MAXIMUM LOSS REDUCTION BY OPTIMAL PLACEMENT OF CAPACITOR ON RADIAL DISTRIBUTION SYSTEM

Thesis submitted in partial fulfillment of the requirements for the award of degree of

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in

Power Systems & Electric Drives

Thapar University, Patiala

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, "**Maximum Loss Reduction by Optimal Placement of Capacitor on Radial Distribution System**" in partial fulfillment of the requirements for the award of degree of Master of Engineering in Power system & electric drives submitted in Electrical & Instrumentation engineering department of Thapar University, Patiala ,is an authentic record of my own work carried out under the supervision of *Lecturer Suman Bhullar* and refers other researcher's works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted anywhere for the award of any other degree.

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This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

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ABSTRACT

Transfer of electric energy from the source of generation to the customer via the transmission and distribution networks is accompanied by losses. The majority of these losses occur on the distribution system. It is widely recognized that placement of shunt capacitors on the distribution system can lead to a reduction in power losses.

Reduction of I^2R loss in distribution systems is very essential to improve the overall efficiency of power delivery. The I^2R loss can be separated into two parts based on the active and reactive components of branch currents. This thesis work presents a method of minimizing the loss associated with the reactive component of branch currents by placing shunt capacitors. This method first determines a sequence of nodes to be compensated by capacitors. The size of the optimal capacitor at the compensated nodes is then determined by optimizing the loss saving equation with respect to the capacitor currents. The performance of the proposed method was investigated on distribution systems consisting of 28 buses and it was found that a significant loss saving can be achieved by placing optimal capacitors in the system.

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Chapter #1

Introduction

1.1 Electrical Power System

Electrical power is transmitted by high voltage transmission lines from sending end substation to receiving end substation. At the receiving end substation the voltage is stepped down to a lower value (say 66kV or 33kV or 11kV). The secondary transmission system transfer power from this receiving end substation to secondary substation. A secondary substation consists of two or more step down power transformers together with voltage regulating equipments, buses and switchgear. At the secondary substation voltage is stepped down to 11kV. The portion of the power network between a secondary substation and consumers is known as distribution system. The distribution system can be classified into primary and secondary system. Some large consumers are given high voltage supply from the receiving end substations or secondary substation.

The area served by a secondary substation can be subdivided into a number of sub- areas. Each sub area has its primary and secondary distribution system. The primary distribution system consists of main feeders and laterals. The main feeder runs from the low voltage bus of the secondary substation and acts as the main source of supply to sub-feeders, laterals or direct connected distribution transformers. The lateral is supplied by the main feeder and extends through the load area with connection to distribution transformers. The distribution transformers are located at convenient places in the load area. They may be located in specially constructed enclosures or may be pole mounted. The distribution transformers for a large multi storied building may be located within the building itself. At the distribution transformer the voltage is stepped down to 400V and power is fed into the secondary distribution systems. The secondary distribution system consists of distributors which are laid along the road sides. The service connections to consumers are tapped off from the distributors. The main feeders, laterals and distributors may consist of overhead lines or cables or both. The distributors are 3 phase, 4 wire circuits, the neutral wire being necessary to supply the single phase loads. Most of the residential and commercial consumers are given single phase supply. Some large residential and commercial consumers get 3 phase supply. The service connections of consumers are known as service mains.

The consumer receives power from the distribution system. The main part of distribution system includes:

1. Receiving substation
2. Sub- transmission lines
3. Distribution substation located nearer to the load centre
4. Secondary circuits on the LV side of the distribution transformer.
5. Service mains

Unlike main EHV-AC transmission systems, the distribution systems have several service lines, several distribution transformers and associated primary and secondary circuitry and one or two receiving substations. Unlike transmission systems distribution systems are more complicated and have to face more problems like voltage drop during peak load time and voltage rise during off peak load. In addition to above problems distribution transformer is overloaded during most period.

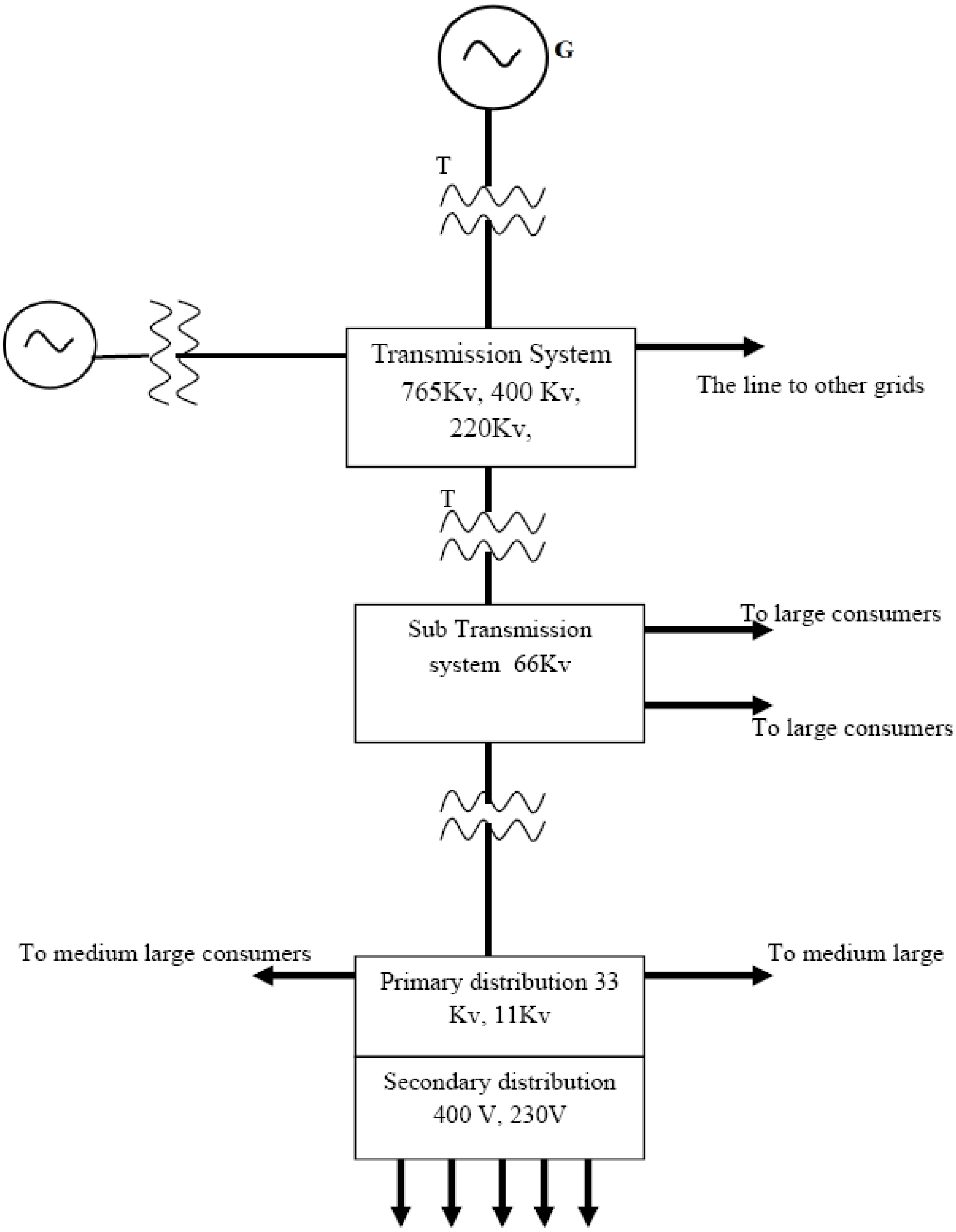


Figure 1.1 Single Line Power System Network

1.2 Distribution System

The part of power system which distributes electric power for local use is known as distribution system.

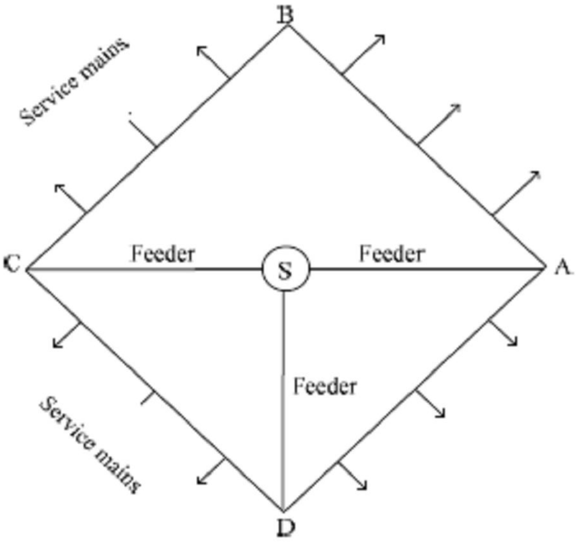


Figure 1.2 Single line diagram of a typical low tension distribution system.

