.38	(1)
+	–	–	–	583.12	24057.00	24640.12	a
–	+	–	–	544.62	24080.06	24624.68	b
+	+	–	–	601.66	24056.26	24657.92	ab
–	–	+	–	513.08	24075.54	24588.62	c
+	–	+	–	570.86	24062.28	24633.14	ac
–	+	+	–	538.62	24081.02	24619.64	bc
+	+	+	–	599.16	24063.26	24662.42	abc
–	–	–	+	536.60	24079.02	24615.62	d
+	–	–	+	599.64	24059.26	24658.90	ad
–	+	–	+	565.38	24064.80	24630.18	bd
+	+	–	+	624.92	24052.78	24677.70	abd
–	–	+	+	533.84	24075.54	24609.38	cd
+	–	+	+	593.38	24055.50	24648.88	acd
–	+	+	+	558.38	24084.78	24643.16	bcd
+	+	+	+	624.92	24038.78	24663.70	abcd

6.3.1 2^4 Factorial Design for Line Loss after Reactive Power Compensation with Optimal Voltage at Substation Regulator

Factor effect estimates, sums of squares, and percentage contributions are shown in Table 6.17. The important effect that emerges from this analysis are A, B, and D. Temperature, A, has the most significant effect on line loss, and its percentage contribution is 76.23%, where capacitor size, C, has the least significant effect on line loss with a percentage contribution of 0.56%. ANOVA for selected factorial model is shown in Table 6.18. In reduced ANOVA, the model is selected in a such way that residuals lie between –4.5 MWh/year and +4.5 MWh/year.

TABLE 6.17

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN FOR LINE LOSS AFTER REACTIVE POWER COMPENSATION WITH OPTIMAL VOLTAGE AT SUBSTATION

Factors	**Effect Estimate**	**Sum of Squares**	**% Contribution**
A-Temperature	61.10	14932.80	76.232
B-Capacitor Price	26.10	2724.84	13.910
C-Capacitor Size	-5.26	110.46	0.564
D-Capacitor Phase kVAr	20.95	1755.61	8.962
AB	-0.19	0.14	0.001
AC	0.00	0.00	0.000
AD	1.07	4.54	0.023
BC	1.38	7.62	0.039
BD	1.44	8.24	0.042
CD	1.25	6.25	0.031
ABC	2.63	27.56	0.141
ABD	1.06	4.49	0.023
ACD	0.87	3.06	0.016
BCD	-0.88	3.06	0.016
ABCD	0.00	0.00	0.000

TABLE 6.18

ANOVA FOR SELECTED FACTORIAL MODEL FOR LINE LOSS AFTER REACTIVE POWER COMPENSATION WITH OPTIMAL VOLTAGE AT SUBSTATION

Source	**Sum of Squares**	**df**	**Mean Square**	**F Value**	**p-value Prob > F**
Model	19523.75	4	4880.94	826.51	< 0.0001
A-Temperature	*14932.84*	*1*	*14932.84*	*2528.64*	*< 0.0001*
B-Capacitor Price	*2724.84*	*1*	*2724.84*	*461.41*	*< 0.0001*
C-Capacitor Size	*110.46*	*1*	*110.46*	*18.70*	*0.0012*
D-Capacitor Phase kVAr	*1755.61*	*1*	*1755.61*	*297.29*	*< 0.0001*
Residual	64.96	11	5.91		
Cor Total	19588.71	15			

The regression model for line loss after reactive power compensation with optimal voltage at the substation can be given in terms of a coded factor by equation (6.7).

$$P_{Loss} = 569.16 + 30.55*A + 13.05*B - 2.63*C + 10.47*D \quad (6.7)$$

In terms of actual factor, the equation for line loss can be given by equations (6.7.1) to (6.7.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Loss} = 413.12 + 2.444*T + 34.8*C_p \quad (6.7.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Loss} = 407.86 + 2.444*T + 34.8*C_p \quad (6.7.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Loss} = 434.06 + 2.444*T + 34.8*C_p \quad (6.7.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Loss} = 428.80 + 2.444*T + 34.8*C_p \quad (6.7.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Line Loss After Reactive Power Compensation with Optimal Voltage at Substation

For line loss, $R^2 = \frac{19523.75}{19588.71} = 0.9967$, which implies that the 99.67 % variability in line loss can be explained by equation (6.7). $F = \frac{0.9967/4}{(1-0.9967)/[16-(4+1)]} = 830.58$, $F_{\alpha,v_1,v_2} = F_{0.01,4,11} = 5.67$. Since $F > F_{\alpha,v_1,v_2}$, the null hypothesis H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.7) is nonzero. Hence, this F test indicates that the multiple regression model presented by (6.7) can be used for predicting line loss after reactive power compensation with optimal voltage at the substation. The normal probability plot of residuals is shown in Figure 6.146. The predicted versus actual plot for line loss is shown in Figure 6.147. Residuals versus factor effects are plotted in Figures 6.148 to 6.151.

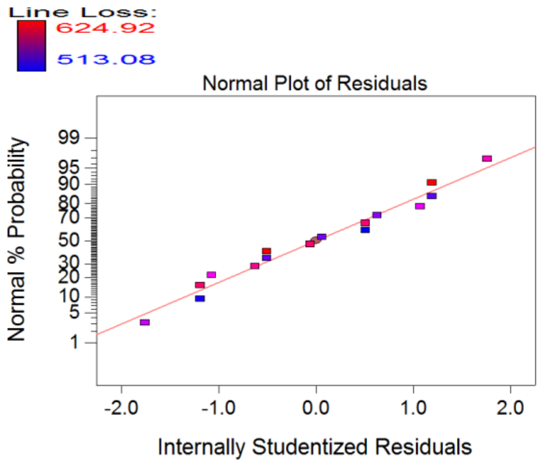


Figure 6.146: Normal probability plot of residuals for line loss after reactive power compensation with optimal voltage

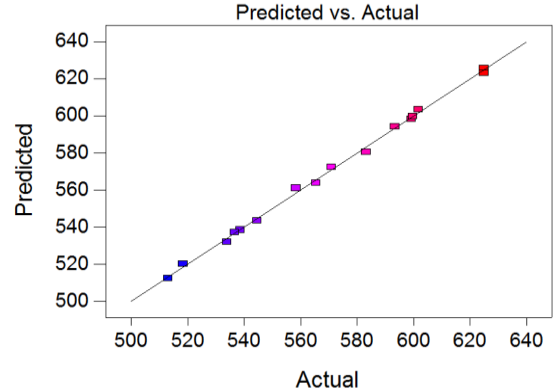


Figure 6.147: Predicted vs. actual plot for line loss after reactive power compensation with optimal voltage

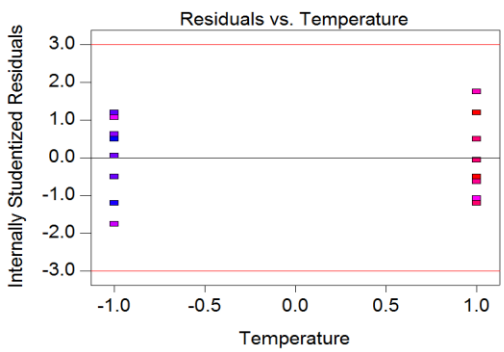


Figure 6.148: Residuals vs. temperature plot for line loss after reactive power compensation with optimal voltage

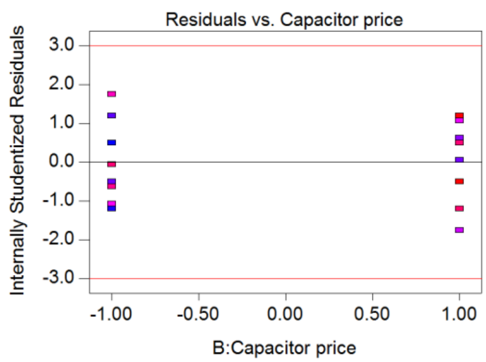


Figure 6.149: Residuals vs. capacitor price plot for line loss after reactive power compensation with optimal voltage

From the residuals versus factors plots shown in Figures 6.150 and 6.151, it can be seen that if the factor level changes, then there is no significant variation in residuals of line loss after reactive power compensation with optimal voltage at the substation, whereas there are significant variations in residuals with the variation of factor level for the first and second cases. Half-normal and normal probability plots of factor effects are shown in Figures 6.152 and 6.153. The main effects of A, B, C, and D are plotted in Figures 6.154 to 6.157.

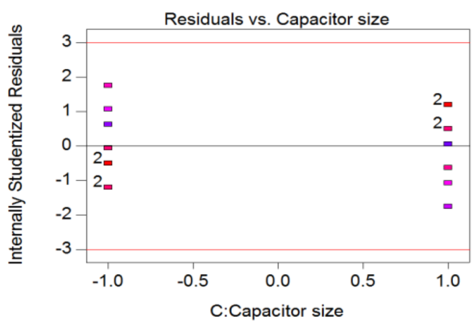


Figure 6.150: Residuals vs. capacitor size plot for line loss after reactive power compensation with optimal voltage

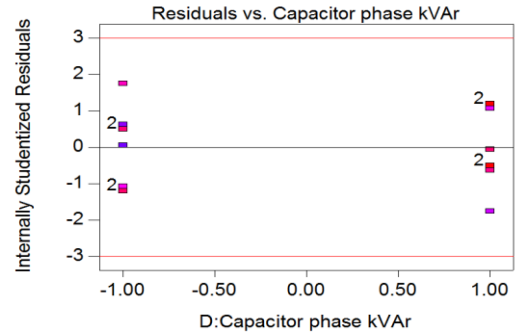


Figure 6.151: Residuals vs. capacitor phase kVAr plot for line loss after reactive power compensation with optimal voltage

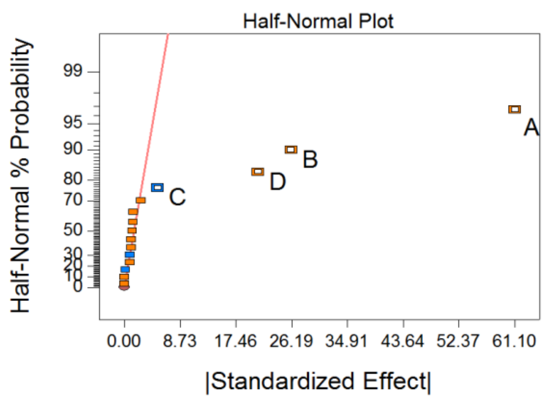


Figure 6.152: Half-normal plot of factor effects on line loss after reactive power compensation with optimal voltage

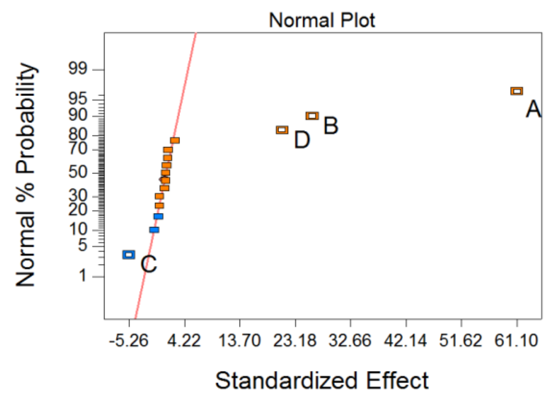


Figure 6.153: Normal plot of factor effects on line loss after reactive power compensation with optimal voltage

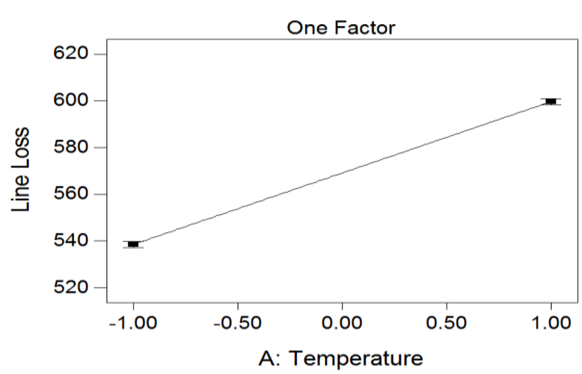


Figure 6.154: Line loss vs. temperature after compensation with optimal voltage

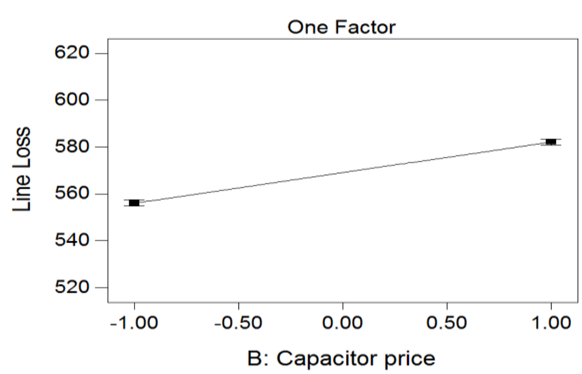


Figure 6.155: Line loss vs. capacitor price after compensation with optimal voltage

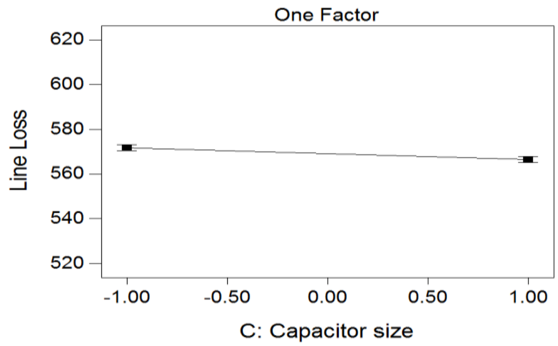


Figure 6.156: Line loss vs. capacitor size after compensation with optimal voltage

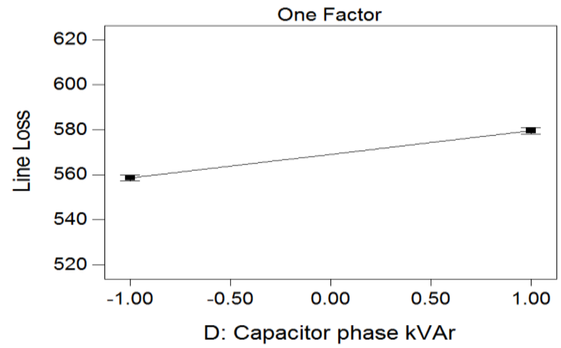


Figure 6.157: Line loss vs. capacitor phase kVAr after compensation with optimal voltage

Only the BD interaction effect, which is the greatest among other two-factor interaction effects, is shown in Figures 6.158 to 6.160. As can be seen, there is a lack of interaction between capacitor price and capacitor phase kVAr. Irrespective of capacitor price, line loss is higher when capacitor phase kVArs are evenly distributed.

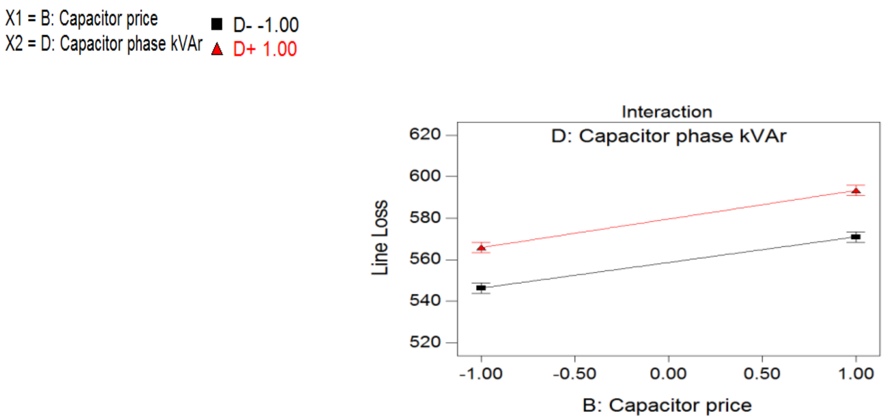


Figure 6.158: Line loss vs. capacitor price and capacitor phase kVAr after reactive power compensation with optimal voltage

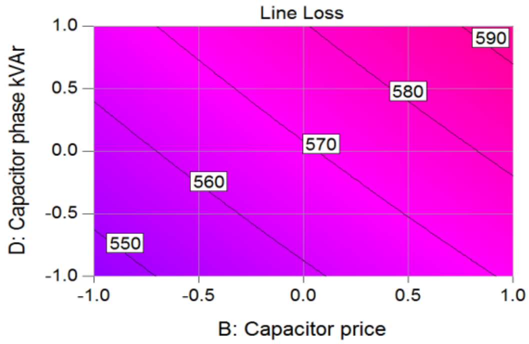


Figure 6.159: Contour plot of capacitor price vs. capacitor phase kVAr for line loss after compensation with optimal voltage

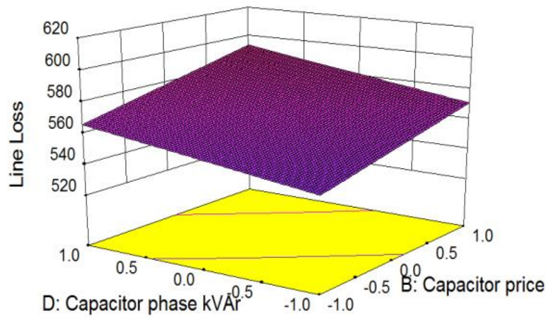


Figure 6.160: Response surface for line loss vs. capacitor price and capacitor phase kVAr after compensation with optimal voltage

Cube Plots of Line Loss after Compensation with Optimal Voltage at Substation Regulator

In Figure 6.161, it is shown that with three variables—temperature, capacitor price, and capacitor size—line loss is minimized (522.93 MWh/year) at a lower temperature, lower capacitor price, and discrete capacitor size. Figure 6.162 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—line loss is minimized (515.08 MWh/year) at a lower temperature, lower capacitor price, and when capacitor phase kVArs are in the ratio of reactive power flow through the line.

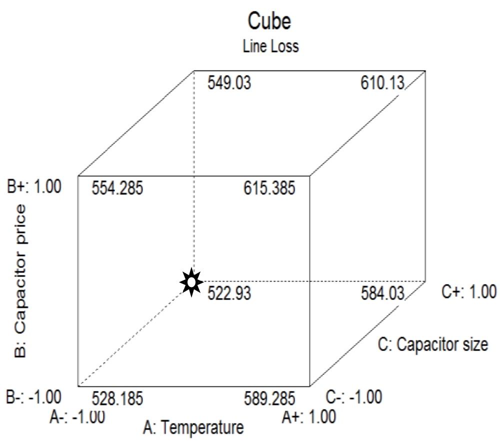


Figure 6.161: Line loss vs. temperature, capacitor price, and capacitor size after compensation with optimal voltage

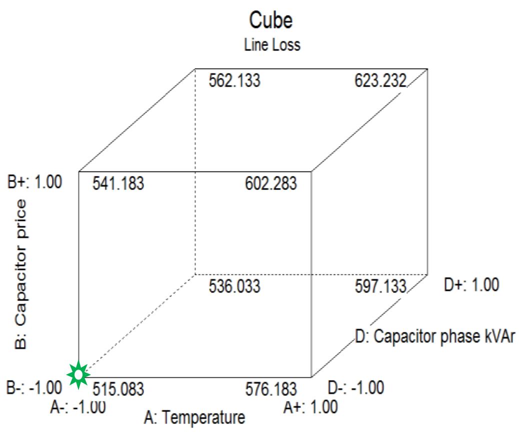


Figure 6.162: line loss vs. temperature, capacitor price, and capacitor phase kVAr after compensation with optimal voltage

In Figure 6.163, it is shown that with three variables—temperature, capacitor size, and capacitor phase kVAr—line loss is minimized (525.5 MWh/year) at a lower temperature, discrete capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line. With three variables—capacitor price, capacitor size, and capacitor phase kVAr—line loss is minimized (543.005 MWh/year) at a lower capacitor price, discrete capacitor size, and when capacitor phase kVArs are in the ratio of reactive power flow through the line as shown in Figure 6.164.

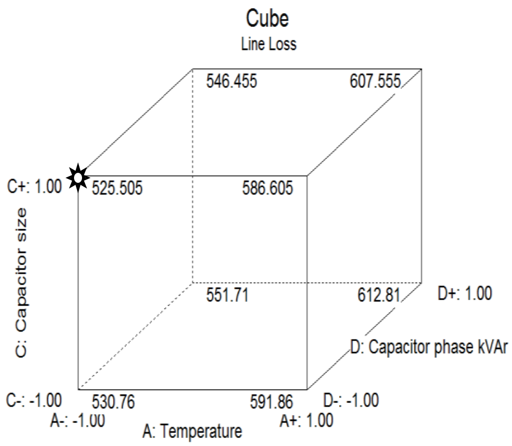


Figure 6.163: line loss vs. temperature, capacitor size and capacitor phase kVAr after compensation with optimal voltage

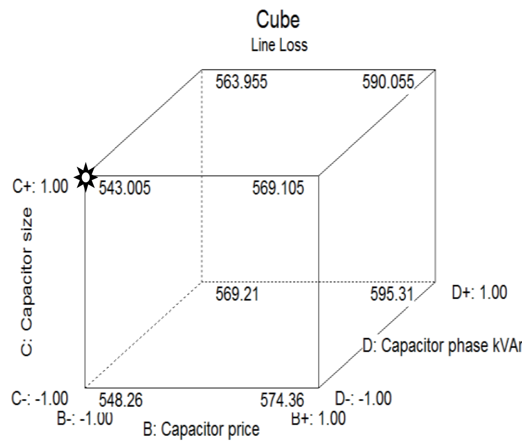


Figure 6.164: Line loss vs. capacitor price, capacitor size and capacitor phase kVAr after compensation with optimal voltage

Factor level combinations that minimize line loss for three-factor combinations out of four factors are shown by star marks in the cube plots. The minimum (515.08 MWh/year) of all minimum line loss (522.93 MWh/year, 515.08 MWh/year, 525.5 MWh/year, 543.005 MWh/year) occurs at a lower temperature, lower capacitor price, and when capacitor phase kVArs are in the ratio of reactive power flow through the line; this combination of factor levels is indicated by a green star in Figure 6.162.

For three-factor combinations, the optimal combinations of factor levels that minimize line loss for three—cases namely (i) line loss after reactive power compensation without voltage reduction, (ii) line loss after reactive power compensation with minimum voltage at the substation, and (iii) line loss after reactive power compensation with optimal voltage at the substation—are summarized in Table 6.15. Among three-factor combinations, line loss is minimized at a factor combination of temperature, capacitor price, and capacitor phase kVArs, which are the three dominant one-factor effects on line loss for three cases, as shown in Tables 6.3, 6.10, and 6.17; these three-factor-level combinations that minimize line loss are shown in italics in Table 6.19.

TABLE 6.19

OPTIMAL COMBINATION OF FACTOR LEVELS FOR MINIMUM LINE LOSS FOR THREE CASES

Case	**Factor Combinations**			
	Temperature, Capacitor Price, Capacitor Size	**Temperature, Capacitor Price, Capacitor Phase kVAr**	**Temperature, Capacitor Size, Capacitor Phase kVAr**	**Capacitor Price, Capacitor Size, Capacitor Phase kVAr**
After Reactive Power Compensation	Lower temperature, lower capacitor price, and discrete capacitor size	*Lower temperature, lower capacitor price, and capacitor phase kVArs in ratio of reactive power flow through the line*	Lower temperature, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line	Lower capacitor price, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line
After Reactive Power Compensation + Minimum Voltage at Substation	Lower temperature, lower capacitor price, and discrete capacitor size	*Lower temperature, lower capacitor price, and capacitor phase kVArs in ratio of reactive power flow through the line*	Lower temperature, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line	Lower capacitor price, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line
After Reactive Power Compensation + Optimal Voltage at Substation	Lower temperature, lower capacitor price, and discrete capacitor size	*Lower temperature, lower capacitor price, and capacitor phase kVArs in ratio of reactive power flow through the line*	Lower temperature, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line	Lower capacitor price, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line

Optimal Combination of Factor Levels for Minimum Line Loss

6.3.2 2^4 Factorial Design for Load Demand after Reactive Power Compensation with Optimal Voltage at Substation Regulator

Factor effect estimates, sums of square, and percentage contribution are shown in Table 6.20. The important effects from this analysis are the main effects of A, B, and D and the interaction effects of AB, BC, BD, ABC, ABD, ACD, and ABCD. ANOVA for the selected model is shown in Table 6.21. In reduced ANOVA, the model is selected in such a way that residuals lie between –2.5 MWh/year and +2.5 MWh/year.

