Addis Ababa University

Addis Ababa Institute of Technology (AAiT)

Department of Electrical and Computer Engineering

IMPROVING VOLTAGE PROFILE AND LOSS REDUCTION OF DISTRIBUTION SUBSTATION USING CAPACITOR BANKS

CASE STUDY: COTEBE DISTRIBUTION SUBSTATION

By: Getahun Mengesha

THESIS SUBMITTED TO ADDIS ABABA INSTITUTE OF TECHNOLOGY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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ELECTRICAL ENGINEERING

Advisor: Dr.-Ing. Fekadu Shewarega

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Addis Ababa University
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DECLARATION

I, the undersigned, declare that this MSc thesis is my original work, has not been presented for fulfillment of a degree in this or any other university, and all sources and materials used for the thesis have been acknowledged.

Name: Getahun Mengesha
Signature: _____________
Place: Addis Ababa
Date of submission: July 2017

This thesis work has been submitted for examination with my approval as a university advisor.

Dr. Ing. Fekadu Shewarega________________
Advisor's Name Signature

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ABSTRACT

Electric transmission and distribution system are the intermediate stages in the transfer of electrical power from the central generating station to the consumers. Minimization of power losses and improvement of voltage profile are the most essential concerns of any electric utility to support increased load requirement. The voltage at buses reduces due to insufficient amount of reactive power in the network and consequently power losses increases. There are many numerous activities which have been tried to minimize distribution loss like upgrading MV and LV distribution conductors, taps changing and installing new capacitor.

In this thesis work, optimal placements of the capacitors have been suggested. A methodology to determine the optimal capacitor locations and their sizes to improve voltage profile and to minimize the line loss of the distribution system has been developed. The study has been carried out on COTEBE Substation having 42 buses radial distribution system. The optimal capacitor placement is determined by the repetitive load flow to achieve the total minimum system loss. DIGSILENT Powerfactory software is used for Power flow analysis to determine the power loss and voltage profile of the system. The location of reactive power support allocation has been studied according to the highest reactive power flow which has been observed. Loss sensitivity method has been used to determine the optimal capacitor location. The results of the loss sensitivity are used for the optimal capacitor size selection.

The proposed objective function is the minimization of the total investment cost due to reactive power support for loss reduction and voltage profile improvement. Different available capacitors values are used for the test cases, starting from 10KVAr to 10MVAr and the capacitor sizes of 2.2MVAr and 3.3MVAr are selected as an optimization solution. The selected test case result make that the total grid loss to decrease from 0.583MW to 0.413MW and the minimum voltage level to increase from 0.905(p.u) to 0.959(p.u). Due to this, the Ethiopian Electric Utility can save 26,132.33$ per annum with the payback period of Fifteen months.

Keywords: Capacitor Placement, DIGSILENT Powerfactory, Loss Minimization, Voltage Improvement, Cost benefit analysis, Distribution Network in Ethiopia

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LIST OF ABBREVIATIONS

A Ampere

AAC All Aluminum Conductor

AAAC All Aluminum Alloy Conductor

AC Alternating Current

ACSR Aluminum Conductor Steel Reinforced

CB Circuit Breaker

CT Current Transformer

EEP Ethiopian Electric Power

EEU Ethiopian Electric Utility

EEPCO Ethiopian Electric Power Corporation

IEEE International Electrical and Electronics Engineers

kVAr Kilovolt Ampere Reactive

kVA Kilovolt Ampere

kA Kilo Ampere

kV Kilo Volt

kWh Kilo watt hour

kW Kilo watt

LV Low Voltage

MV Medium Voltage

MVA Mega volt ampere

MW Mega watt

OCP Optimal Capacitor Placement

P Active power

PF Power factor

RDS Radial Distribution System

rms Root mean square

Q Reactive power

Z_C Characteristic Impedance

CHAPTER ONE

INTRODUCTUON

1.1 Background

Electric power is transmitted from the 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.

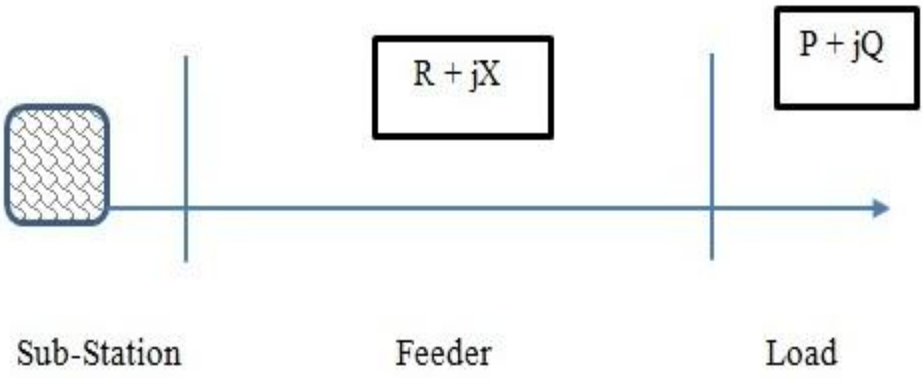

Figure 1.1: Model of Electric power flow

This power loss, for one phase and three phases of a line respectively, is given by

$$P_{loss}=I^2*R \tag{1.1}$$

and

$$P_{loss} = 3|I|^2 * R,\ |I|^2 = \frac{P^2+Q^2}{3\,v^2} \rightarrow P_{loss} = \frac{P^2+Q^2}{3\,v^2} * R \tag{1.2}$$

Where, P_{loss} is the active power loss, I is the current magnitude, V is the voltage Magnitude, P is active power, Q is reactive power 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 has increased. 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. The greater the increase in load demand, the greater the power loss on transmission and distribution lines. At this critical time Ethiopia is faced relatively high power interruption. It is importance to maximize the efficiency of the Ethiopian Electric power networks in order to ensure that maximum power is transmitted through the networks. This implies that network technical losses must be kept to a minimum for all network loading conditions. Shunt capacitor banks are extensively used for reactive power compensation to reduce power loss and to control voltage in a distribution system. 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. The Causes of Voltage drop affects the voltage profile of the network. Reactive power compensation benefits utilities in several ways. 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. Therefore, the impact of load types on power consumption, line loss in a voltage reduction and the feeder should be designed and analyzed to accommodate Reactive Power.

Good Voltage Profile is used to maintain stable and reliable electricity Network since the load on the grid varies with time. It is used to avoid damage to network equipment and customer sensitive supplies. Electrical equipment is built to withstand certain voltage deviations so it is important to maintain supply voltages within contractual obligations. To maintain good and dependable network voltage profiles, the increased interconnections between Networks of different sizes, different connection rules, different characteristics and unique sensitivities are need to be considered.

Optimizing the cost of technical losses (copper and iron) is used for voltage regulation.

Constraints

There are a number of operational interventions that could be employed to improve the network voltage profile one of which is the optimal placement of capacitors. Although there is no doubt those capacitors have a technical capability of injecting the much needed reactive power (MVArs) into the power system which helps to improve the voltage profile and to minimize losses, it requires a strategy to carefully determine the optimal position(s) at which to connect these capacitor(s). When deciding on the placement of the capacitor banks, careful consideration will have to be given to a number of limitations and constraints.

Among many of the considerations to be bringing in mind are the following:

- Availability of adequate installation space for the capacitor bank
- Cost of installation and maintenance of the capacitor banks.
- Positioning capacitors on the network
- Voltage limitation

1.2 Statement of the Problem

This Research discusses on the optimal placement of capacitor banks on a Distribution network which is supplied by the feeder from COTEBE Distribution Substation. An optimization problem is formulated problem of power loss and improvements of voltage profile of COTEBE electrical power distribution system are obtained.

1.3 Objectives

General Objectives

The main objective of this study is to find the optimal solution to improve voltage profile and to reduce power loss on distribution systems using optimal placement of capacitor.

Specific Objectives

The specific objectives are:

1. To study and model Cotebe electrical power distribution system

2. To calculate power loss and voltage drop of the existing distribution system of COTEBE Distribution Substation which is supplied by 33KV feeder.
3. To find optimal capacitor placements and sizes for improving voltage profile and reducing power loss.
4. To evaluate power loss reduction and improvement in voltage profile with optimal placement of capacitor.
5. To carry out cost benefit analysis in respect of optimal capacitor placement.
6. To recommend most appropriate means of power loss reduction and voltage profile improvement for COTEBE Distribution Substation based on the findings of this research.

1.4 Literature Review

Initially, the problem of capacitor location has been handled with analytical methods; the description of one of the methods of reactive power allocation with the objective function of loss reduction in distribution systems is presented. This method is called 2/3 rule: Using capacitors to supply reactive power reduces the amount of current in the line. Since line losses are a function of the current squared, $I^{2*}R$, reducing reactive power flow on lines significantly reduces losses. Engineers widely use the “2/3 rule” for sizing and placing capacitors to optimally reduce losses. “Neagle and Samson”[3] developed a capacitor placement approach for uniformly distributed lines and showed that the optimal capacitor location is the point on the circuit where the reactive power flow equals half of the capacitor VAR rating. From this, they developed the 2/3 rule for selecting and placing capacitors. For a uniformly distributed load, the optimal size capacitor is 2/3 of the VAR requirements of the circuit. The optimal placement of this capacitor is 2/3 of the distance from the substation to the end of the line. For this optimal placement for a uniformly distributed load, the substation source provides VARs for the first 1/3 of the circuit, and the capacitor provides VARs for the last 2/3 of the circuit (see figure 1.2 shown below).

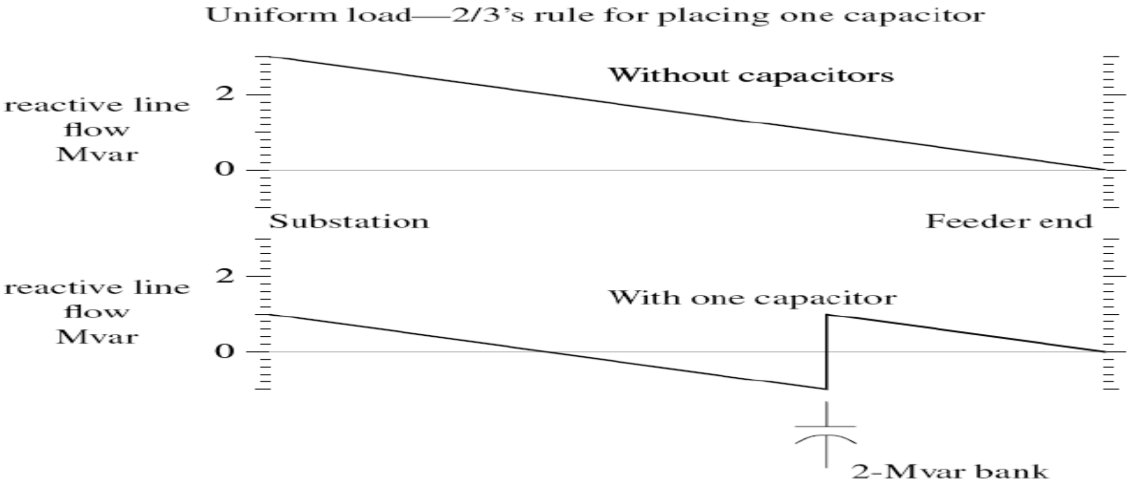

Figure 1.2: Optimal capacitor loss reduction using the two-thirds rule

A generalization of the 2/3 rule for applying *n* capacitors to a circuit is to size each one to 2/(2*n*+1) of the circuit VAR requirements. Apply them equally spaced, starting at a distance of 2/(2*n*+1) of the total line length from the substation and adding the rest of the units at intervals of 2/(2*n*+1) of the total line length. The total VARs supplied by the capacitors is 2*n*/(2*n*+1) of the circuit's VAR requirements. So to apply three capacitors, size each to 2/7 of the total VARs needed, and locate them at per unit distances of 2/7, 4/7, and 6/7 of the line length from the substation. "Grainger and Lee" provided another simple and optimal method for capacitor placement. This method is useful for circuits with any load profile, not just for uniformly distributed load profile. Here also the main principle is to place the capacitor at the point of circuit where the reactive power equals one half of capacitor rating. With this 1/2KVAr rule, the capacitor supplies half of its VARs downstream and half are sent up stream. The 2/3 rule as well as the method suggested by Grainger and Lee are very simple and usable methods, but these theories can be applied to the radial distribution systems. When we are working with looped networks of power systems, the comparably simple method like 2/3 rule or method by Grainger and Lee for capacitor placements becomes not applicable and another solution should be found. The looped power systems are usually the higher voltage level systems compared to radial distribution networks. Very interesting method for optimal reactive power allocation for loss minimization and voltage improvement can be found in [4]. In this method the artificial immune system is used for reactive power planning.

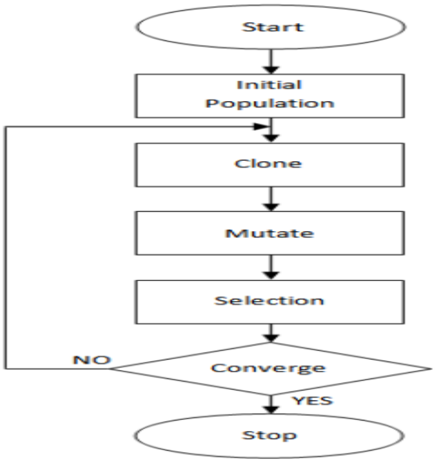

Figure 1.3: The flow chart for artificial immune system technique

Artificial immune system uses an idea which is taken from immunology in order to develop systems capable of performing different tasks in various areas of research. The authors are reviewing the clone selection concept together with the affinity maturation process and demonstrate that these biological principles can be very useful for development of useful computational tools. The artificial immune system optimization technique is implemented in following steps: first the initial values for the reactive power supports are generated randomly. After implementing the load flow, the total system losses are calculated. This technique is repeated until ten values of total losses subject to voltage range are obtained at each bus. As a second step the size of the reactive power support and losses are cloned. Then the value of clone was mutated and the load flow is run again and the new value of total system loss is obtained. The process is repeated until the minimal total system loss is obtained. The flow chart of the method using artificial immune system is taken from [4] and shown at figure 1.3

Shunt capacitor Sizing for radial distribution feeders with distorted substation voltages is explained in [5]. The objective of this method is to algorithm for optimizing shunt capacitor sizes on radial distribution lines with no sinusoidal substation voltages such that the rms voltages and their corresponding total harmonic distortion lie within prescribed values. A simple heuristic numerical algorithm that is based on the method of local variations is proposed to determine an optimal solution.

A new technique for loss reduction using compensating capacitors applied to distribution systems with varying load condition has been proposed in reference [6]. T.S.A Salam. A.Y Chikhap and R Hackam method allocates capacitors to certain nodes which are selected by first identifying the branch which has the largest losses due to reactive power. Then the node which has the largest reactive power is selected. The capacitor is determined by differentiating the system losses with respect to load connected to that node. The compensating capacitors are placed at these optimal locations with appropriate VAR ratings to achieve maximum benefits in dollar savings. The variation of the load during the year is considered. The capital and installation costs of the capacitors are also taken into account. Optimal Sizing of Capacitors placed on a radial distribution system is explained by M.e. Baran and F.F Wu the reference [7].