In general, the distribution system is the electrical system between the substation fed by the transmission system and the consumer’s meters. It generally consists of feeders, distributors and the service mains. Figure 1.2 shows the single line diagram of a typical low tension distribution system.

(i) *Feeders:* A feeder is a conductor, which connects the sub-station (or localized generating station) to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that the current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

(ii) *Distributor:* A distributor is a conductor from which tappings are taken for supply to the consumers. In Figure1.2, AB, BC, CD, and DA are the distributors. The current through a distributor is not constant because tapping are taken at various places along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 10% of rated value at the consumer’s terminals.

(iii) *Service mains*: A service mains is generally a small cable which connects the distributor to the consumer terminals.

1.3 Objectives of Distribution Systems

1. Planning, modernization and automation.
2. To provide service connection to various urban, rural and industrial consumer in the allocated area.
3. Maximum security of supply and minimum duration of interruption.
4. Safety of consumers, utility personnel
5. To provide electricity of accepted quality in terms of:

a. Balanced three phase supply.
b. Good power factor.
c. Voltage flicker within permissible limits.
d. Less voltage dips.
e. Minimum interruption in power supply.

1.4 Classification of Distribution Systems

A distribution system may be classified according to:

(i) Nature of current: According to nature of current, distribution system may be classified as (a) d.c. distribution system and (b) a.c. distribution system. Now-a-days a.c. system is universally adopted for distribution of electric power as it is simpler and more economical than direct current method.

(ii) Type of construction: According to type of construction, distribution system may be classified as (a) overhead system and (b) underground system. The overhead system is generally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the underground system is used at places where overhead construction is impracticable or prohibited by the local laws.

(iii) Scheme of connection: According to scheme of connection, the distribution system may be classified as (a) radial system, (b) ring main system and (c) inter-connected system. Each scheme has its own advantages and disadvantages.

1.5 Connection Scheme of Distribution System

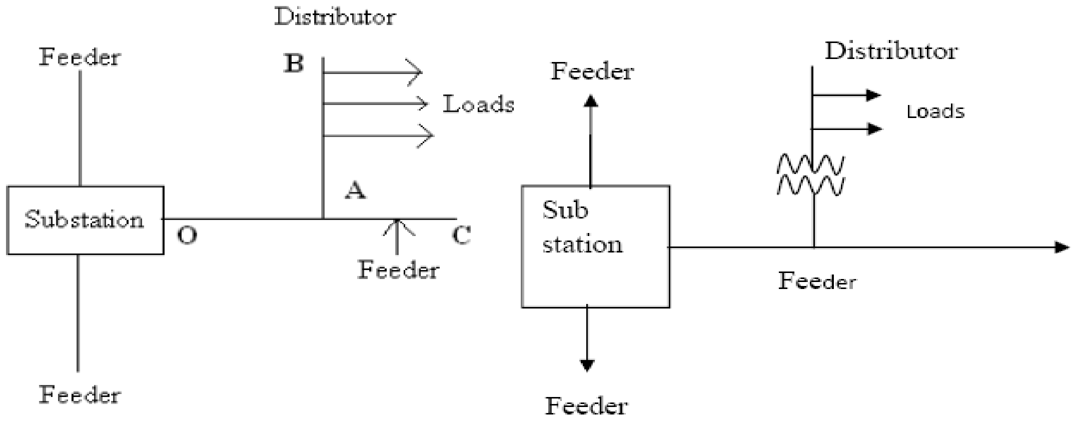
All distribution of electrical energy is done by constant voltage system. In practice, the following distribution circuits are generally used:

(i) Radial System: In this system, separate feeders radiate from a single sub-station and feed the distributors at one end only. Figure 1.3 (a) shows a single line diagram of a radial system for DC system. Distribution where a feeder OC supplies a distributor AB at point A. Obviously, the distributors are fed at one point only i.e. point A in this case. Figure 1.3 (b) shows a single line diagram of radial system for AC distribution. The radial system is employed only when power is generated at low voltage and the sub-station is located at the centre of load. This is the simplest distribution circuit and has the lowest initial cost. However, it suffers from the following drawbacks:

(a) The end of the distributor nearest to the feeding point will be heavily loaded.

(b) The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the sub-station.

(c) The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes. Due to these limitations, this system is used for short distances only.



(a) Distribution for DC Systems (b) Distribution for AC Systems

Figure1.3 Single line diagram of Radial System

(ii) Ring main system: In this system, the primaries of distribution transformers from a loop. The loop circuit starts from the sub-station bus-bars, makes a loop through the area to be served, and returns to the sub-station. Figure 1.4 shows the single line diagram of ring main system for AC. Distribution where sub-station supplies to the closed feeder LMNOPQRS of the feeder through distribution transformers.

The ring main system has the following advantages:

a. There are less voltage fluctuations at consumer's terminals

b. The system is very reliable as each distributor is fed via two feeders.

In the event of fault on any section of the feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the feeder SRQPONM.

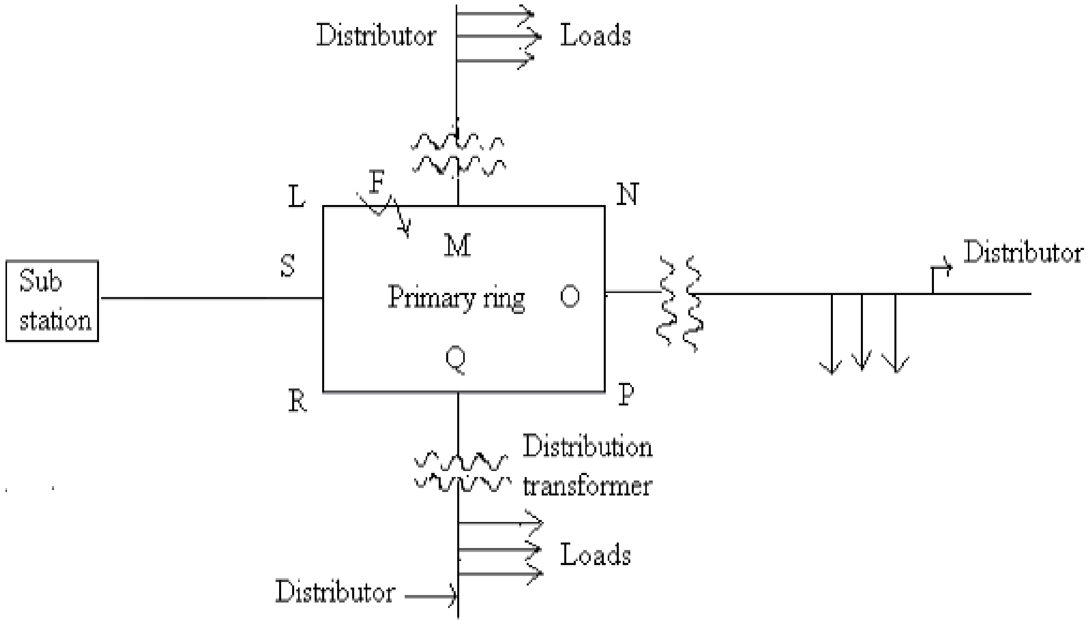


Figure 1.4 Ring Main Systems

(iii)Interconnected system: When the feeder ring is energized by two or more than two generating stations or sub stations, it is called inter-connected system. Figure 1.5 shows the single line diagram of interconnected system where the closed feeder ring ABCD is supplied by two sub-stations S1 and S2 at points D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers.

The interconnected system has the following advantages:

a. It increases the service reliability.

b. Any area fed from one generating station during peak load hours can be fed from the other generating station. This reduces reserve power capacity and increases efficiency of the system.