TABLE 6.20

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN FOR LOAD DEMAND AFTER REACTIVE POWER COMPENSATION WITH OPTIMAL VOLTAGE AT SUBSTATION

Factors	Effect Estimate	Sum of Squares	% Contribution
A-Temperature	-22.59	2040.33	74.297
B-Capacitor price	-3.43	47.06	1.714
C-Capacitor size	0.31	0.38	0.014
D-Capacitor phase kVAr	-6.25	156.25	5.689
AB	-2.31	21.34	0.777
AC	-1.68	11.29	0.411
AD	-1.87	13.99	0.509
BC	3.16	40.32	1.468
BD	-3.62	52.27	1.904
CD	-0.63	1.56	0.057
ABC	-5.31	112.57	4.099
ABD	-2.25	20.16	0.734
ACD	-6.88	189.61	6.905
BCD	0.13	0.07	0.002
ABCD	-3.12	38.94	1.418

TABLE 6.21

ANOVA FOR SELECTED FACTORIAL MODEL FOR LOAD AFTER REACTIVE POWER COMPENSATION WITH OPTIMAL VOLTAGE AT SUBSTATION

Source	Sum of Squares	df	Mean Square	F Value	P-Value Prob > F
Model	2718.86	10	271.89	49.81	0.0002
A-Temperature	*2040.33*	*1*	*2040.33*	*373.80*	*< 0.0001*
B-Capacitor Price	*47.06*	*1*	*47.06*	*8.62*	*0.0324*
D-Capacitor Phase kVAr	*156.25*	*1*	*156.25*	*28.63*	*0.0031*
AB	*21.34*	*1*	*21.34*	*3.91*	*0.1049*
BC	*40.32*	*1*	*40.32*	*7.39*	*0.0419*
BD	*52.27*	*1*	*52.27*	*9.58*	*0.0270*
ABC	*112.57*	*1*	*112.57*	*20.62*	*0.0062*
ABD	*20.16*	*1*	*20.16*	*3.69*	*0.1127*
ACD	*189.61*	*1*	*189.61*	*34.74*	*0.0020*
ABCD	*38.94*	*1*	*38.94*	*7.13*	*0.0443*
Residuals	27.29	5	5.46		
Cor Total	2746.15	15			

The regression model for load demand after reactive power compensation with optimal voltage at the substation can be given in terms of a coded factor by equation (6.8).

$$P_{Load} = 24066.93 - 11.29*A - 1.71*B - 3.12*D - 1.16*A*B + 1.59*B*C - 1.81*B*D - 2.65*A*B*C - 1.12*A*B*D - 3.44*A*C*D - 1.56*A*B*C*D \qquad (6.8)$$

In terms of actual factors, load demand can be given by equations (6.8.1) to (6.8.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Load} = 24134.34667 - 1.5424*T - 12.3733*Cp + 0.224*T*Cp \qquad (6.8.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Load} = 24071.58667 - 0.2363*T + 13.5467*Cp - 0.241*T*Cp \qquad (6.8.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Load} = 24094.03333 - 0.2154*T - 4.1067*Cp - 0.254*T*Cp \qquad (6.8.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Load} = 24031.9933 + 1.0715*T + 46.7733*Cp - 1.384*T*Cp \qquad (6.8.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Load Demand after Reactive Power Compensation with Optimal Voltage at Substation:

For line loss, $R^2 = \frac{2718.86}{2746.15} = 0.99$, which implies that 99% variability in line loss can be explained by equation (6.6). $F = \frac{0.99/10}{(1-0.99)/[16-(10+1)]} = 49.5$, $F_{\alpha,v_1,v_2} = F_{0.01,10,5} = 10.05$. Since $F > F_{\alpha,v_1,v_2}$, the null hypothesis H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.8) is nonzero. Hence, this F test indicates that the multiple regression model presented by equation (6.8) can be used for predicting load after reactive power compensation with optimal voltage at subsation. The normal probability plot of residuals is shown in Figure 6.165. The predicted versus actual plot for load demand is shown in Figure 6.166. Residuals versus factor effects are plotted in Figure 6.167 to 6.170.

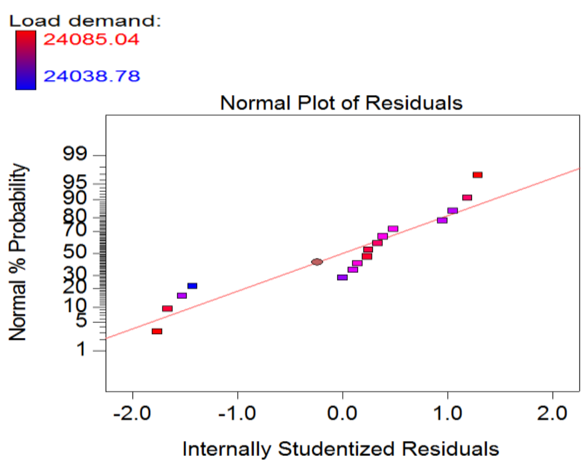


Figure 6.165: Normal probability plot of residuals for load demand after reactive power compensation with optimal voltage

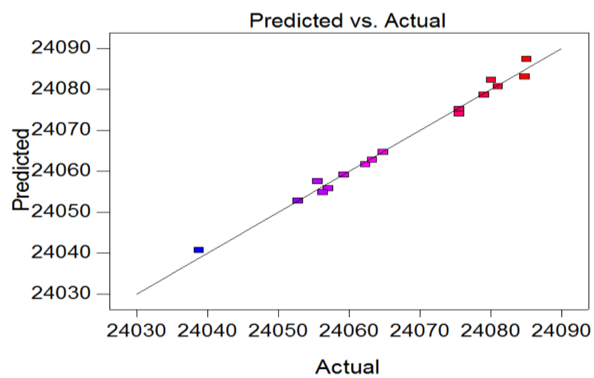


Figure 6.166: Predicted vs. actual plot for load demand after reactive power compensation with optimal voltage

Figures 6.167 to 6.170 show that, if factor levels change, there are no significant variations in residuals of load demand after reactive power compensation with optimal voltage at the substation. The half-normal and normal probability plots of the factor effects are shown in Figures 6.171 and 6.172, respectively.The effects of A, B, C, and D are plotted in Figures 6.173 to 6.176.

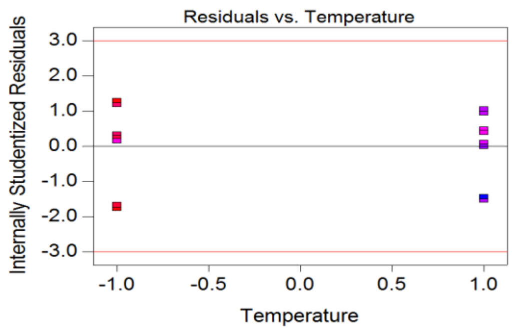


Figure 6.167: Residuals vs. temperature plot for load demand after reactive power compensation with optimal voltage

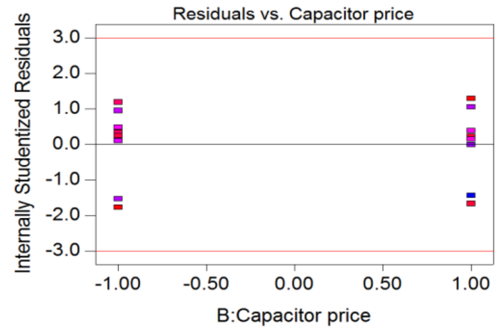


Figure 6.168: residuals vs. capacitor price plot for load demand after reactive power compensation with optimal voltage

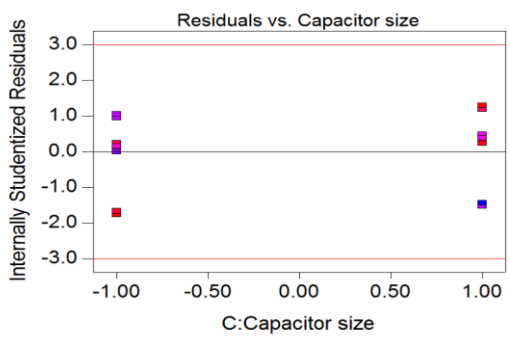


Figure 6.169: Residuals vs. capacitor size plot for load demand after reactive power compensation with optimal voltage

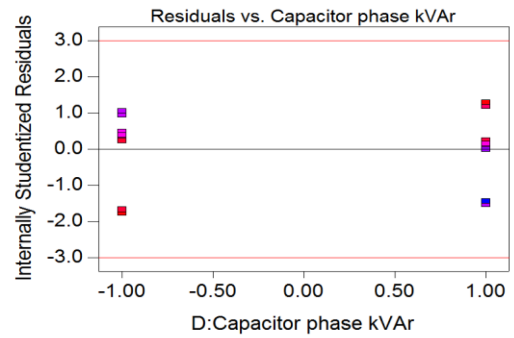


Figure 6.170: Residuals vs. capacitor phase kVAr plot for load demand after reactive power compensation with optimal voltage

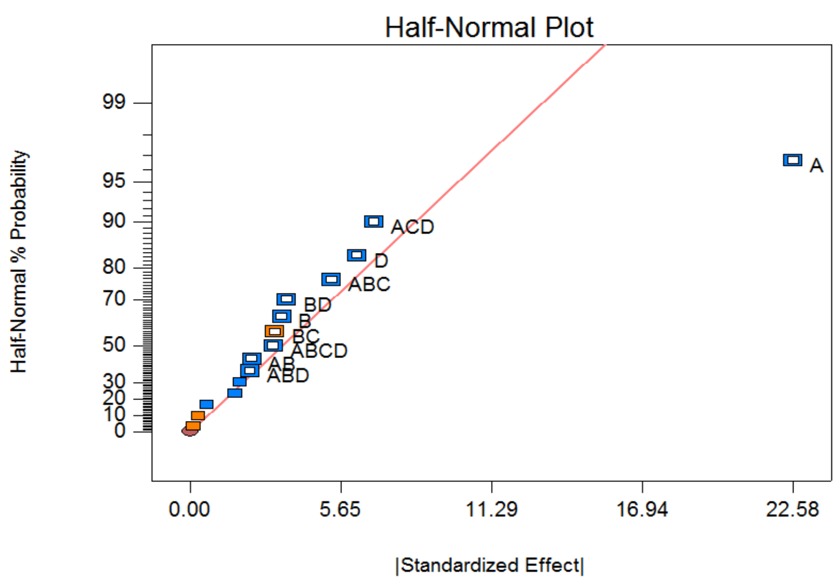


Figure 6.171: Half-normal plot of factor effects on load demand after reactive power compensation with optimal voltage

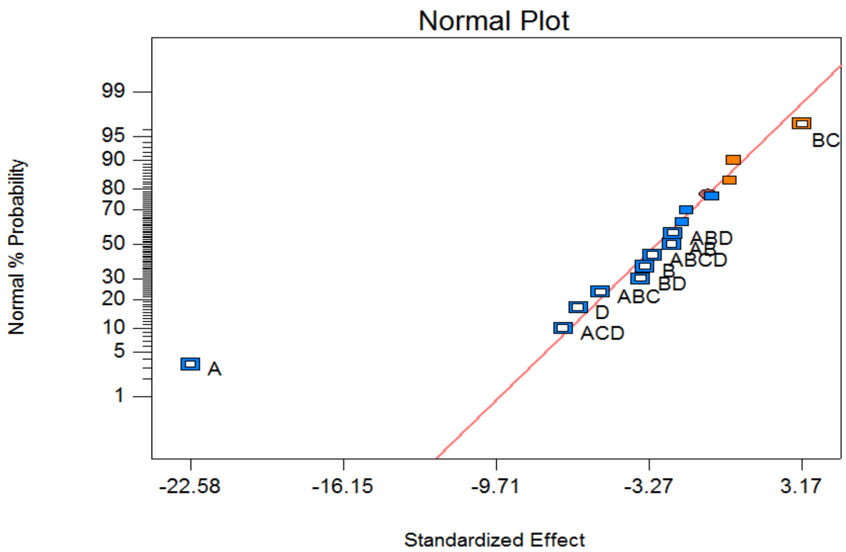


Figure 6.172: Normal plot of factor effects on load demand after reactive power compensation with optimal voltage

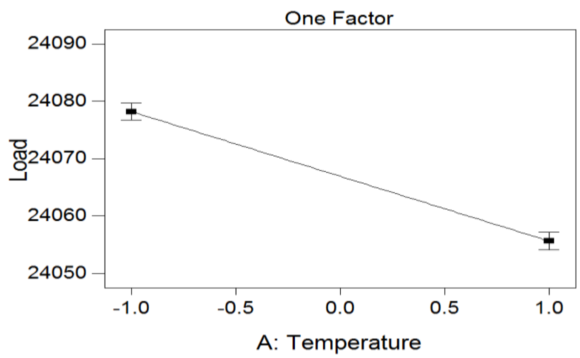


Figure 6.173: Load vs. temperature after compensation with optimal voltage

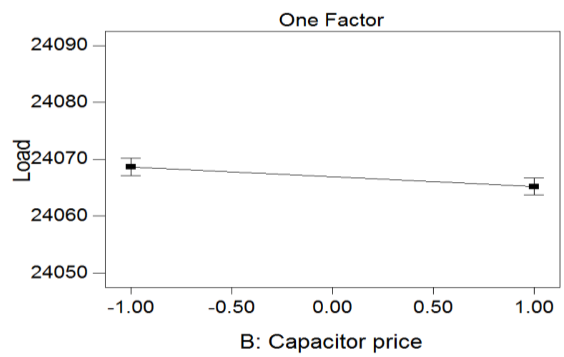


Figure 6.174: Load vs. capacitor price after compensation with optimal voltage

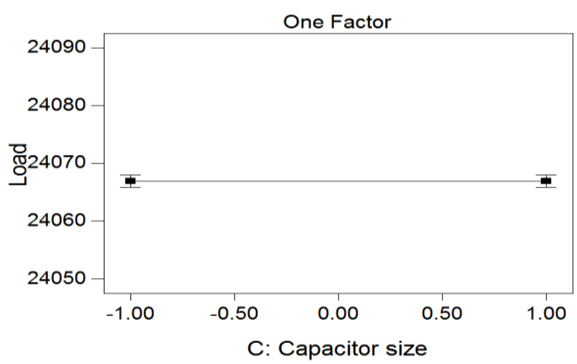


Figure 6.175: Load vs. capacitor size after reactive power compensation with optimal voltage

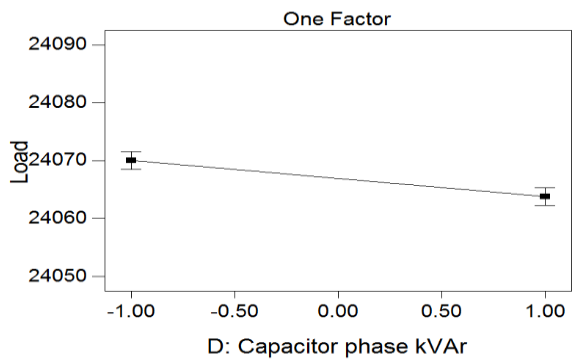


Figure 6.176: Load vs. capacitor phase kVAr after reactive power compensation with optimal voltage

The significant two-factor interaction effects AB, BC, and BD are shown in Figures 6.177 to 6.185.

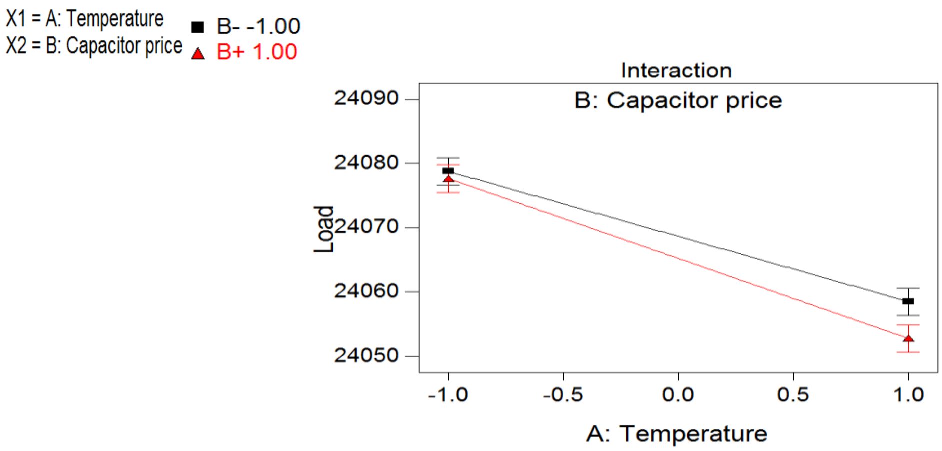


Figure 6.177: Load vs. temperature and capacitor price after reactive power compensation with optimal voltage at substation

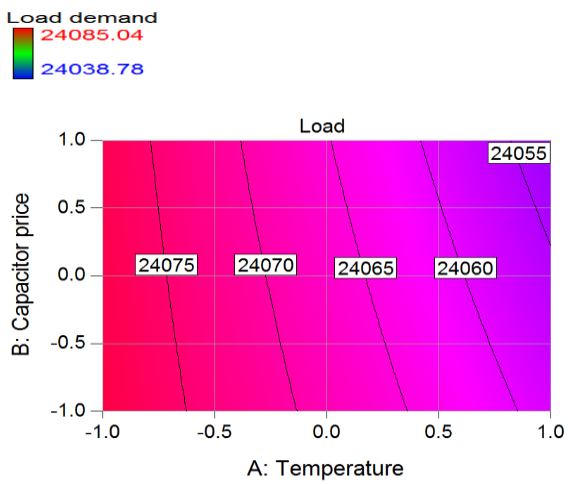


Figure 6.178: Contour plot of temperature vs. capacitor price for load after compensation with optimal voltage

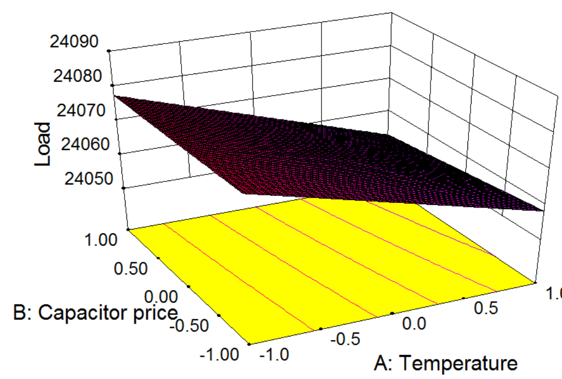


Figure 6.179: Response surface for load vs. temperature vs. capacitor price after compensation with optimal voltage

The AB interaction indicates that, effect of capacitor price on load at high temperature is larger than its effect at low temperature. Figures 6.180 to 6.182 indicate there is an interaction effect of capacitor price and capacitor size on load demand after reactive power compensation with optimal voltage at substation.

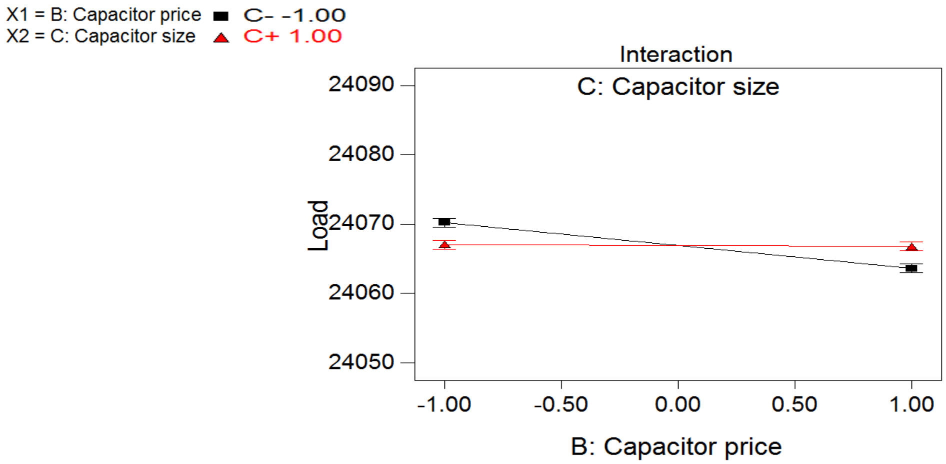


Figure 6.180: Load vs. capacitor price and capacitor size after reactive power compensation with optimal voltage

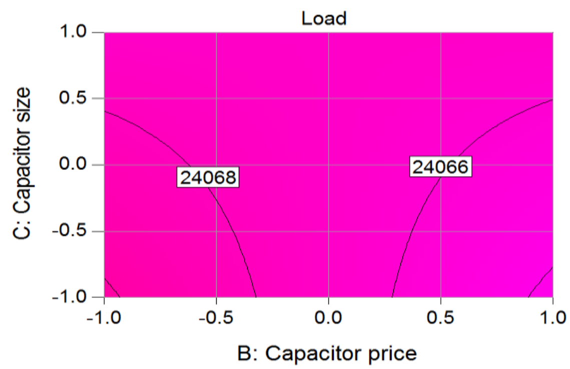


Figure 6.181: Contour plot of capacitor price vs. capacitor size for load after compensation with optimal voltage

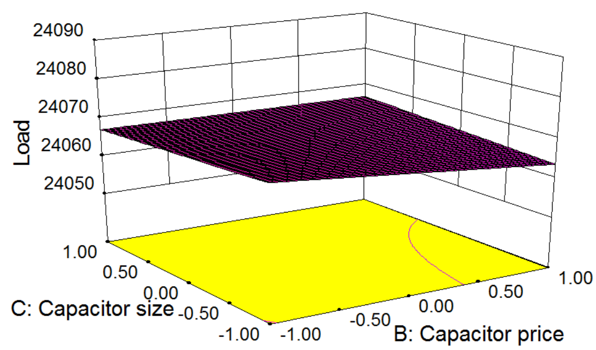


Figure 6.182: Response surface for load vs. capacitor price and capacitor size after compensation with optimal voltage

Figures 6.183 to 6.185 also indicate that there is an interaction effect of capacitor price and capacitor phase kVAr on load demand after reactive power compensation with optimal voltage at the substation, whereas there is no interaction effect of capacitor price and capacitor phase kVAr on load demand after reactive power compensation without voltage reduction or with minimum permissible voltage at the substation.