The capacitor sizing problem is a special case of the general capacitor placement problem. The problem is to determine the optimal size of capacitors placed on the nodes of a radial distribution system so that the real power losses will be minimized for a given load profile. This problem is formulated as a nonlinear programming problem. The ac power flow model of the system, constraints on the node voltage magnitudes, and the cost of capacitors are explicitly incorporated in the formulation. This paper gives a new formulation of the power flow equations in a radial distribution network and a numerically robust, computationally efficient solution scheme. Classification of Capacitor allocation Techniques has been dealt within in reference [8].M. M. A. Salma and A. Y. Chikhani method describes the evolution of the research and provides an evaluation of the practicality and accuracy of the capacitor placement algorithms in the literature. The intent of this paper is not to provide a complete survey of all the literature in capacitor allocation, but to provide researchers and utility engineers further insight into the choices of available capacitor allocation techniques and their respective merits and short comings A simplified Network approach to the VAR control problem for radial distribution system is considered in the reference [9]. According to this method proposed by M. M. A. Salma and A. Y. Chikhani, the capacitors are assumed to be located optimally at the feeder branches. The optimal compensation levels (capacitor size) are represented by dependent current sources located at the branch connected bus. The solution of the equivalent circuit for the distribution system yields the values of the voltage at any bus. The actual compensation level is then determined by substituting the bus voltage in the dependant current source formula. The method is simple and needs no sophisticated optimization technique. It can be used as online controller and as well as in the planning stage. It can be easily adapted in the expert system configuration. This paper present a new technique [10] for placing fixed capacitors in radial distribution systems based on genetic algorithms (GA).Rojas L.; Garcia, R.; Roa, L. gives Current optimization models of capacitor placement only consider losses reduction and voltage profile simultaneously, but the compensation cost and the load changes are not taken into account as part of the objective function. Also, the result may be not the best choice because this is a very large optimization problem and there are too many combinations. We present a general approach for the optimal solution of this problem considering all the parameters of the distribution system involved: capacitor cost and loss cost. An exhaustive search through all possible solutions is needed. Therefore, Tabu search in DIGSILENT is an ideal candidate to solve this situation. Sundhararajan, and Pahwa, present a new design methodology for determining the size, location, type and number of capacitors to be placed on a radial distribution system is presented [11]. The objective is to minimize the peak power losses and the energy losses in the distribution system considering the capacitor cost. A sensitivity analysis based method is used to select the candidate locations for the capacitors. An optimization method using DIGSILENT Powerfactory software is proposed to determine the optimal selection of capacitors. Test results have been presented along with the discussion of the software. Power losses in distribution system have become the most concerned issue in power losses analysis in any power system. In the effort of reducing power losses within distribution system, reactive power compensation has become increasingly important as it affects the operational, economical and quality of service for electric power systems. Nallagownden, P.; Thin, L.T; Guan, N.C.; Mahmud [12] presents the application of genetic algorithm approach for reactive power loss reduction in RDS. Cook [13] considered the effects of fixed capacitors on radial distribution network with distributed loads and considered the reduction in energy loss. A methodology has been used to determine the ratings and location of fixed capacitors on the radial feeder for periodic load cycle. Cook [14] considered fixed and switched capacitors and discussed the methodology to decide the timing for the operation of switched capacitors. Maxwell [15] suggested there are several benefits of capacitor placement. Major benefits are due to the reduction in kVA input, kW demand and energy loss. Schmill [16] considered feeders with uniformly distributed and randomly distributed loads. A simplified method for capacitor application has been developed. Bae [17] presented an analytical method for capacitor allocation, under different assumptions. A number of methods have been proposed in the literature [18-24] for the distribution networks. Shirmohammadi *et al.* [18] has proposed a load flow method for distribution networks using a multi-port compensation technique and basic formulations of Kirchhoff's Laws. Rajicic [20] has modified the fast decoupled load flow method to suit high R/X ratio nature of distribution system. Various methods [18-23] have been reported for the load flow of radial distribution system. Ghosh and Das [21] have proposed a method for the load flow of radial distribution network using the evaluation based on algebraic expression of receiving end voltage. Teng [23, 24] has proposed the load flow of radial distribution system employing bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices. Based on all of the method above, many programs have been developed to solve the problem of optimal capacitor placement. Most of current commercial software is using numerical programming method to solve the optimal capacitor problem. The DIGSILENT Power factory software has been used to find optimal capacitor placement proved an efficient tool for optimal capacitor placement in distribution system. In this thesis the 42 bus radial Test System is used in the DIGSILENT Power factory software, as powerful tools for the analysis and simulation work. DIGSILENT Power factory is used to perform load flow analysis and an optimization analysis to find optimal capacitor location and size for power loss reduction and voltage profile improvement with calculation of an investment cost savings.

1.5 Methodology

The Research is starting from defining the problem, identifying constraints to be considered, relevant data collection (network parameters and load profiles) and revising literature review to carry out the analysis in DIGSILENT Environment on the network for compensation. One line diagram of 42 buses power system with certain rated values of components as suggested by the tool is used. It consists of one supply source in the system which is coming out from the substation at bus 1 with voltage value of 33KV and also consists of 41 PQ constant load buses. All the drawings are being done by applying the DIGSILENT Powerfactory software tool. The software tool is then used to model Network parameters like lines, transformers, loads and paragraph changes. Power loss on the lines and voltage profile on buses are obtained from the base case Power flow result using the DIGSILENT tool. The result of the power flow is used to do sensitivity analysis to determine the optimum candidate location using range of capacitor values. The power flow results together with the sensitivity analysis's result are used to get the optimum capacitor size in the same ranges capacitor values (now we will installed the selected capacitor values). Finally the power flows for new selected optimal capacitor size on optimal location are done using the same software tool. Therefore from the results, records of all the data regarding the Voltage profile at each bus, the losses on the lines and the size of the optimal capacitor at the optimal location with saving amount are determined.

In general, all the above mentioned procedure is illustrated by the following flow chart shown in Figure 1.4. The flow chart shown below illustrates that

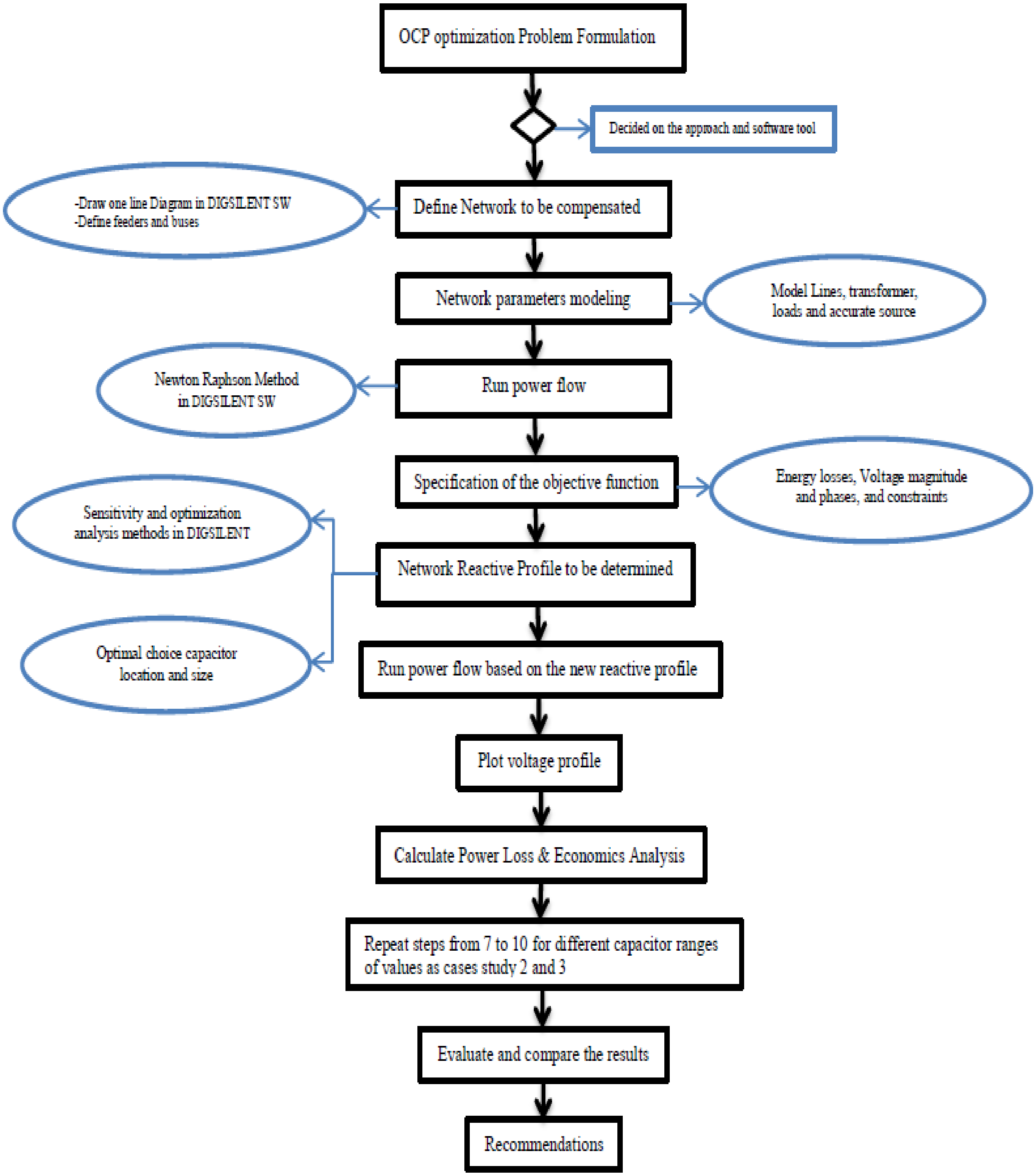

Figure 1.4 Proposed methodologies

1.6 Scope of the Thesis

The scope of this research is limited to the Existing Distribution networks as per EEP and EEU standard voltages definition and it focus on distribution system that is only supplied from the 33kv Feeder system. Although there are many ways of solving this research problem, this research investigates the use of DIGSILENT Powerfactory Software to solve the above mentioned optimization problem. DIGSILENT Powerfactory Software has been specifically chosen due to their reliability, robustness and versatility of consistently finding solutions to multi-objective optimization problems. In this case an optimal capacitor position needs to be located for various levels of network dynamics (i.e. different loading conditions and different network configurations).

1.7 Organization of the Thesis

The thesis is organized into five chapters which are briefly summarized as follows.

The first chapter presents the introduction including background, statement of the problem, objectives, Literature Review, methodology, scope and organization of the thesis. Chapter two focuses on Distribution system modeling and analysis which include electrical power distribution system, distribution system network configuration, modeling of distribution system, power loss in distribution system and capacitor placement for loss reduction. In chapter three, Capacitor Placement in Distribution System Using DIGSILENT Powerfactroy Software includes loss sensitivity method for candidate bus selection and capacitor allocation method for size selection are discussed. Chapter four discusses on the simulation results for optimal capacitor placement and results of power flow analysis for both with and with capacitor placement and also the cost benefit analysis for capacitor placement is presented.

Finally, the conclusions, recommendations and future works are discussed in the fifth chapter.

CHAPTER TWO

DISTRIBUTION SYSTEM MODELING AND ANALYSIS

2.1 Introduction

Improving voltage profile and power loss are one of the biggest challenges in electric power utility of developing countries. The electricity demand has been grown rapidly. As a result, a poor voltage profile with higher loss has not reliability if no proper measures are put in place. While the utilities have no sufficient funds for expansion their grid and source, it is necessary to reduce power loss. This chapter presents distribution system modelling and analysis for power loss reduction and to reduce the voltage drop in distribution system.

2.2 Electrical Power Distribution System

Electrical distribution substation networks consist of primary distribution feeder, distribution Transformer, distributors and service mains.

The transmitted electric power is stepped down in substations, for primary distribution purpose. Now these stepped down electric power is fed to the distribution transformer through primary distribution feeders.

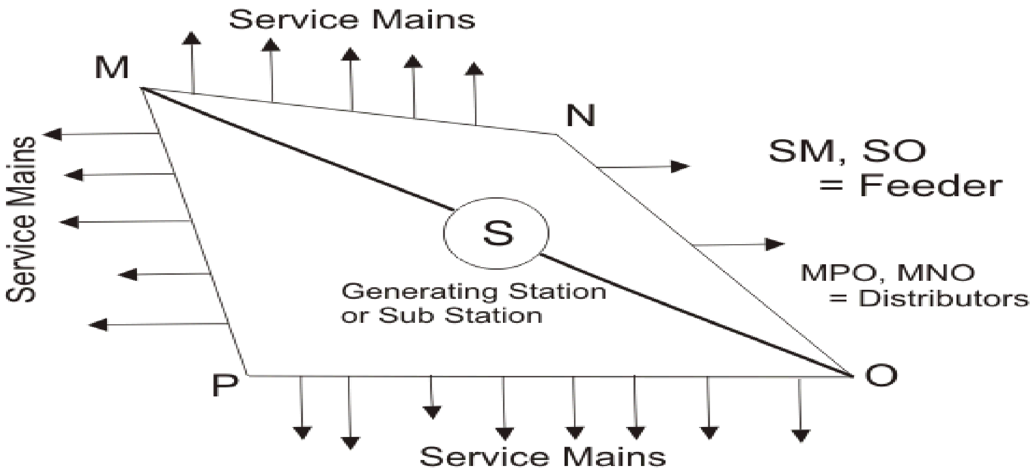

Figure 2.1: Electric Power Distribution Network

Distribution transformers are mainly three phase pole mounted type. The secondary of the transformer is connected to distributors. Different consumers are fed electric power by means of the service mains. These service mains are tapped from different points of distributors. The distributors can also be re-categorized by distributors and sub distributors. Distributors are directly connected to the secondary of distribution transformers whereas sub distributors are tapped from distributors. Service mains of the consumers may be either connected to the distributors or sub distributors depending upon the position and agreement of consumers. In this discussion of electrical power distribution system, we have already mentioned about both feeders and distributors. Both feeder and distributor carry the electrical load, but they have one basic difference. Feeder feeds power from one point to another without being tapped from any intermediate point. As because there is no tapping point in between, the current at sending end is equal to that of receiving end of the conductor. The distributors are tapped at different points for feeding different consumers; and hence the current varies along their entire length.

2.3 Distribution System Network Configuration

2.3.1 Radial Electrical Power Distribution System

In early days of electrical power distribution system, different feeders came out in radial from the substation and connected to the primary of distribution transformer.

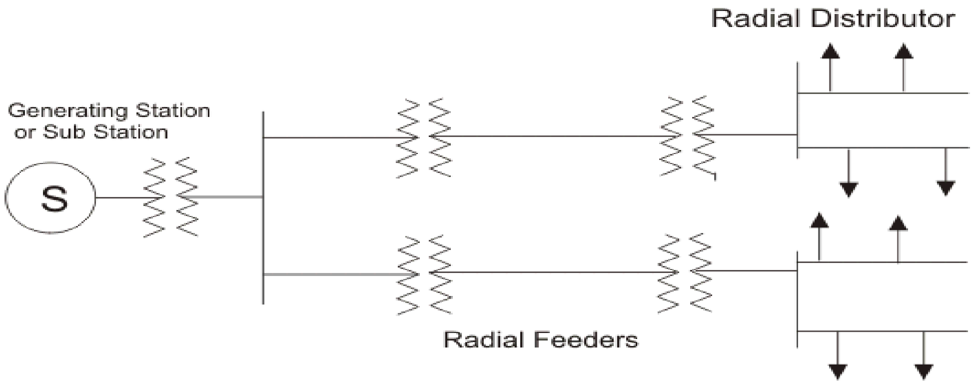

Figure 2.2: Radial Electric Power Distribution system

But radial electrical power distribution system has one major drawback that in case of any feeder failure, the associated consumers would not get any power as there was no alternative path to feed the transformer. In case of transformer failure also, the power supply is interrupted. In other words the consumer in the radial electrical distribution system would be in darkness until the feeder or transformer was rectified.

2.3.2 Ring Main Electrical Power Distribution System

The drawback of radial electrical power distribution system can be overcome by introducing a ring main electrical power distribution system. Here one ring network of distributors is fed by more than one feeder. In this case if one feeder is under fault or maintenance, the ring distributor is still energized by other feeders connected to it. In this way the supply to the consumers is not affected even when any feeder becomes out of service. In addition to that the ring main system is also provided with different section isolates at different suitable points. If any fault occurs on any section, of the ring, this section can easily be isolated by opening the associated section isolators on both sides of the faulty zone transformer directly.

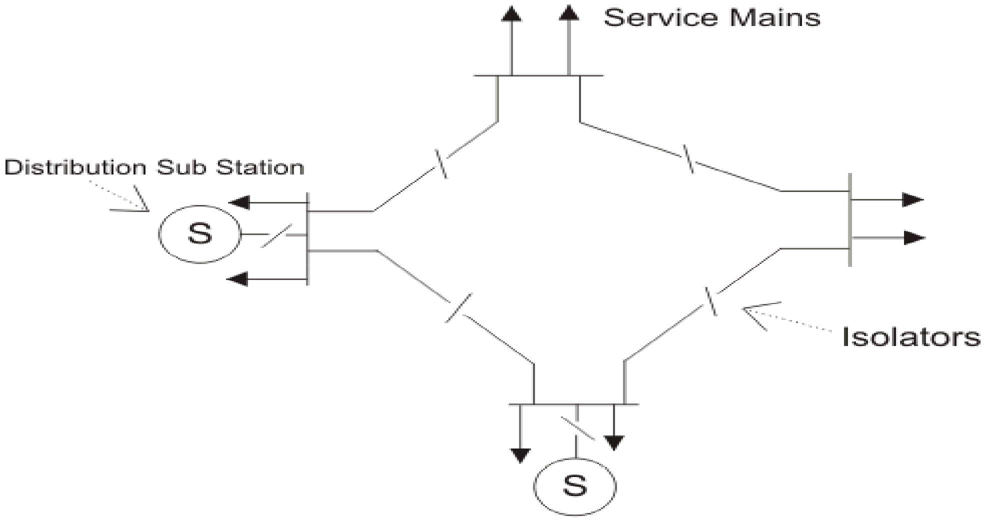

Figure 2.3: Ring Electric Power Distribution system

In this way, supply to the consumers connected to the healthy zone of the ring, can easily be maintained even when one section of the ring is under shutdown. The number of feeders connected to the ring main electrical power distribution system depends upon the maximum demand of the system, the total length of the ring main distributor and the voltage regulation required.

