An Efficient Method for the Practical Planning of Radial Distribution Network

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DEDICATED

TO

MY PARENTS

CERTIFICATE

*This is to certify that my work presented in this thesis entitled **"An Efficient Method for the Practical Planning of Radial Distribution Network"** submitted in partial fulfillment of the requirement for the award of the degree of **Master of Engineering** in **Power Systems & Electric Drives** at **Thapar University, Patiala**, is an original record under supervision and guidance of **Ms. Aabha.***

The matter embodied in this report has not been submitted anywhere for the award of any degree.

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ABSTRACT

The close propinquity of distribution network to the consumers of electricity, it has become necessity to explore the area of practical planning of distribution system. In this work the practical planning of distribution system include the selection of optimal conductor size selection and capacitor placement in radial distribution network.

The optimal conductor size selection, in this work, is based on a practical method which combines the current density based method and a heuristic index directed method. The load flow analysis is carried out to the distributed system power flow. The capacitor placement includes the voltage constraint and load variation. This is done by coggin method. Coggin method is search technique in which quadratic convergence is used. The problem capacitor placement has been represented by a objective function and minimal of the objective function is found using coggin method.

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CHAPTER 1

INTRODUCTION

The distribution system is an important part of an electric power system. As stated in [1], the capital investment in the distribution system constitutes a significant portion of the total amount spent in the entire power system. Due to the recent market deregulation, this portion may become even larger. Furthermore, since the distribution systems operate at the low voltage levels, the losses are usually higher compared to those in other parts of the system. Thus, the distribution system rates high in economic importance, which makes careful planning and design most worthwhile.

1.1 INTRODUCTION TO ELECTRICAL POWER SYSTEM

Electrical energy is produced through an energy conversion process. The electric power system is a network of interconnected components which generate electricity by converting different forms of energy, (potential energy, kinetic energy, or chemical energy are the most common forms of energy converted) to electrical energy; and transmit the electrical energy to load centres to be used by the consumer. The production and transmission of electricity is relatively efficient and inexpensive, although unlike other forms of energy, electricity is not easily stored and thus must generally be used as it is being produced.

The electric power system consists of three main subsystems: the generation subsystem, the transmission subsystem, and the distribution subsystem. Electricity is generated at the generating station by converting a primary source of energy to electrical energy. The voltage output of the generators is then stepped-up to appropriate transmission levels using a step-up transformer. The transmission subsystem then transmits the power close to the load centres. The voltage is then stepped-down to appropriate levels. The distribution subsystem then transmits the power close to the customer where the voltage is stepped-down to appropriate levels for use by a residential, industrial, or commercial customer. In this chapter, a brief description of the common methods of converting energy to electric power, and each power subsystem will be discussed.

1.1.1 Generation Systems

Generation Plants produce electrical energy from another form of energy such as fossil fuels, nuclear fuels, or hydropower. Generation Substations connect generation plants to transmission lines through a step-up transformer that increases voltage to transmission levels.

Generation plants consist of one or more generating units that convert mechanical energy into electricity by turning a prime mover coupled to an electric generator. Most prime movers are driven by steam produced in a boiler fired by coal, oil, natural gas, or nuclear fuel. Others may be driven by nonthermal sources such as hydroelectric dams and wind farms. Generators produce line-to-line voltages between 11 kV and 30 kV.

The ability of generation plants to supply all of the power demanded by customers is referred to as system adequacy. Three conditions must be met to ensure system adequacy. First, available generation capacity must be greater than demanded load plus system losses. Second, the system must be able to transport demanded power to customers without overloading equipment. Third, customers must be served within an acceptable voltage range.

System adequacy assessment is probabilistic in nature. Each generator has a probability of being available, a probability of being available with a reduced capacity, and a probability of being unavailable. This allows the probability of all generator state combinations to be computed. To perform an adequacy assessment, each generation state combination is compared to hourly system loads for an entire year. If available generation cannot supply demanded load or constraints are violated, the system is inadequate and load must be curtailed. Generation adequacy assessments produce the following information for each load bus:

(1) The combinations of generation and loading that require load curtailment, and
(2) The probability of being in each of these inadequate state combinations.