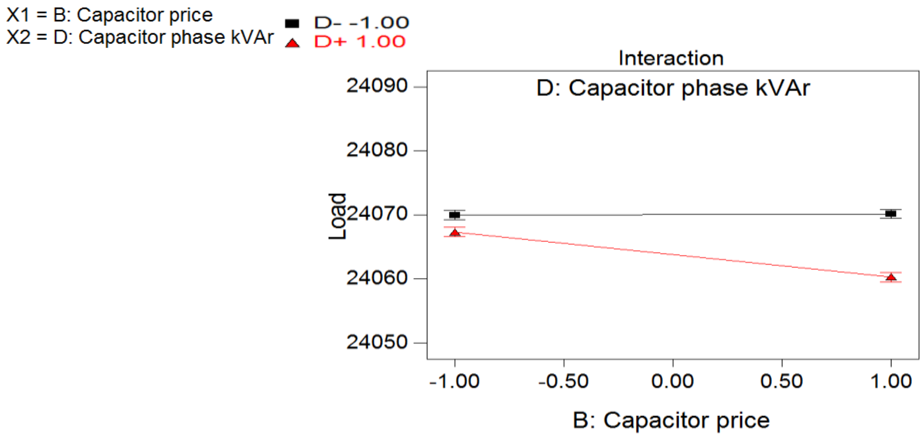


Figure 6.183: Load vs. capacitor price and capacitor phase kVAr after reactive power compensation with optimal voltage

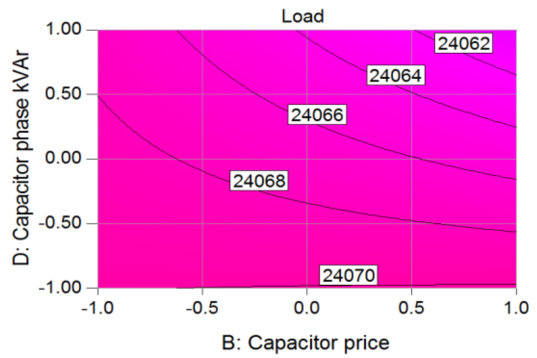


Figure 6.184: Contour plot of capacitor price vs. capacitor phase kVAr for load after compensation with optimal voltage

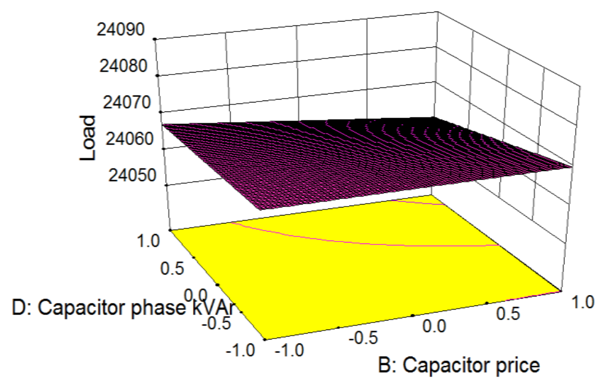


Figure 6.185: Response surface for load vs. capacitor price vs. capacitor phase kVAr after compensation with optimal voltage

Cube Plots of Load Demand after Reactive Power Compensation with Optimal Voltage at Substation

In Figure 6.186, it can be seen that with three variables—temperature, capacitor size, and capacitor price—load demand after reactive power compensation with optimal voltage is minimized (24,051.02 MWh/year) at a higher temperature, higher capacitor price, and discrete capacitor size. Figure 6.187 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—load demand is minimized (24,046.9 MWh/year) at a higher temperature, higher capacitor price, and evenly distributed capacitor phase kVArs.

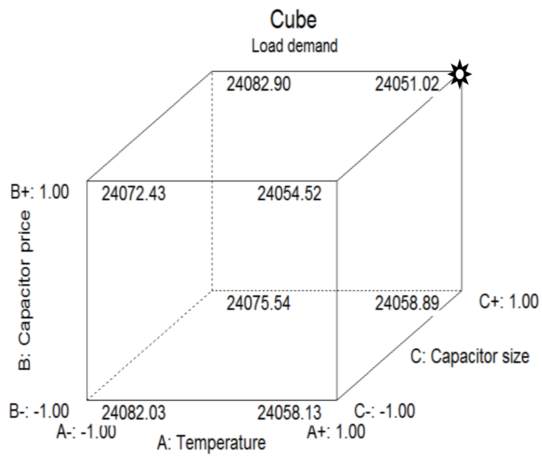


Figure 6.186: Cube plot of load vs. temperature, capacitor price and capacitor size after reactive power compensation with optimal voltage

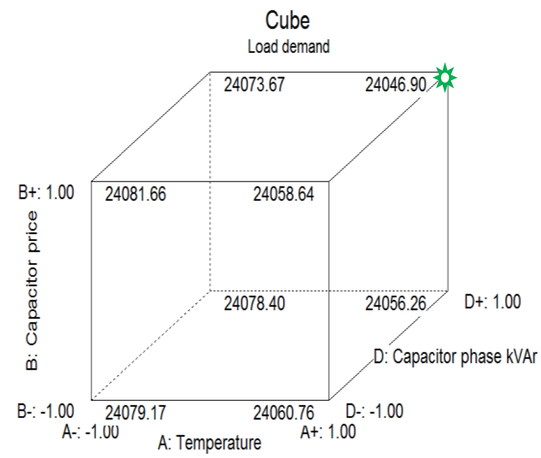


Figure 6.187: Cube plot of load vs. temperature, capacitor price and capacitor phase kVAr after reactive power compensation with optimal voltage

With three variables—temperature, capacitor size, and capacitor phase kVAr—load is minimized (24,047.45 MWh/year) at a higher temperature, discrete capacitor size, and evenly distributed capacitor phase kVArs, as shown in Figure 6.188. In Figure 6.189, it can be seen that with three variables—capacitor price, capacitor size, and capacitor phase kVAr—load is minimized (24,058.54 MWh/year) at a higher capacitor price, continuous capacitor size, and evenly distributed capacitor phase kVArs.

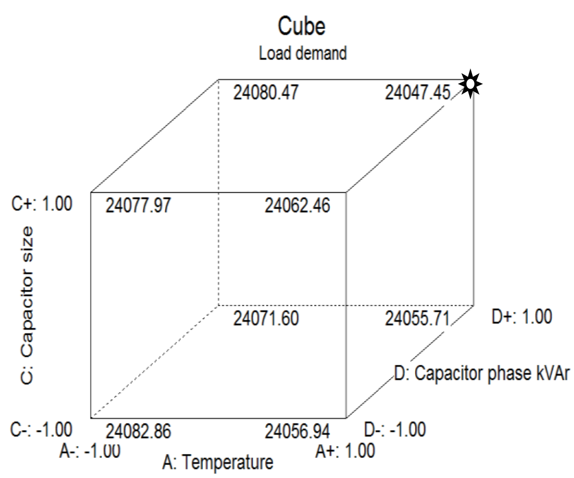


Figure 6.188: Cube plot of load vs. temperature, capacitor size, and capacitor phase kVAr after reactive power compensation with optimal voltage

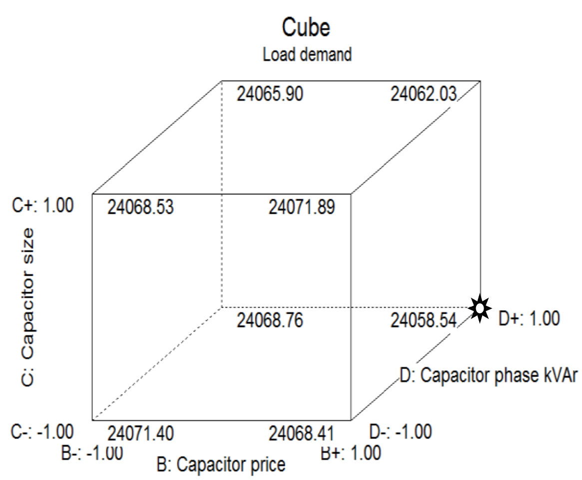


Figure 6.189: Cube plot of load vs. capacitor price, capacitor size, and capacitor phase kVAr after reactive power compensation with optimal voltage

Factor level combinations that minimize loads for three-factor combinations out of four factors are shown by star marks in the cube plots. The minimum (24,046.9 MWh/year) of all minimum loads (24,051.02 MWh/year, 24,046.9 MWh/year, 24,047.45 MWh/year, 24,058.54 MWh/year) occurs at a higher temperature, higher capacitor price, and evenly distributed capacitor phase kVArs; this combination of factor levels is indicated by a green star in Figure 6.187.

For three-factor combinations, the optimal combinations of factor levels that minimize load demand for three cases are summarized in Table 6.22. Among the three-factor combinations, load is minimized at a factor combination of temperature, capacitor size, and capacitor phase kVArs for first and second cases, and those factors are the three dominant one-factor effects on load demand for the first and second cases, as shown in Tables 6.5 and 6.12, respectively, and these three-factor-level combinations that minimize load are shown in italics in Table 6.22. For third cases, load is minimized at a factor combination of temperature, capacitor price, and capacitor phase kVArs, which are the three dominant one-factor effects on load for the third case, as shown in Table 6.20, and these three-factor-level combinations that minimize load are shown in italics in Table 6.22.

TABLE 6.22

OPTIMAL COMBINATION OF FACTOR LEVELS FOR MINIMUM LOAD DEMAND FOR THREE CASES

Case	**Factor Combinations**			
	Temperature, Capacitor Price, Capacitor Size	**Temperature, Capacitor Price, Capacitor Phase kVAr**	**Temperature, Capacitor Size, Capacitor Phase kVAr**	**Capacitor Price, Capacitor Size, Capacitor Phase kVAr**
After Reactive Power Compensation	Higher temperature, higher capacitor price, and continuous capacitor size	Higher temperature, higher capacitor price, and evenly distributed capacitor phase kVArs	*Higher temperature, continuous capacitor size, and evenly distributed capacitor phase kVArs*	Higher capacitor price, continuous capacitor size, and evenly distributed capacitor phase kVArs
After Reactive Power Compensation + Minimum Voltage at Substation	Lower temperature, lower capacitor price, and discrete capacitor size	Lower temperature, lower capacitor price, and capacitor phase kVArs in the ratio of reactive power flow through the line.	*Lower temperature, continuous capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line.*	Higher capacitor price, continuous capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line.
After Reactive Power Compensation + Optimal Voltage at Substation	Higher temperature, higher capacitor price, and discrete capacitor size	*Higher temperature, higher capacitor price, and evenly distributed capacitor phase kVArs*	Higher temperature, discrete capacitor size, and evenly distributed capacitor phase kVArs	Higher capacitor price, continuous capacitor size, and evenly distributed capacitor phase kVArs

Optimal Combination of Factor Levels for Minimum Load Demand

6.3.3 2^4 Factorial Design for Energy Generation after Reactive Power Compensation with Optimal Voltage at Substation Regulator

Effect estimates, sums of squares, and percentage contribution are shown in Table 6.23.

TABLE 6.23

FACTOR EFFECT ESTIMATES AND SUMS OF SQUARES FOR 2^4 FACTORIAL DESIGN FOR ENERGY GENERATION AFTER REACTIVE POWER COMPENSATION WITH OPTIMAL VOLTAGE AT SUBSTATION

Factors	Effect Estimate	Sum of Square	% Contribution
A-Temperature	38.52	5933.62	63.7076
B-Capacitor Price	22.67	2055.72	22.0716
C-Capacitor Size	-4.95	97.81	1.0502
D-Capacitor Phase kVAr	14.70	864.36	9.2804
AB	-2.49	24.90	0.2673
AC	-1.68	11.29	0.1212
AD	-0.81	2.59	0.0278
BC	4.56	82.99	0.8910
BD	-2.18	19.01	0.2041
CD	0.63	1.56	0.0167
ABC	-2.68	28.73	0.3085
ABD	-1.19	5.62	0.0603
ACD	-6.01	144.48	1.5512
BCD	-0.75	2.22	0.0238
ABCD	-3.12	38.94	0.4181

The important effects from this analysis are the main effects of A, B, C, and D and the ACD interaction effect. ANOVA for the selected model is shown in Table 6.24. In reduced ANOVA, model is selected in such a way that residuals lie between –5.60 MWh/year and +5.60 MWh/year.

TABLE 6.24

ANOVA FOR SELECTED FACTORIAL MODEL FOR ENERGY GENERATION AFTER REACTIVE POWER COMPENSATION WITH OPTIMAL VOLTAGE AT SUBSTATION

Source	Sum of Squares	df	Mean Squares	F Value	p-value Prob > F
Model	9217.92	7	1316.85	109.83	< 0.0001
A-Temperature	*5933.62*	*1*	*5933.62*	*494.88*	*< 0.0001*
B-Capacitor Price	*2055.72*	*1*	*2055.72*	*171.45*	*< 0.0001*
C-Capacitor Size	*97.81*	*1*	*97.81*	*8.16*	*0.0213*
D-Capacitor Phase kVAr	*864.36*	*1*	*864.36*	*72.09*	*< 0.0001*
BC	*82.99*	*1*	*82.99*	*6.92*	*0.0301*
ACD	*144.48*	*1*	*144.48*	*12.05*	*0.0084*
ABCD	*38.94*	*1*	*38.94*	*3.25*	*0.1092*
Residuals	95.92	8	11.99		
Cor Total	9313.84	15			

The regression model for energy generation after reactive power compensation with optimal voltage at the substation, can be given in terms of a coded factor by equation (6.9).

$$P_{Gen} = 24636.09 + 19.26*A + 11.33*B - 2.47*C + 7.35*D + 2.28*B*C - 3.01*A*C*D - 1.56*A*B*C*D \quad (6.9)$$

In terms of actual factors, energy generation can be given by equations (6.9.1) to (6.9.4).

Capacitor size continuous and phase kVArs are in the ratio of reactive power flow

$$P_{Gen} = 24522.9633 + 1.8408*T + 36.6133*Cp - 0.3328*T*Cp \quad (6.9.1)$$

Capacitor size discrete and phase kVArs are in the ratio of reactive power flow

$$P_{Gen} = 24520.7633 + 1.2408*T + 23.8133*Cp + 0.3328*T*Cp \quad (6.9.2)$$

Capacitor size continuous and phase kVArs are evenly distributed

$$P_{Gen} = 24560.1633 + 1.2408*T + 11.6533*Cp + 0.3328*T*Cp \quad (6.9.3)$$

Capacitor size discrete and phase kVArs are evenly distributed

$$P_{Gen} = 24512.9633 + 1.8408*T + 48.7733*Cp - 0.3328*T*Cp \quad (6.9.4)$$

Model Adequacy, Hypotheses Test, and Residuals for Energy Generation after Reactive Power Compensation with Optimal Voltage at Substation

For line loss, $R^2 = \frac{SS_{Model}}{SS_{Total}} = \frac{9217.92}{9313.84} = 0.9897$, which implies that the 98.97% variability in energy generation can be explained by equation (6.9). $F = \frac{R^2/k}{(1-R^2)/[n-(k+1)]} = \frac{0.9897/7}{(1-0.9897)/[16-(7+1)]} = 109.81$. $F_{\alpha,v_1,v_2} = F_{0.01,7,8} = 6.18$. Since $F > F_{\alpha,v_1,v_2}$, the null hypothesis H_0 is rejected, and it can be concluded that at least one of the model coefficients in equation (6.9) is nonzero. Hence, this F test indicates that the multiple regression model presented by equation (6.9) can be used for predicting energy generation after reactive power compensation with optimal voltage at the substation. The normal probability plot of residuals is shown in Figure 6.190. The predicted versus actual plot for energy generation is shown in Figure 6.191. Residuals versus factor effects are plotted in Figures 6.192 to 6.195.

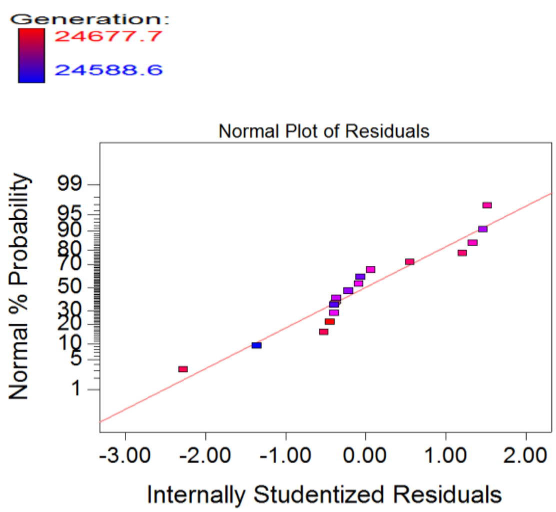


Figure 6.190: Normal probability plot of residuals for generation after reactive power compensation with optimal voltage

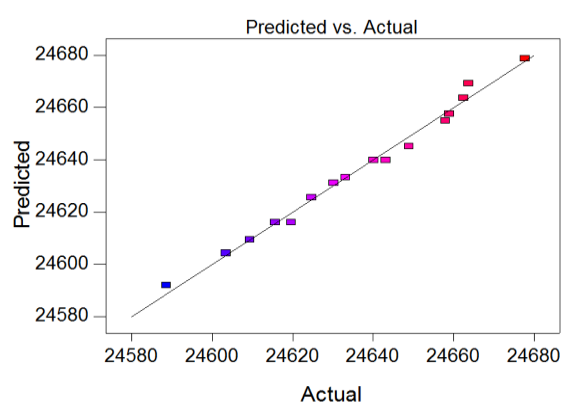


Figure 6.191: Predicted vs. actual plot for generation after reactive power compensation with optimal voltage

In Figure 6.192, it is shown that at a lower temperature, residuals are smaller than they are at a higher temperature. Figure 6.194 also shows that residuals at a continuous capacitor size are smaller than residuals at a discrete capacitor size. Comparing the residuals in energy generation among three cases—(i) energy generation after reactive power compensation, (ii) energy generation after reactive power compensation with minimum permissible voltage at the substation, and (iii) energy generation after reactive power compensation with optimal voltage at the substation—it can be seen that residuals noticeably change in case (i) and (iii), due to the variation of factor levels.

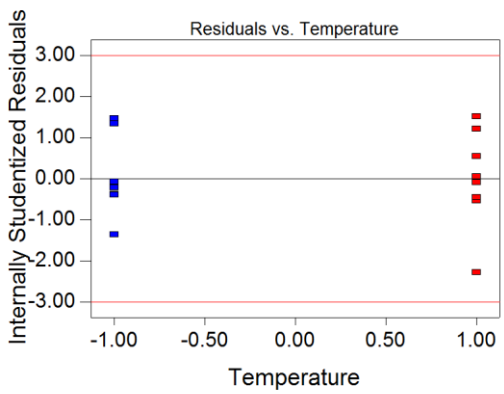


Figure 6.192: Residuals vs. temperature plot for generation after reactive power compensation with optimal voltage

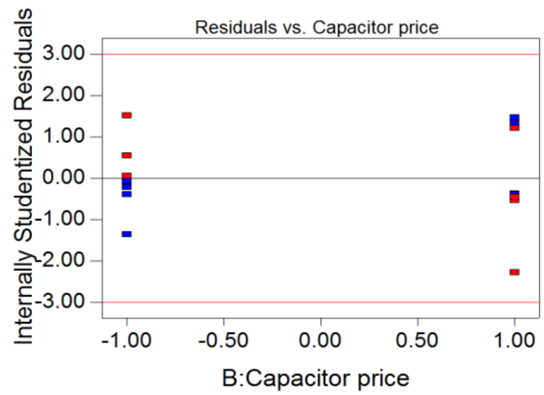


Figure 6.193: Residuals vs. capacitor price plot for generation after reactive power compensation with optimal voltage

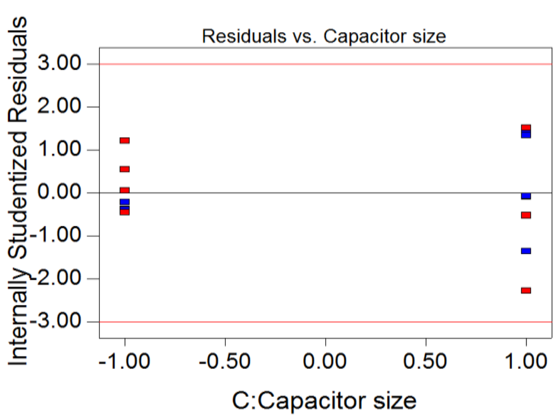


Figure 6.194: Residuals vs. capacitor size plot for generation after reactive power compensation with optimal voltage

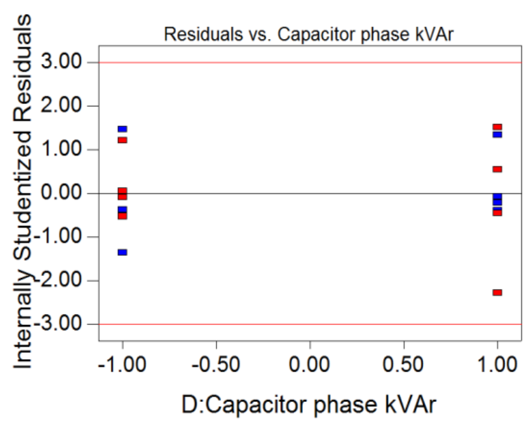


Figure 6.195: Residuals vs. capacitor phase kVAr plot for generationafter reactive power compensation with optimal voltage

The half-normal and normal probability plots of the factor effects are shown in Figures 6.196 and 6.197, respectively. The effects of A, B, C, and D are plotted in Figures 6.198 to 6.201.