The sub distributors and service mains are taken off may be via distribution transformer at different suitable points on the ring depending upon the location of the consumers. Sometimes, instead of connecting service main directly to the ring, sub distributors are also used to feed a group of service mains where direct access of ring distributor is not possible.

2.4 Modeling of Distribution Systems

In power engineering, the load flow of a power network provides the steady state solution through which various parameters of interest like currents, voltages, losses etc… can be calculated. The load flow study is an important part of distribution systems analysis and it is used in operational as well as planning stages. Many real time applications in the distribution automation system such as networks optimization, reactive power planning, switching, state estimation and so forth, need the support of a robust and efficient power flow method. Such a power flow solution method must be able to model the special features of distribution system.

Modelling of system elements and distribution load flow analysis are discussed in section. Power distribution system is the heart of power system, it constitutes of major portion of any power system. Distribution systems are mostly radial or near radial in structure, multi-phase, unbalanced, grounded or ungrounded operation. It has a larger R/X ratio, Distributed load are mostly unbalanced. It consists of large number of nodes and branches.

Power distribution network plays the role of providing energy to end users connected at low or medium voltage and still considered as a mere termination of the transmission grid. It is Characterizing by unidirectional power flow and simple protection ensuring safe and economical operation of the power system.

The inability of the conventional load flow techniques coupled with the above raised issues demands a power flow technique that gives the status of the distribution system for planning and operation purpose. To run a load flow, it is necessary with appropriately model the different components in the distribution system. The following sections will show how lines, loads, transformer and capacitors can be modeled [2] for load flow technique.

2.4.1 Line Model

The overhead line models described in this thesis is applicable to both the line element for single circuits and the line coupling for multiple coupled circuits.

Lumped parameters: this model can be used with acceptable accuracy for short lines or relative long lines at low frequencies.

Distributed parameters: It should be preferred to model long lines or in calculations when high frequencies. The models are available for steady-state calculations (load flow, short circuit or frequency sweep calculations among others).

Line Models for Steady-State Analysis

Line models for steady-state analysis are formulated in frequency domain. An accurate representation of the transmission line, including the effect of its distributed parameters is therefore possible.

General Equations of a Transmission Line

Equations (2.1) and (2.2) describe the incremental transmission line model of elemental length Δx depicted in Figure 2.4 in frequency domain.

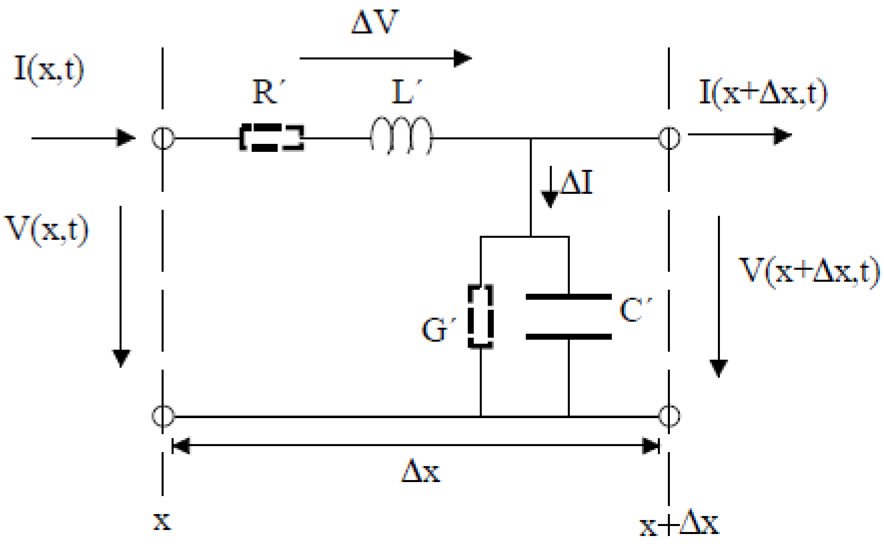

Figure 2.4: Model for a line of elemental length

$$\frac{\partial v}{\partial x} = I(x) * Z' \tag{2.1}$$

$$\frac{\partial I}{\partial x} = V(x) * Y' \tag{2.2}$$

Z′ is the series impedance per-unit length corresponding to the line voltage drop and Y′ the shunt admittance representing the current drawn to earth per-unit length as defined in (2.3) and (2.4) respectively.

$$Z' = \sqrt{R' + jwL'} \tag{2.3}$$

$$Y' = \sqrt{G' + jwC'} \tag{2.4}$$

The second derivatives of (2.1) and (2.2) with respect to x let us separate the voltage from the current and build the system of differential equations (2.5) and (2.6).

$$\frac{\partial^2 v}{\partial^2 x} = Z' * Y' * V(x) \tag{2.5}$$

$$\frac{\partial^2 I}{\partial^2 x} = Z' * Y' * I(x) \tag{2.6}$$

The general solution is of the form:

$$V(x) = K_1 * e^{(\gamma * x)} + K_2 * e^{(-\gamma * x)} \tag{2.7}$$

$$Z_c * I(x) = -K_1 * e^{(\gamma * x)} + K_2 * e^{(-\gamma * x)} \tag{2.8}$$

Where, Z_C is the characteristic impedance of the line as defined in (2.9) and γ the propagation constant (2.10). Both Z_C and γ are frequency-dependent and uniquely characterize the behaviour of the transmission line.

$$Zc = \frac{\sqrt{Z'}}{Y'} \qquad (2.9)$$

$$\gamma = \sqrt{Z' * Y'} \qquad (2.10)$$

K1 and K2 are adjusted to verify the border conditions at nodes. According to the references in Figure 3.2:

$$x = 0 => \begin{cases} v(x = 0) = v_s \\ I(x = 0) = I_s \end{cases} \quad \text{And} \quad x = l => \begin{cases} v(x = l) = v_r \\ I(x = l) = -I_r \end{cases}$$

$$V_r = (\frac{Vs-Is*Zc}{2}) * e^{(\gamma*l)} + (\frac{Vs+Is*Zc}{2}) * e^{(-\gamma*l)} \qquad (2.11)$$

$$I_r = (\frac{Vs-Is*Zc}{2*Zc}) * e^{(\gamma*l)} + (\frac{Vs+Is*Zc}{2*Zc}) * e^{(-\gamma*l)} \qquad (2.12)$$

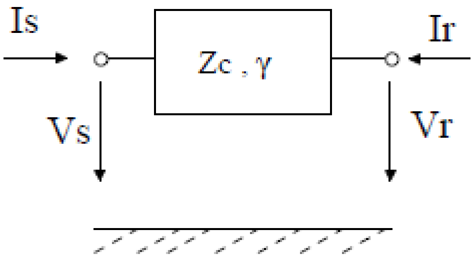

Figure 2.5 Border conditions

Using matrix representation, (2.11) and (2.12) can be rewritten in terms of hyperbolic functions as (2.13), which is usually known as ABCD parameter representation of two-port networks.

$$\begin{bmatrix} Vr \\ Ir \end{bmatrix} = \begin{bmatrix} COS(\gamma * l) & -Zc * Sin(\gamma * l) \\ \frac{1}{Zc} * Sin(\gamma * l) & -COS(\gamma * l) \end{bmatrix} * \begin{bmatrix} Vs \\ Is \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} * \begin{bmatrix} Vs \\ Is \end{bmatrix} \qquad (2.13)$$

Equation (3.13) describes accurately the input-output relationship of the line.

2.4.2 Load Model

The load model plays a significant role in customer load energy consumption, in reactive power compensation, in a voltage reduction program and in voltage stability analysis of a distribution network system. 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 ($V_J = V_I – Z*I$). 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. A balanced load can be represented either as constant power, constant current, constant impedance or as an exponential load.

In power systems, electrical load consists of various different types of electrical devices, from incandescent lamps and heaters to large arc furnaces and motors. It is often very difficult to identify the exact composition of static and dynamic loads in the network. This load composition can also vary depending on factors such as the season, time of day etc. The general load model diagram is shown in Figure 2.6

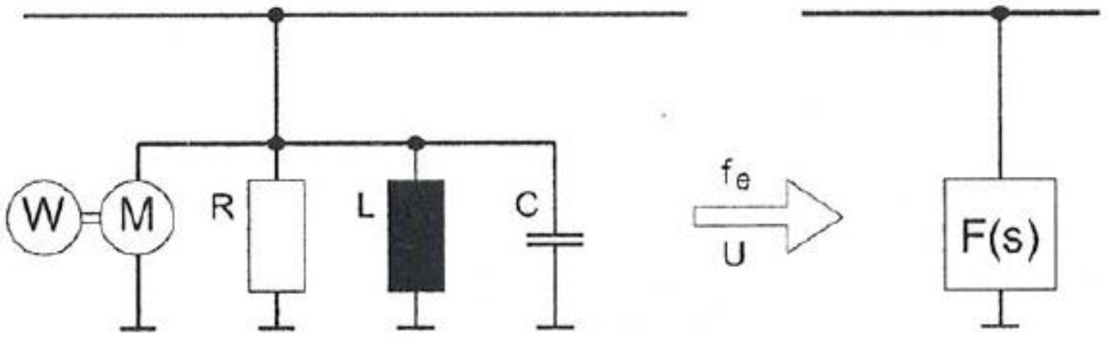

Figure 2.6 General Load Model

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 are explained below:

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

$$P_{Load} = (V/V_r)^2 * P^r_{Load} \tag{2.14}$$

$$Q_{Load} = (V/V_r)^{2\,*} Q^r_{Load} \tag{2.15}$$

Where P^r_{Load} and Q^r_{Load} are the rated loads at voltage V_r, and P_{Load} and Q_{Load} are the loads at voltage V. Incandescent lighting, resistive water heaters, electric stoves, and clothes dryers are examples of constant impedance loads. In this thesis, most of the residential and commercial loads are modeled with this constant impedance load model.

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

$$P_{Load} = (V/V_r)* P^r_{load} \tag{2.16}$$

$$Q_{Load} = (V/V_r)* Q^r_{load} \tag{2.17}$$

Welding units and electroplating processes are constant current loads. The small industries mainly use constant loads with big percentage, so our research use constant current load model for most of small industries.

Constant Power Load Model: The active and reactive powers 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. The big industries are modeled with constant power load Model in DIGSILENT Powerfactory Environment.

2.4.3 Transformer Model

The Two winding transformer model

The two-winding transformer model is a very detailed model for various kinds of three-phase, two-winding transformers in power systems. It can represent e.g. network transformers, block transformers, phase shifters or MV-voltage regulators. The model makes special consideration for auto-transformers.

The Three winding transformer

Three winding transformer is a Three port element connecting Three cubicles in the network. Power factory comes with a built-in model for three-winding transformers. The sequence equivalent models of the three-winding transformer including generalized tap changers (for phase and magnitude). The Negative sequence models are identical to the positive sequence model. In this thesis paper the positive and zero sequence models are selected for both Two Winding and Three winding.

2.4.4 Load Flow Analysis

Load flow calculations are used to analyze power systems under steady state conditions. The load flow calculates the active and reactive power flows for all branches, and the voltage magnitude and phase for all nodes.

Network Representation

A load flow calculation determines the voltage magnitude and the voltage angle of the nodes, and the active and reactive power flow on branches. Usually, the network nodes are represented by specifying two of these four quantities. Depending on the quantities specified, nodes can be classified as [1]:

PV nodes: constant active power and voltage magnitude are specified. This type of node is used to represent generators whose active power and voltage magnitude are controlled, and synchronous condensers. In order to consider equipment limits under abnormal conditions (as mentioned in the previous section), reactive power limits for the corresponding network components are also used as input information.

PQ nodes: active and reactive powers are specified. This type of node is used to represent loads and generators with fixed dispatch. Loads can also be set to change (from their original P_o and Q_o values at nominal voltage) as a function of the voltage of the node to which the load itself is connected.

Slack bus: voltage magnitude and angle are fixed. In traditional load flow calculations the slack node (associated with a synchronous generator or an external network) carries out the balancing of power in the system.

Device nodes: special nodes used to represent devices such as HVDC converters, SVSs, etc., with specific control conditions (for example the control of active power flow at a certain MW threshold in a HVDC converter).

In contrast to other power system calculation programs, Powerfactory does not directly define the node characteristic of each bus bar. Instead, more realistic control conditions for the network elements connected to these nodes are defined.

For example, synchronous machines are modeled by controlled power factor, controlled by constant active and reactive power (PQ), controlled by constant voltage, constant active power (PV) on the connected bus and by secondary controller ('slack', SL).

AC Load Flow

In Powerfactory the nodal equations used to represent the analyzed networks are implemented using Newton-Raphson (Current Equations) and Newton-Raphson (Power Equations, classical). In both formulations, the resulting non-linear equation systems must be solved by an iterative method. The Newton-Raphson method is used as its non-linear equation solver. For large transmission systems, especially when heavily loaded, the standard Newton-Raphson algorithm using the "Power Equations" formulation usually converges best. Distribution systems, especially unbalanced distribution systems, usually converge better using the "Current Equations" formulation.

This paper are assumed, the three-phase radial distribution networks are to be balanced and hence represented by their single-line diagram. The system is represented by its positive-phase sequence network. The operating conditions of the system are selected. The static operating state of the system is then specified by the constraints on voltage at the network buses.

Load Flow Analysis of Low Voltage Systems: In a low voltage system every load may consist of a fixed component with a deterministic amount of power demand plus a variable component comprising many different, small loads, such as lights, refrigerators, televisions; whose power varies stochastically between zero and a maximum value. So under such conditions, Power Factory uses a probabilistic load flow calculation, which is able to calculate both maximum and average currents as well as the average losses and maximum voltage drops.

2.4.5 System Input Data

The following points are implemented for load flow analysis:

(*i*) Draw a single-line diagram of the system.

(*ii*) Assuming AC load flow, balanced three phase system, the distribution system is represented by its positive-phase sequence network of shunt branches. The linear impedances and shunt admittances in per-unit values are then found, including, shunt capacitor ratings and transformer ratings and transformer tapping.

(*iii*) The operating conditions of the system are selected. The static operating state of the system is then specified by the constraint on voltage at the network buses. Then actual load flow in all distribution system lines is computed.

The data for 132/45/33/15 kV COTEBE Distribution Substation of Ethiopian Electric Power has been taken for test. The feeder 33 kV from this substation has highest loss and voltage drop more than other feeders that are going out from the same substation. The 33kv feeder supplied by a 132/33 kV, 16 MVA power transformer from the 132/45/33/15 kV COTEBE Distribution Substation grid. It supply different types of customers like water supply stations, small and large industrial loads, residential and commercial customers that are located around COTEBE area in Addis Ababa and also in LEGETAFO Town, Ethiopia. The single line diagram of this feeder has been shown as in Figure 2.7 that includes the load, line parameters and diagrams. The 33kv Feeder has been modeled as the radial system with 42 bus systems. Line and load datum are used as input for the power flow calculation. The lower and upper voltage magnitude limits are taken as 0.95 Pu and 1.05 Pu at all buses according to EEP & EEU standard. The input active and reactive powers as well as line datum are shown in table 2.1, 2.2 & Appendix A

Table 2.1 Active and Reactive loads as an input

Name of the Load	Active Power (MW)	Reactive Power (MVAr)
W_L1	0.2146	0.195056
W_L2	0.12975	0.1144
W_L3	0.5655	0.454
W_L4	0.3588	0.287
I_L5	0.33201	0.409
W_L6	0.12415	0.1451474
I_L7	0.03036	0.03455
I_L8	0.37352	0.524613
I_L9	0.3219	0.292584
I_L10	2.78844	4.019486
I_L11	0.19411	0.2656357
R_L12	0.832	0.624
Q_L13	0.1288	0.09659999
Q_L14	0.01817	0.01410146
Q_L15	0.01817	0.01410146
Q_L16	0.06256	0.06745552
Q_L17	0.11178	0.08092733

Name of the Load	Active Power (MW)	Reactive Power (MVAr)
Q_L18	0.01863	0.01348789
Q_L19	0.01886	0.01316436
Q_L20	0.56018	0.5091634
Q_L21	0.03772	0.02632872
Q_L22	0.03818	0.02565712
Q_L23	0.03312	0.0319228
Q_L24	0.07452	0.05395155
Q_L25	0.10366	0.09704949
Q_L26	0.249	0.167329
R_L27	0.01932	0.01247949
R_L28	0.33615	0.2258942
R_L29	0.4698	0.3401293
R_L30	0.2436	0.1573501
R_L31	0.12035	0.08087569
R_L32	0.0391	0.024232
R_L33	0.0391	0.024232
R_L34	0.19671	0.1321899
R_L35	0.03864	0.02495898
R_L36	0.01955	0.012116
R_L37	0.02236	0.01326
R_L38	0.2407	0.1617514
R_L39	0.7695	0.5571083
R_L40	0.02	0.01239488
R_L41	0.01955	0.012116

From the table 2.1, we observed that the total active and reactive loads are 10.33292MW and 10.3678MVAr respectively, R_L, Q_L, W_L and I_L mean Residential and commercial, Quarry, Water supply and Industrial Loads respectively. The loads that are collected for the load profiles are highly distributed on real network. So that for demonstration and analysis calculation purpose, the researcher merged some loads by their own category.