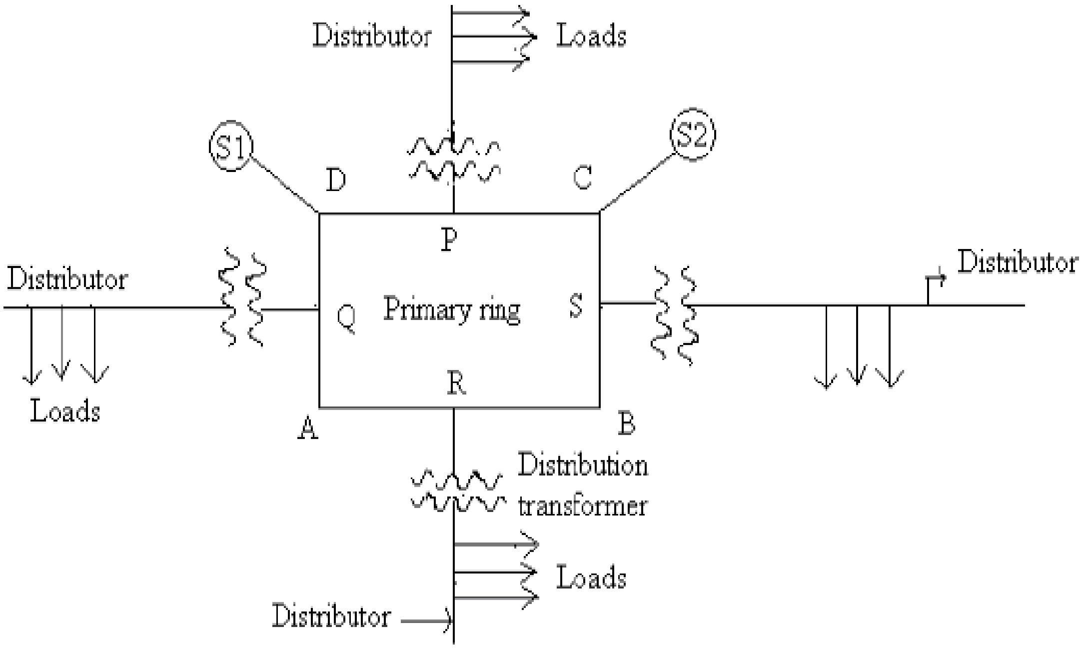


Figure 1.5 Interconnected Systems

1.6 Requirement of a Distribution System

A considerable amount of effort is necessary to maintain an electric power supply within the requirements of various types of consumers. Some of the requirements of a good distribution system are: proper voltage, availability of power on demand, and reliability.

(i) Proper Voltage: One important requirement of a distribution system is that voltage variations at consumers' terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumer's terminals are within permissible limits. The statutory limit of voltage variations is +/-10% of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 244 V while the lowest voltage of the consumer should not be less than 216 V.

(ii) Availability of Power Demand: Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers. This necessitates that operating staff must continuously study load patterns to predict in advance those major load changes that follow the known schedules.

(iii) Reliability: Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This calls for reliable service. Unfortunately electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by (a) inter-connected system, (b) reliable automatic control system and (c) providing additional reserve facilities.

1.7 Need of capacitor

Most loads on an electrical distribution system can be placed in one of three categories: Resistive, Inductive or Capacitive. The most common of these three on modern systems is the inductive load. Typical examples include transformers, fluorescent lighting and AC induction motors. All inductive loads require two kinds of power to function properly:

- Active power (kW) - actually performs the work
- Reactive Power (kvar) - sustains the electro-magnetic field

As an example with an unloaded AC motor, one might expect the no-load current to drop near zero. In truth, however, the no-load current will generally show a value between 25% and 30% of full load current. This is because of the continuous demand for magnetizing current by any induction load.

1.8 How to produce reactive power

In electrical terms, capacitance is also considered as a “reactive power” component but in fact its characteristic in an electric circuit is to neutralize or compensate for the inductive reactive power. Thus we have an item of electrical equipment which can be used to effectively offset a proportion of the reactive power drawn from the supply.

Without capacitors connected the motors draw active and reactive power and the transformer feeding the installation is fully loaded. With appropriately rated capacitors connected in parallel with the motors the reactive power drawn from the supply is neutralized and the transformer only feeds active power. This means that the reactive power supplied by the Electricity Board is reduced and reactive power charges eliminated. The power capacitor is however a static device (no moving parts) so maintenance is minimal. They are also electrically very efficient so their use on a network makes no significant increase in the active power requirement from the supply authority.

1.9 Considerations When Applying Capacitors on Distribution Systems

1.9.1 Introduction

The capacitor is a source of reactive power. Applying shunt capacitors to primary distribution feeders provides an alternate source of reactive power to reduce the level of reactive power provided by the supply. There was a time when the application of capacitors on a wide scale basis was unusual because losses didn’t cost that much and regulators handled the voltage drop quite well.

Things have changed. Losses are a major concern. . The value of capacitors has shifted from voltage concerns in the fist half of the 20th century, to loss reduction during the oil crisis, and now to equipment utilization considerations. Voltage quality, due to more sensitive loads, is an issue. Finally, in today’s world of cutting costs, capacitors are seen as the cheap way to reduce losses and get more watts out of what’s already there.

1.9.2 Benefits of Capacitors

The proper application of capacitors serves to reduce the system current and raise the system voltage. This accomplishes following benefits:

1. Reduces loading of thermally limited equipment.
2. Reduces system voltage drop
3. Reduces system losses.
4. Improvement of stability.

The application of capacitors benefits the entire system and the value of these benefits for the entire system should be considered when considering how many capacitors should be installed. It should not be overlooked that kilovars flowing through the system cause reactive as well as real losses. This means that when a certain quantity of kilovars is required at the load, more than that will be required at the source of the kvars.

1.9.3 Typical Placement Studies

Most utilities try to apply capacitors “optimally”. Years ago, when voltage levels were low and wire sizes were smaller, an “optimal placement study” might mean placement of the capacitor banks to obtain a reasonable voltage profile. Today, optimum placement normally means place to minimize losses at the lowest cost.

Placement Studies are normally performed in one of two ways:

- Place capacitors until optimum power factor is reached (point where the cost of adding bank exceeds value of losses reduction and equipment utilization benefits).
- Place capacitors until a predetermined power factor is met. This number is sometimes quite arbitrary.

Optimal placement would be easy if the load didn’t change. The problem with placement studies is that loads change during the day, week, month and most schemes have to deal with all these changes as best they can. The var needs change dramatically over a fairly brief period of time. The challenge to the distribution engineer is to pick the correct size of the banks to be used, the placement of these banks and minimize the cost.

1.9.4 Considerations in Locating Capacitors

Shunt capacitors provide reactive power locally, resulting in reduced maximum kVA demand, improved voltage profile, reduced line/feeder losses, and decreased payments for the energy. Maximum benefit can be obtained by installing the shunt capacitors at the load. This is not always practical due to the size of the load, distribution of the load, and voltage level.

Switched capacitors provide additional flexibility to control system voltage, power factor, and losses. Switched capacitors are usually applied with some type of automatic switching control.

Using shunt capacitors to supply the leading currents required by the load relieves the generator from supplying the part of the inductive current. The system benefits due to the application of shunt capacitors include:

- Reactive power support.
- Voltage profile improvements.
- Line and transformer loss reductions.
- Release of power system capacity.
- Savings due to increased energy loss.

1.10 Literature Survey

A lot of literature is available on this topic. The solution techniques for the capacitor allocation problem can be classified into four categories: analytical, numerical programming, heuristic, and artificial intelligence-based (AI-based). Here is the literature survey that is relevant with the work carried out for this thesis work.

Neagle and Samson have presented in their paper titled ‘Loss Reduction from Capacitors Installed on Primary Feeders’ assume the load is uniformly distributed along the feeder. Where two banks are to be installed, they consider equally sized banks or one bank to be twice the size of the other. They consider only peak kilowatt loss savings with fixed capacitors and ignore the cost of capacitors. For installation of three or four banks, equally sized capacitors were assumed. [1]

Cook in paper ‘Analysis of Capacitor Application as Affected by load Cycle’ also addresses application of fixed capacitors to a uniformly distributed load. However, instead of considering reduction of peak power losses, savings are based on energy loss reduction considering a time-varying load [2]. This analysis is extended in Cook ‘Optimizing the Application of Shunt Capacitors for Reactive-Volt-Ampere Control and Loss Reduction’ to include switched capacitors. Savings are calculated based on reduction of both peak power losses and energy losses [3]. Cook in paper ‘Calculating Loss Reduction Afforded by Shunt Capacitor Application’ describes an incorrect method for calculating loss reduction often used in the literature. The correct method is also presented [4].

Chang in his paper ‘Optimum Allocation of Shunt Capacitors and Voltage Regulators on Primary Feeders’ assumes a feeder with a uniform load and a concentrated end load. Accounting for both peak power losses and energy losses, he determines the optimal location of a fixed capacitor and the resulting savings, given the capacitor size. The optimal solution is determined by considering each of the available capacitor sizes [5-6].