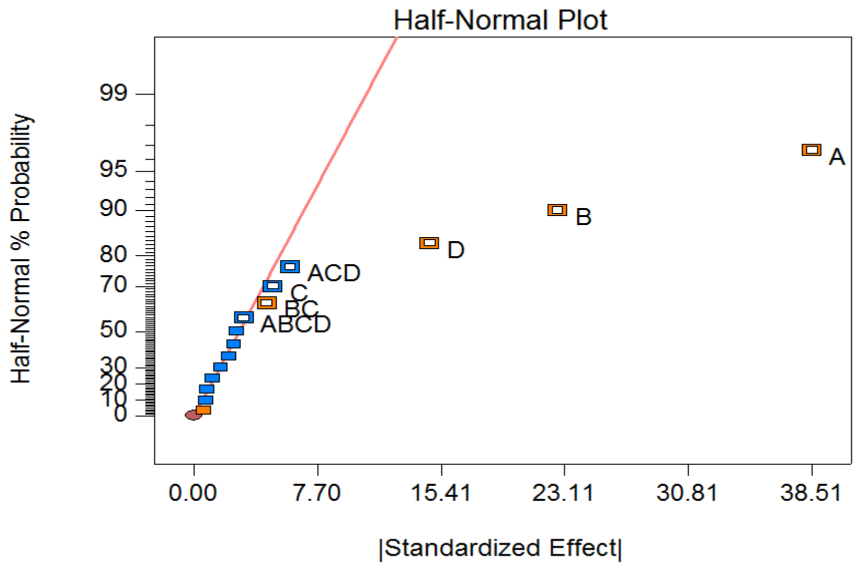


Figure 6.196: Half-normal plot of factor effects on energy generation after reactive power compensation with optimal voltage

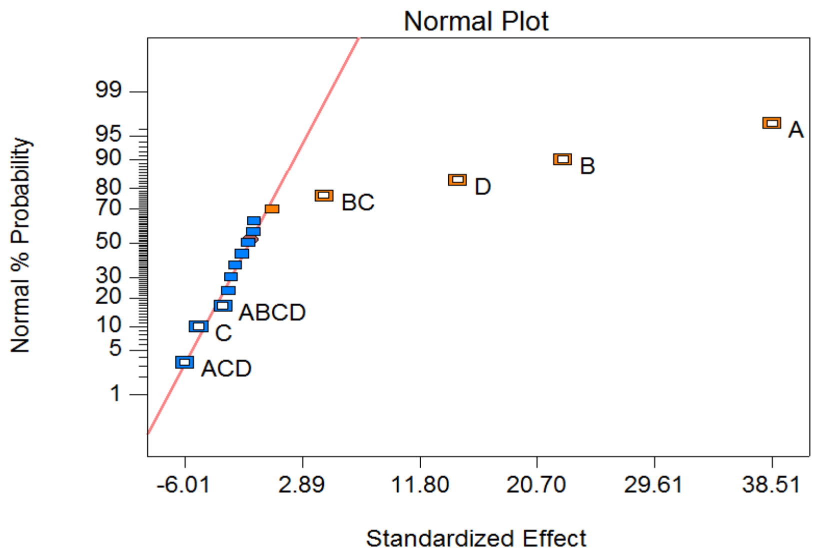


Figure 6.197: Normal plot of factor effects on energy generation after reactive power compensation with optimal voltage

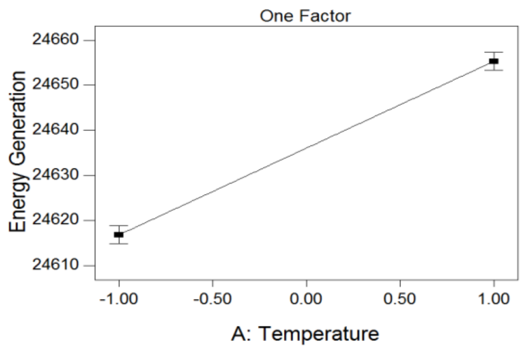


Figure 6.198: Genertion vs. temperature after compensation with optimal voltage

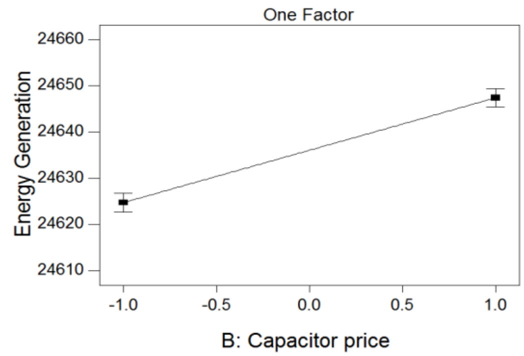


Figure 6.199: Generation vs. capacitor price after compensation with optimal voltage

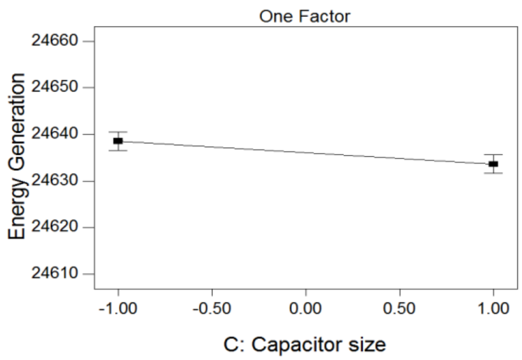


Figure 6.200: Generation vs. capacitor size after reactive power compensation with optimal voltage

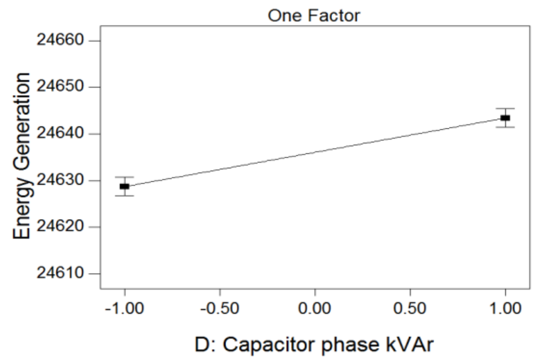


Figure 6.201: Generation vs. capacitor phase kVAr after reactive power compensation with optimal voltage

The BC interaction effect that is considered in the regression medel is shown in Figures 6.202 to 6.204.

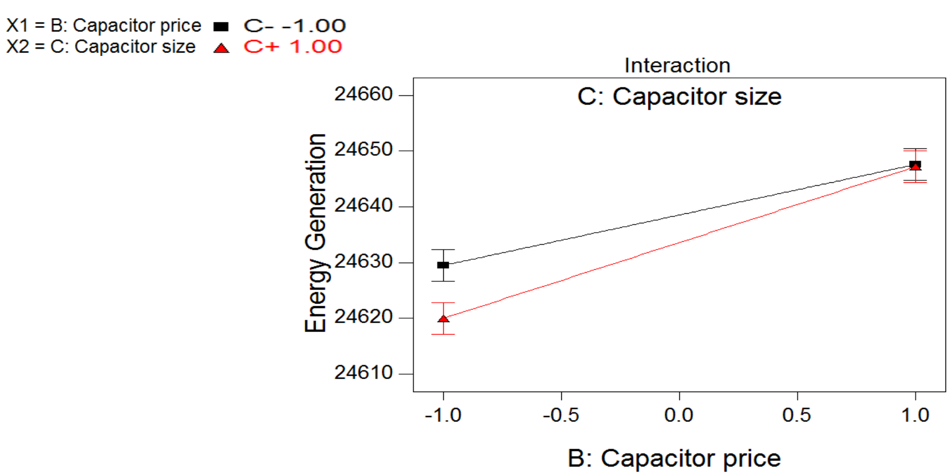


Figure 6.202: Generation vs. capacitor price and capacitor size after reactive power compensation with optimal voltage

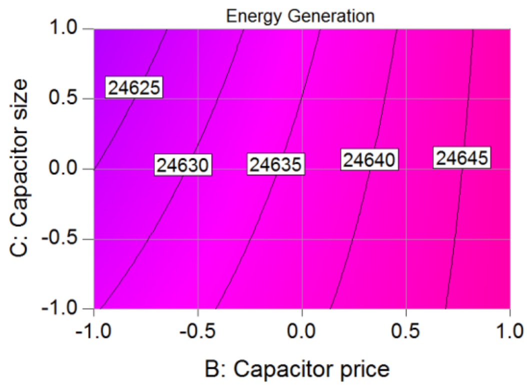


Figure 6.203: Contour plot of capacitor price vs. capacitor size for generation after compensation with optimal voltage

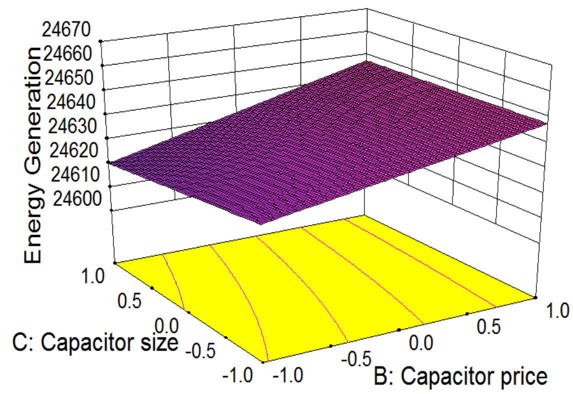


Figure 6.204: Response surface for generation vs. capacitor price vs. capacitor size after compensation with optimal voltage

The BC interaction shown in Figure 6.202 indicates that at a lower capacitor price, the effect of capacitor size on generation is larger than its effect at a higher capacitor price.

Cube Plots of Energy Generation after Reactive Power Compensation with Optimal Voltage at Substation

In Figure 6.205, it can be seen that with three variables—temperature, capacitor price, and capacitor size—energy generation after reactive power compensation with optimal voltage, is minimized (24,601 MWh/year) at a lower temperature, lower capacitor price, and discrete capacitor size, and this combination of factor levels is indicated by a star in the cube plot. Figure 6.206 shows that with three variables—temperature, capacitor price, and capacitor phase kVAr—energy generation is minimized (24,598.1 MWh/year) at a lower temperature, lower capacitor price, and capacitor phase kVArs in the ratio of reactive power flow through the line.

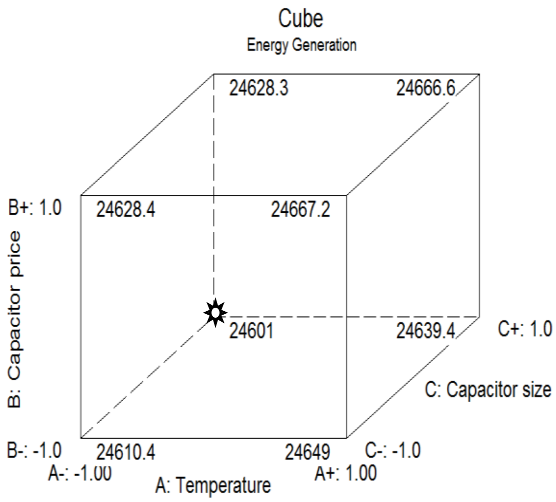


Figure 6.205: Cube plot of generation vs. temperature, capacitor price, and capacitor size after reactive power compensation with optimal voltage

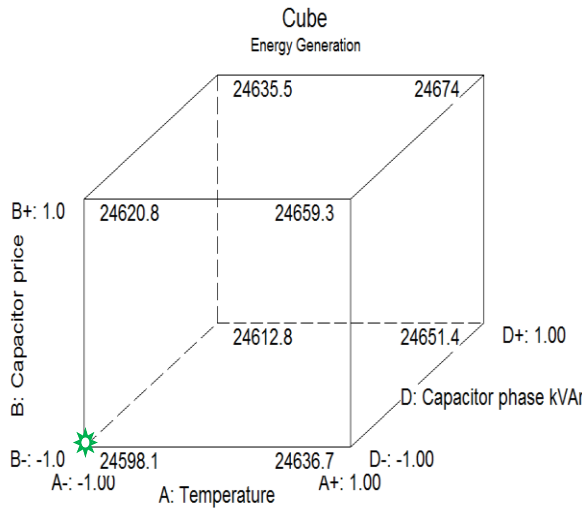


Figure 6.206: Cube plot of generation vs. temperature, capacitor price, and capacitor phase kVAr after reactive power compensation with optimal voltage

With three variables—temperature, capacitor size, and capacitor phase kVAr—generation is minimized (24,604 MWh/year) at a lower temperature, discrete capacitor size, and capacitor phase kVArs in the ratio of reactive power flow through the line, as shown in Figure 6.207. In Figure 6.208, it is shown that with three variables—capacitor price, capacitor size, and capacitor phase kVAr—generation is minimized (24,612.7 MWh/year) at a lower temperature, lower capacitor price, and capacitor phase kVArs in the ratio of reactive power flow through the line.

The minimum (24,598.1 MWh/year) of all minimum generation (24,601 MWh/year, 24,598.1 MWh/year, 24,604 MWh/year, 24,612.7 MWh/year) occurs at a higher temperature, higher capacitor price, and evenly distributed capacitor phase kVArs; this combination of factors' levels is indicated by a green star in Figure 6.206. For the three-factor combinations, the optimal combination of factor levels that minimize generation for three cases are summarized in Table 6.25. Again, among three-factor combinations, minimum generation occurs at the factor combination of temperature, capacitor price, and capacitor phase kVArs for all three cases, and those factors are the three dominant one-factor effects on generation for three cases, as shown in

Tables 6.7, 6.14, and 6.23, respectively; these three-factor-level combinations that minimize generation are shown in italics in Table 6.25.

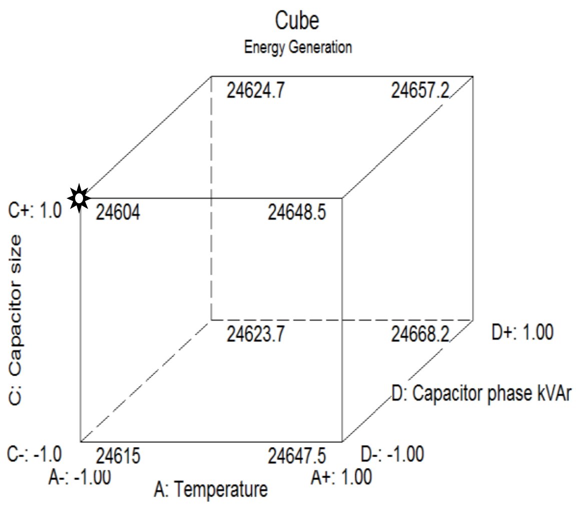


Figure 6.207: Cube plot of generation vs. temperature, capacitor size, and capacitor phase kVAr after reactive power compensation with optimal voltage

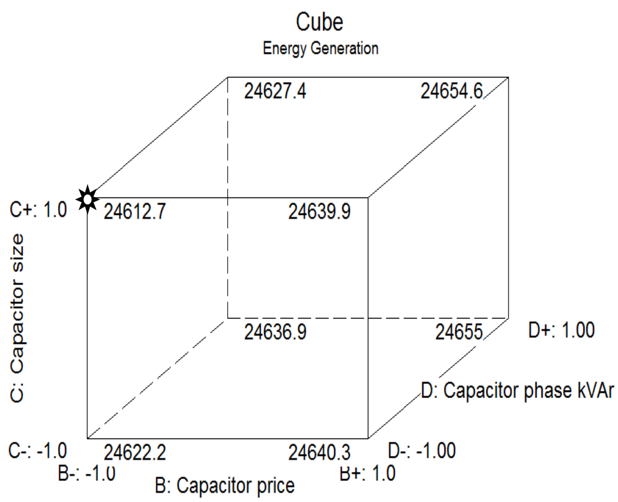


Figure 6.208: Cube plot of generation vs capacitor price, capacitor size, and capacitor phase kVAr after reactive power compensation with optimal voltage

TABLE 6.25

OPTIMAL COMBINATION OF FACTOR LEVELS FOR MINIMUM GENERATION FOR THREE CASES

Case	Factor Combinations				
	Temperature, Capacitor Price, Capacitor Size	**Temperature, Capacitor Price, Capacitor Phase kVAr**	**Temperature, Capacitor Size, Capacitor Phase kVAr**	**Capacitor Price, Capacitor Size, Capacitor Phase kVAr**	
After Reactive Power Compensation	Lower temperature, lower capacitor price and continuous capacitor size	*Lower temperature, lower capacitor price, and evenly distributed capacitor phase kVArs*	Lower temperature, continuous capacitor size, and evenly distributed capacitor phase kVArs	Lower capacitor price, continuous capacitor size, and evenly distributed capacitor phase kVArs	**Optimal Combination of Factor Levels for Minimum Generation**
After Reactive Power Compensation + Minimum Voltage at Substation	Lower temperature, lower capacitor price and discrete capacitor size	*Lower temperature, lower capacitor price, and capacitor phase kVArs in ratio of reactive power flow through the line*	Lower temperature, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line	Lower capacitor price, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line	
After Reactive Power Compensation + Optimal Voltage at Substation	Lower temperature, lower capacitor price and discrete capacitor size	*Lower temperature, lower capacitor price, and capacitor phase kVArs in ratio of reactive power flow through the line*	Lower temperature, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line	Lower capacitor price, discrete capacitor size, and capacitor phase kVArs in ratio of reactive power flow through the line	

6.4 Conclusion

The 2^4 factorial design was used to determine the joint effect of ambient temperature, capacitor price, capacitor size, and capacitor phase kVArs on line loss, load, and generation. The factor effects on those responses are demonstrated for three cases—(i) line loss, load, and generation after reactive power compensation; (ii) line loss, load, and generation after reactive power compensation with minimum voltage at substation; and (iii) line loss, load, and generation after reactive power compensation with optimal voltage at the substation.

The 2^4 factorial design shows the lack of interaction effects on line loss for all three cases; therefore, line loss can be presented by a linear function of ambient temperature, price, size, and phase kVArs of the capacitor. Significant interaction effects are seen on load; therefore, load demand is a nonlinear function of ambient temperature, price, size, and phase kVArs of the capacitor. A larger number of interaction effects on load are seen in the second and third cases. Interaction effects are also seen on energy generation, so energy generation is a nonlinear function of ambient temperature, price, size, and phase kVArs of capacitor. A larger number of interaction effects are seen on energy generation in the second case.

The three dominant one-factor effects on line loss for all cases are ambient temperature, capacitor price, and capacitor phase kVArs. The optimal combination of factor levels that minimizes line loss is at a lower temperature, lower capacitor price, and capacitor phase kVArs in the ratio of reactive power flow through the line.

The three dominant one-factor effects on load for the first and second cases are ambient temperature, capacitor size, and capacitor phase kVArs; the optimal combination of factor levels that minimizes load for the first case is a higher temperature, continuous capacitor size, and evenly distributed capacitor phase kVArs, and for the second case, that combination is a lower temperature, continuous capacitor size, and capacitor phase kVArs in the ratio of reactive power flow through the line. The three dominant one-factor effects on load demand for the third case are ambient temperature, capacitor price, and capacitor phase kVArs, and the optimal combination of factor levels that minimizes load is a higher temperature, higher capacitor price, and evenly distributed capacitor phase kVArs into the three-phase capacitor.

Three dominant one-factor effects on generation for all three cases are ambient temperature, capacitor price, and capacitor phase kVArs, where temperature effect is the most significant. The optimal combination of factor levels that minimizes generation for the first case is lower temperature, lower capacitor price, and evenly distributed capacitor phase kVArs, and for the second and third cases, that combination is a lower temperature, lower capacitor price, and capacitor phase kVArs in the ratio of reactive power flow through the line.

CHAPTER 7

IMPACT OF VOLTAGE REDUCTION AND AMBIENT TEMPERATURE ON POWER CONSUMPTION, LINE LOSS, AND GENERATION

A voltage-reduction program is one strategy applied by utilities to reduce energy consumption and peak demand. In previous work, only customer load energy consumption and efficiency at reduced voltages are discussed, but the effect on total energy consumption and thus power generation/supply is not. In this chapter, the impact of voltage reduction on power generation/supply is discussed. Since bus voltage depends on line resistance, which varies with ambient temperature, the impact of temperature on power consumption, line loss, and generation is discussed as well. Results are presented based on the types of load to demonstrate how the load model plays an important role in that analysis. All analyses are tested on the IEEE 13-bus system.

Conservation voltage regulation (CVR), also referred to as conservation voltage reduction, is the long-term practice of controlling distribution voltage levels in the lower range of ANSI or CAN standard acceptable levels in order to reduce demand and energy consumption [4]. However, in some cases, active power losses may increase with a decrease of voltage applied at the substation [19]. Voltage reduction not only reduces the peak load demand during emergency situations but also reduces energy generation, thus eliminating the building of a new generation facility and ultimately resulting in reduced greenhouse gas emissions, which is currently a challenging issue. Since appliances such as lights bulbs and other electrical devices operate efficiently at reduced voltages, utilities can provide service at the lower end of the acceptable voltage level with no detriment to customers [19].

7.1 Impact of Voltage Reduction on Energy Consumption and Line Loss

At reduced voltage, voltage-dependent loads consume less power, and the percentage of reduction in power consumption depends on the type of the load. Among the three load models discussed in Chapter 1, the constant impedance load model has the largest amount of load reduction at reduced voltage because its energy consumption is directly proportional to the voltage squared. Therefore, customers who have a significant number of constant impedance loads will have the greatest benefit from a voltage reduction. A comparison of reduction in power consumption is given as

$$\Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{P}} < P_{\mathrm{Load}}^{\mathrm{C}} < \Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{Z}} \quad (7.1)$$

where $\Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{P}}$ is the reduction in power consumption at reduced voltage when the constant power load is dominant, $P_{\mathrm{Load}}^{\mathrm{C}}$ is the reduction in power consumption when constant current load is dominant and $\Delta \mathrm{P}_{\mathrm{Load}}^{\mathrm{Z}}$ is the reduction in power consumption when the constant impedance load is dominant in the composite load model, given the same amount of load in the systems.

In Chapter 4 on the impact of load type on line loss in a voltage-reduction program, it was found that at reduced voltage, line loss increases for the system with a dominant constant power load and decreases for the system with a dominant constant impedance load. For the system with a dominant constant current load, those losses increase if the percentage of the constant power load is greater than the percentage of the constant impedance load, and they decrease if the percentage of the constant impedance load is greater than the percentage of the constant power load.

Test results for an IEEE 13-bus system are shown in Tables 7.1 to 7.6 for different percentages of load types at two different temperatures, 25^0C and 50^0C.

Constant Power Load Dominant in Composite Load Model

TABLE 7.1

SYSTEM WITH CONSTANT POWER LOAD DOMINANT
AND AMBIENT TEMPERATURE 25^0 C

Constant Power Load: 2768 kW, 1653 kVAr Constant Impedance Load: 358 kW, 218 kVAr Constant Current Load: 340 kW, 231 kVAr Capacitor: 700 kVAr								
Substation Voltage (V)	**Load (kW)**	**Reduction in Demand (kW)**	**(kVAr)**	**Line Loss (kW)**	**(kVAr)**	**Power Supplied from Substation (kW)**	**(kVAr)**	**Reduction in Supplied Power (kW)**
122	3473	--	--	100	322	3573	1722	--
121	3465	8	5	101	326	3566	1732	7
120	3457	16	10	103	330	3560	1742	13
119	3448	25	16	104	335	3552	1754	21
118	3440	33	20	105	339	3546	1763	27
117	3430	43	27	107	345	3538	1776	35
116	3420	53	33	109	351	3529	1789	44

TABLE 7.2

SYSTEM WITH CONSTANT POWER LOAD DOMINANT
AND AMBIENT TEMPERATURE 50^0 C

Constant Power Load: 2768 kW, 1653 kVAr Constant Impedance Load: 358 kW, 218 kVAr Constant Current Load: 340 kW, 231 kVAr Capacitor: 700 kVAr								
Substation Voltage (V)	**Load (kW)**	**Reduction in Demand (kW)**	**(kVAr)**	**Line Loss (kW)**	**(kVAr)**	**Power Supplied from Substation (kW)**	**(kVAr)**	**Reduction in Supplied Power (kW)**
122	3469	--	--	111	324	3580	1726	--
121	3461	8	5	112	328	3574	1736	6
120	3454	15	10	114	332	3567	1745	13
119	3444	25	16	115	337	3560	1758	20
118	3437	32	20	117	341	3554	1767	26
117	3427	42	27	119	347	3546	1779	34
116	3416	53	33	121	353	3537	1793	43

Constant Impedance Load Dominant in Composite Load Model

TABLE 7.3

SYSTEM WITH CONSTANT IMPEDANCE LOAD DOMINANT
AND AMBIENT TEMPERATURE 25^0 C

Constant Impedance Load: 2768 kW, 1653 kVAr Constant Power Load: 358 kW, 218 kVAr Constant Current Load: 340 kW, 231 kVAr Capacitors: 700 kVAr								
Substation Voltage (V)	**Load (kW)**	**Reduction in Load (kW)**	**(kVAr)**	**Line Loss (kW)**	**(kVAr)**	**Power Supplied from Substation (kW)**	**(kVAr)**	**Reduction in Supplied Power (kW)**
122	3494	--	--	100	323	3594	1739	--
121	3454	40	24	99	320	3553	1721	41
120	3415	79	47	98	317	3513	1704	81
119	3366	128	77	97	314	3463	1682	131
118	3302	192	115	96	309	3398	1655	196
117	3265	229	137	95	306	3361	1639	233
116	3220	274	165	94	303	3314	1618	280

TABLE 7.4

SYSTEM WITH CONSTANT IMPEDANCE LOAD DOMINANT
AND AMBIENT TEMPERATURE 50^0 C

Constant Impedance Load: 2768 kW, 1653 kVAr Constant Power Load: 358 kW, 218 kVAr Constant Current Load: 340 kW, 231 kVAr Capacitors: 700 kVAr								
Substation Voltage (V)	**Load (kW)**	**Reduction in Load (kW)**	**(kVAr)**	**Line Loss (kW)**	**(kVAr)**	**Power Supplied from Substation (kW)**	**(kVAr)**	**Reduction in Supplied Power (kW)**
122	3480	--	--	110	322	3590	1733	--
121	3440	40	24	109	319	3549	1716	41
120	3401	79	47	108	316	3509	1699	81
119	3352	128	77	107	313	3460	1677	130
118	3288	192	115	106	308	3394	1649	196
117	3252	228	137	105	305	3357	1633	233
116	3207	273	164	104	302	3311	1614	279

Constant Current Load Dominant in Composite Load Model

TABLE 7.5

SYSTEM WITH CONSTANT CURRENT LOAD DOMINANT
AND AMBIENT TEMPERATURE 25^0 C

Constant Current Load: 2768 kW, 1653 kVAr Constant Power Load: 358 kW, 218 kVAr Constant Impedance Load: 340 kW, 231 kVAr Capacitor: 700 kVAr								
Substation Voltage (V)	**Load (kW)**	**Reduction in Load (kW)**	**(kVAr)**	**Line Loss (kW)**	**(kVAr)**	**Power Supplied from Substation (kW)**	**(kVAr)**	**Reduction in Supplied Power (kW)**
122	3476	--	--	100	321	3576	1726	--
121	3452	24	15	100	321	3552	1721	24
120	3428	48	30	100	321	3527	1716	49
119	3398	78	48	100	322	3498	1710	78
118	3357	119	73	100	322	3457	1701	119
117	3334	142	87	100	322	3434	1697	142
116	3312	164	101	100	322	3412	1692	164

TABLE 7.6

SYSTEM WITH CONSTANT CURRENT LOAD DOMINANT
AND AMBIENT TEMPERATURE 50^0 C

Constant Current Load: 2768 kW, 1653 kVAr Constant Power Load: 358 kW, 218 kVAr Constant Impedance Load: 340 kW, 231 kVAr Capacitor: 700 kVAr								
Substation Voltage (V)	**Load (kW)**	**Reduction in Load (kW)**	**(kVAr)**	**Line Loss (kW)**	**(kVAr)**	**Power Supplied from Substation (kW)**	**(kVAr)**	**Reduction in Supplied Power (kW)**
122	3467	--	--	110	321	3577	1724	--
121	3443	24	15	110	322	3553	1719	24
120	3418	49	30	110	322	3529	1714	48
119	3389	78	48	111	322	3500	1709	77
118	3348	119	73	111	322	3459	1700	118
117	3325	142	87	111	323	3436	1695	141
116	3303	164	101	111	323	3413	1690	164

If voltage is reduced from 122 V to 118 V, then it can be seen from Tables 7.1, 7.3, and 7.5 that $\Delta P_{Load}^{P} = 33$ kW, $\Delta P_{Load}^{Z} = 192$ kW, and $\Delta P_{Load}^{C} = 119$ kW, with load initially equal in each case, and these reductions in load satisfy equation (7.1). In Table 7.1, line loss increases for a dominant constant power load; in Table 7.3, line loss decreases for a dominant constant impedance load; and in Table 7.6, it can be seen that there is no significant change in line loss because of the dominant constant current load. The change in losses is greater for the constant power load than for the constant impedance load.