Line Parameters

The available input overhead lines parameters, length and type of the lines data for the existing network is summarized in Table 2.2 & Appendix A [25]

Table 2.2: Technical data of conductors

Code of conductor	**R**	**X**	**I_{sc} (kA)**	**I_{rated} (A)**	**Type of conductor**
AAC25	1.179	0.379	2.1	145	OH Bare
AAC50	0.578	0.36	4.3	225	OH Bare
AAC95	0.307	0.34	8.1	340	OH Bare
XLPE AAAC150	0.183	0.34	8.4	385	OH XLPE Covered
XLPE AAAC95	0.279	0.32	5.3	282	OH XLPE Covered

The 33kv feeder single line diagram of the radial distribution system is taken for power flow analysis as shown below.

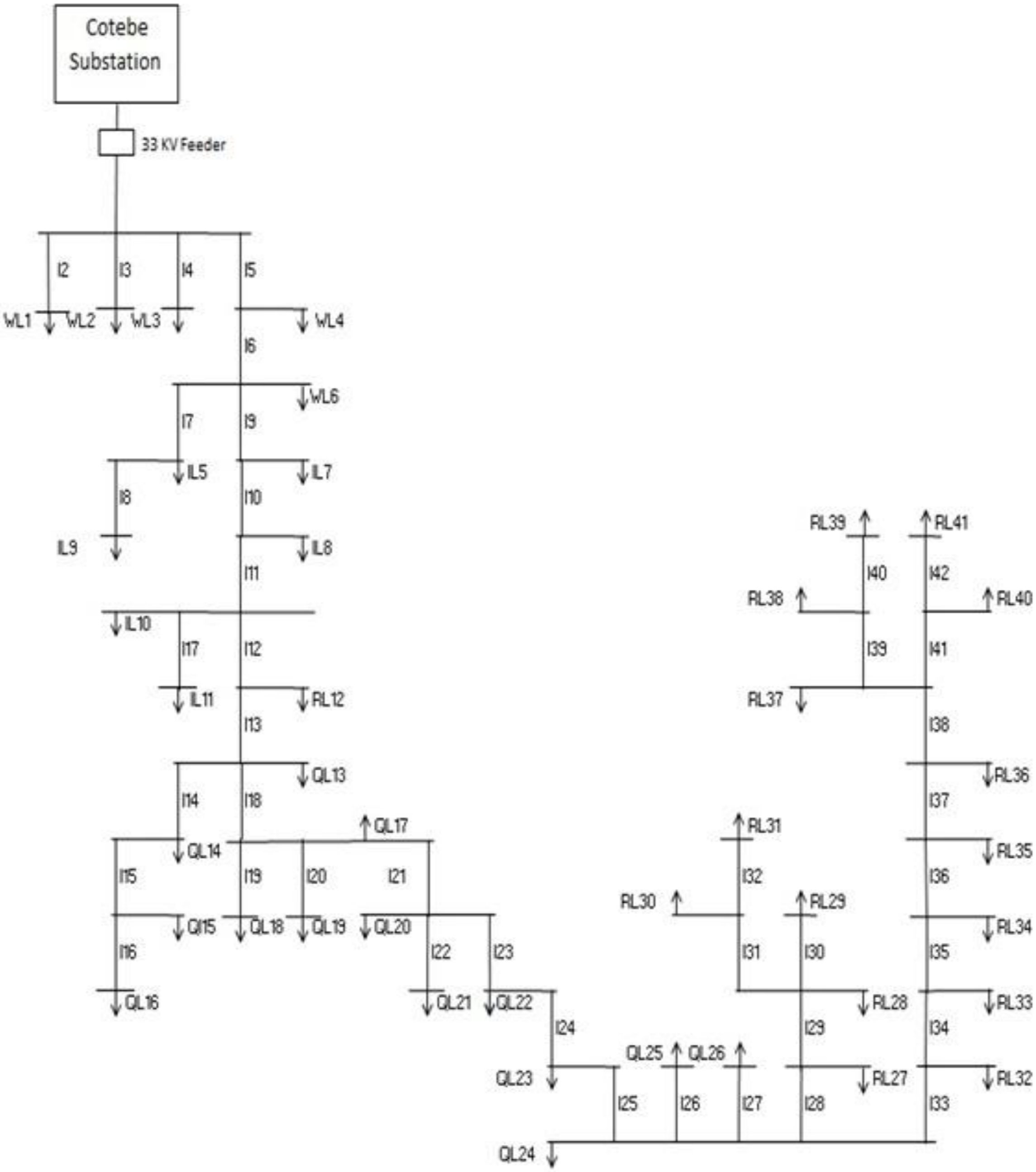

Figure 2.7:Single line diagram of 33KV Feeder cable of distribution system

2.5 Power Loss in Distribution System

Power distribution system is the part of power system that delivers energy directly from suppliers to customers operating at several voltage levels [1]. In the situation of increasing scarcity of resource and escalating cost of energy supply, the important of energy conservation and reduction in loss in the system is felt vital. System loss reduction is one of principle ways of achieving conservation in the electric power supply sector. In the process of delivering electricity to customers, loss has been occurred in generation, transmission, and distribution system. In the literature, there are many reports that discuss about loss. In distribution system, the grid is almost in radial so the level voltage, load density are the main factors concerning about the system loss.

Distribution network loss includes both technical and non-technical loss. In this study, only technical loss was considered. Technical loss has been consisting mainly of power dissipation in the electrical system components such as transmission lines, power transformers, measurement systems, etc. It is possible to compute and control the power system in question consists of known quantities of loads. Using computation tools for calculating power flow, loss and equipment status in power systems has been developed in nearly years. Improvements in information technology and data acquisition have made the calculation and verification easier. Loss depends on various factors, such as load density, inadequate designs, and improper maintenance, etc. There may be significant proportion of unaccounted loss due to inaccuracy in meters, flat rate tariff structure, error of customer billing, pilferage of energy and unauthorized use of electricity. Most of them fall under non-technical loss. The reduction in system loss can result in substantial saving in energy has been increased in the power capacity supply. Technically, there are many solutions to reduce distribution system loss, such as network reconfiguration, load balancing, taps changing, and capacitor installation. Among these, capacitor placement has been considered as one of the most economical option.

2.6 Capacitor Placement for Loss Reduction and Voltage Profile Improvement

Capacitors have been very commonly used to provide reactive power compensation in distribution systems. Also, capacitors have been provided to minimize power and energy loss and to maintain the voltage profile within the acceptable limits. The amount of compensation provided is very much linked to the placement of capacitors in the distribution system, which is essentially determination of the location, size, number and type of capacitors to be placed in the system. The capacitor placement problem is a well-researched topic and has been addressed by many authors in the past.

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 [26]. The power factor during off-peak hours is normally high; therefore, heavy capacitor compensation may lead to over-voltage problems during this time [27]. This situation poses certain limitations regarding capacitor compensation and hence leads to the concept of fixed and switched capacitor applications [27]. The minimum size of capacitors connected at all load levels can be considered as fixed capacitors, and others are considered as switched capacitors.

Capacitor Operating Mode

Fixed mode – the capacitor is permanently put in service and is only taken out of service during either planned or unplanned maintenance.

Switched mode – the capacitor is only put in service when needed or during predefined times. Switched banks require a switch and control circuit/ device, which makes it more costly compared to the fixed bank.

Capacitor Voltage Limit

The size or rating of any Capacitor can be determined using the following expression:

$$KVAr_{perphase} = \frac{2\pi * f * C * v^2}{1000} \quad (2.18)$$

Where: *f* is the grid frequency in Hertz (Hz), C is the capacitance in micro Farads (F) and V is the network voltage where the capacitor is connected in (kV)

The above formula indicates that the relationship between the voltage applied across the capacitor bank and the reactive power produced by the Capacitor. Let ignore the variation of the frequency on the grid and therefore assume that *f* and *C* are constant, there is a parabolic relationship between the Capacitor MVArs and the system kV, i.e. as the voltage varies, the VAr output of the capacitor varies by a voltage squared factor. It is because of this mathematical relationship that Capacitors need to be switched into service shortly before the network voltages are depressed due to the rising load profile.

CHAPTER THREE

CAPACITOR PLACEMENT IN DISTRIBUTION SYSTEM USING DIGSILENT POWERFACTORY SOFTWARE

3.1 Introduction

In this section loss minimization in electrical power distribution system is discussed. Digsilent Powerfactory software is used to find the optimal capacitor placement. This software is used for power flow analysis, for candidate bus selection and capacitor size selection. Sensitivity analysis is used to find the buses for capacitor placement. Mathematical formulation for the problem is formulated. The objective function is used to minimize the total cost which is the sum of power loss cost, capacitor installation cost and capacitor maintenance cost.

3.2 Loss Minimization in Electrical Power Distribution System

Loss Minimization in power system has assumed greater significance, because substantial amount of generated power is being wasted as losses in Transmission and distribution system. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at the distribution level. The following methods are adopted for reduction of distribution system losses reactive power compensation, high voltage distribution system, grading of conductor and feeder reconfiguration

Among the above listed methods, the reactive power compensation is most commonly used method for loss reduction in distribution system. The distribution network is usually compensated by either series or shunt capacitors. Series capacitors increase Power Transfer Capability of a line while shunt capacitors have the following benefits.

(i) Reduce real and reactive power loss in the system
(ii) Increase voltage level at the load and power factor of source
(iii) Improve voltage regulation
(iv) Improve stability
(v) Improve power factor of the system

However to achieve these objective(s), the optimal locations of capacitors and sizes should be find out. Certainly, the locations and sizes of the capacitors will be influenced by the objective under consideration.

The idea for optimal capacitor placement is to determine the location, type and the size of capacitors to be installed in the nodes of the radial distribution network. The economic benefits due to energy loss reduction are weighted against the cost of installation of such capacitors while keeping the voltage profile of the system within defined limits.

3.3 Optimal Capacitor Placement using Digsilent Powerfactory Software

DIGSILENT Powerfactory [28] is the most economical solution, as data handling, modelling capabilities and overall functionality replace a set of other software systems, thereby minimising project execution costs and training requirements. The all-in-one Powerfactory solution promotes highly-optimised workflow.

DIGSILENT Powerfactory is easy to use and caters for all standard power system analysis needs, including high-end applications in new technologies such as wind power and distributed generation and the handling of very large power systems. In addition to the stand-alone solution, the Powerfactory engine can be smoothly integrated into GIS, DMS and EMS supporting open system standards.

3.3.1 Advantage of Using Powerfactory

- Economical all-in-one solution with broad coverage of state-of-the-art power system applications
- Extensive and flexible modelling capabilities with rich suite of power equipment models and libraries
- Supports all network representations and phase technologies, i.e. any kind of radial or meshed 1-, 2-, 3- and 4-wire (combined) AC and DC networks

- Powerful network diagrams and graphic/visualisation features
- Unique data management concept including project versioning and archiving mechanisms, master/derived concepts with compare and merge tools
- Unlimited opportunities in process optimisation based on integrated scripting functionality
- Rich interfacing and system integration options (e.g. GIS, SCADA, EMS)

3.3.2 Load Flow Analysis in Digsilent Powerfactroy Software

Within the Load Flow analysis environment, the accurate representation of a variety of network configurations and power system components is possible.

DIGSILENT Powerfactory offers a selection of calculation methods, including a full AC Newton-Raphson technique (balanced and unbalanced) and a linear DC method. The enhanced non-decoupled Newton-Raphson solution technique with current or power mismatch iterations, typically yields round-off errors below 1kVA for all buses.

The implemented algorithms exhibit excellent stability and convergence. Several iteration levels guarantee convergence under all conditions, with optional automatic relaxation and modification of constraints. The DC load flow, solving for active power flows and voltage angles, is extremely fast and robust (linear system; no iterations required). Any combination of meshed 1-, 2-, and 3-phase AC and/or DC systems can be represented and solved simultaneously, from HV transmission systems, down to residential and industrial loads at LV voltage levels. Neutral conductors can be modelled explicitly. The Load Flow tool accurately represents unbalanced loads, generation, grids with variable neutral potentials, HVDC systems, DC loads, adjustable speed drives, SVSs and FACTS devices, etc., for all AC and DC voltage levels.

DIGSILENT Powerfactory offers a new, intuitive and easy-to-use modelling technique which avoids the definition of bus types such as SL, PV, PQ, PI, AS, etc. Powerfactory simply provides the control mechanisms and device characteristics which are found in reality.

3.3.3 Capacitor Placement in Digsilent powerfactory

Capacitor Placement determines the optimal locations, types and sizes of capacitors to be installed in radial distribution networks. The economic benefits due to energy loss reduction are weighted against the installation costs of the capacitors while keeping the voltage profile within defined limits. The Digsilent powerfactory has user definable library of proposed capacitor candidates together with annual installation costs. It considers benefits due to loss reduction, voltage limits and maximum total investment costs. It Support load profiles, Calculated results of set of locations where capacitors should be installed, which type of capacitor(s) should be installed at each site, and whether or not a switched capacitor is proposed, User-friendly presentation of results with fully-integrated post-processing features.

The Final result of the optimization process is the locations for the installation of capacitors, the types and sizes of capacitors to be installed for the different load levels. The two different optimization search methods are used to determine the optimum location and size of capacitors as searching engine in the optimization Process in DIGSILENT Environment.

Gradient search - this search is fast and mostly will find a solution that performs well - even if not mathematically exact global optimum. Tabu Search - this search finds the exact optimum, but time consuming

Tabu search method is selected (which is featured in DIGSILENT Power factory Environment) to find the location and size of capacitor after evaluation is done on the cost of power loss and total capacitor cost for the three cases of capacitor ranges values.

The General Tabu search algorithm is shown below

Step 1: choose an initial solution i in S. Set $i^*=i$ and $k=0$.

Step 2: Set $k=k+1$ and generate a subset V^* of solution in $N(i,k)$

Step 3: Choose a best j in V^* and set $i=j$.

Step 4: If $f(i) < f(i^*)$ then set $i^*=i$.

Step 5: If a stopping condition is met then stop. Else go to Step 2.

Here the optimization for 42-bus radial distribution system has been discussed. The base case load flow solution for distribution system using the DIGSILENT Powerfactory software is done and discussed in Chapter 3. Then the potential buses for capacitor placement by using loss sensitivity method in the same DIGSILENT Powerfactory Environment are identified. From the loss sensitivity factor result, the potential buses for shunt capacitor placement are obtained. These potential buses should be preserved as candidate buses. Then after identifying the candidate buses, the sizing of the optimal capacitor are attempted and obtained for three cases in same software Environment. The capacitor allowable ranges mentioned above with specification [29] are used.

Problem Formulation

The aim of the present work is to find out the location and sizes of the shunt capacitor so as to maximize the net saving by minimizing the annual total network cost which are a sum of two parts: cost of line losses and cost of all installed capacitors.

The costs of capacitors are listed in Appendix E. Mathematical formulation of the terms used in objective function is given below:

Energy loss Cost (ELC):

If I_i is the current of section i in time duration T, then loss in section i is given by:

$$E_{Li} = I_i * I_i * R_i * T \tag{3.1}$$

The Energy loss (EL) in time T of a feeder with n sections can be calculated as:

$$E_L = \sum_{i=1}^{n} E_{Li} \tag{3.2}$$

The Energy loss cost (E_{LC}) can be calculated by multiplying eq. (3.2) with the energy rate (C_e)

$$E_{LC} = C_e \times E_L \tag{3.3}$$

Where, EL is energy loss (kW) in section i in time duration T

I_i is the current of the section I

R_i is the resistance of section i

T is the time duration

C_e is the energy rate

E_{LC} is corresponding to the annual cost of Energy losses due to line loss

Capacitor Cost (C_C):

Capacitor cost is divided into two terms: initial Capacitor cost (installation cost plus cost to buy the capacitor) and Operation and Maintenance (O&M) costs.