Duran in his work ‘Optimum number, location and size of shunt capacitors in radial distribution feeders: A dynamic programming approach’ proposes a dynamic programming approach to find the number, locations, and sizes of fixed capacitor banks on a feeder with discrete loads. Algorithms are presented for the special cases of no capacitor cost, capacitor cost proportional to installed capacity, and cost proportional to installed capacity plus a fixed cost per capacitor bank [7].

Grainger and Lee in their work ‘Optimum size and location of shunt capacitors for reduction of losses on distribution feeders’ propose a methodology which considers non-uniform feeders and non-uniform loads. It transforms a feeder with different wire sizes into an equivalent uniform feeder. It also accounts for non-uniform reactive load distribution by introducing the concept of the normalized reactive current distribution function. The objective function used consists of the peak power loss reduction, energy loss reduction, and a linear cost of capacitors. Constant voltage is assumed and only fixed capacitors are considered [8].

Salama M.M.A et. al. in their work ‘Control of Reactive Power in Distribution Systems with an End-load and Fixed Load Condition’ assume a fixed load condition and a uniform feeder. A concentrated load at the end of the feeder is dealt with separately.

They transform a non-uniform feeder into an equivalent uniform feeder using the “base resistance” technique The objective function does not include energy loss reduction and a linear capacitor cost is assumed [9].

Baran and Wu in their work ‘Optimal capacitor placement on radial distribution systems’ formulate the problem as a nonlinear, mixed integer programming problem. The solution method is decomposed into levels. The top level, called the “master problem”, is an integer programming problem which determines the number and location of capacitors. The bottom level, called the “slave problem”, is used to determine the sizes of the capacitors. The slave problem is further decomposed into smaller problems referred to as base problems. These base problems are solved by an algorithm developed for a special capacitor placement problem called the “sizing problem”. Capacitor cost is approximated by a linear function and a fixed charge. Finally, a heuristic procedure determines whether the capacitors are of the fixed or switched type [10].

Salama and Chikhani in their work ‘A Simplified Network Approach to the Var Control Problem for Radial Distribution Systems’ attempt to formulate the problem in a simple manner, without the use of a sophisticated optimization technique. Laterals are handled by first treating each lateral as a separate feeder. The shunt capacitor location and size is then determined to reduce peak power and energy losses. If the savings for the lateral is zero or negative, no capacitor is placed on that lateral. After determining whether capacitors should be placed on each lateral, the optimum size and location for all the capacitors is determined [12].

Abdel-Salam et al. in their paper ‘A new technique for loss reduction using compensating capacitors applied to distribution systems with varying load condition’ uses heuristic technique for reactive loss reduction in distribution network The method allocates capacitors to certain nodes (sensitive nodes) which are selected by first identifying the branch which has the largest losses due to reactive power. The capacitor rating is determined by differentiating the system losses with respect to the load connected to that node [13].

Ng, Salama and Chikhani in their paper ‘Capacitor allocation by approximate reasoning: fuzzy capacitor placement’ applied FST to the capacitor placement problem by using fuzzy approximate reasoning. Voltage and power loss indices of the distribution system nodes are modelled by membership functions and a fuzzy expert system (FES) containing a set of heuristic rules performs the inferencing to determine a capacitor placement suitability index of each node. Capacitors are placed on the nodes with the highest suitability [14].

Baghzouz and Ertem in their paper ‘Shunt Capacitor Sizing for Radial Distribution Feeders with Distorted Substation voltages’ present an algorithm for optimizing shunt capacitor sizes on radial distribution lines with distorted voltages, such that the RMS voltages and their total harmonic distortion lie within prescribed limits. A heuristic algorithm based on the Method of Local Variations is employed. Since only a local optimal solution is guaranteed, it is suggested that several runs with different initial solutions be made to identify other local optimal solutions [17].

Rinker and Rembert in their work ‘Using the Reactive Current Profile of a Feeder to Determine Optimal Capacitor Placement’ claim that biggest problem in placing capacitors is a lack of data concerning the reactive current profile along the feeder. They address acquisition and treatment of data which is used to determine the size and placement of both fixed and switched capacitors [18].

Das in his paper ‘Optimal placement of capacitors in radial distribution system using a Fuzzy-GA method’ uses a fuzzy-genetic algorithm to solve the capacitor placement problem to improve the voltage profile and maximizes the net savings [19].

Shao et al. in paper ‘A Capacitor Placement Expert System’ propose an expert system solution approach that is based on a heuristic graph search method using an evaluation function [20].

Yang and Huang in ‘Solution to Capacitor Placement Problem in a Radial Distribution System Using Tabu Search Method’ use a Tabu Search in which the search is biased toward solutions with a better objective function, while special features of the algorithm prevent the solution from being trapped at **a** local optimum solution [21].

Based on the analysis of existing techniques, Goswami and Basu in ‘A new algorithm for the reconfiguration of distribution feeders for Loss minimization’ develops an algorithm which is based on the concept of optimum flow pattern and is determined by solving the KVL and KCL (Kirchhoff’s voltage and current laws) equations of the network. The optimum flow pattern of a single loop formed by closing a normally open switch is found out and the flow pattern is established in the radial network by opening a closed switch. This process is repeated till the minimum loss configuration is obtained [23].

Kaplan in paper ‘Optimization of Number, Location, Size Control Type, and Control Setting of Shunt Capacitors on Radial Distribution Feeders’ presents a heuristic approach which was claimed to make none of the simplifying assumption used in much of the earlier work. The approach first determines the “best” locations and types (fixed or switched) for the smallest available standard capacitor size. After placement of these initial capacitors, an attempt is made to improve savings by the addition of larger banks or by combination of smaller banks into larger units [25].

Chiang Et al. in paper ‘Optimal Capacitor Placements in Distribution Systems: Part I, Part II’ treat capacitor cost as a step-like function and capacitor sizes as discrete variables. The formulation allows the switched capacitors to be switched as a block or in several consecutive steps as load varies. The proposed solution method is based on the simulated annealing optimization technique [30].

1.11 Objectives of the Research

This thesis work presents a method of minimizing the loss associated with the reactive component of branch currents by placing shunt capacitors. The objectives are divided into the following:

- Find a sequence of buses to be compensated through finding the highest loss saving by a singly located capacitor.
- The optimal size of multiple capacitors is then determined by minimizing the loss saving equation with respect to the capacitor current.

1.12 Organization of Thesis Work

Chapter 1 has presented the introduction of distribution system, load modeling, size of feeder conductor, Considerations When Applying Capacitors on Distribution Systems, and literature survey, objectives of the research, scope of the research and organization of the research.

Chapter 2 presents an efficient algorithm to solve the radial distribution power flow problem in complex mode. . The linear equations are solved to determine the bus voltages and branch currents in terms of new variable as complex numbers.

Chapter 3 proposes a method of minimizing the loss associated with the reactive component of branch currents by placing optimal capacitors at proper locations.

Chapter-4 outlines the results. The results of the number of buses to be compensated after optimal sizing and location of capacitors are shown.

Chapter-5 presents the overall conclusions and future scope of research work.

Chapter #2

Power Flow Analysis

2.1 Introduction

Power flow analysis is concerned with describing the operating state of an entire power system, by which we mean a network of generators, transmission lines, and loads that could represent an area as small as a municipality or as large as several states. Given certain known quantities—typically, the amount of power generated and consumed at different locations— load flow analysis allows one to determine other quantities. The most important of these quantities are the voltages at locations throughout the transmission system, which, for alternating current (AC), consist of both a magnitude and a time element or phase angle. Once the voltages are known, the currents flowing through every transmission link can be easily calculated. Thus the name power flow or load flow, as it is often called in the industry: given the amount of power delivered and where it comes from, power flow analysis tells us how it flows to its destination.

This Chapter presents an efficient algorithm to solve the radial distribution power flow problem in complex mode. The relationship between the complex branch powers and complex bus powers is derived as a non singular square matrix known as element incidence matrix. The power flow equations are rewritten in terms of a new variable as linear recursive equations. The linear equations are solved to determine the bus voltages and branch currents in terms of new variable as complex numbers. The advantage of this algorithm is that it does not need any initial value and easier to develop the code since all the equations are expressed in matrix format. This method could be applied to distribution systems having voltage-controlled buses also.