7.2 Impact of Reduced Voltage on Power Generation/Supply

Previous work on power conservation by lowering voltage has considered only the reduction in power consumption by customer loads. If power conservation in generation or supply is considered through a voltage-reduction program, then it is necessary to account for line loss along with a reduction in loads. Reduction in active power generation or supply from a substation at reduced voltage can be given as

$$\Delta P_{Gen} = \Delta P_{Load} + \Delta P_{Loss} \tag{7.2}$$

If shunt capacitors are connected to the system, then the reduction in reactive power generation or supply from the substation at reduced voltage can be given by

$$\Delta Q_{Gen} + \Delta Q_{Cap} = \Delta Q_{Load} + \Delta Q_{Loss}$$

$$\Rightarrow \Delta Q_{Gen} = \Delta Q_{Load} + \Delta Q_{Loss} - \Delta Q_{Cap} \tag{7.3}$$

where ΔP_{Gen} and ΔQ_{Gen} are the reduction in active and reactive power generation/supply, respectively, from the substation; ΔP_{Load} and ΔQ_{Load} are the reduction in active and reactive power load, respectively; ΔP_{Loss} and ΔQ_{Loss} are the reduction in active and reactive line loss, respectively; and ΔQ_{Cap} is the reduction in the capacitor's reactive power at reduced voltage.

It was shown in Chapter 4 on the impact of load type on line loss in a voltage-reduction program that, at reduced voltage, line loss increases for the system with a dominant constant power load and decreases for the system with a dominant constant impedance load. Now, if the decrement of a quantity at a reduced voltage is considered positive and the increment of a quantity is considered negative, then

$$\left.\begin{array}{l} \Delta P_{Load} > 0, for\ all\ types\ of\ composite\ load\ models \\ \Delta P_{Loss} < 0, for\ dominant\ constant\ power\ load \\ \Delta P_{Loss} > 0, for\ dominant\ constant\ impedance\ load \\ \Delta P_{Loss} < 0, for\ dominant\ constant\ current\ load\ with\ \text{constant} \\ \qquad power\ load\ greater\ than\ constant\ impedance\ load \\ \Delta P_{Loss} > 0, for\ dominant\ constant\ current\ load\ with\ \text{constant} \\ \qquad impedance\ load\ greater\ than\ constant\ power\ load \\ \Delta P_{Load} \gg |\Delta P_{Loss}| \end{array}\right\} \tag{7.4}$$

Therefore,

$$\Delta P_{Load} + \Delta P_{Loss} > 0$$

$$\Rightarrow \Delta P_{Gen} > 0$$

Hence, the active power supply from the substation will decrease with a reduction in voltage for all composite load models.

As shown in equation (7.1), $\Delta P_{Load}^{P} < \Delta P_{Load}^{C} < \Delta P_{Load}^{Z}$; therefore, by equations (7.1), (7.2), and (7.4), for the same amount of voltage reduction, the largest reduction (ΔP_{Gen}) in the power generation/supply from the substation can be seen in the system with a dominant constant impedance load. A comparison of reductions in the power generation/supply from the substation at reduced voltage is shown as

$$\Delta P_{Gen}^{P} < \Delta P_{Gen}^{C} < \Delta P_{Gen}^{Z} \tag{7.5}$$

where ΔP_{Gen}^{P} is the reduction in power generation/supply for the system with a dominant constant power load, ΔP_{Gen}^{C} is the reduction in power generation/supply for the system with a dominant constant current load, and ΔP_{Gen}^{Z} is the reduction in power generation/supply for the system with a dominant constant impedance load. The system with a dominant constant impedance load will have maximum benefit in terms of energy conservation on both the demand and generation sides through a voltage-reduction program. For example, if voltage is reduced from 122 V to 118 V, then from Tables 7.1, 7.3, and 7.5, then $\Delta P_{Gen}^{P} = 27$ kW, $\Delta P_{Gen}^{Z} = 196$ kW, and $\Delta P_{Gen}^{C} = 119$ kW, respectively, where the same amount of rated loads are in the system, and these reductions in real power generation satisfy equation (7.5).

Due to voltage reduction, the reactive power supply from the substation will decrease if

$$\Delta Q_{Gen} > 0$$

$$\Rightarrow \quad \Delta Q_{Load} + \Delta Q_{Loss} > \Delta Q_{Cap} \qquad (7.6)$$

or will increase if

$$\Delta Q_{Gen} < 0$$

$$\Rightarrow \quad \Delta Q_{Load} + \Delta Q_{Loss} < \Delta Q_{Cap} \qquad (7.7)$$

Now, at reduced voltage

$$\Delta Q_{Cap} > 0 \qquad (7.8)$$

$$\Delta Q_{Load} > 0, \textit{ for all types of composite load models} \qquad (7.9)$$

System with Dominant Constant Power Load

For the system with a dominant constant power load,

$$\Delta Q_{Loss} < 0 \qquad (7.10.1)$$

For this system, at reduced voltage, the reduction in total reactive load is less than the reduction in reactive power delivered by the capacitors, i.e., $\Delta Q_{Load} < \Delta Q_{Cap}$. Therefore, $\Delta Q_{Load} + \Delta Q_{Loss} < \Delta Q_{Cap}$, i.e., the reactive power supply from the substation will increase. For example, in Tables 7.1 and 7.2 where the constant power load is dominant, the reactive power supply from the substation increases with a reduction in voltage for the condition in equation (7.7). In Table 7.1, it can be seen that when voltage is reduced from 122 V to 118 V, ΔQ_{Load} = 20 kVAr, ΔQ_{Loss} = (322 – 339) = –17 kVAr, and ΔQ_{Cap} = (705 – 661) = 44 kVAr, since ($\Delta Q_{Load} + \Delta Q_{Loss}$ = 20 + (–17)) < (44 = ΔQ_{Cap}); therefore, the reactive power supply from the substation increases from 1722 kVAr to 1763 kVAr with the reduction in voltage, where ΔQ_{Gen} = (1722 – 1763) = (20 – 17 – 44) kVAr.

System with Dominant Constant Impedance Load

For the system with a dominant constant impedance load,

$$\Delta Q_{Loss} > 0 \tag{7.10.2}$$

Here, at reduced voltage, the reduction in total reactive load is greater than the reduction in reactive power delivered by the capacitors, i.e., $\Delta Q_{Load} > \Delta Q_{Cap}$. Therefore, for a dominant constant impedance load, $\Delta Q_{Load} + \Delta Q_{Loss} > \Delta Q_{Cap}$, i.e., reactive power supply from substation will decrease. For example, in Tables 7.3 and 7.4, where constant impedance load is dominant, the reactive power supply from the substation decreases with a reduction in voltage for the condition in equation (7.6). In Table 7.3, it can be seen that when voltage is reduced from 122 V to 118 V, ΔQ_{Load} = 115 kVAr, ΔQ_{Loss} = (323–309) = 14 kVAr, and ΔQ_{Cap} = (705 – 660) = 45 kVAr, since ($\Delta Q_{Load} + \Delta Q_{Loss}$ = 115 + 14) > (45= ΔQ_{Cap}), so the reactive power supply from the substation decreases from 1,739 kVAr to 1,655 kVAr with a voltage reduction where ΔQ_{Gen} = (1739 – 1655) = (115 + 14 – 45) kVAr.

System with Dominant Constant Current Load

For the system with a dominant constant current load with constant power load greater than constant impedance load,

$$\Delta Q_{Loss} < 0 \tag{7.10.3}$$

For the system with a dominant constant current load with constant impedance load greater than constant power load,

$$\Delta Q_{Loss} > 0 \tag{7.10.4}$$

For the system with a dominant constant current load, at reduced voltage, the reduction in total reactive load is greater than the reduction in reactive power delivered by the capacitors, i.e. $\Delta Q_{Load} > \Delta Q_{Cap}$, and the percentage of increment/decrement in line loss is small. Therefore, for a dominant constant current load, $\Delta Q_{Load} + \Delta Q_{Loss} > \Delta Q_{Cap}$, i.e., the reactive power supply from the substation will decrease. For example, in Tables 7.5 and 7.6, where the constant current load is dominant, the reactive power supply from the substation decreases with a reduction in voltage for the condition in equation (7.6). The increase or decrease in power generation at reduced voltage is summarized in Table 7.7.

TABLE 7.7

IMPACT OF VOLTAGE REDUCTION ON POWER GENERATION

Composite Load Model	**Active Power Generation**	**Reactive Power Generation**
Constant Power Load Dominant	Decrease	Increase
Constant Impedance Load Dominant	Decrease	Decrease
Constant Current Load Dominant	Decrease	Decrease

The analysis of the impact of voltage reduction on reactive power generation is based on a system with shunt power factor correction capacitors. If there are no shunt capacitors, the analysis for the impact of voltage reduction on reactive power generation would be the same as the analysis done for active power generation, and reactive power generation would decrease for all composite load models.

Figures 7.1 to 7.4 show how load, power supply, line loss, load reduction, and power supply reduction vary with the reduction in voltage.

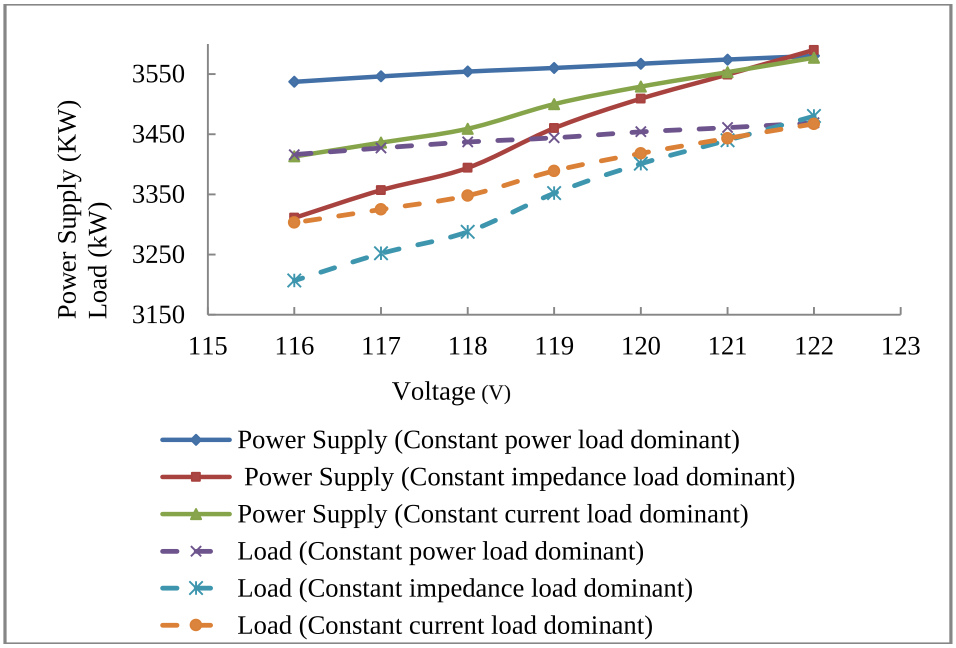


Figure 7.1: Real power supply and load vs. voltage for each load model

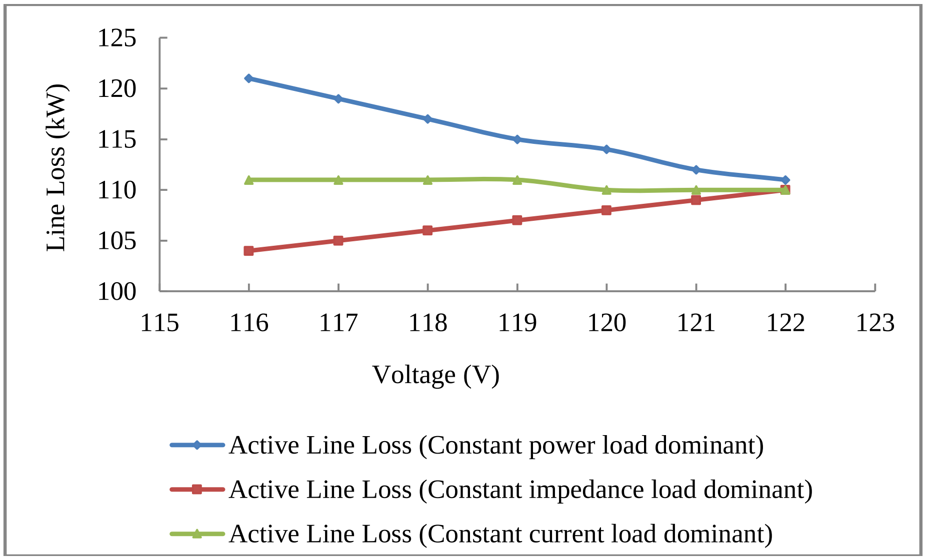


Figure 7.2: Line loss vs. voltage for each load model

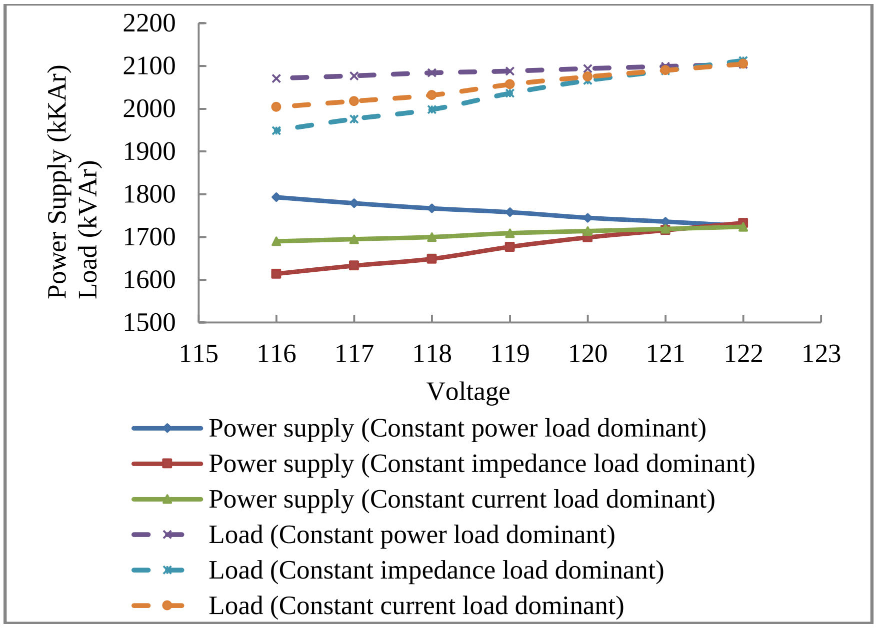


Figure7.3: Reactive power supply and reactive load vs. voltage for each load model

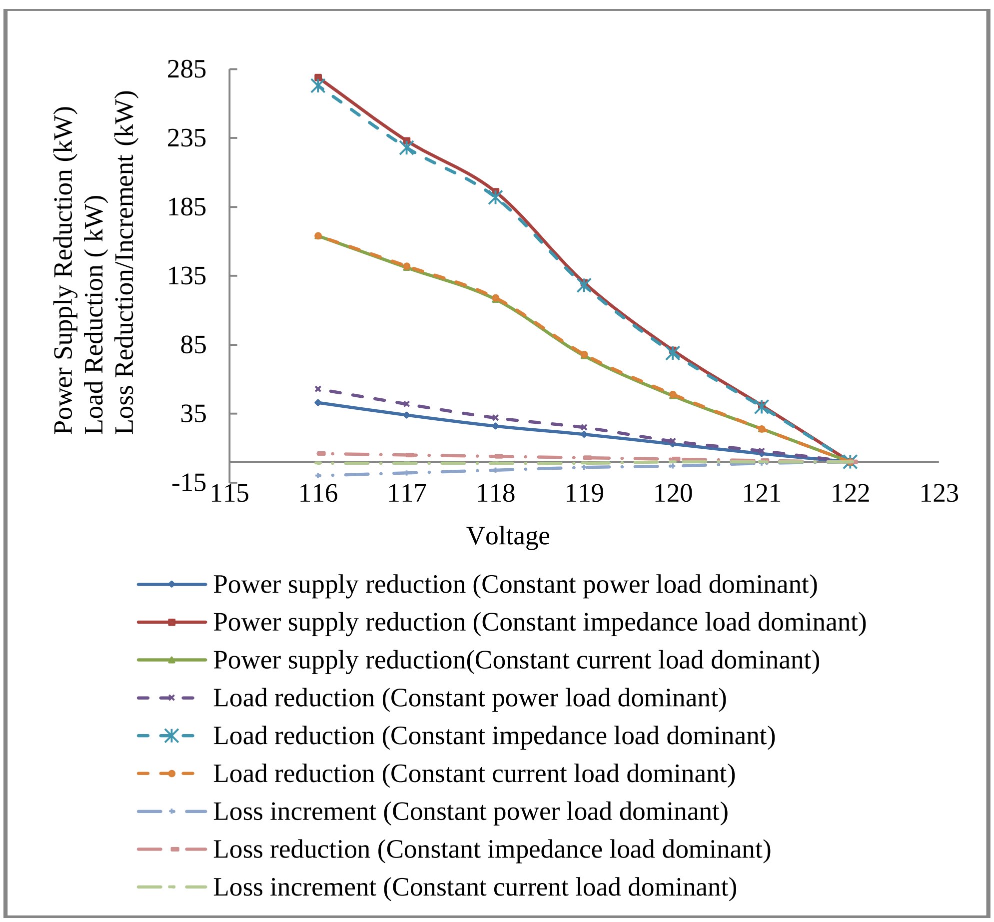


Figure 7.4: Supply, load, and loss reduction vs. voltage for each load model

7.3 Impact of Temperature on Power Consumption, Line Loss, and Generation/Supply

It is known that at a higher temperature, the resistance of a line will increase and consequently line loss (I^2R) will increase, but with voltage-dependent loads, such as constant impedance and constant current, the load will decrease because the line drop (IZ) increases with the increase in resistance at a higher temperature, thus leading to a decrease in the node voltage, and finally, the voltage-dependent load will consume less power at a higher temperature. For example, as shown in Table 7.1, at 122 V, power consumption and line loss at 25^0C are 3,473 kW and 100 kW, respectively, and in Table 7.2, at the same voltage (122 V), power consumption and line loss at 50^0C are 3,469 kW and 111 kW, respectively.

Here it needs to be mentioned that, as voltage drops at a higher temperature, the reduced voltage again affects line loss, and whether line loss will increase or decrease at that reduced voltage depends on the types of load, as discussed in Chapter 4. For the system with a dominant constant impedance load, line loss decreases at a reduced voltage, which is caused by a rise in temperature and, again, increases with an increase in resistance due to the temperature rise, but an increment in line loss for an increase in resistance due to temperature rise is greater than a decrement in line loss due to voltage reduction caused by a temperature rise, so the line loss will increase at a higher temperature. For the system with a dominant constant power load, line loss increases at a reduced voltage caused by temperature rise, and again line loss increases with an increase in resistance due to temperature rise; therefore, line loss will increase to a greater degree. Similarly, for the system with a dominant constant current load, due to a temperature rise, resultant line loss will increase by an amount that is less than the increment in line loss for the system with a dominant constant power load but greater than the increment in line loss for the system with a dominant constant impedance load. Based on the type of load, a comparison of increments in line loss due to temperature rise is given as

$$\Delta P_{Loss}^{Z} < \Delta P_{Loss}^{C_z} < \Delta P_{Loss}^{C_p} < \Delta P_{Loss}^{P} \quad (7.11)$$

where ΔP_{Loss}^{Z} is the increment in line loss due to temperature rise for the system with a dominant constant impedance load; $\Delta P_{Loss}^{C_z}$ is the increment in line loss for the system with a dominant constant current load, where the percent of constant impedance load is greater than the percent of constant power load; $\Delta P_{Loss}^{C_p}$ is the increment in line loss for the system with a dominant constant current load, where the percent of constant power load is greater than the percent of constant impedance load; and ΔP_{Loss}^{P} is the increment in line loss for the system with a dominant constant power load. For example, when temperature rises from 25^0C to 50^0C, at 118 V, it can be seen from Tables 7.1 and 7.2 that ΔP_{Loss}^{P} = (117 – 105) = 12 kW, from Tables 7.3 and 7.4 that ΔP_{Loss}^{Z} = (106 – 96) = 10 kW, and from Tables 7.5 and 7.6 that ΔP_{Loss}^{C} = (111 – 100) = 11 kW, and these reductions in line loss due to temperature rise satisfy the equation (7.11). The effect of temperature on line loss and load is also presented in the flow chart in Figure 7.5.