Therefore capacitor cost is expressed as:

$$C_C = C_{Ci} + (C_{cv} \times Q_{ck}) + C_{O\&M} \quad (3.4)$$

Where,

C_{Ci} is the constant installation cost of capacitor.

C_{cv} is the cost of capacitor per kVAr

Q_{ck} is the rating of capacitor on bus K in kVAr

$C_{O\&M}$ is Operation and maintenance cost

C_C is the annual total cost of capacitors

The cost function is obtained by combining equations (3.3) and (3.4); this cost function is considered as the objective function to be minimized in the present work. The cost function Y is therefore expressed as:

$$Y = C_e \times E_L = \sum_{i=1}^{n} E_{Li} \quad + \sum_{i=1}^{m} [C_{ci} + (C_{cv} \times Q_{ck}) + C_{O\&M} \quad (3.5)$$

Where, n is the number of buses

m is the number of installed capacitors

Y is the cost function for minimization

By minimizing the cost function, the net saving due to the reduction of energy losses for a given period of time including the cost of capacitors is given below:

$$Net\ saving = BE_L - C_C \qquad (3.6)$$

Where, $BE_L = E_{LC}$ (without capacitor) – E_{LC} (with capacitor)
BE_L is benefit due to energy loss reduction.
E_{LC} (without capacitor) is energy loss cost without capacitor.
E_{LC} (with capacitor) is energy loss cost with capacitor.

3.4 Candidate Bus Selection using Loss Sensitivity Factor

To identify the location for capacitor placement in distribution system Loss Sensitivity Factors have been used. The loss sensitivity factor is able to predict which bus will have the biggest loss reduction when a capacitor is placed. Therefore these sensitive buses can serve as candidate buses for the capacitor placement. The estimation of these candidate buses basically helps in reduction of the search space for the optimization problem. As only few buses can be candidate buses for compensation.

In this step test capacitors are installed at all bus bars in the system and the effect of the installation on the total annual system cost is evaluated. The size of the test capacitors used to evaluate the cost benefit can be selected according to the minimum available capacitor size is used, maximum available capacitor size is used, different available capacitor sizes between minimum and maximum available capacitor size, the capacitor size is determined by the peak reactive power of the load and the capacitor size best fitting to the reactive energy consumption of the load is used.

In this research paper, three best ranges of capacitor values are used after testing for capacitor values starting from 10kVAr to 10MVAr. It is observed that for small capacitor values below 100kVAr and for big capacitor values above 7.3MVAr, the cost cannot be minimized. For the test, different ranges of capacitor values are taken as test cases method. As test case one, the range of capacitor values starting from 0.1MVAr to 2.5MVAr is used. As second test case, the range of capacitor values starting from

0.1MVAr to 5.5MVar is used. As third test case, the range of capacitor values starting from 0.1Mvar to 7.3Mvar is used.

The step size of 50KVAr is used for capacitor values between 0.1MVAr to 1.1MVAr and 100KVAr for capacitor values between 1.2MVAr to 7.3MVAr)

For all cases, the evaluated cost is used to select the candidate place for capacitor placement. The values of loss sensitivity analysis have been arranged and ranked in ascending order of cost evaluation. The top ones with minimum cost values have better chances to be selected as candidate locations.

CHAPTER FOUR
SIMULATION STUDIES AND ANALYSIS OF RESULTS

4.1 Introduction

In this chapter, simulation studies are carried out and analysis of the results are presented. Power flow analysis is carried out to investigate the power loss, the associated cost and voltage profile with and without the optimal capacitor placement of capacitors. Further, the cost benefit analysis is presented at the end of this chapter. The optimization procedure was implemented in DIGSILENT Powerfactroy Software environment and tested on balanced 42 buses radial distribution system. Loss Sensitivity method discussed in Chapter 4.3 has been used to find out the potential buses for capacitor placement. The potential buses are selected by loss sensitivity method in DIGSILENT Powerfactory software Environment. These candidate buses together with different capacitor values mentioned in 3.3.4 have been used as an input to find out optimal capacitor size. So from the overall result, the researcher observed that the optimization method for optimal capacitor allocation caused the power losses reduction on the lines and voltages profile improvement on buses of the real COTEBE 33KV Feeder distribution system with good investment cost saving as case study.

The effectiveness of compensation is discussed for maximum annual saving after considering saving due to energy loss cost and capacitor cost.

4.2 Optimal Capacitor Placement on 42 Buses RDS

The 33-bus radial distribution system, as shown in Figure 2.7 above, has the following details:

Number of buses = 42

Number of lines = 41

Slack Bus No =1

Base Voltage=33KV

Base MVA=16 MVA

Total real power demand=10.3329KW
Total reactive power demand=10.3678KVAr
Minimum voltages limit=0.95
Maximum voltages limit=1.05

The load flow of the distribution system is obtained using the method discussed in Chapter 2. The Loss Sensitivity Factor as discussed in section 3.4 has been used to identify the potential buses for shunt capacitor placement. The buses have been sorted and selected as candidate bus for capacitor installation according to the sum of power loss cost using sensitivity method in DIGSILENT Powerfactory software Environment. Different potential buses are selected for the three cases**.** The capacitor value has been taken as a discrete variable [29].Among all the potential buses, those which have less losses cost, are taken as candidate buses on the Feeder. The size of the test capacitors has been used to evaluate the cost benefit according to the minimum and maximum available capacitor size and the peak reactive power requirements. The capacitor sizes selections have been determined by using the same software tool on selected candidate buses. The capacitor size best fitting to the reactive energy consumption of the loads have been used**.** The comparisons for three test cases (mentioned above) are made between the losses with capacitor placed and losses without capacitor placement. The Loss Cost without optimal capacitor placement of capacitor is found to be 229,557.58$.
Buses Number 39, 27, 40, 41, 29, 31, 35 and bus number 30 are selected as potential buses for capacitor Placement for Case 1.
Buses Number 24, 25, 30, 17, 34 and bus number 13 are selected as potential buses for capacitor Placement for Case 2.
Buses Number 39, 31, 37, 41and bus number 28 are selected as potential Buses for capacitor Placement for Case 3.
The comparisons are done with the initial power loss cost (before sensitivity analysis is done). So these candidate buses in all cases are used for further optimization analysis (for optimum size selection) and cost estimation.

After the final optimization program for capacitor size selection, the following new minimal are founded

Table 4.1: The Size and Cost of Capacitors selected on the candidate buses for Case 1

Bus number	New capacitor Value (MVAr)	Cost of capacitor ($)
39	1.2	15250.00
29	1.1	14400.00
27	0.55	9100.00
31	2.3	22950.00

Table 4.2: The Size and Cost of Capacitors selected on the candidate buses for Case 2

Bus number	New capacitor Value (MVAr)	Cost of capacitor($)
17	3.3	29950.00
25	2.2	22200.00

Table 4.3: The Size and Cost of Capacitors selected on the candidate buses for Case 3

Bus number	New capacitor Value (MVAr)	Cost of capacitor($)
31	7.3	50650.00

4.3 Power Flow Analysis without Capacitor Placement

The power flow results obtained after simulations of the power system model on DIGSILENT Powerfactory software are presented in tabular form. Tabular form of both voltage magnitude and phase angles are given in Table 4.7.The Active and Reactive power losses on the lines are given in Table 4.8.

From the Table 4.7 load flow result, Most of the voltage values are below the voltage limits according to the EEP and EEU standard. Therefore, voltage drop is encountered on most of the distribution System as a problem to be solved.

Table 4.4 Base case load flow solution of voltage magnitudes and phase angles of 42 bus RDS (Without capacitor placement)

Name of bus bar	Voltage Magnitude (p.u)	Angle (deg)
Bar 33KV	1	0
1	0.958	-0.27
2	0.958	-0.27
3	0.958	-0.27
4	0.950	-0.40
5	0.941	-0.54
6	0.940	-0.54
7	0.940	-0.54
8	0.935	-0.68
9	0.931	-0.78
10	0.927	-0.87
11	0.926	-0.90
12	0.927	-0.87
13	0.924	-0.95
14	0.924	-0.95
15	0.923	-0.95
16	0.923	-0.95
17	0.921	-1.03
18	0.921	-1.03
19	0.921	-1.0.
20	0.919	-1.10
21	0.919	-1.10
22	0.915	-1.26
23	0.914	-1.26
24	0.912	-1.31
25	0.912	-1.31

Name of bus bar	Voltage Magnitude (p.u)	Angle (deg)
26	0.912	-1.31
27	0.911	-1.33
28	0.910	-1.34
29	0.910	-1.34
30	0.910	-1.34
31	0.910	-1.34
32	0.911	-1.34
33	0.911	-1.35
34	0.911	-1.36
35	0.910	-1.37
36	0.908	-1.40
37	0.906	-1.42
38	0.906	-1.43
39	0.905	-1.45
40	0.906	-1.42
41	0.906	-1.42

Table 4.5 Base case load flow solution of Active and Reactive power losses on lines of 42 bus RDS (Without capacitor placement)

Name of the line	Active Power Loss(MW)	Reactive Power Loss (MVAr)
line 2(*l*2)	0.00088	0.00086
line 3(*l*3)	0.00076	0.00072
line 4(*l*4)	0.00097	0.00093
line 5(*l*1)	0.055	0.102
line 6(*l*6)	0.056	0.103
line 7(*l*7)	0.00097	0.00098
line 8(*l*8)	0.001	0.00089

Name of the line	**Active Power Loss(MW)**	**Reactive Power Loss (MVAr)**
line 9(*l*9)	0.021	0.038
line 10(*l*10)	0.014	0.027
line 11(*l*11)	0.011	0.417
line 12(*l*12)	0.002	0.005
line 13(*l*13)	0.005	0.009
line 14(*l*14)	0.00021	0.00016
line 15(*l*15)	0.00016	0.00014
line 16(*l*16)	0.00014	0.00013
line 17(*l*17)	0.00085	0.001
line 18(*l*18)	0.006	0.011
line 19(*l*19)	0.00008	0.00007
line 20(*l*20)	0.00008	0.00007
line 21(*l*21)	0.005	0.011
line 22(*l*22)	0.00011	0.0001
line 23(*l*23)	0.007	0.012
line 24(*l24*)	0.002	0.005
line 25(*l*25)	0.002	0.005
line 26(*l*26)	0.00099	0.00098
line 27(*l*27)	0.00088	0.00086
line 28(*l*28)	0.001	0.002
line 29(*l*29)	0.001	0.001
line 30(*l*30)	0.0009	0.00089
line 31(*l*31)	0.00089	0.00088
line 32(*l*32)	0.00021	0.00013
line 33(*l*33)	0.002	0.001
line 34(*l*34)	0.002	0.001
line 35(*l*35)	0.001	0.001
line 36(*l*36)	0.001	0.001

Name of the line	Active Power Loss(MW)	Reactive Power Loss (MVAr)
line 37(*l*37)	0.002	0.001
line 38(*l*38)	0.02	0.01
line 39(*l*39)	0.00099	0.00096
line 40(*l*40)	0.001	0.001
line 41(*l*41)	0.00011	0.0001
line 42(*l42*)	0.00008	0.00007

4.4 Power Flow Analysis With Capacitor Placement

From the above three Test Cases, the results show that the optimal capacitor placement using DIGSILENT Powerfactory Software optimally reduced the power losses on the grid and improved voltage profile of the buses. All cases are good options for voltage improvement on the buses and power losses reduction on the lines of the distribution system with good investment costs saving, however case two can be the best choice for the Utility to use relative to case one and case three in terms of the given objectives. Therefore, the researcher selected and recommended case two as the final optimization analysis method with the given capacitor range values for case study of COTEBE Substation Distribution system.

Table 4.6 Load flow solution of 42 Bus RDS for Case 1

Name of Bus Bar	Voltage Magnitude (p.u)	Angle (deg)
Bar 33Kv	1	0
1	0.969	-0.64
2	0.969	-0.64
3	0.969	-0.65
4	0.962	-0.73
5	0.954	-0.94
6	0.954	-0.94
7	0.953	-0.94

Name of Bus Bar	Voltage Magnitude (p.u)	Angle (deg)
8	0.950	-1.18
9	0.947	-1.28
10	0.945	-1.53
11	0.944	-1.54
12	0.945	-1.60
13	0.943	-1.64
14	0.943	-1.64
15	0.943	-1.64
16	0.943	-1.64
17	0.942	-1.77
18	0.942	-1.77
19	0.942	-1.77
20	0.941	-1.88
21	0.941	-1.88
22	0.940	-2.08
23	0.939	-2.09
24	0.939	-2.24
25	0.938	-2.24
26	0.938	-2.24
27	0.938	-2.28
28	0.938	-2.28
29	0.938	-2.28
30	0.938	-2.35
31	0.938	-2.92
32	0.938	-2.28
33	0.938	-2.30
34	0.938	-2.32
35	0.938	-2.35
36	0.937	-2.45
37	0.936	-2.54
38	0.936	-2.56
39	0.936	-3.18
40	0.936	-2.57
41	0.936	-2.57

Table 4.7 Load flow solution of 42 Bus RDS for Case 2

Name of Bus Bar	**Voltage Magnitude (p.u)**	**Angle(deg.)**
Bar 33Kv	1	0
1	0.979	-0.78
2	0.978	-0.78
3	0.978	-0.79
4	0.972	-1.02
5	0.966	-1.27
6	0.965	-1.27
7	0.965	-1.27
8	0.963	-1.53
9	0.962	-1.72
10	0.961	-1.90
11	0.960	-1.95
12	0.960	-1.90
13	0.960	-2.07
14	0.960	-2.07
15	0.962	-2.07
16	0.962	-2.07
17	0.959	-2.24
18	0.959	-2.24
19	0.959	-2.24
20	0.959	-2.41
21	0.959	-2.41
22	0.961	-2.69
23	0.961	-2.80
24	0.962	-2.92
25	0.962	-2.92
26	0.962	-2.92
27	0.962	-3.00
28	0.962	-3.06
29	0.962	-3.06
30	0.962	-3.07
31	0.963	-3.12
32	0.963	-2.99
33	0.963	-3.03
34	0.963	-3.05

Name of Bus Bar	Voltage Magnitude (p.u)	Angle(deg.)
35	0.964	-3.10
36	0.965	-3.34
37	0.966	-3.53
38	0.967	-3.58
39	0.968	-3.77
40	0.966	-3.53
41	0.966	-3.53

Table 4.8 Load Flow solution of 42 Bus RDS for Test Case 3

Name of Bus Bar	Voltage Magnitude (p.u)	Angle(deg.)
Bar 33Kv	1	0
1	0.972	-0.56
2	0.973	-0.56
3	0.972	-0.57
4	0.965	-0.72
5	0.957	-0.95
6	0.957	-0.95
7	0.956	-0.96
8	0.954	-1.15
9	0.951	-1.30
10	0.949	-1.44
11	0.948	-1.48
12	0.948	-1.44
13	0.947	-1.57
14	0.947	-1.57
15	0.946	-1.56
16	0.946	-1.56
17	0.946	-2.21
18	0.946	-1.70
19	0.946	-1.70
20	0.944	-1.80
21	0.944	-1.80
22	0.941	-1.95
23	0.940	-2.02
24	0.939	-2.08

Name of Bus Bar	Voltage Magnitude (p.u)	Angle(deg.)
25	0.939	-2.08
26	0.939	-2.08
27	0.938	-2.10
28	0.937	-2.11
29	0.937	-2.11
30	0.937	-2.11
31	0.937	-2.12
32	0.939	-2.11
33	0.938	-2.11
34	0.938	-2.13
35	0.937	-2.14
36	0.935	-2.17
37	0.933	-2.20
38	0.933	-2.20
39	0.932	-2.22
40	0.933	-2.20
41	0.933	-2.20

From Tables 4.6, 4.7 and 4.8, we observe that the voltage profile have shown improvements after the optimization programme is implemented on COTEBE Distribution system relative to power flow result without capacitor placement shown in table 4.4. For instance, the minimum Voltage levels increased from 0.905(p.u) to 0.936(p.u), from 0.905(p.u) to 0.959(p.u) and from 0.905(p.u) to 0.932(p.u) for Test Case 1, Test Case 2 and Test Case 3 respectively. So these show that the optimization programme that is used to improve the voltage profile in DIGSILENT Environment with the selected parameter settings, are the good choice.

4.5 Cost Benefit Analysis of Capacitor Placement

The costs benefit analysis of capacitors placement for different cases are carried out using DIGSILENT Powerfactory software and are presented below.