2.2 Notations

N-no of buses

I_{ij}-Branch current flowing through element ij

I_j-Bus current of node j

V_j-Bus voltage of node j

S_{ij}-Complex power flowing from node i to node j

S_{ji}-Complex power flowing received at node j from node i

S_j-Specified Bus power at bus j

Z_{ij}-Impedance of element ij

PL_{ij}-Power loss of element ij

The distribution systems are characterized by their prevailing radial nature and high R/X ratio. This renders the load flow problem ill conditioned.

This chapter exploits the radial structure of the distribution network and the relationship between the bus powers and branch powers is expressed as a non-singular square matrix known as element incidence matrix. The chapter is organized into two sections. The first section derives the method for PQ buses and second section deals with treatment of voltage-controlled buses.

2.3 Distribution power flow

The power flow equations for a radial distribution system are derived as the relationship between the specified complex bus powers and the bus voltages. Let is the complex power S_{ij} flowing from bus 'i' to bus'j'.

$$S_{ij} = P_{ij} + iQ_{ij} = V_i(Vi^* - Vj^*)Y_{ij}^* \qquad (2.1)$$

The 'i'th bus powers are expressed as

$$P_i + Q_i = \sum_{i \in k(i)} P_{ij} + iQ_{ij} = \sum_{i \in k(i)} V_i (V_i^* - V_j^*) Y_{ij}^* \qquad (2.2)$$

Where k(i) is the set of nodes connected to node i, and Pi /Qi denote the real/reactive power at node i. The complex non linear equations (2.2) are to be solved to determine the bus voltages. The real and imaginary parts of the equations are separated and solved using numerical methods. [15]

2.4 Formulation of method for load buses

The basis for the proposed method is that an N bus radial distribution network has only N-1 lines (elements) and the branch currents (powers) can be expressed in terms of bus currents (powers). For an element ij connected between nodes 'i' and 'j' the bus current of node j can be expressed as a linear equation.

$$I_j = I_{ij} - \sum I_{ij(j)} \tag{2.3}$$

k(j) is the set of nodes connected to node j. For the slack bus the power is not specified so it is excluded and the relationship between bus currents and branch currents are derived as a non-singular square matrix.

$$I_{bus} = K.I_{branch} \tag{2.4}$$

$$I_{bus} = [I_{b2} I_{b3} ... I_{bn} \quad]^T \tag{2.5}$$

The matrix K is element incidence matrix. It is a non singular square matrix of order N. The elemental incidence matrix is constructed in a simple way same like bus incidence matrix. In this matrix K each row is describing the element incidences. The elements are numbered in conventional way i.e. the no of element 'ij' is j-1.

1. The diagonal elements of matrix K are one. The variable j is denoting the element number.

K(j, j) =1

2. For each 'j'th element let m (j) is the set of element numbers connected at its receiving end.

K(j, m(j)) = -1

3. All the remaining elements are zero. It can be observed that all the elements of matrix K below the main diagonal are zero.

$$I_{branch} = K^{-1} I_{bus} \tag{2.6}$$

The relationship between the branch currents and bus currents can be extended to complex branch powers and bus powers. The sending end power and the receiving end powers are not same due to transmission loss. The transmission loss is included as the difference between the sending end/receiving end powers.

The relationship between branch powers and bus powers is established in same way of bus/branch currents. Multiplying both sides by element incidence matrix K

$$S_{bus} = K[S_{branch}^{sending} - TL_{branch}] \tag{2.7}$$

$$S_{branch} = K^{-1}.S_{bus} + TL_{branch} \tag{2.8}$$

The power flow equations are complex quadratic equations .A new variable Rij is introduced for each element ‘ij’ and the equations becomes recursively linear.

$$R_{ij} = V_i(V_i^* - V_j^*) \tag{2.9}$$

The branch power of 'ij' th element is expressed in terms of R_{ij}

$$S_{ij} = P_{ij} + iQ_{ij} = R_{ij}Y_{ij}^* \tag{2.10}$$

$$R_{ij} = S_{ij}Z_{ij}^* \tag{2.11}$$

The above method is summarized as follows:

1. For the first iteration transmission losses are initialized as zero for each element.
2. From the bus powers specified the branch powers are determined as per equation (2.7 & 2.8).
3. The variable Rij. is determined for each element using equation (2.11).
4. The bus voltage, branch current and bus current are determined from R_{ij}.

$$V_j = V_i - \frac{R_{ij}^*}{V_i^*} \tag{2.12}$$

$$I_{ij} = \frac{R_{ij}^*}{V_I^*}Y_{ij} \tag{2.13}$$

5. The bus currents are determined from (2.2) and bus powers are calculated. Since the transmission losses are neglected in the first iteration there will be mismatch between the specified powers and calculated powers. The mismatch is a part of the transmission loss. $PL_{ij}r$ is the transmission loss part for ‘ij’th element for ‘r’th iteration. Transmission loss of each element is the summation of the transmission loss portions of all previous iterations.

$$PL_{ij}^{r} = S_{j}^{spec} -{}^{r-1}V_{j}^{r-1}I_{j}^{*} \tag{2.14}$$

It can be concluded that the power flow solution always exists for a distribution system irrespective of the R/X ratio if it is having connectivity from the source (slack bus) to all the nodes. The limitations of the algorithm are being investigated in view of voltage stability limit. For system having less transmission loss the algorithm will perform faster. The convergence criteria is that the ‘r’th iteration of the transmission loss part of each element should be less than the tolerance value.

Chapter #3

Capacitor Placement for Loss Reduction

3.1 Introduction

Capacitor banks are added to radial distribution systems for power factor correction, loss reduction, voltage profile improvement and in a more limited way, circuit capacity increases. With these various objectives in mind, and subject to operating constraints, optimal capacitor placement aims to determine capacitor types, sizes, locations and control schemes.

A distribution system connects consumers to the high-voltage transmission system. Because of lower voltage, and hence higher current, the I^2R loss in a distribution system is significantly high compared to that in a high-voltage transmission 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 methodology was developed only for radial networks because most of systems are deployed in a radial basis due to their simple operation and low investment costs.

In general, a distribution system is fed at only one point and the structure of the network is mainly radial. For such a system all active power demands and losses must be supplied by the source at the root bus. However, addition of shunt capacitors can generate the reactive power and therefore it is not necessary to supply all reactive power demands and losses by the source. Thus, there is a provision to minimize the loss associated with the reactive power flow through the branches.

As already stated that the use of capacitors in power systems has many other well-known benefits which include improvement of the system power factor, improvement of the system voltage profile and reduction of losses due to the compensation of the reactive component of the power flow. If all the nodes have capacitors giving the same reactive power as the loads at these nodes, it will be expected that almost no reactive power will flow on the distribution feeders, and the losses due to reactive power will be almost zero. However, although this type of compensation of the reactive power gives minimum system losses, it is not practical because the cost of the compensating capacitors may exceed the benefits gained from reducing the energy losses. [10]

The capacitor placement problem is a well research topic that has been addressed by many authors in the past. All approaches differ from each other by way of their problem formulation and problem solution methods employed.

This chapter provides a method of minimizing the loss associated with the reactive component of branch currents by placing optimal capacitors at proper locations. The method first finds the location of the capacitor in a sequential manner. Once the capacitor locations are identified, the optimal capacitor size at each selected location is determined through optimizing the loss saving equation. The method was tested on two different distribution systems and very encouraging results were found.

3.2 Background

The total I^2R loss (P_{Lt}) in a distribution system having n number of branches is given by

$$P_{Lt} = \sum_{i=1}^{n} I_i^2 R_i \tag{3.1}$$

Here I_i and R_i are the current magnitude and resistance, respectively, of the i^th^ branch. The branch current can be obtained from the load flow solution. The branch current has two components; active (I_a) and reactive (I_r). The loss associated with the active and reactive components of branch currents can be written as

$$P_{La} = \sum_{i=1}^{n} I_{ai}^2 R_i \tag{3.2}$$

$$P_{Lr} = \sum_{i=1}^{n} I_{ri}^2 R_i \tag{3.3}$$

Reducing the inductive reactive portion of the line loading, would reduce the reactive losses. With a highly inductive load we want to reduce the level of inductive load current. This is done by the addition of shunt capacitors.

Note that for a given configuration of a single-source radial network, the active current component I_a depends only on the circuit load. The loss $\boldsymbol{P_{La}}$, associated with the active component of branch currents cannot be minimized because all active power must be supplied by the source at the root bus. However, the loss $\boldsymbol{P_{Lr}}$ associated with the reactive component of branch currents can be minimized by supplying part of the reactive power demands locally. The purpose is to locate these capacitors in the points where they can improve best the technical circuit performance.