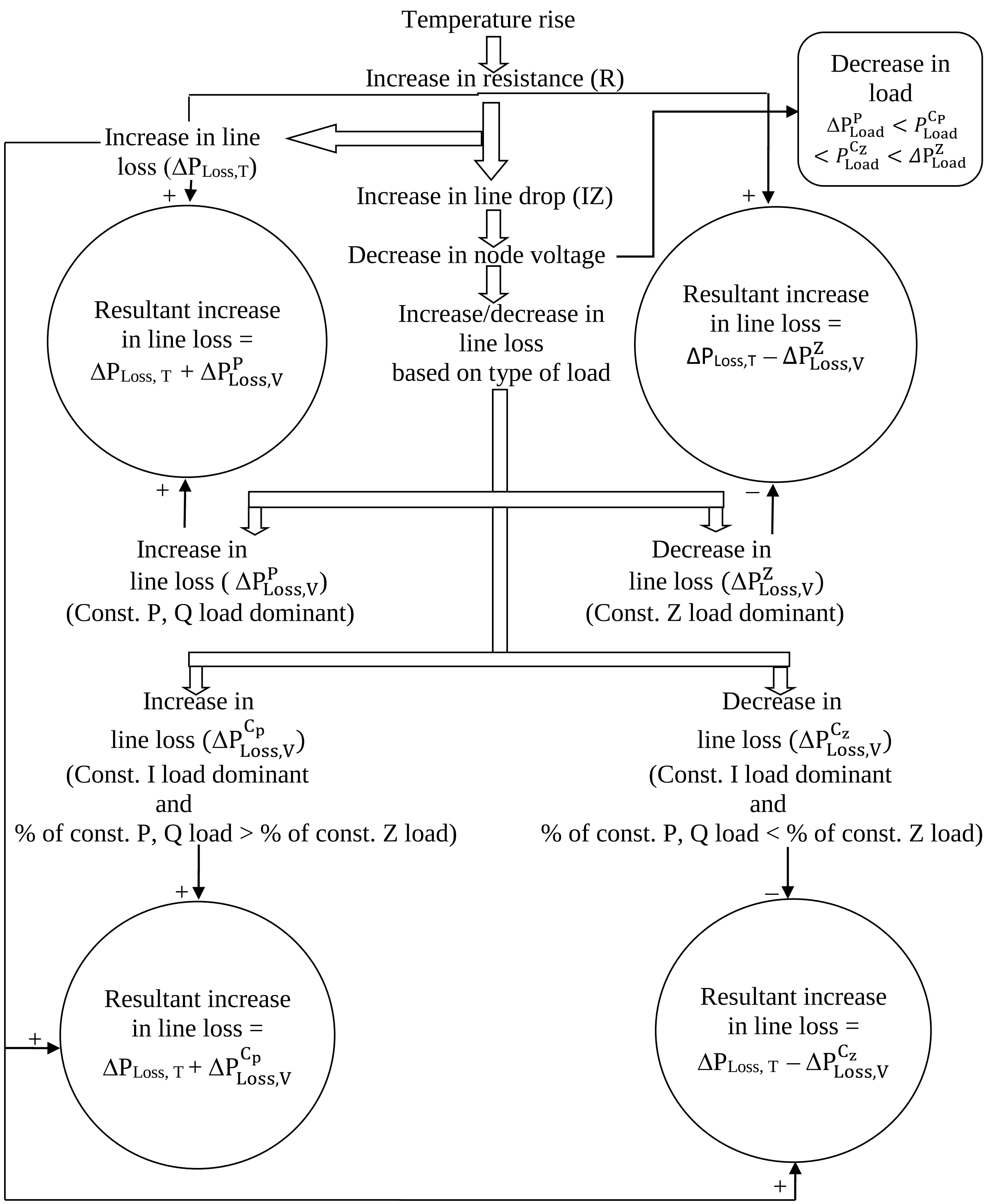


Figure 7.5: Flow chart showing effect of temperature on line loss and load

Now, due to the rise in temperature, the variation in power generation is the summation of the decrement in load and increment in line loss and can be given as

$$\Delta P_{Gen} = \Delta P_{Load}\downarrow + \Delta P_{Loss}\uparrow \quad (7.12)$$

Now, if $\Delta P_{Loss}\uparrow > \Delta P_{Load}\downarrow$, i.e., the increment in line loss is greater than the decrement in load, then power generation will increase due to temperature rise.

If, $\Delta P_{Load}\downarrow > \Delta P_{Loss}\uparrow$, i.e., the decrement in load is greater than the increment in loss, then power generation will decrease due to the rise in temperature. Whether, the decrement in load is greater or less than the increment in line loss depends on the type of load.

Impact of Temperature on Generation for System with Dominant Constant Power Load

For the system with a dominant constant power load, a rise in temperature will cause the increment of line loss to be greater than the decrement in load, i.e., $\Delta P_{Loss}\uparrow > \Delta P_{Load}\downarrow$, because most loads are constant power loads; therefore, at a higher temperature, the power supply increases in that system. For example, in Tables 7.1 and 7.2, it can be seen that at 122 V, as the temperature rises from 25^0C to 50^0C, the decrement in power consumption ΔP^{P}_{Load} = (3,473 – 3,469) = 4 kW, and the increment in line loss ΔP^{P}_{Loss} = (111 – 100) = 11 kW; therefore, the increment in power generation/supply $\left(\Delta P^{P}_{Gen}\right)$ is (11 – 4) kW = 7 kW and so power generation increases by 7 kW from 3,573 kW at 25^0C to 3,580 kW at 50^0C.

Impact of Temperature on Generation for System with Dominant Constant Impedance Load

For the system with a dominant constant impedance load where the power consumption is proportional to the voltage squared, the decrement in load for voltage reduction caused by a rise in temperature is greater than the increment in line loss for a temperature rise, i.e., $\Delta P_{Load}\downarrow > \Delta P_{Loss}\uparrow$; therefore, power generation will decrease at a higher temperature. For example, in Tables 7.3 and 7.4, it can be seen that at 122 V, as temperature rises from 25^0C to 50^0C, the decrement in power consumption ΔP_{Load}^{Z} = (3494 – 3480) = 14 kW, and the increment in line loss ΔP_{Loss}^{Z} = (110 – 100) = 10 kW; therefore, the decrement in power generation/supply $\left(\Delta P_{Gen}^{P}\right)$ is (14 – 10) kW = 4 kW, and the power generation decreases by 4 kW from 3,594 kW at 25^0C to 3,590 kW at 50^0C.

Impact of Temperature on Generation for System with Dominant Constant Current Load

For the system with a dominant constant current load, the increment in line loss for a rise in temperature is greater than the decrement in load due to reduced voltage caused by the temperature rise, i.e., $\Delta P_{Loss} \uparrow > \Delta P_{Load} \downarrow$; therefore, power generation will increase at a higher temperature. For example, in Tables 7.5 and 7.6, it can be seen that at 122 V, as the temperature rises from 25^0C to 50^0C, the decrement in power consumption ΔP_{Load}^{C} = (3476 – 3467) = 9 kW, and the increment in line loss ΔP_{Loss}^{C} = (110 – 100) = 10 kW; therefore, the increment in power generation/supply $\left(\Delta P_{Gen}^{P}\right)$ is (10 – 9) kW = 1 kW, and the power generation increases by 1 kW from 3,576 kW at 25^0C to 3,577 kW at 50^0C. Due to the temperature rise, the variation in bus voltage, load, line loss, and power generation are summarized in Table 7.8.

TABLE 7.8

IMPACT OF TEMPERATURE RISE ON BUS VOLTAGE, LOAD, LINE LOSS, AND POWER GENERATION

Composite Load Model	**Bus Voltage**	**Load**	**Line Loss**	**Power Generation**
Constant Power Load Dominant	Decrease	Decrease	Increase	Increase
Constant Impedance Load Dominant	Decrease	Decrease	Increase	Decrease
Constant Current Load Dominant	Decrease	Decrease	Increase	Increase

Figures 7.6 to 7.11 show how power consumption, generation, and line loss vary with ambient temperature and reduced voltage for different types of composite load models.

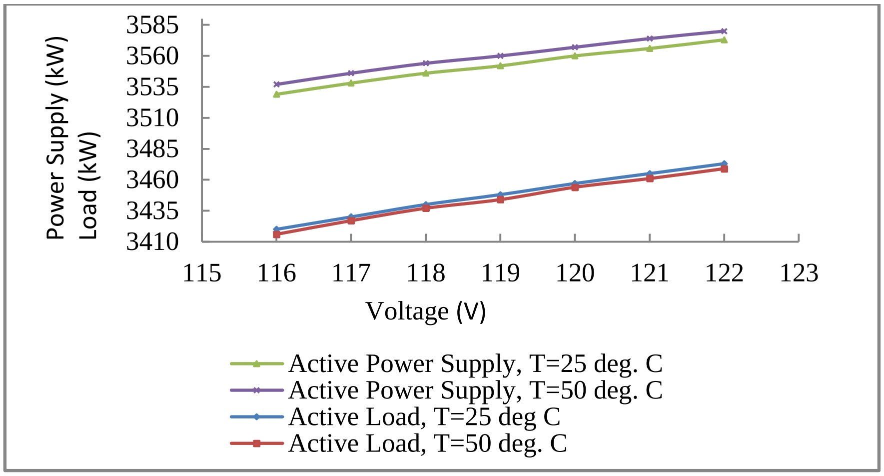


Figure 7.6: Generation/supply and load vs. voltage for dominant constant power load

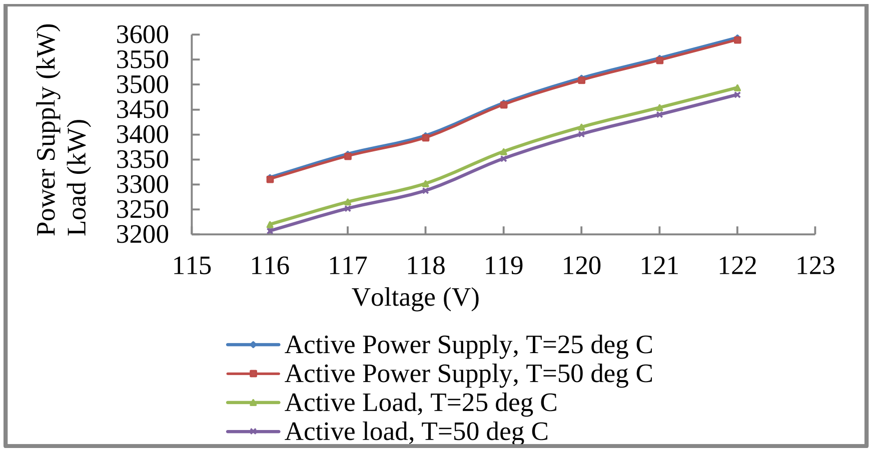


Figure 7.7: Generation/supply and load vs. voltage for dominant constant impedance load

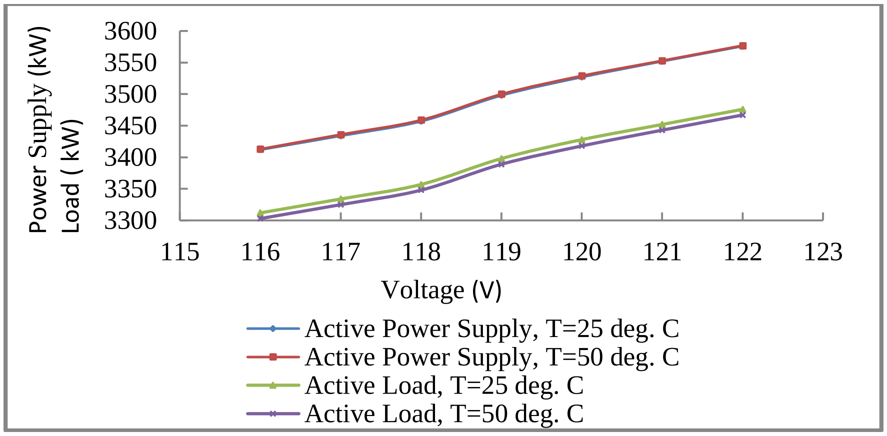


Figure 7.8: Generation/supply and load vs. voltage for dominant constant current load

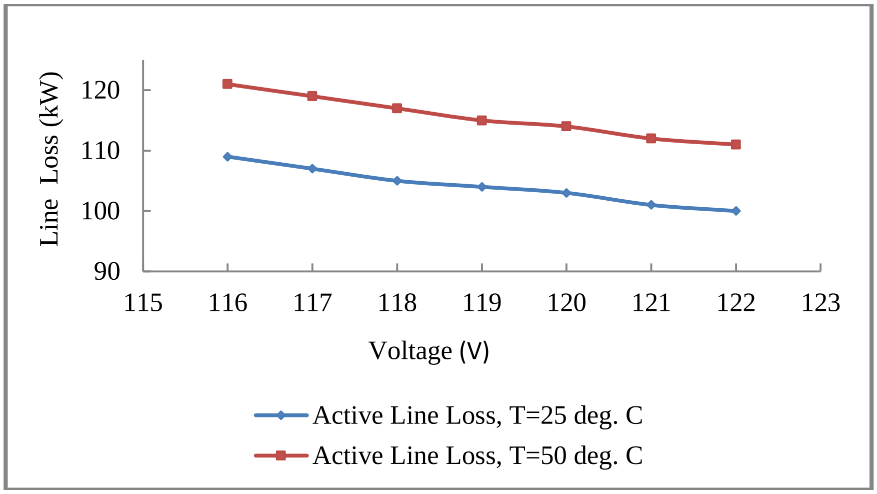


Figure 7.9: Line loss vs. voltage for dominant constant power load

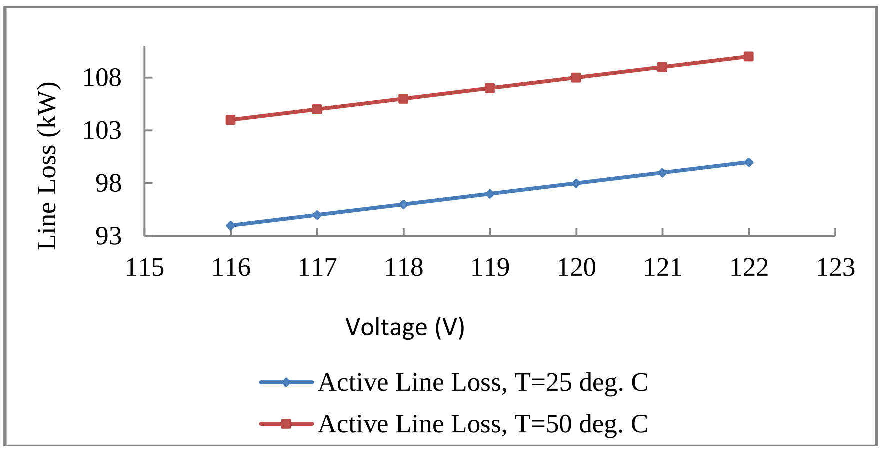


Figure 7.10: Line loss vs. voltage for dominant constant impedance load

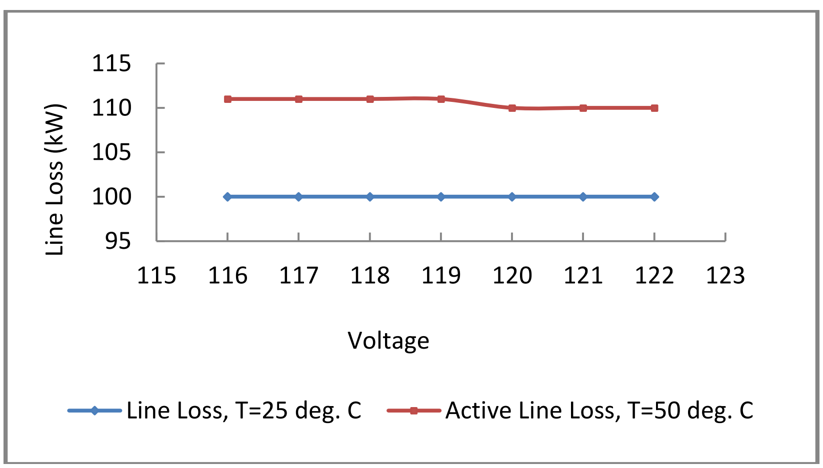


Figure 7.11: Line loss vs. voltage for dominant constant current load

The rise in temperature also leads to an increase in the cooling load in the system, and that increasing load will again affect line loss. The interaction between this increasing load and line loss due to temperature rise is not covered in this chapter but will be discussed in future work.

7.4 Conclusion

The impact of both reduced voltage and ambient temperature on power consumption, line loss and generation are discussed in this chapter. Voltage reduction causes a decrease in both active and reactive power consumption for all composite load models; active power generation also decreases for all composite load models. Reactive power generation increases for a system with dominant constant power load and decreases for a system with dominant constant impedance load or dominant constant current load, when shunt capacitors are used on the system. Among all composite load models, the system with dominant constant impedance load will have the maximum reduction in both active power consumption and generation at reduced voltage. These complexities should be considered in the design and implementation of voltage-reduction programs.

Due to the temperature rise, bus voltage decreases, and consequently load demand decreases while line loss increases for all composite load models. A system with dominant constant power load has the largest increment in line loss; active power generation increases for the systems with dominant constant power and constant current load, and decreases for the system with dominant constant impedance load.

CHAPTER 8

STUDY OF JOINT EFFECT OF VOLTAGE REDUCTION AND AMBIENT TEMPERATURE ON LOAD, LINE LOSS, AND GENERATION

In Chapter 7, the effect of each factor—voltage and ambient temperature—on load, line loss, and generation is discussed separately. If both factors are considered to change simultaneously, then their joint effect on power consumption, line loss, and generation needs to be investigated. Two-factor factorial design can be used to determine the individual and joint effects of voltage and ambient temperature on load, line loss, and power generation. Tukey [35] developed a test that can be used in determining if an interaction between voltage and ambient temperature is present. The sum of squares of the interaction effect is given by

$$SS_N = \frac{\left[\sum_{i=1}^{a} \sum_{j=1}^{b} y_{ij} y_{i.} y_{.j} - y_{..} \left(SS_A + SS_B + \frac{y_{..}^2}{ab} \right) \right]^2}{abSS_A SS_B} \tag{8.1}$$

with 1 degree of freedom, and

$$SS_{Error} = SS_{Residual} - SS_N \tag{8.2}$$

with [(a-1)(b-1) – 1] degrees of freedom, where *a* and *b* are the number levels of factors *A* and *B*, respectively; y_{ij} is the *j*th observation from factor level *i*; $y_{i.}$ is the total of the observations under the *i*th factor level; $y_{.j}$ is the total of the observations in block *j*; $y_{..}$ is the grand total of all observations; SS_A and SS_B are the sum of squares effect for factors *A* and *B*, respectively; and SS_{Error} and $SS_{Residual}$ are the sum of squares of errors and residuals, respectively.

Hypothesis Test: The test statistic given by equation (8.3) is used to test the presence of the interaction effect.

$$F_0 = \frac{SS_N}{SS_{Error}/[(a-1)(b-1)-1]} \tag{8.3}$$

If $F_0 > F_{\alpha,1,(a-1)(b-1)-1}$, then the hypothesis of no interaction must be rejected. At a given significance level of α, the rejection region is $F > F_{\alpha,v_1,v_2}$, where $v_1 = 1$ and $v_2 = (a–1)(b–1)–1$.

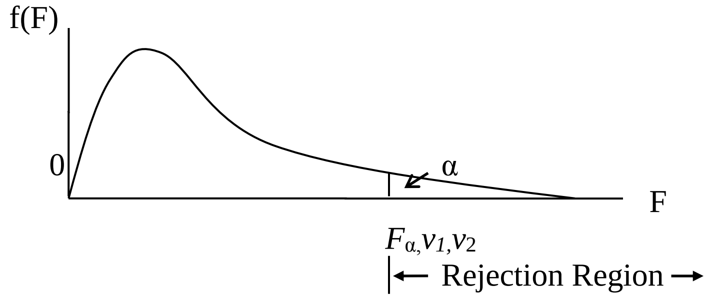


Figure 8.1: Rejection region for F statistic

8.1 Two-Factor Factorial Design for Load Demand

Two temperature levels, 25^0C and 50^0C, are considered, along with seven voltage levels, 122 V to 116 V. Design Expert statistical software was used for the two-factor factorial design. Load demand data and variance analyses for load are shown in Tables 8.1 and 8.2.

TABLE 8.1

LOAD DEMAND DATA FROM TABLES 7.1 AND 7.2

Temperature (^{0}C)	**Voltage (V)**							
	122	**121**	**120**	**119**	**118**	**117**	**116**	$y_{i.}$
25	3473	3465	3457	3448	3440	3430	3420	*24133*
50	3469	3461	3454	3444	3437	3427	3416	*24108*
$y_{.j}$	*6942*	*6926*	*6911*	*6892*	*6877*	*6857*	*6836*	*48241*$= y_{..}$

TABLE 8.2

ANOVA FOR LOAD DEMAND SHOWN IN TABLE 8.1

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_0	$F_{\alpha,v1,v2}$
Temperature	44.64	1	44.64	277.002	16.26
Voltage	4300.86	6	716.81	4447.704	10.67
Interaction	0.05132	1	0.05132	0.318453	16.26
Error	0.80582	5	0.16116		
Total	4346.36	13			

In the variance analysis in Table 8.2, it can be seen that $F_0 > F_{\alpha,v_1,v_2}$ for the individual effects of temperature and voltage, implying that temperature and voltage significantly affect load demand. The mean square (716.81) for voltage is much higher than the mean square (44.64) for temperature, indicating that voltage has a greater impact on load than temperature. For the interaction of temperature and voltage, $F_0 < F_{\alpha,v_1,v_2}$; therefore, the interaction effect on load can be rejected. A fitted regression model for load in terms of coded factors (+1, 0, –1) can be given as

$$P_{Load} = 3445.79 - 1.79*A + 25.21*B[1] + 17.21*B[2] + 9.71*B[3] + 0.21*B[4] - 7.29*B[5] - 17.29*B[6] \quad (8.4)$$

where A is the coded variable (–1 or +1) that represents the temperature; and B[1], B[2], B[3], B[4], B[5], and B[6] are coded variables (–1, 0 or +1) for voltages defined in Table 8.3.

TABLE 8.3

VOLTAGE LEVELS AND THEIR CODED VALUES

	Voltage (V)						
	122	**121**	**120**	**119**	**118**	**117**	**116**
B[1]	1	0	0	0	0	0	–1
B[2]	0	1	0	0	0	0	–1
B[3]	0	0	1	0	0	0	–1
B[4]	0	0	0	1	0	0	–1
B[5]	0	0	0	0	1	0	–1
B[6]	0	0	0	0	0	1	–1

How load varies with temperature and voltage are shown in Figure 8.2. The lines in Figure 8.2 are parallel, indicating that there is no interaction between temperature and voltage, i.e., the joint effect of temperature and voltage on load can be neglected. It can be seen in Figure 8.2 that load decreases as temperature increases, and these decrements in load are small because of the dominant constant power load.

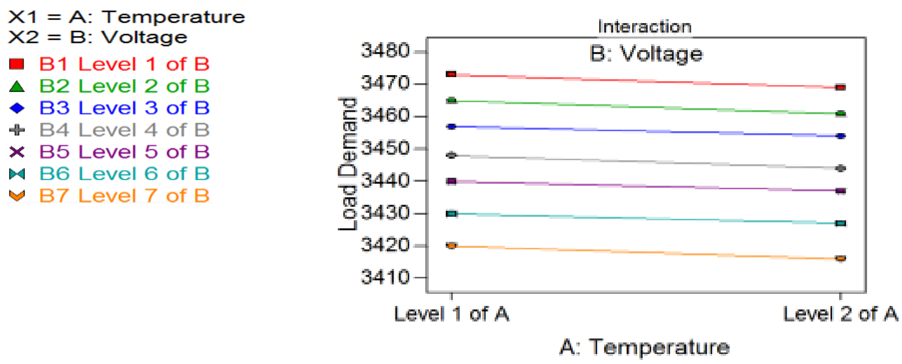


Figure 8.2: Load vs. temperature and voltage

8.2 Two-Factor Factorial Design for Line Loss

Line loss data and variance analyses are shown in the Tables 8.4 and 8.5, respectively. As shown in Table 8.5, $F_0 > F_{\alpha,v_1,v_2}$ for individual effects of temperature and voltage, therefore, their individual effects on line loss is significant. The effect of temperature on line loss is greater than the effect of voltage because the mean square for temperature (457.14) is much higher than the mean square for voltage (23.29). As also shown in Table 8.5, $F_0 < F_{\alpha,v_1,v_2}$, for the interaction of temperature and voltage, therefore interaction effect on line loss can be rejected.