Test Case 1: For test capacitor values starting from 0.1MVAr to 2.5MVAr
0.55MVAr, 1.1MVAr, 1.2MVAr and 2.3MVAr capacitor sizes at bus numbers 27, 29, 39 and 31 respectively are selected as an optimization solution. These caused the total grid losses to decrease from 0.583MW to 0.460MW and the total current in feeder from 0.064kA to 0.056kA. The results show that the total final cost (power losses plus capacitors costs which is equal to 208,701.38dollar, after the optimization) has been decreased from the initial total loss cost (before the optimization which is equal to 229,557.58) value by 20,856.20dollar so that the utility (EEU) can save 20,856.20$ per annum with the payback period of Eighteen months.

Test Case 2: For test capacitor values starting from 0.1MVAr to 5.5MVAr
2.2MVAr and 3.3MVAr capacitor sizes at bus numbers 25 and 17 are selected as an optimization solution respectively. These caused the total grid losses to decrease from 0.583MW to 0.413MW and the total current in feed from 0.064kA to 0.051kA.The results show that the total finial cost (power losses plus capacitors costs which is equal to 203,425.25dollar, after the optimization) has been decreased from the initial total loss cost (before the optimization which is equal to 229,557.58) value by 26,132.33dollarso that the utility (EEU) can save 26,132.33$ per annum with the payback period of Fifteen months.

Test Case 3: For test capacitor values starting from 0.1MVAr to 7.3MVAr
7.3MVar capacitor size at bus number 31 is selected as an optimization solution. These caused the total grid losses to decrease from 0.583MW to 0.44MW and the total current in feeder from 0.064kA to 0.055kA. The results show that the total final cost (power losses plus capacitors costs which is equal to 206,437.88dollar, after the optimization) has been decreased from the initial total loss cost (before the optimization which is equal to 229,557.58) value by 23,119.70dollar. So that the utility (EEU) can save 23119.70$ per annum with the payback period of twenty months.

The total cost of losses without capacitor placement is 229,557.58 dollar while those obtained with placement of capacitors in specified locations discussed able is presented in Tables 4.9, 4.10 and 4.11given below.

Table 4.9 Costs after optimal capacitor placement for Test Case 1

	Before Optimization	**After Optimization**	**Saved Cost**
Costs of Power losses ($)	229,557.58	147001.38	82556.20
Costs of New Capacitors ($)	-	61700.00	-
Total Costs($)	229,557.58	208701.38	20856.20

Table 4.10: Saved Costs after optimal capacitor placement for Test Case 2

	Before Optimization	**After Optimization**	**Saved Costs**
Costs of Power losses ($)	229,557.58	151275.25	79282.33
Costs of New Capacitors ($)	-	52150.00	-
Total Costs($)	229,557.58	203425.25	26132.33

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Table 4.11: Saved Costs after optimal capacitor placement for Test Case 3

	Before Optimization	**After Optimization**	**Saved Costs**
Costs of Power losses ($)	229,557.58	155,787.88	73769.70
Costs of New Capacitors ($)	-	50650.00	-
Total Costs($)	229,557.58	206437.88	23119.70

CHAPTER FIVE

Conclusions, Recommendations and Future work

5.1 Conclusions

In this thesis, the method for successful capacitor placement with the objective of power losses reduction and improving voltage profile together with cost benefit analysis is proposed. The study has been carried out on COTEBE Substation, Ethiopia for 42 buses radial distribution system. After testing for capacitor values starting from 10kVAr to 10MVAr, it is observed that for small capacitor values below 100kVAr and for big capacitor values above 7.3MVAr, the cost cannot be minimized. For the test, three ranges of capacitor values are taken as test cases method. As test case one, the range of capacitor values starting from 0.1MVAr to 2.5MVAr is used. As second test case, the range of capacitor values starting from 0.1MVAr to 5.5MVar is used. As third test case, the range of capacitor values starting from 0.1Mvar to 7.3Mvar is used. Among these the second test case is selected due to its best power loss reduction, voltage improvement and cost saving amount.

As we could observe from our result, if we make investments for addition of reactive power using optimal placement of capacitors, reduced power losses cost will easily recover the investment cost. However this was not true for all cases and some cases were not successful and effective. Our result made on existing power system shows, that in some cases even though the losses are reduced, the investment cost could be so high and economically is not effective to implement. The suggested method of reactive power addition for the loss reduction purpose becomes more effective and economically worthwhile in power systems with higher loads and where peak-hour operations are longer. For being able to significantly improve Voltage profile and to reduce losses, “reactive power” should be optimally placed. So, optimal capacitor placement can reduce losses and improve voltage profile with good investment saving.

5.2 Recommendations

Based on the above stated conclusions, the following recommendations are made:

- Operations and Planning Engineers need to consider optimal installation of capacitors for voltage improvement and power loss minimisation.
- The Optimal Capacitor Placement methodology needs to be reviewed by the Utility to use it in the planning and operational stage.

5.3 Suggestions for Future Work

In this thesis the way of active power loss reduction method with proper application of reactive power sources to the system is discussed and analyzed. However the method considers and the simulation has been done only for the peak hour operations, when the system is heavy loaded. During the rest of the time load is decreased and therefore the system is becoming able to transfer the needed power without overloading the system components. Accordingly the losses are becoming lower. In such a case, when the loads are lowered, the reactive power sources, which we applied to the system during the peak hour operations, become excessive and their injected reactive power can cause even more losses and destructive over voltages. Therefore it’s very important the reactive power sources to be properly operated and switched to the system only in case when they will be needed, i.e. during the heavy loads of the system.

Another issue to be considered is the transient on the system at the moment of connecting reactive power sources on the system. As it is essential to apply the reactive power sources to the system only during peak hours, the problem of transients becomes urgent for consideration while planning the locations and sizing of reactive sources. The other point is that the scope of this research is covered only on the optimal capacitor allocation for power loss and voltage profile improvement. Therefore, it is necessary to consider the Optimal Capacitor sizing and placement using DIGSILENT Powerfactory Software for further research methods.

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28. Power System Analysis DIgSILENT PowerFactory software, Version 14 Manual *http://www.digsilent.de*

29. Specification of franke's MV capacitor banks and capacitors, *http://www.frankeenergy.com*

Appendix A: Length and Type of the Distribution Lines

Name of the line	Length (km)	Type of the line
Line 1 (*l*1)	16	XLPE 150mm^2
line 2(*l*2)	3.45	AAC95
line 3(*l*3)	1.63	AAC95
line 4(*l*4)	2	AAC95
line 5(*l*1)	2.02	XLPE 150mm^2
line 6(*l*6)	2.06	XLPE 150mm^2
line 7(*l*7)	1.3	XLPE 95 mm^2
line 8(*l*8)	2.45	AAC95
line 9(*l*9)	2.52	XLPE 150mm^2
line 10(*l*10)	1.8	XLPE 150mm^2
line 11(*l*11)	1.8	XLPE 150mm^2
line 12(*l*12)	0.5	XLPE 150mm^2
line 13(*l*13)	1.3	XLPE 150mm^2
line 14(*l*14)	0.9	AAC50
line 15(*l*15)	9	AAC50
line 16(*l*16)	0.3	AAC50
line 17(*l*17)	1.3	XLPE 95 mm^2
line 18(*l*18)	1.9	XLPE 150mm^2
line 19(*l*19)	0.2	AAC50
line 20(*l*20)	2	AAC50
line 21(*l*21)	1.9	XLPE 150mm^2
line 22(*l*22)	0.25	AAC50
line 23(*l*23)	3.4	XLPE 150mm^2
line 24(*l24*)	1.4	XLPE 150mm^2
line 25(*l*25)	1.4	XLPE 150mm^2
line 26(*l*26)	0.6	AAC25

Name of the line	**Length (km)**	**Type of the line**
line 27(*l*27)	1	AAC50
line 28(*l*28)	2.18	AAC95
line 29(*l*29)	1.4	AAC95
line 30(*l*30)	1.8	AAC95
line 31(*l*31)	1.4	AAC95
line 32(*l*32)	1.4	AAC95
line 33(*l*33)	1.62	XLPE 150mm^2
line 34(*l*34)	0.9	XLPE 150mm^2
;line 35(*l*35)	0.5	XLPE 150mm^2
line 36(*l*36)	1.3	XLPE 150mm^2
line 37(*l*37)	4.4	XLPE 150mm^2
line 38(*l*38)	3.47	AAC95
line 39(*l*39)	0.99	AAC95
line 40(*l*40)	3.71	AAC95
line 41(*l*41)	4.45	AAC50
line 42(*l*42)	3.7	AAC50

Appendix B: Load flow Calculation in DigSilent Powerfactory

A. Load flow Calculation in DPS (Without Capacitor Placement)

DIgSI/info - Start Newton-Raphson Algorithm...

Iteration 1	Node	Iteration Time	Load	Iteration Time
	5	3.10e-002	IL5	3.10e-002
	9	5.12e-003	IL9	5.12e-003
	6	2.94e-003	WL6	2.94e-003
	12	2.85e-003	RL12	2.85e-003
	3	2.31e-003	WL3	2.31e-003
	7	2.20e-003	IL7	2.20e-003
	20	1.46e-003	QL20	1.46e-003
	10	1.42e-003	IL10	1.42e-003
	25	1.01e-003	QL25	1.01e-003
	1	8.15e-004	WL1	8.15e-004
	2	5.20e-004	WL2	5.20e-004
	13	2.80e-004	QL13	2.80e-004
	8	2.68e-004	IL8	2.68e-004
	26	2.49e-004	QL26	2.49e-004
	17	2.39e-004	QL17	2.39e-004
	24	2.02e-004	QL24	2.02e-004
	14	1.72e-004	QL14	1.72e-004
	4	1.50e-004	WL4	1.50e-004
	16	1.49e-004	QL16	1.49e-004
	23	9.30e-005	QL23	9.30e-005
	22	8.81e-005	QL22	8.81e-005
	21	7.59e-005	QL21	7.59e-005
	19	3.63e-005	QL19	3.63e-005
	18	3.51e-005	QL18	3.51e-005
	15	3.20e-005	QL15	3.20e-005

	36	1.92e-012	RL36	1.92e-012
	33	9.24e-013	RL33	9.24e-013
	40	7.37e-013	RL40	7.37e-013
	39	5.97e-013	RL39	5.97e-013
	11	5.26e-013	IL11	5.26e-013
	27	4.33e-013	RL27	4.33e-013
	34	4.26e-013	RL34	4.26e-013
	32	3.84e-013	RL32	3.84e-013
	30	3.43e-013	RL30	3.43e-013
	31	3.27e-013	RL31	3.27e-013
	37	3.13e-013	RL37	3.13e-013
	38	2.40e-013	RL38	2.40e-013
	29	2.28e-013	RL29	2.28e-013
	41	2.23e-013	RL41	2.23e-013
	35	2.04e-013	RL35	2.04e-013
	28	1.74e-013	RL28	1.74e-013
Iteration 2	5	5.75e-007	IL5	5.75e-007
	9	9.23e-008	IL9	9.23e-008
	6	5.22e-008	WL6	5.22e-008
	12	5.06e-008	RL12	5.06e-008
	3	3.99e-008	WL3	3.99e-008
	7	3.42e-008	IL7	3.42e-008
	20	3.03e-008	QL20	3.03e-008
	10	2.27e-008	IL10	2.27e-008
	25	2.20e-008	QL25	2.20e-008
	1	1.17e-008	WL1	1.17e-008
	2	7.52e-009	WL2	7.52e-009
	13	6.65e-009	QL13	6.65e-009
	8	5.73e-009	IL8	5.73e-009

	26	5.02e-009	QL26	5.02e-009
	17	4.40e-009	QL17	4.40e-009
	24	4.17e-009	QL24	4.17e-009
	14	3.47e-009	QL14	3.47e-009
	4	2.62e-009	WL4	2.62e-009
	16	2.46e-009	QL16	2.46e-009
	23	1.91e-009	QL23	1.91e-009
	22	1.88e-009	QL22	1.88e-009
	21	1.82e-009	QL21	1.82e-009
	19	8.89e-010	QL19	8.89e-010
	18	8.79e-010	QL18	8.79e-010
	15	8.46e-010	QL15	8.46e-010
	36	1.11e-016	RL36	1.11e-016
	33	1.11e-016	RL33	1.11e-016
	40	5.55e-017	RL40	5.55e-017
	39	5.55e-017	RL39	5.55e-017
	11	5.55e-017	IL11	5.55e-017
	27	2.78e-017	RL27	2.78e-017
	34	2.78e-017	RL34	2.78e-017
	32	1.39e-017	RL32	1.39e-017
	30	1.04e-017	RL30	1.04e-017
	31	6.94e-018	RL31	6.94e-018
	37	3.47e-018	RL37	3.47e-018
	38	3.47e-018	RL38	3.47e-018
	29	3.47e-018	RL29	3.47e-018
	41	1.73e-018	RL41	1.73e-018
	35	8.38e-019	RL35	8.38e-019
	28	8.59e-020	RL28	8.59e-020

```
DIgSI/info - Newton-Raphson converged with 2 iterations
DIgSI/info - Load flow calculation successful
```

B. Load flow Calculation in DPS(With capacitor placement for Test Case 1)

DIgSI/info - Start Newton-Raphson Algorithm...

	Node	Iteration Time	Load	Iteration Time
	5	2.58e-002	IL5	2.58e-002
	9	4.05e-003	IL9	4.05e-003
	6	2.47e-003	WL6	2.47e-003
	12	2.22e-003	RL12	2.22e-003
	3	2.08e-003	WL3	2.08e-003
	7	1.91e-003	IL7	1.91e-003
	20	1.84e-003	QL20	1.84e-003
	10	1.21e-003	IL10	1.21e-003
	25	1.12e-003	QL25	1.12e-003
	1	7.26e-004	WL1	7.26e-004
	2	4.64e-004	WL2	4.64e-004
	13	3.47e-004	QL13	3.47e-004
	8	3.39e-004	IL8	3.39e-004
	26	3.02e-004	QL26	3.02e-004
	17	2.61e-004	QL17	2.61e-004
	24	2.20e-004	QL24	2.20e-004
	14	1.88e-004	QL14	1.88e-004
	4	1.41e-004	WL4	1.41e-004
	16	1.33e-004	QL16	1.33e-004
	23	1.21e-004	QL23	1.21e-004
	22	1.07e-004	QL22	1.07e-004
	21	9.71e-005	QL21	9.71e-005
	19	4.44e-005	QL19	4.44e-005
	18	4.33e-005	QL18	4.33e-005
	15	4.15e-005	QL15	4.15e-005
	36	7.11e-015	RL36	7.11e-015

	33	6.77e-015	RL33	6.77e-015
	40	2.11e-015	RL40	2.11e-015
	39	1.19e-015	RL39	1.19e-015
	11	1.11e-015	IL11	1.11e-015
	27	9.99e-016	RL27	9.99e-016
	34	9.44e-016	RL34	9.44e-016
	32	5.97e-016	RL32	5.97e-016
	30	1.70e-016	RL30	1.70e-016
	31	1.60e-016	RL31	1.60e-016
	37	1.32e-016	RL37	1.32e-016
	38	1.04e-016	RL38	1.04e-016
	29	1.01e-016	RL29	1.01e-016
	41	5.38e-017	RL41	5.38e-017
	35	5.20e-017	RL35	5.20e-017
	28	4.68e-017	RL28	4.68e-017
Iteration 2	5	4.14e-007	IL5	4.14e-007
	9	6.48e-008	IL9	6.48e-008
	6	3.51e-008	WL6	3.51e-008
	12	3.50e-008	RL12	3.50e-008
	3	3.00e-008	WL3	3.00e-008
	7	2.46e-008	IL7	2.46e-008
	20	2.28e-008	QL20	2.28e-008
	10	2.12e-008	IL10	2.12e-008
	25	1.39e-008	QL25	1.39e-008
	1	7.04e-009	WL1	7.04e-009
	2	6.52e-009	WL2	6.52e-009
	13	5.59e-009	QL13	5.59e-009
	8	4.84e-009	IL8	4.84e-009
	26	4.62e-009	QL26	4.62e-009