1.1.2 Transmission Systems

Electric power transmission is the bulk transfer of electrical power, a process in the delivery of electricity to consumers. A power transmission network typically connects power to multiple substations near a populated area. The wiring from substations to customers is referred to as Electricity distribution, following the historic business model separating the wholesale electricity transmission business from distributors who deliver the electricity to the homes. Electric power transmission allows distant energy sources (such as hydroelectric power plants) to be connected to consumers in population centres, and may allow exploitation of low-grade fuel resources such as coal that would otherwise be too costly to transport to generating facilities.

Usually transmission lines use three phase alternating current (AC). Single phase AC current is sometimes used in a railway electrification system. High-voltage direct current systems are used for long distance transmission, or some undersea cables, or for connecting two different ac networks.

Transmission Systems transport electricity over long distances from generation substations to transmission or distribution substations. Typical US voltage levels include 69 kV, 115 kV, 138 kV, 161 kV, 230 kV, 345 kV, 500 kV, 765 kV, and 1100 kV. Transmission Switching Stations serve as nodes in the transmission system that allow transmission line connections to be reconfigured. Transmission Substations are transmission switching stations with transformers that step down voltage to subtransmission levels. Subtransmission Systems transport electricity from transmission substations to distribution substations. Typical US voltage levels include 34.5 kV, 46 kV, 69 kV, 115 kV, 138 kV, 161 kV, and 230 kV.