TABLE 8.4

LINE LOSS DATA FROM TABLES 7.1 AND 7.2

Temperature (^{0}C)	**Voltage (V)**							
	122	**121**	**120**	**119**	**118**	**117**	**116**	$y_{i.}$
25	100	101	103	104	105	107	109	*729*
50	111	112	114	115	117	119	121	*809*
$y_{j.}$	*210*	*213*	*217*	*219*	*222*	*226*	*230*	*1538* = $y_{..}$

TABLE 8.5

ANOVA FOR LINE LOSS SHOWN IN TABLE 8.4

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_0	$F_{\alpha,v1,v2}$
Temperature	457.14	1	457.14	10349.21	16.26
Voltage	139.71	6	23.29	527.16	10.67
Interaction	0.6362	1	0.6362	0.576	16.26
Error	0.2209	5	0.0442		
Total	597.71	13			

The regression model for line loss in terms of coded factors can be presented as

$$P_{Loss} = 109.86 + 5.71*A - 4.36*B[1] - 3.36*B[2] - 1.36*B[3] - 0.36*B[4] + 1.14*B[5] + 3.14*B[6] \quad (8.5)$$

Line loss versus temperature and voltage are plotted in Figure 8.3. As shown, there is no interaction effect of temperature and voltage on line loss. It can also be seen that line loss increases with the increase in temperature and decreases with the increase in voltage, because of dominant constant power load in the system.

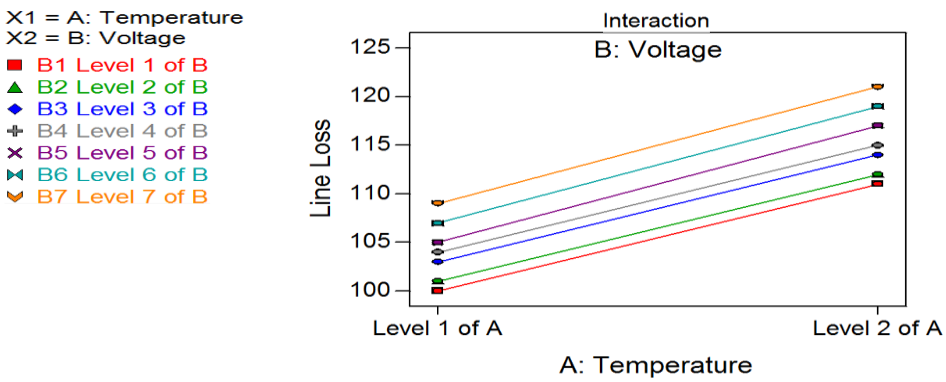


Figure 8.3: Line loss vs. temperature and voltage

8.3 Two-Factor Factorial Design for Power Generation/Supply

Power generation/supply data and variance analyses are shown in the Tables 8.6 and 8.7, respectively. In the variance analysis in Table 8.7, $F_0 > F_{\alpha,v_1,v_2}$, for individual effects of temperature and voltage; therefore, their individual effects on power generation are significant. Since the mean square for voltage (477.79) is greater than the mean square for temperature (208.29), the effect of voltage on power generation is greater than the effect of temperature. For the interaction of temperature and voltage on generation, $F_0 < F_{\alpha,v_1,v_2}$; therefore, the interaction effect on generation can be rejected.

TABLE 8.6

POWER GENERATION/SUPPLY DATA FROM TABLES 7.1 AND 7.2

Temperature (^{0}C)	**Voltage (V)**							
	122	**121**	**120**	**119**	**118**	**117**	**116**	$y_{j.}$
25	3573	3566	3560	3552	3546	3538	3529	*24864*
50	3580	3574	3567	3560	3554	3546	3537	*24918*
$y_{.j}$	*7153*	*7140*	*7127*	*7112*	*7100*	*7084*	*7066*	*49782* = $y_{..}$

TABLE 8.7

ANOVA FOR POWER GENERATION SHOWN IN TABLE 8.6

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	F_0	$F_{\alpha,v1,v2}$
Temperature	208.29	1	208.29	2393.03	16.26
Voltage	2866.71	6	477.79	5489.36	10.67
Interaction	0.27909	1	0.27909	3.20655	16.26
Error	0.43519	5	0.08703		
Total	3075.71	13			

A regression model for power generation/supply in trems of coded factors can be given by equation (8.6)

$$P_{Gen} = 3555.86 + 3.86*A + 20.64*B[1] + 14.14*B[2] + 7.64*B[3] + 0.14*B[4] - 5.86*B[5] - 13.86*B[6] \quad (8.6)$$

The variation in power generation/supply is shown in Figure 8.4.

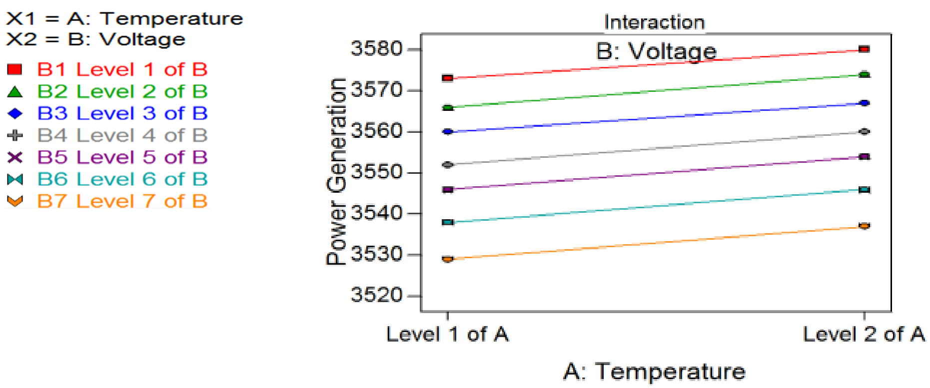


Figure 8.4: Power generation/supply vs. temperature and voltage

Since, the lines in Figure 8.4 are parallel, there is no interaction between temperature and voltage, i.e., the joint effect of temperature and voltage on generation is negligible. Figure 8.4 shows that power generation/supply increases as temperature inceases, because, in the system with dominant constant power load, the increment in line loss is greater than the decrement in load, as shown previously in Figures 8.2 and 8.3.

8.4 Conclusion

The joint effects of voltage and ambient temperature on load, line loss, and power generation/supply are presented by a two-factor factorial design. Even though the joint effects of voltage and temperature on load, line loss, and generation are negligible, the individual effects of voltage and temperature are significant. The effect of temperature on line loss is greater than the effect of voltage on line loss. The effect of voltage on load demand and power generation is greater than the effect of temperature on either.

With the increase in temperature, line loss increases but load decreases. Since the percentage of increment in line loss is greater than the percentage of decrement in load for a system with a constant power load dominant, the power generation/supply increases as the temperature rises.

With the increase in voltage, line loss decreases for the system with a constant power load dominant, but the load demand increases. Since the percentage of increment in load is greater than the percentage of decrement in line loss, the power generation/supply increases as voltage rises.

CHAPTER 9

ANALYSIS OF NEGATIVE LINE LOSS, HIGHER VOLTAGE AT DOWNSTREAM NODE, AND ACTIVE AND REACTIVE COMPONENTS OF CAPACITOR CURRENT

In IEEE's load flow simulation results for a 13-bus system, it was found that power losses in some lines are negative. In the study in this dissertation, it was also found that voltage at the downstream node is higher than voltage at the upstream node, even though all current flows from the upstream to the downstream node. This chapter presents the analysis of how negative line loss in a phase and higher voltage at the downstream node appear in an AC power system. It has also been shown that even though a capacitor generates reactive power only, its current has both active and reactive current components with respect to the system reference.

A distribution system is a practically unbalanced system because of unbalanced loads and having a single phase and two phase lines. From an operational standpoint, unbalanced conditions typically occur in the normal operation of aggregated loads, or during short periods of abnormal operation with unbalanced faults or with one/two phases out of service [37]. The symmetrical condition also does not hold in the distribution system because of the presence of untransposed lines, unequal three-phase off-nominal tap ratios of transformers, or components (loads or local generators) connected in a two-phase or single-phase mode [37]. Negative line loss may appear in the lighted loaded phase in an unbalanced system. Generally there are two approaches to measure power losses. One is the classical approach, where line loss is computed as the difference between input and output power of a line. In this approach, losses in neutral and in dirt are included in each single phase of a three-phase line. In the other approach, line loss is computed as phase resistance multiplied by current squared. In this second approach, losses in neutral and in dirt need to be calculated separately to determine the total three-phase losses. It must be mentioned here that although single-phase line loss may appear negative in the first approach, the total three-phase losses in the first approach are the same as total three-phase losses found in the second approach, as shown in [38]. Although, negative line loss appears in the classical approach of line-loss computation, there is no physical explanation for negative line loss where positive line loss is considered to be electrical energy that dissipates as heat energy when electric current flows through the line. Carpaneto et al. [37] proposed a resistive component-based loss partitioning (RCLP) method. Their results show that, even though single-phase line loss obtained by the RCLP method differs from line loss obtained by the classical approach, the three-phase line loss obtained by the RCLP method is the same as the three-phase line loss obtained using the classical approach.

In this chapter, section 9.1 presents how negative line losses appear in the classical approach of line-loss calculation. In section 9.2, it is shown how downstream node voltage is higher than upstream node voltage in an AC system. Finally in section 9.3, it is demonstrated that even though the capacitor is the reactive power source, its current has both active and reactive components with respect to the system reference.

9.1 Analogy of Negative Line Loss

Formulation of Line Loss Equation and Condition for Negative Line Loss

Figure 9.1 shows a line between the upstream bus n and the downstream bus m.

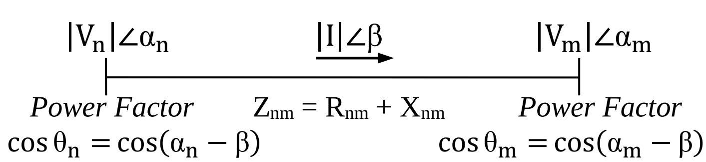


Figure 9.1: Line between upstream bus n and downstream bus m

Line Loss = Input Power – Output Power

$$P_{Loss} + jQ_{Loss} = V_n I^* - V_m I^*$$

$$= |V_n|\angle\alpha_n * |I|\angle-\beta - |V_m|\angle\alpha_m * |I|\angle-\beta$$

$$= |V_n||I|\angle(\alpha_n - \beta) - |V_m||I|\angle(\alpha_m - \beta)$$

$$= |V_n||I|\angle\theta_n - |V_m||I|\angle\theta_m \qquad (9.1)$$

Active power loss is

$$P_{Loss} = |V_n||I|\cos\theta_n - |V_m||I|\cos\theta_m \qquad (9.2)$$

where input power is the power leaving the upstream node n, and output power is the power entering into the downstream node m; $|V_n|\angle\alpha_n$ is the voltage at the upstream node n; $|V_m|\angle\alpha_m$ is the voltage at the downstream node m; $|I|\angle\beta$ is the current in the line between the node n and m; and $\theta_n = (\alpha_n - \beta)$ and $\theta_m = (\alpha_m - \beta)$ are the power factor angles at node n and m, respectively. From equation (9.2), it can be seen that active line loss will be negative if

$$P_{Loss} < 0,$$

$$\Rightarrow \text{if} \quad |V_n||I|\cos\theta_n - |V_m||I|\cos\theta_m < 0$$

$$\Rightarrow \text{if} \quad |V_n|\cos\theta_n < |V_m|\cos\theta_m \qquad (9.3)$$

<u>Case 1</u>: Voltage at the upstream node leads both the voltage at downstream node and line current, as shown in Figure 9.2.

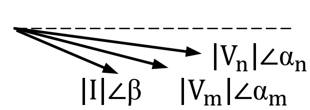


Figure 9.2: Phasor diagram for upstream and downstream node voltage and line current for case 1

Because voltage $|V_n|\angle\alpha_n$ leads voltage $|V_m|\angle\alpha_m$,

$$\alpha_n > \alpha_m$$

$$\Rightarrow \ (\alpha_n - \beta) > (\alpha_m - \beta)$$

$$\Rightarrow \ \cos(\alpha_n - \beta) < \cos(\alpha_m - \beta)$$

$$\Rightarrow \ \cos(\theta_n) < \cos(\theta_m) \tag{9.4}$$

Since, by equation (9.4), $\cos\theta_n < \cos\theta_m$ in equation (9.3), there is a possibility of $|V_n|\cos\theta_n < |V_m|\cos\theta_m$, i.e., $P_{Loss} < 0$, even though $|V_n| > |V_m|$. If the upstream node voltage is lower than the downstream node voltage ($|V_n| < |V_m|$), which may occur in an AC system, as discussed in section 9.2, then it is guaranteed that $|V_n|\cos\theta_n < |V_m|\cos\theta_m$, i.e., active line loss will be negative.

<u>Case 2</u>: Voltage at the upstream node lags behind the voltage at the downstream node and leads the line current, as shown in Figure 9.3.

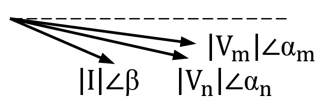


Figure 9.3: Phasor diagram for upstream and downstream node voltage and line current for case 2

Because the voltage $|V_n|\angle\alpha_n$ lags behind the voltage $|V_m|\angle\alpha_m$,

$$\alpha_n < \alpha_m$$

$$\Rightarrow \ (\alpha_n - \beta) < (\alpha_m - \beta)$$

$$\Rightarrow \ \cos(\alpha_n - \beta) > \cos(\alpha_m - \beta)$$

$$\Rightarrow \ \cos(\theta_n) > \cos(\theta_m) \tag{9.5}$$

Even though, by equation (9.5), $\cos\theta_n > \cos\theta_m$ in equation (9.3), there is still the possibility that $|V_n|\cos\theta_n < |V_m|\cos\theta_m$, i.e. $P_{Loss} < 0$, if the upstream node voltage is lower than the downstream node voltage ($|V_n| < |V_m|$), which could happen very rare. If the upstream node voltage is higher than the downstream node voltage ($|V_n| > |V_m|$), then it is guaranteed that active line loss cannot be negative.

Case 3: Voltage at the upstream node leads the voltage at the downstream node and lags behind the line current, as shown in Figure 9.4.

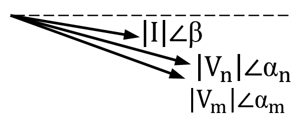


Figure 9.4: Phasor diagram for upstream and downstream node voltage and line current for case 3

Because voltage $|V_n|\angle\alpha_n$ leads voltage $|V_m|\angle\alpha_m$,

$$\alpha_n > \alpha_m$$

$$\Rightarrow \ (\alpha_n - \beta) > (\alpha_m - \beta)$$

[Since $(\alpha_n - \beta) < 0$ and $(\alpha_m - \beta) < 0$, multiplying both sides by –1]

$$\Rightarrow \ -(\alpha_n - \beta) < -(\alpha_m - \beta)$$

$$\Rightarrow \ \cos(-(\alpha_n - \beta)) > \cos(-(\alpha_m - \beta))$$

[Since $\cos(-(\alpha_n - \beta)) = \cos(\alpha_n - \beta)$ and $\cos(-(\alpha_m - \beta)) = \cos(\alpha_m - \beta)$]

$$\Rightarrow \ \cos(\alpha_n - \beta) > \cos(\alpha_m - \beta)$$

$$\Rightarrow \ \cos(\theta_n) > \cos(\theta_m) \tag{9.6}$$

Even though, by equation (9.6), $\cos\theta_n > \cos\theta_m$ in equation (9.3), there is still the possibility that $|V_n|\cos\theta_n < |V_m|\cos\theta_m$, i.e., $P_{Loss} < 0$, if the upstream node voltage is lower than the downstream node voltage ($|V_n| < |V_m|$). If the upstream node voltage is higher than the downstream node voltage ($|V_n| > |V_m|$), then it is guaranteed that active line loss cannot be negative.

Case 4: Voltage at the upstream node lags behind both the voltage at the downstream node and the line current, as shown in Figure 9.5.

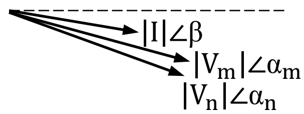


Figure 9.5: Phasor diagram for upstream and downstream node voltage and line current for case 4

Because voltage $|V_n|\angle\alpha_n$ lags behind voltage $|V_m|\angle\alpha_m$,

$$\alpha_n < \alpha_m$$

$$\Rightarrow \quad (\alpha_n - \beta) < (\alpha_m - \beta)$$

[Since $(\alpha_n - \beta) < 0$, and $(\alpha_m - \beta) < 0$, multiplying both side by –1]

$$\Rightarrow \quad -(\alpha_n - \beta) > -(\alpha_m - \beta)$$

$$\Rightarrow \quad \cos(-(\alpha_n - \beta)) < \cos(-(\alpha_m - \beta))$$

[Since $\cos(-(\alpha_n - \beta)) = \cos(\alpha_n - \beta)$ and $\cos(-(\alpha_m - \beta)) = \cos(\alpha_m - \beta)$]

$$\Rightarrow \quad \cos(\theta_n) < \cos(\theta_m) \tag{9.7}$$

Since by equation (9.7), $\cos\theta_n < \cos\theta_m$ in equation (9.3), there is the possibility that $|V_n|\cos\theta_n < |V_m|\cos\theta_m$, i.e., $P_{Loss} < 0$, even though $|V_n| > |V_m|$. If the upstream node voltage is lower than the downstream node voltage ($|V_n| < |V_m|$), then it is guaranteed that $|V_n|\cos\theta_n < |V_m|\cos\theta_m$, i.e., active line loss will be negative.

By and large, if voltage at the upstream node leads both the voltage at the downstream node and the line current, or if voltage at the upstream node lags behind both the voltage at the downstream node and the line current, then the power factor at the downstream node is greater than the power factor at the upstream node; therefore, there is the possibility of having a negative line loss in this classical approach of line-loss calculation. In this case, if the downstream node voltage is higher than the upstream node voltage, then it is guaranteed that the input power at the upstream node is lower than the output the power at the downstream node, i.e., negative line loss is guaranteed. If the upstream node voltage lags behind the downstream node voltage and leads the line current, or if the upstream node voltage leads the downstream node voltage and lags behind the line current, then the power factor at the downstream node is lower than the power factor at the upstream node; therefore, there is no possibility of having a negative line loss, unless the downstream node voltage is higher than the upstream node voltage. The possibilities of occurrence of negative line loss (i.e., input power at the upstream node is less than output power at the downstream node) in the classical approach of line-loss calculation are summarized in Table 9.1.

TABLE 9.1

CONDITIONS OF NEGATIVE LINE LOSS

Lagging/Leading Status	**Power Factor (Pf)**	**Voltage Level Status**	**Occurrence of Negative Line Loss**
Upstream node voltage leads both downstream node voltage and line current or Upstream node voltage lags behind both downstream node voltage and line current	Pf at upstream node < Pf at downstream node	If upstream node voltage > downstream node voltage	Possibility of occurrence of negative line loss
		If upstream node voltage < downstream node voltage	Guarantee of occurrence of negative line loss
Upstream node voltage lags behind downstream node voltage and leads line current or Upstream node voltage leads downstream node voltage and lags behind line current	Pf at upstream node > Pf at downstream node	If upstream node voltage > downstream node voltage	No possibility of occurrence of negative line loss
		If upstream node voltage < downstream node voltage	Possibility of occurrence of negative line loss

Generally, transmission and distribution lines are inductive in nature; therefore upstream node voltage leads both the downstream node voltage and the line current. Upstream node voltage may lag behind the downstream node voltage in a lightly loaded phase in an unbalanced system. Again, line current can lead both upstream and downstream node voltage where too many capacitor banks are connected in the lines for voltage profile improvements and or line-loss reduction .

Example of Negative Line Loss

In the load flow results [10] of the IEEE 13-bus system shown in Figure 9.6, it can be seen that line loss in the line between nodes 650 and 632 in phase b is negative (–3.25 kW), which can be explained by equation (9.3). From IEEE's load flow results, phase b voltage at the substation regulator's secondary side is $V_{bRG60} = 2521.86\angle -120$, phase b voltage at node 632 is $V_{b632} = 2502.65\angle -121.72$, and phase b current in the line between the substation regulator and node 632 is $I = 414.37\angle -140.91$.

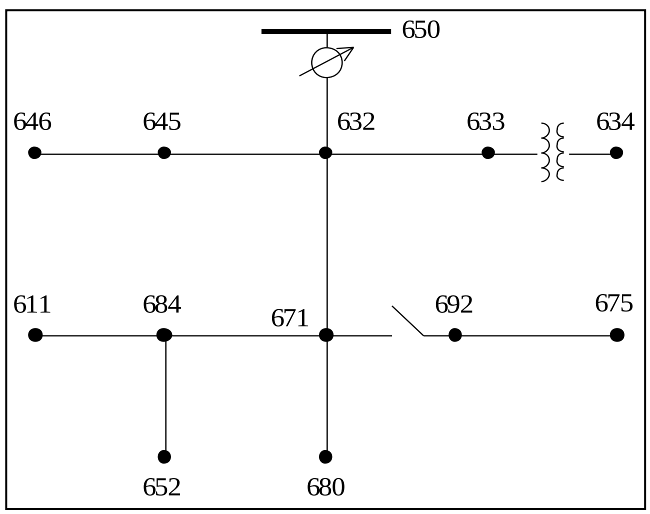


Figure 9.6: IEEE 13-bus test feeder

A phasor diagram of V_{bRG60}, V_{b632}, and I is shown in Figure 9.7

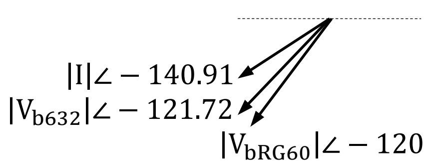


Figure 9.7: Phasor diagram of voltages and line current for line between regulator and node 632

Power loss can be calculated as follows:

$$P_{Loss} = |V_{bRG60}||I| \cos\theta_{bRG60} - |V_{b632}||I| \cos\theta_{b632}$$

$$= 2521.86 * 414.37 * \cos 20.91 - 2502.65 * 414.37 * \cos 19.19$$

$$= 1044.985 * \cos 20.91 - 1037.023 * \cos 19.19 \text{ kW}$$

$$= 1044.985 * 0.93414 - 1037.023 * 0.9444 \text{ kW}$$

The upstream node's power factor is less than the downstream node's power factor

$$= 976.16 - 979.36$$

$$= -3.2 \text{ kW}$$

In the power loss calculation above, it can be seen that although voltage at the upstream node (2521.86 V) is higher than voltage at the downstream node (2502.65 V), the power factor at the upstream node (0.93414) is less than the power factor at the downstream node (0.9444). The higher power factor at the downstream node makes the output power at the downstream node (979.36 kW) greater than the input power at the upstream node (976.16 kW), even though all active power at the downstream node comes from the upstream node. The reason for this higher power factor at the downstream node is that voltage at the upstream node leads both the voltage at the downstream node and the line current, as shown in Figure 9.7.

9.2 Analogy of Higher Voltage at Downstream Node

It is generally known that current flows from high voltage to low voltage, which is true for a DC system but not to an AC system, because, it can be seen that, even though current is flowing from the upstream node to the downstream node, voltage at the downstream node is higher than voltage at upstream node. The reason for having higher voltage at the downstream node in an AC system is because voltage drop in a single phase line depends on mutual impedance and current in the other phases besides self impedance and current of its own phase, as shown in equation (9.8).