	17	4.08e-009	QL17	4.08e-009
	24	3.42e-009	QL24	3.42e-009
	14	2.76e-009	QL14	2.76e-009
	4	1.84e-009	WL4	1.84e-009
	16	1.84e-009	QL16	1.84e-009
	23	1.76e-009	QL23	1.76e-009
	22	1.51e-009	QL22	1.51e-009
	21	1.39e-009	QL21	1.39e-009
	19	8.52e-010	QL19	8.52e-010
	18	8.47e-010	QL18	8.47e-010
	15	8.18e-010	QL15	8.18e-010
	36	2.22e-016	RL36	2.22e-016
	33	1.11e-016	RL33	1.11e-016
	40	5.55e-017	RL40	5.55e-017
	39	5.55e-017	RL39	5.55e-017
	11	5.55e-017	IL11	5.55e-017
	;27	2.78e-017	RL27	2.78e-017
	34	2.78e-017	RL34	2.78e-017
	32	1.39e-017	RL32	6.94e-018
	30	1.04e-017	RL30	6.94e-018
	31	6.94e-018	RL31	3.47e-018
	37	3.47e-018	RL37	3.47e-018
	38	3.47e-018	RL38	3.47e-018
	29	3.47e-018	RL29	1.73e-018
	41	1.73e-018	RL41	1.73e-018
	35	8.38e-019	RL35	8.38e-019
	28	8.59e-020	RL28	8.38e-019

DIgSI/info - Newton-Raphson converged with 2 iterations

DIgSI/info - Load flow calculation successful

C. Load flow Calculation in DPS (With capacitor placement for Test Case 2)

Iteration 1	Node	Iteration Time	Load	Iteration Time
	5	2.55e-002	IL5	2.55e-002
	9	4.00e-003	IL9	4.00e-003
	6	2.45e-003	WL6	2.45e-003
	12	2.18e-003	RL12	2.18e-003
	3	2.06e-003	WL3	2.06e-003
	7	1.89e-003	IL7	1.89e-003
	20	1.84e-003	QL20	1.84e-003
	10	1.19e-003	IL10	1.19e-003
	25	1.10e-003	QL25	1.10e-003
	1	7.21e-004	WL1	7.21e-004
	2	4.61e-004	WL2	4.61e-004
	13	3.48e-004	QL13	3.48e-004
	8	3.32e-004	IL8	3.32e-004
	26	2.18e-004	QL26	2.18e-004
	17	2.17e-004	QL17	2.17e-004
	24	1.89e-004	QL24	1.89e-004
	14	1.52e-004	QL14	1.52e-004
	4	1.39e-004	WL4	1.39e-004
	16	1.32e-004	QL16	1.32e-004
	23	1.19e-004	QL23	1.19e-004
	22	1.06e-004	QL22	1.06e-004
	21	9.68e-005	QL21	9.68e-005
	19	4.46e-005	QL19	4.46e-005
	18	4.35e-005	QL18	4.35e-005
	15	4.17e-005	QL15	4.17e-005
	36	1.11e-012	RL36	6.99e-015
	33	9.50e-013	RL33	6.88e-015

	40	9.20e-013	RL40	2.44e-015
	39	6.31e-013	RL39	1.36e-015
	11	5.61e-013	IL11	1.17e-015
	27	5.20e-013	RL27	9.99e-016
	34	5.02e-013	RL34	9.71e-016
	32	4.47e-013	RL32	6.38e-016
	30	4.38e-013	RL30	1.87e-016
	31	3.77e-013	RL31	1.67e-016
	37	3.65e-013	RL37	1.11e-016
	38	3.29e-013	RL38	1.04e-016
	29	3.23e-013	RL29	8.67e-017
	41	3.13e-013	RL41	5.90e-017
	35	2.89e-013	RL35	5.55e-017
	28	2.88e-013	RL28	5.38e-017
Iteration 2	5	6.15e-008	IL5	3.96e-007
	9	3.33e-008	IL9	6.15e-008
	6	3.32e-008	WL6	3.33e-008
	12	2.78e-008	RL12	3.32e-008
	3	2.34e-008	WL3	2.78e-008
	7	2.13e-008	IL7	2.34e-008
	20	2.03e-008	QL20	2.13e-008
	10	1.31e-008	IL10	2.03e-008
	25	6.72e-009	QL25	1.31e-008
	1	4.41e-009	WL1	6.72e-009
	2	3.85e-009	WL2	6.09e-009
	13	3.18e-009	QL13	4.42e-009
	8	2.61e-009	IL8	4.41e-009
	26	2.47e-009	QL26	3.85e-009
	17	1.69e-009	QL17	3.18e-009

	24	1.69e-009	QL24	2.61e-009
	14	1.62e-009	QL14	2.47e-009
	4	1.41e-009	WL4	1.69e-009
	16	1.32e-009	QL16	1.69e-009
	23	7.88e-010	QL23	1.62e-009
	22	7.84e-010	QL22	1.41e-009
	21	7.60e-010	QL21	1.32e-009
	19	2.04e-012	QL19	7.88e-010
	18	1.73e-012	QL18	7.84e-010
	15	1.53e-012	QL15	7.60e-010
	36	9.70e-013	RL36	1.11e-016
	33	9.57e-013	RL33	1.11e-016
	40	7.69e-013	RL40	5.55e-017
	39	7.05e-013	RL39	5.55e-017
	11	6.91e-013	IL11	5.55e-017
	27	6.50e-013	RL27	2.78e-017
	34	4.96e-013	RL34	1.39e-017
	32	4.71e-013	RL32	6.94e-018
	30	3.64e-013	RL30	6.94e-018
	31	3.55e-013	RL31	6.94e-018
	37	3.41e-013	RL37	3.47e-018
	38	3.37e-013	RL38	3.47e-018
	29	3.02e-013	RL29	3.47e-018
	41	2.99e-013	RL41	1.73e-018
	35	2.70e-013	RL35	8.38e-019
	28	2.65e-013	RL28	8.38e-019

DIgSI/info - Newton-Raphson converged with 2 iterations

DIgSI/info - Load flow calculation successful

D. Load flow Calculation in DPS (With capacitor placement for Test Case 3)

Iteration 1	Node	Iteration Time	Load	Iteration Time
	5	2.09e-002	IL5	2.09e-002
	9	3.04e-003	IL9	3.04e-003
	6	2.11e-003	WL6	2.11e-003
	12	2.02e-003	RL12	2.02e-003
	3	1.84e-003	WL3	1.84e-003
	7	1.61e-003	IL7	1.61e-003
	20	1.61e-003	QL20	1.61e-003
	10	1.36e-003	IL10	1.36e-003
	25	8.21e-004	QL25	8.21e-004
	1	6.34e-004	WL1	6.34e-004
	2	4.06e-004	WL2	4.06e-004
	13	4.01e-004	QL13	4.01e-004
	8	3.92e-004	IL8	3.92e-004
	26	3.52e-004	QL26	3.52e-004
	17	3.02e-004	QL17	3.02e-004
	24	2.18e-004	QL24	2.18e-004
	14	1.73e-004	QL14	1.73e-004
	4	1.39e-004	WL4	1.39e-004
	16	1.27e-004	QL16	1.27e-004
	23	1.16e-004	QL23	1.16e-004
	22	1.14e-004	QL22	1.14e-004
	21	1.08e-004	QL21	1.08e-004
	19	5.26e-005	QL19	5.26e-005
	18	5.15e-005	QL18	5.15e-005
	15	4.90e-005	QL15	4.90e-005
	36	1.41e-012	RL36	1.41e-012

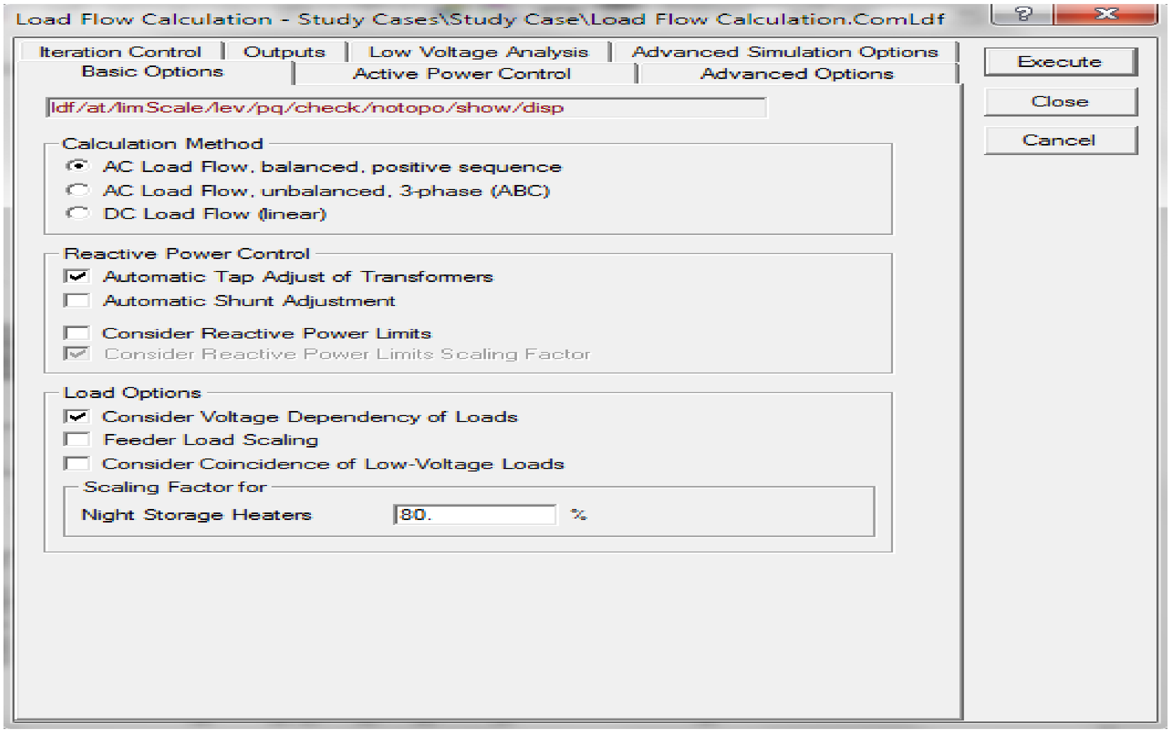
	33	1.14e-012	RL33	1.14e-012
	40	1.06e-012	RL40	1.06e-012
	39	8.53e-013	RL39	8.53e-013
	11	6.82e-013	IL11	6.82e-013
	27	6.60e-013	RL27	6.60e-013
	34	5.90e-013	RL34	5.90e-013
	32	4.98e-013	RL32	4.98e-013
	30	4.85e-013	RL30	4.85e-013
	31	3.98e-013	RL31	3.98e-013
	37	3.91e-013	RL37	3.91e-013
	38	3.91e-013	RL38	3.91e-013
	29	3.87e-013	RL29	3.87e-013
	41	3.11e-013	RL41	3.11e-013
	35	3.10e-013	RL35	3.10e-013
	28	3.00e-013	RL28	3.00e-013
Iteration 2	5	2.38e-007	IL5	2.38e-007
	9	3.43e-008	IL9	3.43e-008
	6	2.53e-008	WL6	2.53e-008
	12	1.93e-008	RL12	1.93e-008
	3	1.88e-008	WL3	1.88e-008
	7	1.84e-008	IL7	1.84e-008
	20	1.63e-008	QL20	1.63e-008
	10	1.43e-008	IL10	1.43e-008
	25	9.34e-009	QL25	9.34e-009
	1	5.46e-009	WL1	5.46e-009
	2	5.12e-009	WL2	5.12e-009
	13	4.63e-009	QL13	4.63e-009
	8	3.97e-009	IL8	3.97e-009
	26	3.34e-009	QL26	3.34e-009

	17	3.18e-009	QL17	3.18e-009
	24	2.87e-009	QL24	2.87e-009
	14	1.83e-009	QL14	1.83e-009
	4	1.52e-009	WL4	1.52e-009
	16	1.49e-009	QL16	1.49e-009
	23	1.43e-009	QL23	1.43e-009
	22	1.26e-009	QL22	1.26e-009
	21	1.15e-009	QL21	1.15e-009
	19	6.91e-010	QL19	6.91e-010
	18	6.90e-010	QL18	6.90e-010
	15	6.71e-010	QL15	6.71e-010
	36	1.86e-012	RL36	1.86e-012
	33	1.46e-012	RL33	1.46e-012
	40	1.00e-012	RL40	1.00e-012
	39	9.23e-013	RL39	9.23e-013
	11	8.21e-013	IL11	8.21e-013
	27	7.45e-013	RL27	7.45e-013
	34	7.43e-013	RL34	7.43e-013
	32	7.39e-013	RL32	7.39e-013
	30	7.00e-013	RL30	7.00e-013
	31	6.93e-013	RL31	6.93e-013
	37	6.56e-013	RL37	6.56e-013
	38	6.47e-013	RL38	6.47e-013
	29	6.24e-013	RL29	6.24e-013
	41	6.01e-013	RL41	6.01e-013
	35	5.88e-013	RL35	5.88e-013
	28	5.72e-013	RL28	5.72e-013

DIgSI/info - Newton-Raphson converged with 2 iterations

DIgSI/info - Load flow calculation successful

Appendix C: Load Flow Dialogue Box for the Case Study



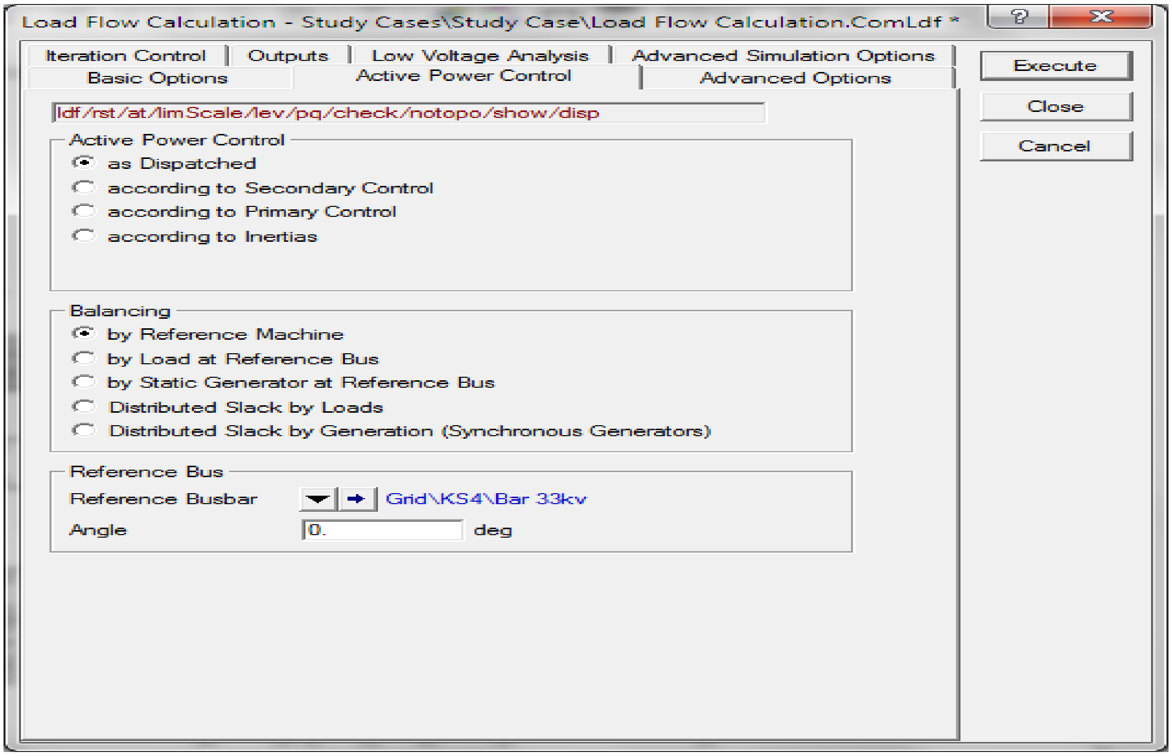
ldf/at/limScale/lev/pq/check/notopo/show/disp

Calculation Method
- ● AC Load Flow, balanced, positive sequence
- ○ AC Load Flow, unbalanced, 3-phase (ABC)
- ○ DC Load Flow (linear)

Reactive Power Control
- ☑ Automatic Tap Adjust of Transformers
- ☐ Automatic Shunt Adjustment
- ☐ Consider Reactive Power Limits
- ☑ Consider Reactive Power Limits Scaling Factor

Load Options
- ☑ Consider Voltage Dependency of Loads
- ☐ Feeder Load Scaling
- ☐ Consider Coincidence of Low-Voltage Loads