3.3 Proposed method

The method used here first identifies a sequence of nodes to be compensated. The sequence is determined by repetitive applications of loss minimization technique by a singly located capacitor. Once the sequence of nodes to be compensated is identified, the corresponding optimal capacitor size at the compensated nodes can be determined simultaneously by minimizing the loss saving equation with respect to the capacitor currents. The procedures of loss minimization by placing a single and multiple capacitors are described in the following sections.

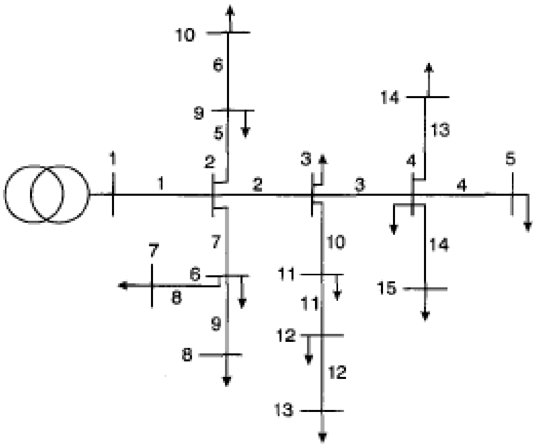


Figure 3.1 Single-line diagram of the 15-bus system

3.4 Loss minimization by a singly located capacitor

Consider a single source radial distribution system with n branches. Let a capacitor C be placed at bus m and α be a set of branches connected between the source and capacitor buses. In Fig. 1, if the capacitor is placed at bus 12 (m = 12), the set α consists of branches 1, 2, 10 and 11. The capacitor draws a reactive current I_c and for a radial network it changes only the reactive component of current of branch set α. The current of other branches ($\notin \alpha$) is unaffected by the capacitor. Thus the new reactive current I_{ri}^{new} of the i^{th} branch is given by [16]

$$I_{ri}^{new} = I_{ri} + D_i I_c \tag{3.4}$$

Where,

$D_i = 1$; if branch $i \in \alpha$

$= 0$; otherwise

Here I_{ri} is the reactive current of the i^{th} branch in the original system obtained from the load flow solution. The loss P_{Lr}^{com} associated with the reactive component of branch currents in the compensated system (when the capacitor is connected) can be written as

$$P_{Lr}^{com} = \sum_{i=1}^{n} (I_{ri} + D_i I_c)^2 R_i \tag{3.5}$$

The loss saving S is the difference between eqns. 3 and 5 and is given by

$$S = P_{Lr} - P_{Lr}^{com}$$

$$S = -\sum_{i=1}^{n} (2 D_i I_{ri} I_c + D_i I_c^2) R_i \tag{3.6}$$

The capacitor current I_c that provides the maximum loss saving can be obtained from

$$\frac{\partial S}{\partial I_c} = -2 \sum_{i=1}^{n} (D_i I_{ri} + D_i I_c) R_i = 0 \tag{3.7}$$

Thus the capacitor current for the maximum loss saving is

$$I_c = -\frac{\sum_{i=1}^{n} D_i I_{ri} R_i}{\sum_{i=1}^{n} D_i R_i} = -\frac{\sum_{i \in \alpha} I_{ri} R_i}{\sum_{i \in \alpha} R_i} \tag{3.8}$$

The corresponding capacitor size is

$$Q_c = V_m I_c \tag{3.9}$$

Here V_m is the voltage magnitude of the capacitor bus m. The above process can be repeated for all buses to get the highest possible loss saving for a singly located capacitor. When the candidate bus is identified and compensated, the above technique can also be used to identify the next and subsequent buses to be compensated for loss reduction. When the sensitive node (where the capacitor is installed) is determined, the nearest available standard MVAR rating or multiple units of the capacitor is chosen. This procedure is repeated until the system losses decrease to almost a steady value, and connecting more capacitors will have only a marginal reduction on the system losses. If there are already capacitors in the distribution power system, they are taken into account in the input data. Using the proposed method, it suffices to connect capacitors only to the sensitive nodes which are few in number to attain very large reduction in the losses arising from the reactive power component.

This will provide only the locations where the capacitors are to be placed. The capacitor size obtained from equation 3.9 is a local optimum value and may not be used when more than one capacitor is placed in the system. The size of the optimal capacitors for multiple locations is to be determined simultaneously, and the procedure for finding the optimal sizes is described in the following section.

3.5 Loss minimization by multiple capacitors

The concept of loss minimization by a singly located capacitor can be extended for multiple capacitors. Let us consider the following:

K=number of capacitor buses

I_c= k dimensional vector consisting of capacitor currents

$\alpha_{j=}$set of branches from the source bus to the jth capacitor bus (j=1, 2, ….., k)

D=a matrix of dimension $n \times k$

The elements of D are considered as

D_{ij} = 1; if branch $i \in \alpha$

= 0; otherwise

In fig. 1 if three capacitors (k=3) are placed at buses 10, 12 and 14, the branch set α s and the matrix DT can be written as

α 1= [1, 5, 6]; α 2= [1, 2, 10, 11]; α 3= [1, 2, 3, 13];

$$\boldsymbol{D}^T = \begin{vmatrix} 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{vmatrix}$$

When the capacitors are placed in the system, the new reactive component of branch currents is given by

$$[I_r^{new}] = [I_r] + [D][I_c] \tag{3.10}$$

The loss $P_{Lr}{}^{com}$ associated with the new reactive currents in the compensated system is

$$P_{Lr}^{com} = \sum_{i=1}^{n} (I_{ri} + \sum_{j=1}^{k} D_{ij} I_{cj})^2 R_i \tag{3.11}$$

The loss saving S obtained by placing the capacitors is the difference between eqns. 3 and 11 and is given by

$$S = -\sum_{i=1}^{n} [(2I_{ri} \sum_{j=1}^{k} D_{ij} I_{cj} + (\sum_{j=1}^{k} D_{ij} I_{cj})^2]R_i \tag{3.12}$$

The optimal capacitor currents for the maximum loss saving can be obtained by solving the following equations:

$$\begin{aligned} &\frac{\partial S}{\partial I_{c1}} = 0 \\ &\frac{\partial S}{\partial I_{c2}} = 0 \\ &\cdots \quad \cdots \\ &\cdots \quad \cdots \\ &\frac{\partial S}{\partial I_{ck}} = 0 \end{aligned} \tag{3.13}$$

After some mathematical manipulations, eqn. 13 can be expressed by a set of linear algebraic equations as follows:

$$[A][I_c]=[B] \tag{3.14}$$

Where **A** is a *k* x *k* square matrix and **B** is a k-dimensional vector. The elements of **A** and **B** are given by

$$A_{jj} = \sum_{i \in \alpha j} R_i \tag{3.15}$$

$$A_{jm} = \sum_{i \in (\alpha j \cap \alpha m)} R_i \tag{3.16}$$

$$B_j = \sum_{i \in \alpha j} I_{ri} R_i \tag{3.17}$$

Only the branch resistances and reactive currents in the original system are required to find the elements of A and B**.** The capacitor currents for the highest loss saving can be obtained from eqn. 14.

$$[I_c]=[A]^{-1}[B] \tag{3.18}$$

Once the capacitor currents are known, the optimal capacitor sizes can be written as

$$[Q_c]=[V_c][I_c] \tag{3.19}$$

Here V_c is the voltage magnitude vector of capacitor buses. The saving in the compensated system can be estimated from eqn. 3.12 using the value of I_C given by eqn. 3.18.