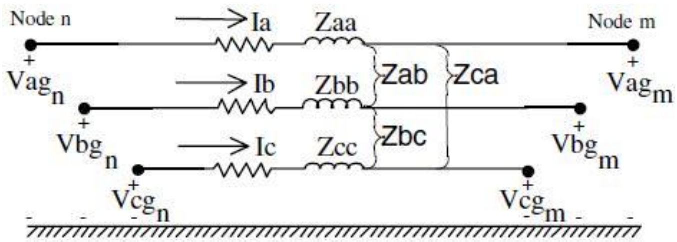


Figure 9.8: Three-phase line

$$\begin{bmatrix} Vag_m \\ Vbg_m \\ Vcg_m \end{bmatrix} = \begin{bmatrix} Vag_n \\ Vbg_n \\ Vcg_n \end{bmatrix} - \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{9.8}$$

$$\Rightarrow Vig_m = Vig_n - \Delta V_i \tag{9.9}$$

Now,

$$|Vig_n| = \sqrt{(\Re e[Vig_n])^2 + (Img[Vig_n])^2} \tag{9.10}$$

$$|Vig_m| = \sqrt{(\Re e[Vig_n] - \Re e[\Delta V_i])^2 + (Img[Vig_n] - Img[\Delta V_i])^2} \tag{9.11}$$

where Vig_n and Vig_m are the voltages of phase i (i = a, b, c) at the upstream and downstream nodes, respectively; ΔV_i is the voltage drop in phase i; $\Re e[Vig_n]$ and $Img[Vig_n]$ are real and imaginary components, respectively, of Vig_n; $\Re e[\Delta V_i]$ and $Img[\Delta V_i]$ are respectively real and imaginary components of ΔV_i.

Now, phase voltage at the downstream node will be higher than phase voltage at the upstream node, if

$$|Vig_m| > |Vig_n|$$

$$\Rightarrow \sqrt{(\Re e[Vig_n] - \Re e[\Delta V_i])^2 + (Img[Vig_n] - Img[\Delta V_i])^2} > \sqrt{(\Re e[Vig_n])^2 + (Img[\Delta V_i])^2}$$

$$\Rightarrow (\Re e[\Delta V_i])^2 + (Img[\Delta V_i])^2 - 2\Re e[Vig_n] * \Re e[\Delta V_i] - 2Img[Vig_n] * Img[\Delta V_i] > 0 \tag{9.12}$$

Similarly, phase voltage at the downstream node will be lower than voltage at the upstream node, if

$$|\mathrm{Vig_m}| < |\mathrm{Vig_n}|$$

$$\Rightarrow \sqrt{(\Re\mathrm{e}[\mathrm{Vig_n}] - \Re\mathrm{e}[\Delta \mathrm{V_i}])^2 + (\mathrm{Img}[\mathrm{Vig_n}] - \mathrm{Img}[\Delta \mathrm{V_i}])^2} \; < \; \sqrt{(\Re\mathrm{e}[\mathrm{Vig_n}])^2 + (\mathrm{Img}[\Delta \mathrm{V_i}])^2}$$

$$\Rightarrow (\Re\mathrm{e}[\Delta \mathrm{V_i}])^2 + (\mathrm{Img}[\Delta \mathrm{V_i}])^2 - 2\Re\mathrm{e}[\mathrm{Vig_n}] * \Re\mathrm{e}[\Delta \mathrm{V_i}] - 2\mathrm{Img}[\mathrm{Vig_n}] * \mathrm{Img}\left[\Delta \mathrm{V_{ig}}\right] < 0 \qquad (9.13)$$

Now, in equation (9.11), if active components of voltage ($\mathrm{Vig_n}$) at the upstream bus and the voltage drop ($\Delta \mathrm{V_i}$) have same sign and reactive components of $\mathrm{Vig_n}$ and $\Delta \mathrm{V_i}$ also have same sign, then, it is guaranteed that voltage at the downstream bus will be lower than the voltage at the upstream bus. Similarly, in equation (9.11), if active components of voltage ($\mathrm{Vig_n}$) and voltage drop ($\Delta \mathrm{V_i}$) have opposite signs and reactive components of $\mathrm{Vig_n}$ and $\Delta \mathrm{V_i}$ also have opposite signs, then it is guaranteed that voltage at the downstream bus will be higher than the voltage at the upstream bus. Again, in equation (9.11), if active components of voltage ($\mathrm{Vig_n}$) and voltage drop ($\Delta \mathrm{V_i}$) have the same sign, but reactive components of voltage ($\mathrm{Vig_n}$) and voltage drop ($\Delta \mathrm{V_i}$) have opposite signs or if active components of voltage ($\mathrm{Vig_n}$) and voltage drop ($\Delta \mathrm{V_i}$) have opposite signs, but reactive components of $\mathrm{Vig_n}$ and $\Delta \mathrm{V_i}$ have same sign, then the downstream bus voltage can be lower or higher than the upstream bus voltage. Figure 9.9 shows how (+ and -) signs of active and reactive components of ($\mathrm{Vig_n}$) and ($\Delta \mathrm{V_i}$) change relative to their locations in 4 quadrants.

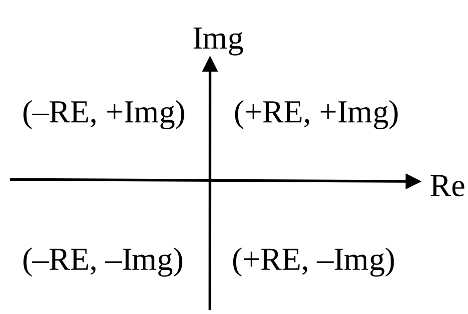


Figure 9.9: Signs (+ and –) in four quadrants

If the voltage phasor (Vig_n) of the upstream bus and voltage drop phasor (ΔV_i), lie in the same quadrant, then corresponding active components of (Vig_n) and (ΔV_i) will have the same sign and corresponding reactive components of Vig_n and ΔV_i will also have the same sign; In this case, it is guaranteed that voltage at the downstream bus will be lower than voltage at the upstream bus.

If the voltage phasor (Vig_n) of the upstream bus and voltage drop phasor (ΔV_i) lie in two different quadrants that are exactly opposite (first and third quadrants or second and fourth quadrants), then the corresponding active components of voltage (Vig_n) and voltage drop (ΔV_i) will have opposite signs and the corresponding reactive components of Vig_n and ΔV_i will also have opposite signs; In this case, it is guaranteed that voltage at the downstream bus will be higher than the voltage at the upstream bus. Again, if voltage phasor (Vig_n) of the upstream bus and voltage drop phasor (ΔV_i) lie in two different quadrants that are adjacent (first and second quadrants or second and third quadrants or third and fourth quadrants or fourth and first quadrants), then the corresponding active components of Vig_n and ΔV_i can have the same or opposite signs; If they have the same sign, then the corresponding reactive components of Vig_n and ΔV_i will have opposite signs; and if they have opposite signs, then the corresponding reactive components of Vig_n and ΔV_i will have the same sign; in both cases, the downstream bus voltage can be lower or higher than the upstream bus voltage. Table 9.2 summarizes the conditions that cause the downstream bus voltage to be higher or lower than the upstream bus voltage.

TABLE 9.2

CONDITIONS OF DOWNSTREAM BUS VOLTAGE
TO BE GREATER OR LOWER THAN UPSTREAM BUS VOLTAGE

Location of Upstream Bus Voltage (Vig_n) and Voltage Drop (ΔVi) Phasors in the Quadrants		**Downstream Bus Voltage Level with Respect to Upstream Bus Voltage Level**
Same Quadrant		$\lvert Vig_m \rvert < \lvert Vig_m \rvert$
Different Quadrants	Exactly Opposite Quadrants	$\lvert Vig_m \rvert > \lvert Vig_m \rvert$
	Adjacent Quadrants	$\lvert Vig_m \rvert < \lvert Vig_m \rvert$ or $\lvert Vig_m \rvert > \lvert Vig_m \rvert$

How the downstream node voltage and voltage drop vary with loads in an AC system were tested on a two-bus system, as shown in Figure 9.10, and the results are shown in Table 9.3.

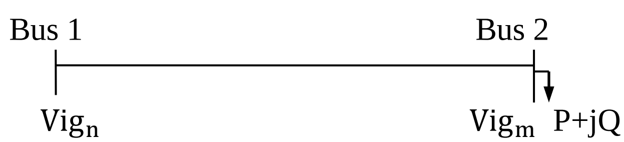
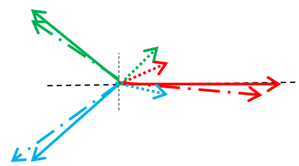
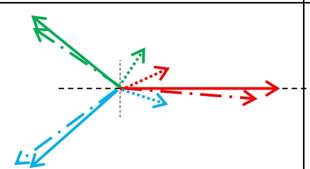
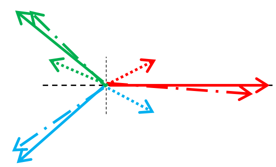
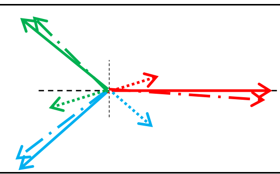
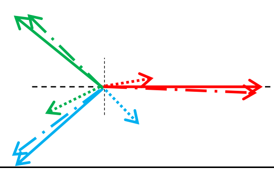
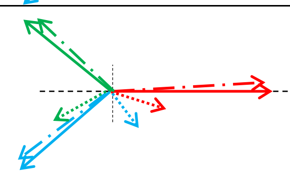
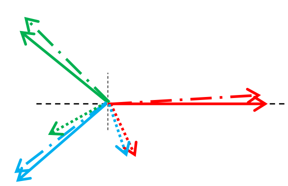
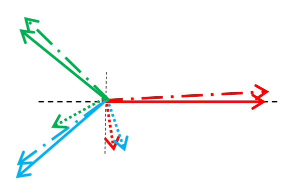


Figure 9.10: Two-bus system

TABLE 9.3

VARIATION IN THE LOCATION OF BUS VOLTAGE PHASORS
AND VOLTAGE DROP PHASORS WITH LOADS

	Bus Voltage (V)	Voltage Drop (V)	Phasor Diagram of Bus Voltages and Voltage Drop	Load (kW, kVAr)
Bus 1	2400 ∠ 0 (2400 + j0) 2400 ∠ –120 (–1200 – j2078.5) 2400 ∠ 120 (–1200 + j2078.5)			
Bus 2	2261.0 ∠ –2.4 (2259 – j95.4) 2426.4 ∠ –121.8 (–1280.2 – 061.2) 2386.9 ∠ 120.7 (–1218.8 + j2052.2)	140.98 + j95.44 (170.2 ∠ 34.1) 80.22 – j17.26 (82.1 ∠ –2.14) 18.75 + j26.22 (32.23 ∠ 54.43)		1000+ j500 500 + j200 300 + j100
	2292.4 ∠ –1.7148 (2291.4 – j68.6) 2406.7 ∠ –121.7(–1265.1– j2047.3) 2389.1 ∠ 120.28 (–1205 + j2063)	108.59 + j68.61(128.4 ∠ 32.3) 65.12 – j31.13 (72.2 ∠ –25.55) 4.97 + j15.5 (16.27 ∠ 72.22)		800 + j400 500 + j200 300 + j100
	2351.7 ∠ –1.03 (2322.1 – j41.6) 2368.1 ∠ –121.6 (–1250.9 – j2033.4) 2394.8 ∠ 119.9 (–1191.9 + j2073.8)	77.89 + j41.56 (88.3 ∠ 28.1) 50.86 – j45.1 (67.97 ∠ –41.6) –8.103 + j4.64 (9.3 ∠ 150.17)		600 + j300 500 + j200 300 + j100
	2351.7 ∠ –0.358 (2351.6 – j14.7) 2368.1 ∠ –121.48 (–1236.9 – j2019.5) 2394.8 ∠ 119.5 (–1179.3 + j2084.3)	48.37 + j14.7 (50.5 ∠ 16.89) 36.88 – j58.9 (69.5 ∠ –57.98) –20.67 – j5.84(21.5 ∠ –164.2)		400 + j200 500 + j200 300 + j100
	2365.90 ∠ –0.029 (2365.9 – j1.2) 2358.7 ∠ –121.4 (–1230.3 – j2012.5) 2396.7 ∠ 119.3 (–1173.2 + j2089.9)	34.13 + j1.15 (34.15 ∠ 1.94) 30.284 – j65.99 (∠ –65.35) –26.78 – j11.4 (72.6 ∠ –156.8)		300 + j150 500 + j200 300 + j100
	2379.9 ∠ 0.29 (2379.9 + j12.1) 2349.6 ∠ –121.38(–1223.8 –j2005.7) 2398.3 ∠ 119.12 (–1167.3 + j2095)	20.14 – j12.1 (23.5 ∠ –30.9) 23.84 – j72.78 (76.5 ∠ –71.8) –32.7 – j16.6 (36.6 ∠ –153.1)		200 + j100 500 + j200 300 + j100
	2394.0∠0.62 (2393.8 + j25.9) 2339.6 ∠ –121.33 (–1216.7 –j1998.3) 2400.4 ∠ 118.93 (–1161.2 + j2100.9)	6.15 – j25.86 (26.58 ∠ –76.6) 16.7 – j80.12 (81.8 ∠ –78.2) –38.8 – j22.4 (44.8 ∠ –150.02)		100 + j50 500 + j200 300 + j100
	2400.1 ∠ 0.776 (2399.9 +j0.032.5) 2335.8 ∠ –121.3 (–1214.6 – j1995.2) 2401.3 ∠ 118.85 (–1158.8 + j2103.2)	0.1 – j32.52 (32.52 ∠ –89.8) 14.6 – j83.26 (84.5 ∠ –80.04) –41.2 – j24.76 (48.06 ∠ –149)		50 + j25 500 + j200 300 + j100

Bus 1 phase a voltage: Bus 2 phase a voltage: Voltage drop in phase a:

Bus 1 phase b voltage: Bus 2 phase b voltage: Voltage drop in phase b

Bus 1phase c voltage: Bus 2 phase c voltage: Voltage drop in phase c:

In the phasor diagram shown in Table 9.3, it can be seen how voltage drop changes its location in the quadrants as load varies, and as such, the location of the downstream node voltage changes as well. For example, when the three-phase load at bus 2 changes from (1,000 kW + j500 kVAr), (500 kW+ j200 kVAr), (300 kW + j100 kVAr) to (200 kW + j100 kVAr), (500 kW+ j200 kVAr), and (300 kW+ j100 kVAr) in phases a, b, and c, respectively, we can see that the voltage drop phasor ΔV_a changes its location from the first quadrant to the fourth quadrant, and that the voltage drop phasor ΔV_c changes its location from the first quadrant to the third quadrant. When the three-phase load (600 kW + j300 kVAr), (500 kW + j200 kVAr), and (300 kW + j100 kVAr) is connected at the downstream bus 2, in phases a, b, and c, respectively, it can be seen that phase c voltage (2394.8 V) at the downstream bus 2 is lower than phase c voltage (2,400 V) at the upstream bus 1, where voltage phasor Vcg_n at the upstream bus 1 and voltage drop phasor ΔV_c lie in the same quadrant (second). Again, when the three-phase load changes to (100 kW + j50 kVAr), (500 kW + j200 kVAr), and (300 kW + j100 kVAr), in respective phases, it can be seen that, phase c voltage (2400.4 V) at the downstream bus 2 is higher than phase c voltage (2400 V) at the upstream bus 1, where voltage phasor Vcg_n at the upstream bus 1 lies in second quadrant, but the voltage drop phasor ΔV_c lies in the third quadrant.

9.3 Active and Reactive Components of Capacitor Current

The power delivered by a capacitor is reactive power, but its output current has active and reactive components with respect to the system reference. The reason for having both active and reactive current components with respect to the system reference is because the capacitor current leads the capacitor bus voltage by 90 degrees, and again, that bus voltage angle is represented with respect to the system reference. Now, the angle of a capacitor current with respect to the system reference is equal to the capacitor bus voltage angle plus 90 degrees; the cosine and sine value of that angle of the capacitor current, make the active and reactive current component of the capacitor current, respectively, where the capacitor's current is only reactive with respect to the capacitor bus voltage. Here it needs to be mentioned that, if Kirchhoff's current law is applied at the capacitor bus and considering the capacitor current reactive, then it does not satisfy Kirchhoff's current law. If the angle of the capacitor current is represented with respect to the system reference where the capacitor current has both active and reactive components, then Kirchhoff's current law is satisfied. These have been explained with the IEEE load flow results for a 13-bus system [10].

Load flow results [10] for a 13-bus system for phase a of bus 675 and line 692–675 follow: Voltage at bus 675, $V_{675} = 0.9835 \angle -5.56^0$, current in line 692-675, $I_{Line} = 205.33 \angle -5.15^0$, constant power load at bus 675, $P_{Load} + jQ_{Load} = 485 + j190$, capacitor's output power, $jQ_{Load} = j193.4$.

Line current: $I_{Line} = 205.33 \angle -5.15^0 = 204.501 - j18.43$

Load current: $|I_{Load}|^2 = \frac{P_{Load}^2 + Q_{Load}^2}{|V|^2}$

$$= \frac{485^2+190^2}{|.9835*2.40177|^2} = 48626.8$$

$$\Rightarrow |I_{Load}| = 205.33$$

If θ is the power factor angle, i.e., the angle between the voltage and the current, then

$$\cos\theta = \frac{485}{\sqrt{485^2+190^2}} = 0.931 \Rightarrow \theta = 21.39$$

Since the load current lags behind the voltage,

$$I_{Load} = 220.5148 \angle (-5.56^0 - 21.39^0) = 196.56 - j99.95.$$

Capacitor current: $I_{Cap} = \frac{Q_{Cap}}{|V|} = \frac{193.44}{.9835*2.40177} = 81.8915$

Here, if the capacitor current is considered to be totally reactive current, i.e., $I_{Cap} = 81.89 \angle 90^0$, then Kirchhoff's current law $(\sum line\ current + load\ current + capacitor\ current = 0)$ is not satisfied at node 675. The capacitor current, I_{Cap}, leads bus voltage, V_{675} ($0.9835 \angle -5.56^0$) by 90^0; therefore, the angle between the system reference and I_{Cap} is $(-5.56^0 + 90^0) = 84.44^0$, and the I_{Cap}, should be given as $I_{Cap} = 81.89 \angle 84.44^0 = 7.93 + j81.51$. It can be seen that I_{Cap} does not make the 90^0 angle with the system reference, which is the phase a voltage of substation regulator; therefore, I_{Cap} has active and reactive current components with respect to the system reference, even though, all of the capacitor output power is reactive and the capacitor current is also reactive with respect to the capacitor bus voltage. A phasor diagram of I_{Line}, I_{Load}, I_{Cap}, and V_{675} are shown in Figure 9.11.

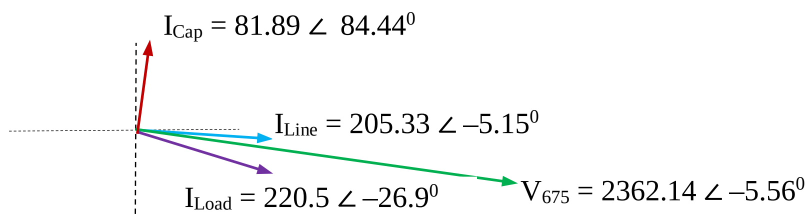


Figure 9.11: Phasor diagram of bus voltage, line current, and capacitor current

Kirchhoff's current law is satisfied with the capacitor current, I_{Cap}, $= 81.89\angle 84.44^0$. It can be seen at node 675 in phase a, that

$$I_{Line} = I_{Load} + I_{Cap}$$

$$\Rightarrow \quad 205.33 \angle -5.15^0 = 220.5 \angle -26.95^0 + 81.89 \angle 84.44^0$$

$$\Rightarrow \quad 204.5 - j18.43 = (196.56 - j99.95) + (7.93 + j81.51)$$

Now, the power flowing through line 692-675 is

$$P_{Line} + jQ_{Line} = V_{675} I^*_{Line}$$

$$= 0.9835 * 2.4017\angle - 5.56 * 205.3\angle - 5.15$$

$$= 485 + j3.47$$

If the law of conservation of power is applied at node 675 in phase a, then

$$(P_{Line} + jQ_{Line}) + (jQ_{cap}) = (P_{Load} + jQ_{Load})$$

$$\Rightarrow \ (485\text{-}j3.4) + (j193.44) = (485 + j190)$$

Here it needs to be mentioned that power consumption by load is equal to the capacitor's power plus power injected through the line, while line current is equal to the capacitor current plus load current.

9.4 Conclusion

Transmission and distribution lines are generally inductive in nature; therefore upstream bus voltage leads both downstream bus voltage and line current; therefore, the power factor at the downstream bus is greater than the power factor at the upstream bus. The higher power factor at the downstream bus is the main reason for the possibility of having a greater output power at the downstream node with respect to input power at the upstream node, even though all the power comes from the upstream node. If the output power at the downstream node is greater than the input power at the upstream node, then negative line loss will be seen, if line loss is calculated as input power minus output power. If the power factor at the downstream node is lower than the power factor at the upstream node, then there is still the possibility of having a negative line loss, if the downstream bus voltage is higher than the upstream bus voltage. If the upstream bus voltage and voltage drop phasors lie in two different quadrants that are exactly opposite, then it is guaranteed that the downstream bus will be higher than the upstream bus voltage; if they lie in two different quadrants that are adjacent, then there may be the possibility of having a downstream bus voltage higher than the upstream bus voltage. If the upstream bus voltage and voltage drop phasors lie in the same quadrant, then it is guaranteed that the downstream node voltage will be lower than the upstream node voltage.

The capacitor delivers the reactive power, but its current has both active and reactive components with respect to the system reference, where all the current of a capacitor is reactive with respect to the capacitor bus voltage. Therefore, active and reactive current components are reference related.

CHAPTER 10

CONCLUSION

A new method for placing and sizing capacitors on a distribution system to better minimize system losses was proposed in this dissertation. How capacitor price, size, and phase kVArs impact the optimization of a capacitor-placement problem and consequently a utility's savings and a customer's electric bill have been presented. Reducing system losses has varying effects on customers and, depending on load type, can increase customer costs.

The importance of voltage reduction and optimal voltage setting techniques during reactive power compensation based on load type have been presented. Voltage-reduction programs, designed to reduce load while maintaining proper system voltages, again depending on load type, have varying effects on system losses, customer consumption, and total load. A model for the variation of line loss and load demand with voltage reduction has been derived based on type of load, and this model can be used as a guide line in a voltage-reduction program. For example, how active and reactive power generation changes with voltage reduction and determination of an optimal voltage setting during reactive power compensation can be explained with this model.

Other factors including outdoor temperature can also have significant effects on losses and load, which can be explained with this model as well. The 2^4 factorial design was used to determine the joint effect of temperature and capacitor price, size, and phase kVAr on load, line loss, and generation. The joint effect of voltage and temperature on load, line loss, and generation was presented by using a two-factor factorial design. These factorial designs would be beneficial to engineers for understanding what combination of factors should be used to operate the system for a best response.

Finally, this dissertation presented how negative line loss in a single-phase and higher voltage at a downstream node would appear in an AC system. It was demonstrated that even though a capacitor generates only reactive power, its current has both active and reactive current components with respect to the system reference.

Numerous voltage-reduction programs for conservation or peak-load reduction are already in use in the U.S. and around the world. The design of these programs, however, has been based on experimental evidence and not on a thorough understanding of how and why such programs work. This dissertation has shown that in some cases, they do not achieve their desired effects, which explains the difference in results obtained by those who have implemented such programs. The results of this dissertation and further work should be considered in the design of future voltage-reduction programs.

The following issues will be considered in future work:

- Impact of distorted substation voltage on the optimal capacitor placement problem.
- Integration of distributed generations (solar, wind, geothermal, biomass) and shunt bank capacitors.
- Interaction between increasing cooling load and line loss due to temperature rise.
- Load variation caused by the plug-in electric vehicle.
- Transient effect caused by switched capacitors.

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