Scaling Factor for
Night Storage Heaters: 80. %

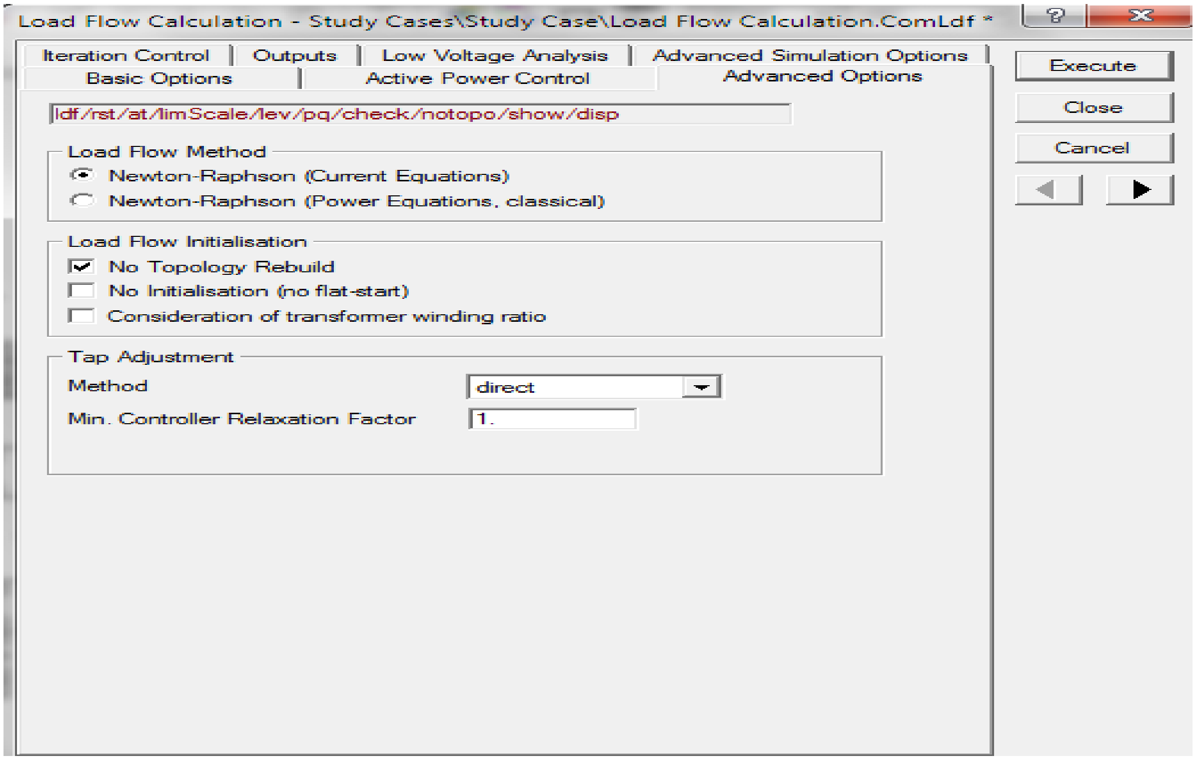


ldf/rst/at/limScale/lev/pq/check/notopo/show/disp

Active Power Control
- ● as Dispatched
- ○ according to Secondary Control
- ○ according to Primary Control
- ○ according to Inertias

Balancing
- ● by Reference Machine
- ○ by Load at Reference Bus
- ○ by Static Generator at Reference Bus
- ○ Distributed Slack by Loads
- ○ Distributed Slack by Generation (Synchronous Generators)

Reference Bus
Reference Busbar: Grid\KS4\Bar 33kv
Angle: 0. deg



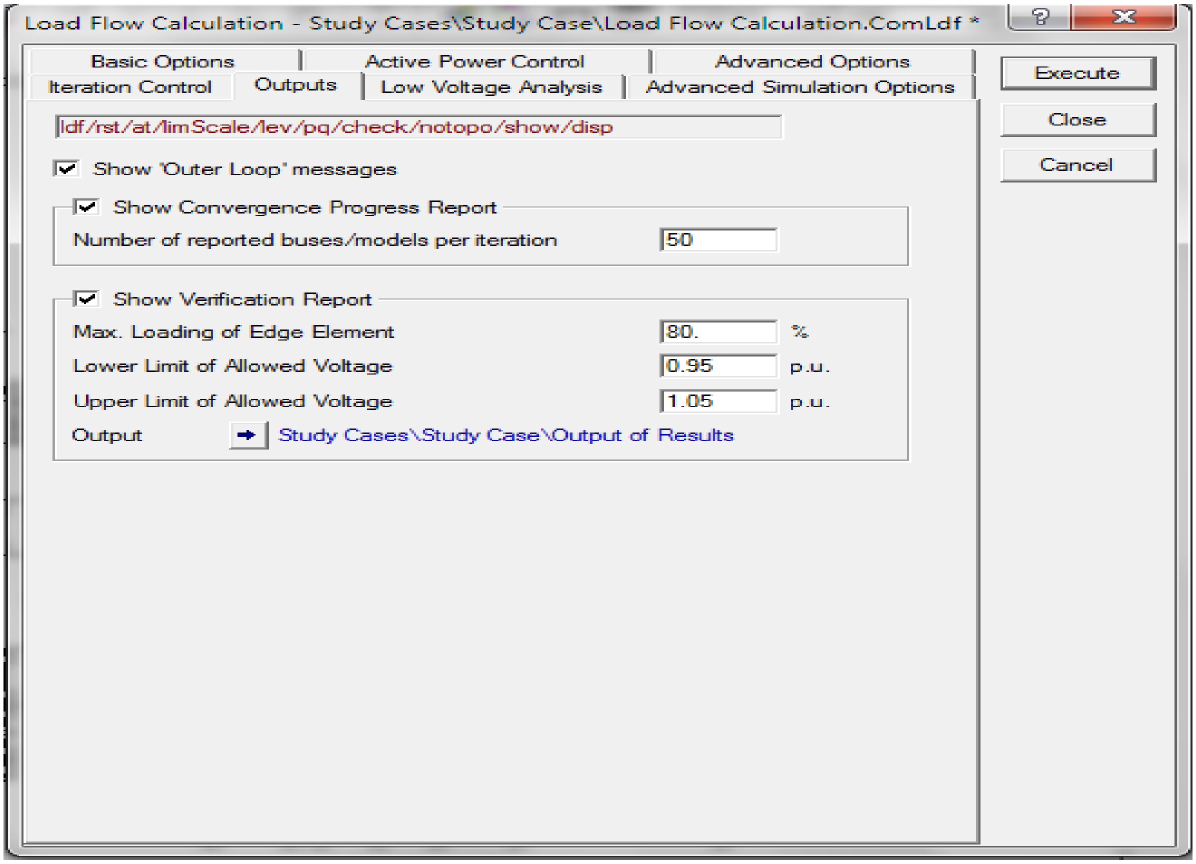
Load Flow Calculation - Study Cases\Study Case\Load Flow Calculation.ComLdf *

ldf/rst/at/limScale/lev/pq/check/notopo/show/disp

Load Flow Method
● Newton-Raphson (Current Equations)
○ Newton-Raphson (Power Equations, classical)

Load Flow Initialisation
☑ No Topology Rebuild
☐ No Initialisation (no flat-start)
☐ Consideration of transformer winding ratio

Tap Adjustment
Method: direct
Min. Controller Relaxation Factor: 1.



Load Flow Calculation - Study Cases\Study Case\Load Flow Calculation.ComLdf *

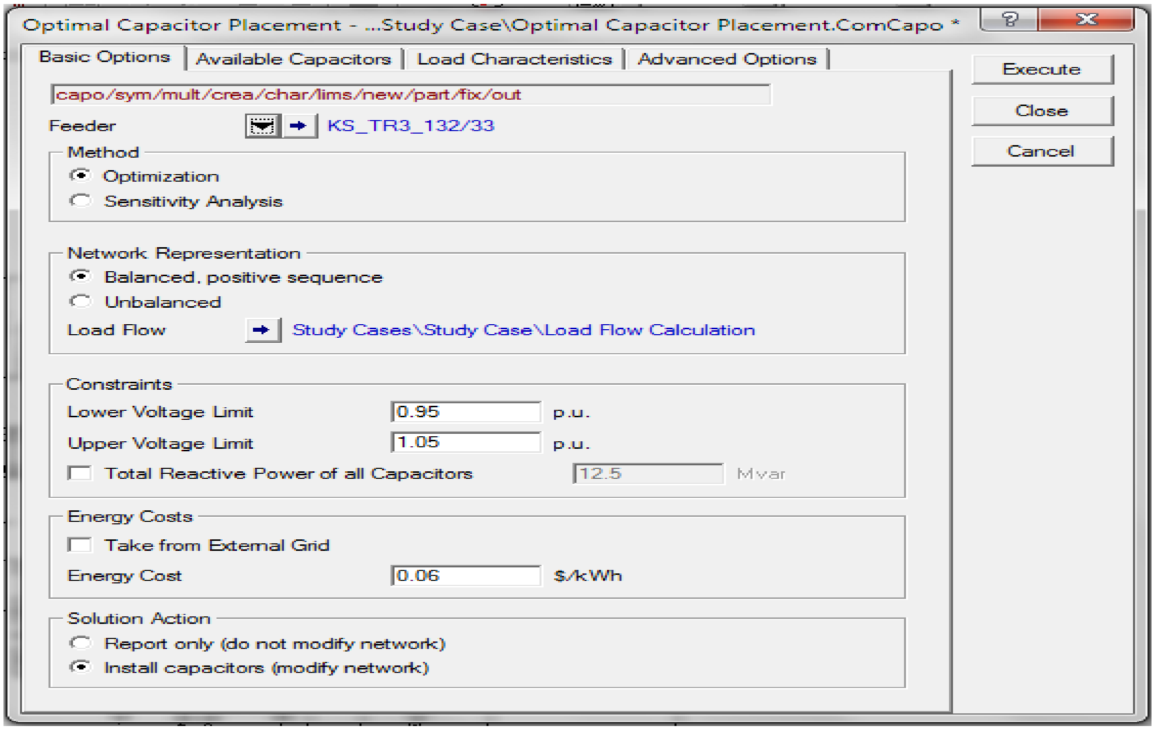
ldf/rst/at/limScale/lev/pq/check/notopo/show/disp

☑ Show 'Outer Loop' messages

☑ Show Convergence Progress Report
Number of reported buses/models per iteration: 50

☑ Show Verification Report
Max. Loading of Edge Element: 80. %
Lower Limit of Allowed Voltage: 0.95 p.u.
Upper Limit of Allowed Voltage: 1.05 p.u.
Output: Study Cases\Study Case\Output of Results

Appendix D: Optimal Capacitor placement Calculation Windows for the Case Study



capo/sym/mult/crea/char/lims/new/part/fix/out

Feeder KS_TR3_132/33

Method
- ● Optimization
- ○ Sensitivity Analysis

Network Representation
- ● Balanced, positive sequence
- ○ Unbalanced

Load Flow Study Cases\Study Case\Load Flow Calculation

Constraints

Lower Voltage Limit 0.95 p.u.

Upper Voltage Limit 1.05 p.u.

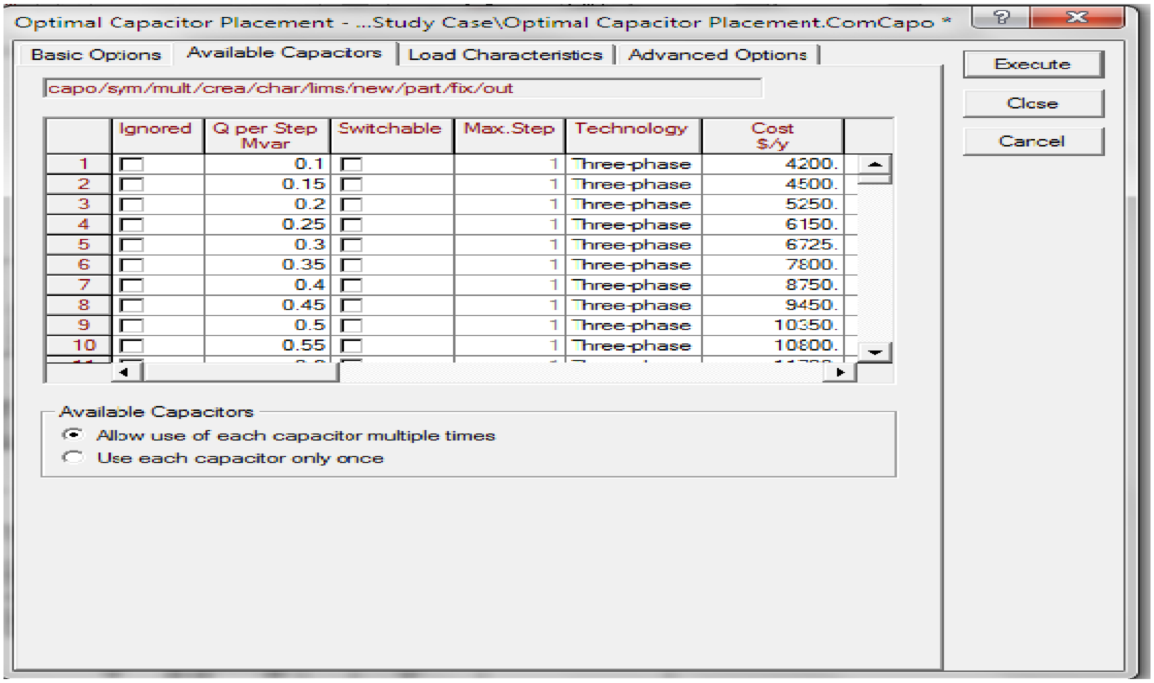
☐ Total Reactive Power of all Capacitors 12.5 Mvar

Energy Costs

☐ Take from External Grid

Energy Cost 0.06 $/kWh

Solution Action
- ○ Report only (do not modify network)
- ● Install capacitors (modify network)



capo/sym/mult/crea/char/lims/new/part/fix/out

	Ignored	Q per Step Mvar	Switchable	Max.Step	Technology	Cost $/y
1	☐	0.1	☐	1	Three-phase	4200.
2	☐	0.15	☐	1	Three-phase	4500.
3	☐	0.2	☐	1	Three-phase	5250.
4	☐	0.25	☐	1	Three-phase	6150.
5	☐	0.3	☐	1	Three-phase	6725.
6	☐	0.35	☐	1	Three-phase	7800.
7	☐	0.4	☐	1	Three-phase	8750.
8	☐	0.45	☐	1	Three-phase	9450.
9	☐	0.5	☐	1	Three-phase	10350.
10	☐	0.55	☐	1	Three-phase	10800.

Available Capacitors
- ● Allow use of each capacitor multiple times
- ○ Use each capacitor only once

Appendix E: Size and Cost of Capacitors

Capacitor size (KVAr)	10	20	30	40	50	60	70	80	90	100
Cost of capacitor($)	1750	1800	1850	1925	2050	2200	2650	2950	3450	4200
Capacitor size (KVAr)	150	200	250	300	350	400	450	500	550	600
Cost of capacitor($)	4500	5250	5700	6300	7050	7600	8150	8650	9100	9450
Capacitor size (KVAr)	650	700	750	800	850	900	950	1000	1050	1100
Cost of capacitor($)	10000	10450	10800	11250	11700	12350	12850	13400	13950	14400
Capacitor size (KVAr)	1200	1300	1400	1500	1600	1700	1800	1900	2000	2100
Cost of capacitor($)	15250	15850	16500	17250	18000	18700	19450	20125	20800	21550
Capacitor size (KVAr)	2200	2300	2400	2500	2600	2700	2800	2900	3000	3100
Cost of capacitor($)	22200	22950	23600	24350	24900	25550	26400	27125	27800	28550
Capacitor size (KVAr)	3200	3300	3400	3500	3600	3700	3800	3900	4000	4100
Cost of capacitor($)	29200	29950	30650	31400	32100	32850	33500	34250	35000	35775
Capacitor size (KVAr)	4200	4300	4400	4500	4600	4700	4800	4900	5000	5100
Cost of capacitor($)	36500	37300	38000	38750	39400	40050	40800	41425	42550	43000
Capacitor size (KVAr)	5200	5300	5400	5500	5600	5700	5800	5900	6000	6100
Cost of capacitor($)	43350	43700	44150	44500	44950	45350	45900	46300	46750	47050
Capacitor size (KVAr)	6200	6300	6400	6500	6600	6700	6800	6900	7000	7100
Cost of capacitor($)	47350	47700	48150	48400	48750	49000	49350	49450	49750	50050
Capacitor size (KVAr)	7200	7300	7400	7500	7600	7700	7800	7900	8000	8100

Cost of capacitor($)	50300	50650	51025	51250	51700	51850	52000	52200	52550	52800
Capacitor size (KVAr)	8200	8300	8400	8500	8600	8700	8800	8900	9000	9100
Cost of capacitor($)	53050	53150	53300	53550	53650	53850	53900	54000	54150	54350
Capacitor size (KVAr)	9200	9300	9400	9500	9600	9700	9800	9900	10000	
Cost of capacitor($)	54500	54675	54800	54950	55100	55250	55400	55650	55800	