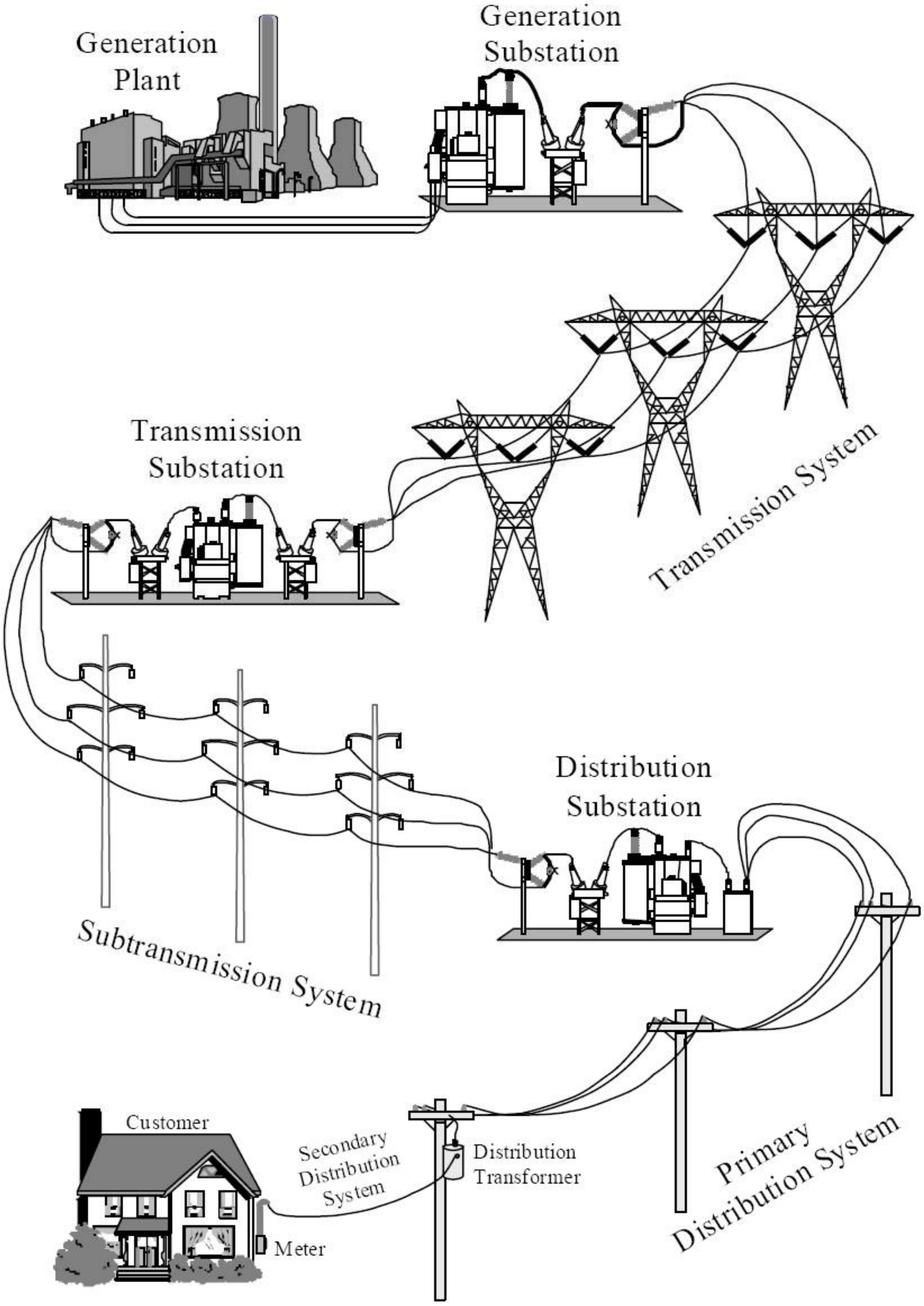

Fig. 1.1 Different Parts of Power Systems

1.1.3 Distribution Systems

Distribution Substations are nodes for terminating and reconfiguring subtransmission lines plus transformers that step down voltage to primary distribution levels.

Primary Distribution Systems deliver electricity from distribution substations to distribution transformers. Voltages range from 4.16 kV to 34.5 kV with the most common being 15-kV class (e.g., 12.47 kV, 13.8 kV).

Distribution Transformers convert primary distribution voltages to utilization voltages. Typical sizes range from 5 kVA to 2500 kVA.

Secondary Distribution Systems deliver electricity from distribution transformers to customer service entrances. Voltages are typically 120/240V single phase, 120/208V three phase, or 277/480V three phase.

1.2 BRIEF OVERVIEW OF DISTRIBUTION SYSTEM

Distribution systems deliver power from bulk power systems to retail customers. To do this, distribution substations receive power from subtransmission lines and step down voltages with power transformers. These transformers supply primary distribution systems made up of many distribution feeders. Feeders consist of a main 3Φ trunk, 2 Φ and 1 Φ laterals, feeder interconnections, and distribution transformers. Distribution transformers step down voltages to utilization levels and supply secondary mains or service drops [3].

Distribution planning departments at electric utilities have historically concentrated on capacity issues, focusing on designs that supply all customers at peak demand within acceptable voltage tolerances without violating equipment ratings. Capacity planning is almost always performed with rigorous analytical tools such as power flow models. Reliability, although considered important, has been a secondary concern usually addressed by adding extra capacity and feeder ties so that certain loads can be restored after a fault occurs.

Distribution systems begin at distribution substations. An elevation and corresponding one-line diagram of a simple distribution substation is shown in Figure 1.2. The substation's source of power is a single overhead subtransmission line that enters from the left and terminates on a take-off (dead-end) structure. The line is connected to a disconnect switch, mounted on this same structure, capable of visibly isolating the substation from the subtransmission line. Electricity is routed from the switch across a voltage transformer through a current transformer to a circuit breaker. This breaker protects a power transformer that steps voltage down to distribution levels. High voltage components are said to be located on the "high side" or "primary side" of the substation.