3.6 Algorithm

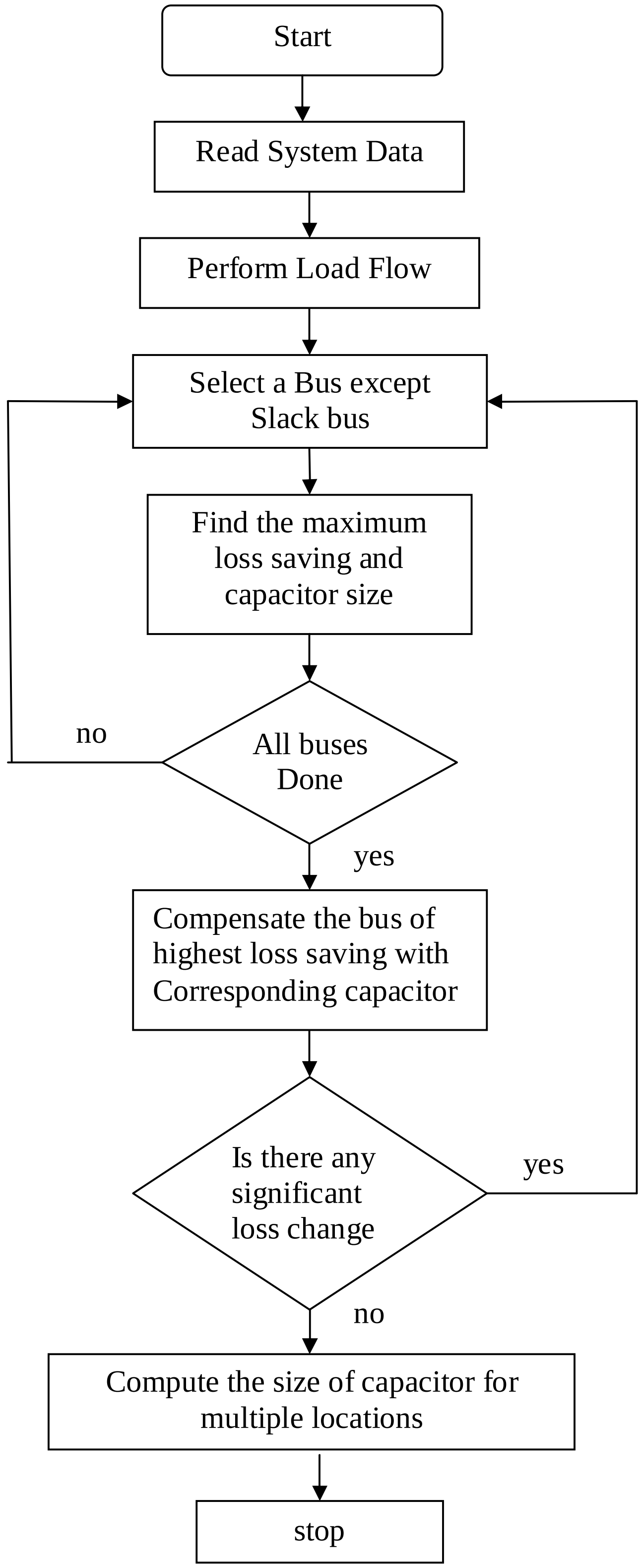
The computational steps involved in finding the optimal capacitor size and location to minimize the loss in a radial distribution system are summarized in following:

1. Run the load flow program and obtain the branch currents. Select a bus and find the maximum loss saving and the corresponding capacitor size from eqns. 3.6 and 3.9 respectively. Repeat this step for all buses in the system, except the source bus. Identify the bus that provides the highest loss saving.
2. Compensate the bus to get the highest loss saving with the corresponding capacitor found from eqn. 3.9.
3. Repeat steps 1 and 2 to get the next capacitor bus and hence the sequence of buses to be compensated until it is found that no significant loss saving can be achieved by further capacitor placement.
4. Once the sequence of buses is known, determine the optimal capacitor sizes and the corresponding loss saving from eqns. 3.9 and 3.12, respectively.

Note that the system load is time-variant and load duration curve of the system can be approximated by a piecewise linear function during which the load level is assumed to be constant. The above algorithm provides the optimal capacitor sizes and locations for a given load level. Determination of overall loss saving for the entire period of the load duration curve requires the application of the above algorithm to each load level. This may suggest different capacitor sizes and, in some cases, at different locations. The problems of different capacitor size and location can be solved by using a combination of fixed and switched capacitors.

The above algorithm can be represented in the form of a flowchart as shown in fig. 3.2.

Figure 3.2 Flowchart



Chapter #4

Results

4.1 Results based on power flow analysis

As already stated that before solving the capacitor placement problem an efficient algorithm is required for finding the node voltages and branch currents at each node of the distribution system as branch currents are required to calculate the real and reactive power losses and the voltages are used in finding the size of capacitors needed to be installed. The algorithm given in chapter 3.2 is implemented on 28 bus system with a total load of (761.04 +j776.50) kVA. The single-line diagram of the 11 kV, 28-bus system is shown in Fig. 4.1. The data of the system are obtained from [15]. The results are given in Table 4.1. This algorithm is coded in MATLAB 7.01 and implemented on Pentium IV 800 MHZ systems. It is performing well in terms of speed and accuracy. The maximum time required is only .016 seconds for distribution system of 28 buses. The advantage of this method is that it does not require a flat start.

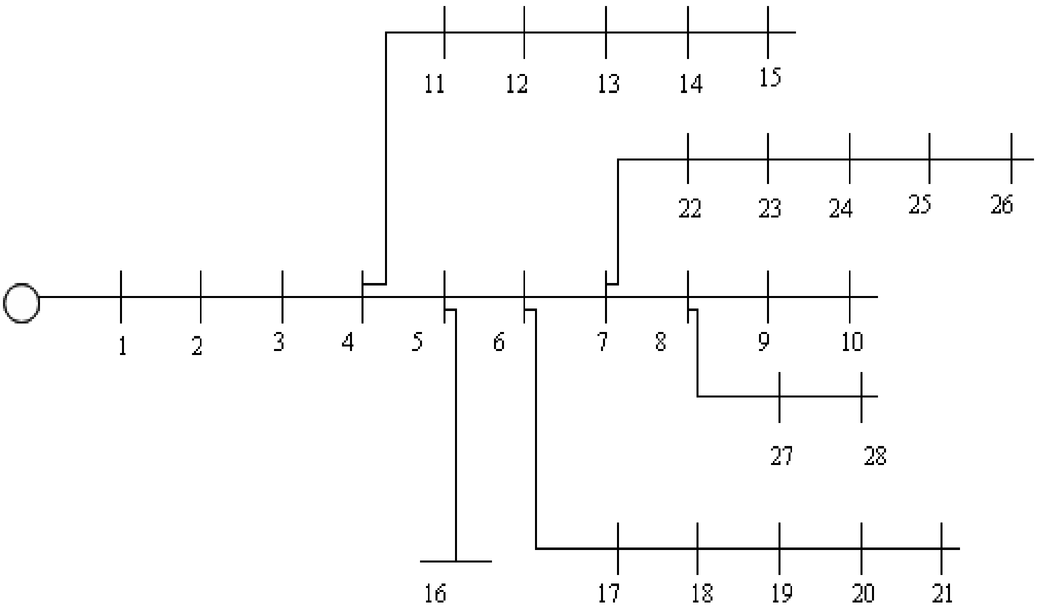


Figure 4.1 Single line diagram of the 28-bus system

Table 4.1-Power flow Solution of a 28 bus system

Node	Voltage Magnitude	Active Power Loss	Reactive Power Loss
1	11.0000	0.00	0.00
2	10.8484	8.2423	8.0981
3	10.6310	11.3209	11.0986
4	10.4759	7.9327	7.7719
5	10.3200	5.6695	5.5259
6	10.2042	3.8132	3.7101
7	10.1033	2.3175	2.2501
8	10.0763	0.2645	0.2575
9	10.0732	0.0063	0.0061
10	10.0705	0.0028	0.0027
11	10.4106	1.0035	0.9932
12	10.3912	0.1960	0.1937
13	10.3795	0.0827	0.0817
14	10.3765	0.0128	0.0126
15	10.3738	0.0078	0.0077
16	10.3076	0.0371	0.0367
17	10.1843	0.1739	0.1697
18	10.1736	0.0869	0.0848
19	10.1552	0.1344	0.1310
20	10.1458	0.0403	0.0393
21	10.1388	0.0085	0.0082
22	10.0715	0.4018	0.3886
23	10.0546	0.1622	0.1567
24	10.0417	0.1140	0.1101
25	10.0388	0.0111	0.0107
26	10.0370	0.0057	0.0055
27	10.0709	0.0336	0.0327
28	10.0695	0.0042	0.0041

4.2 Results Based on Capacitor Placement

The method of loss reduction by capacitor placement was tested on distribution systems consisting of 28 buses. The results obtained in these systems are briefly described in the following Sections.

This 28-bus system has a total load of (761.04 +j776.50) kVA and I^2R loss of 83.27kW. The loss associated with the active and reactive components of branch currents found from the load flow solution is 42.09kW and 41.19kW, respectively. First the optimal size of a singly located capacitor and the corresponding loss saving are determined.A summary of results obtained by the above method in minimizing the loss due to I_r is given in Table 4.2.