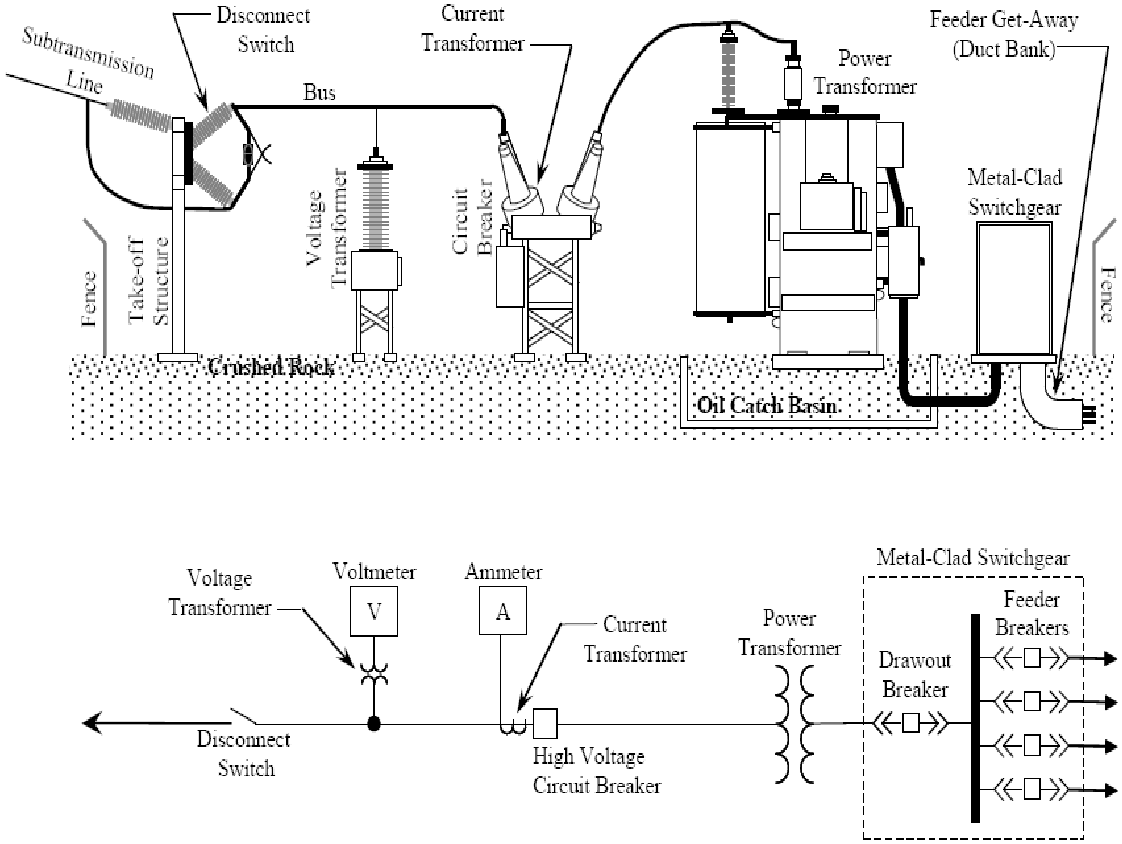

Figure 1.2. A single-line diagram of a distribution substation

1.3 DISTRIBUTION SYSTEM CONFIGURATION

The design of the distribution system mainly depends on the chosen classification of single or three phase, radial or loop network, overhead line or underground cables.

The essential factors to be kept in mind while planning a distribution system are:

1) **Safety:** The safety factor requires the distributors to be laid following:
    i) Proper clearances.
    ii) Voltage safe enough to be used for consumer's gadgets.
2) **Smooth and Even flow of power:** A steady, uniform, non-fluctuating flow of power is necessary to feed loads of all categories of consumers.
3) **Economy:** The third factor is economy. This usually calls for use of higher voltage to ensure minimum losses while distribution power.

1.4 PRIMARY DISTRIBUTION SYSTEMS

Primary distribution systems consist of feeders that deliver power from distribution substations to distribution transformers. A feeder begins with a feeder breaker at the distribution substation. Many will exit the substation in a concrete ductbank (feeder get-away) and be routed to a nearby pole. At this point, underground cable transitions to an overhead three-phase main trunk. The main trunk is routed around the feeder service territory and may be connected to other feeders through normally-open tie points. Underground main trunks are possible, even common in urban areas, but cost much more than overhead construction.

Lateral taps off of the main trunk are used to cover most of a feeder's service territory. These taps are typically 1Φ, but may also be 2 Φ or 3 Φ. Laterals can be directly connected to main trunks, but are more commonly protected by fuses, reclosers, or automatic sectionalizers. Overhead laterals use pole-mounted distribution transformers to serve customers and underground laterals use padmount transformers.

An illustrative feeder showing different types of laterals and devices is shown in Figure 1.3.