Table 4.2 Estimated loss saving and capacitor size of the 28-bus system

No .of bus	Loss saving, kW	Capacitor Size, kvar
2	6.6926	892.299
3	15.8571	851.188
4	22.2737	829.459
5	26.1967	740.9
6	28.754	687.084
7	29.2428	614.053
8	27.586	560.8
9	26.1839	530.363
10	23.9422	483.419
11	17.9534	574.965
12	16.6024	511.031
13	15.4786	465.595
14	14.9269	446.309
15	14.2752	424.633
16	16.8342	534.57
17	25.8687	599.279
18	24.4686	557.513
19	22.2776	493.664
20	20.4243	446.278
21	19.834	352.297
22	27.3403	549.161
23	25.9821	510.007
24	24.9684	481.701
25	24.3016	467.199
26	23.7731	455.809
27	26.6266	537.225
28	26.0907	525.422

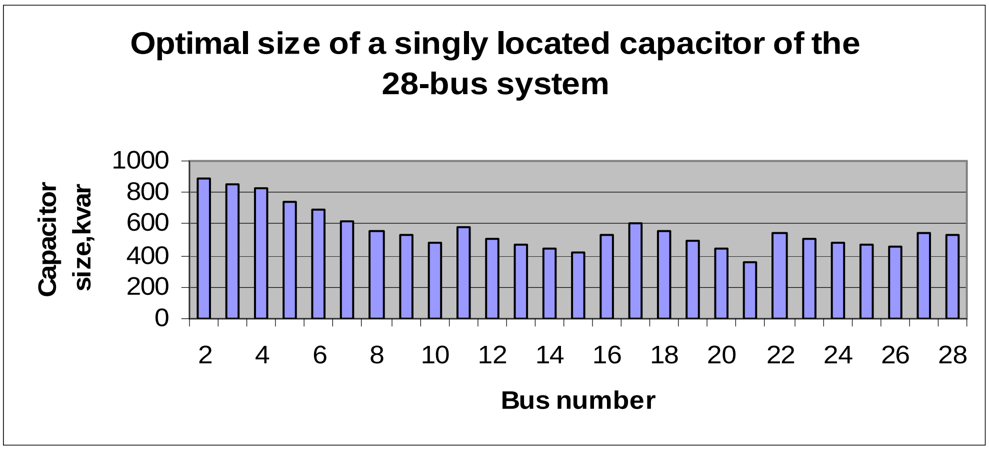


Figure 4.2 Optimal size of a singly located capacitor of the 28-bus system

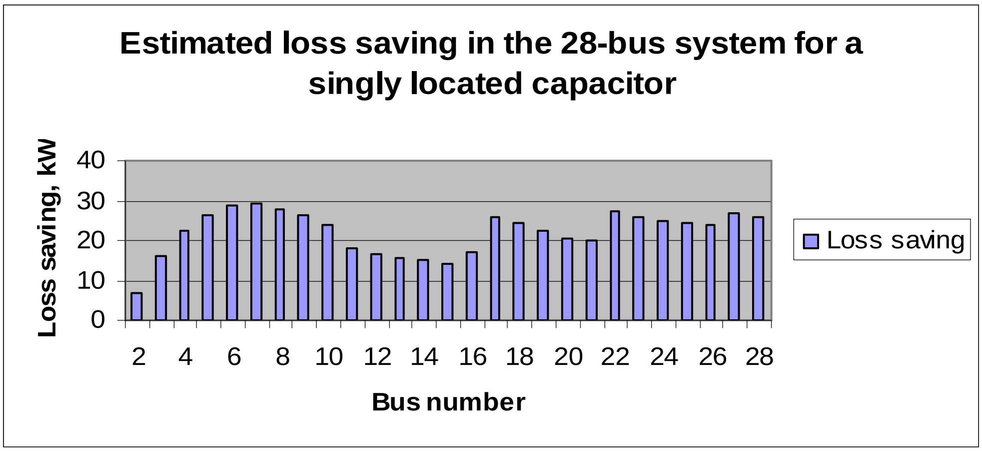


Figure 4.3 Estimated loss saving in the 28-bus system for a singly located Capacitor

It can be noticed in table that the highest loss saving of 29.25kW can be realized by placing a capacitor of 615kVAr at bus 7 as shown in fig. 4.2 and 4.3. When the above procedure is repeated, after placing 615kVAr of capacitor at bus 7, it was found that a second capacitor of 193kVAr at bus 11 would provide a further loss saving of 10.03kW. Thus the sequence of buses to be compensated is 7 and 11.

However, when both buses 7 and 11 are compensated, the technique described in Section 3.5 is to be used to find the optimal capacitor sizes and the corresponding loss saving.

Table 4.3-Summary of results of 28-bus system

	System loss					Compensation and saving	
System description	P_{La}	P_{Lr}	P_{Lt}	*	Bus	Capacitor size, kVAr	Saving kW
Original base system	42.09	41.19	83.28	1	7	615	29.24
615 kvar is placed at bus 7	41.04	11.95	52.99	1	11	194	10.03
615 kvar is placed at bus 7 193 kvar is placed at bus 11	40. 4	1.92	42.32	1	15	29	0 .62
Original base system	42.09	41.19	83.28	2	7 11	465 287	39.3
465 kvar is placed at bus 7 287 kvar is placed at bus 11	41.1	1.89	42.99				

* Number of buses to be compensated

This technique provides a total loss saving of 39.3kW by 752kVAr of capacitors (465kVAr at bus 7 and 287kVAr at bus 11). When the original base system is compensated with the above capacitors, the load flow results indicated that the system loss due to I_r is reduced from 41.19kW to 1.89kW. Thus a saving of 39.3kW has been achieved, which is exactly the same as estimated by above method. The shunt capacitors also improve the voltage profile, and due to the higher voltage the active component of branch current I, (and hence P_{La}) for the constant power load model, is also reduced slightly. The summary of all the results for capacitor placement is shown in Table 4.3.

Chapter #5

Conclusions and Future Scope of Work

5.1 Conclusions

A simple method of minimizing the loss associated with the reactive component of branch currents by placing capacitors in a radial distribution system has been proposed in this work. The method first finds a sequence of buses to be compensated through finding the highest loss saving by a singly located capacitor. The optimal size of multiple capacitors is then determined by minimizing the loss saving equation with respect to the capacitor currents. This involves the solution of a set of linear algebraic equations.

The proposed method was tested on distribution system 28 buses. In the 28-bus system it was found that by placing a total 1400 kvar optimal capacitors at two different locations (buses 7 and 11), the loss associated with the reactive branch currents can be reduced from 41.19kW to 1.92kW that is by more than 95%. In this system a saving of 5 kW per 100 kvar of capacitor bank can be realized.

5.2 Future Scope of work

- Practical implementation of the capacitor placement technique requires further cost-benefit analysis which in turns depends on the costs of capacitor bank and energy saving.
- The repeated simulation results could be used to develop a Model using any artificial intelligence technique which can accurately predict the location and size of capacitor for any load conditions which gives a great promise for practical implementation of the proposed technique.

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Appendix A

TableA.1-Line and load data of a 28 bus system [15]

Branch No.	starting bus	end bus	resistance	Reactance	Real power	Reactive power
1	1	2	1.197	0.82	35.28	36
2	2	3	1.796	1.231	14	14.28
3	3	4	1.306	0.896	35.28	36
4	4	5	1.851	1.268	14	14.28
5	5	6	1.524	1.044	35.28	36
6	6	7	1.905	1.305	35.28	36
7	7	8	1.197	0.82	35.28	36
8	8	9	0.653	0.447	14	14.28
9	9	10	1.143	0.783	14	14.28
10	4	11	2.823	1.172	56	57.13
11	11	12	1.184	0.491	35.28	36
12	12	13	1.002	0.416	35.28	36
13	13	14	0.455	0.189	14	14.28
14	14	15	0.546	0.277	35.28	36
15	5	16	2.55	1.058	35.28	36
16	6	17	1.366	0.567	8.96	9.14
17	17	18	0.819	0.34	8.96	9.14
18	18	19	1.548	0.642	35.28	36
19	19	20	1.366	0.567	35.28	36
20	20	21	3.552	1.474	14	14.28
21	7	22	1.548	0.642	35.28	36
22	22	23	1.092	0.453	8.96	9.14
23	23	24	0.91	0.378	56	57.13
24	24	25	0.455	0.189	8.96	9.14
25	25	26	0.364	0.151	35.28	36
26	8	27	0.546	0.226	35.28	36
27	27	28	0.273	0.113	35.28	36