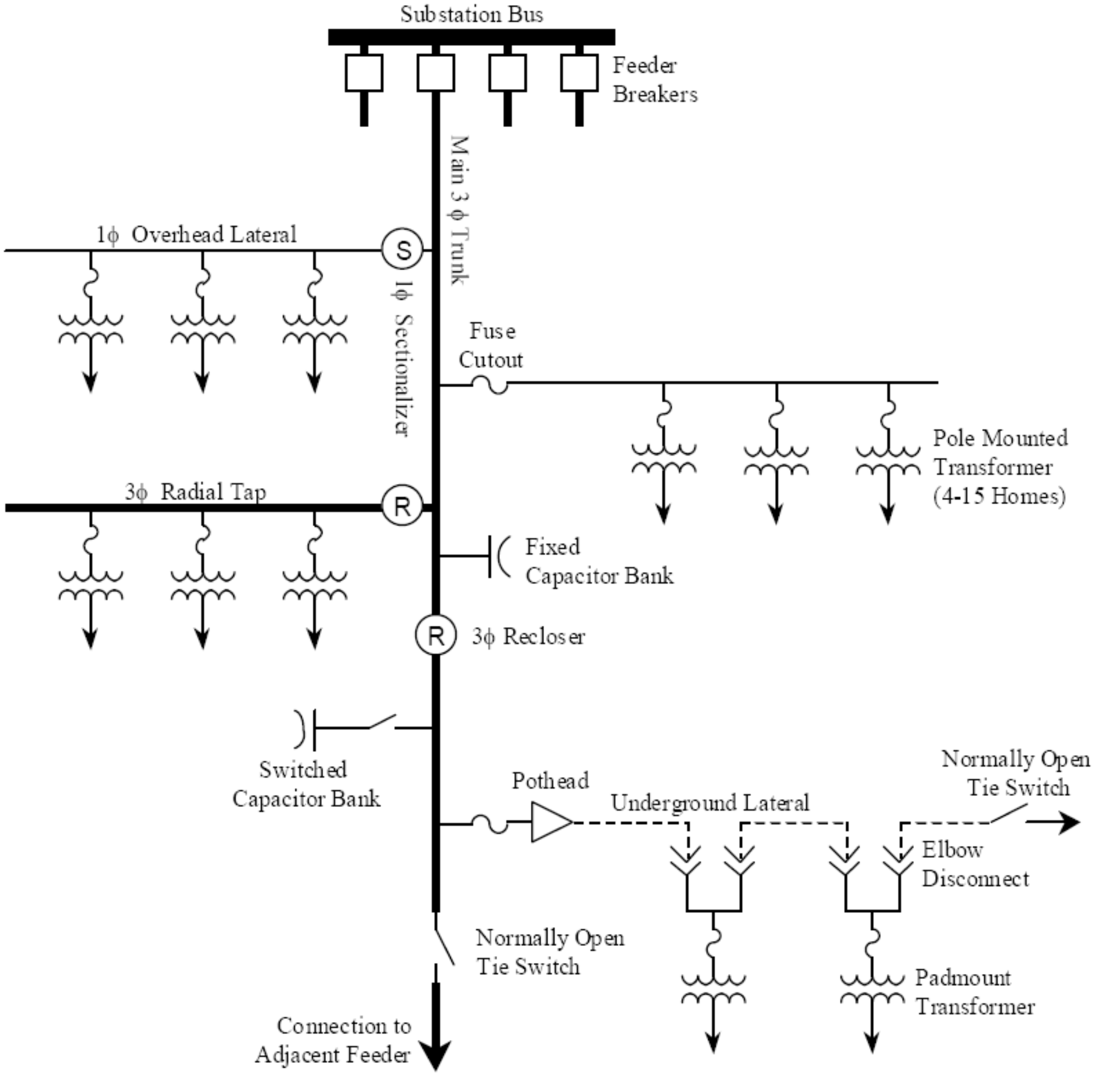

Figure 1.3 A Primary Distribution Feeder Showing Major Components

There are two type of distribution line exists in primary distribution systems- overhead lines and underground lines. In this thesis work, only overhead lines are considered.

In Overhead lines, wires carry load current in an overhead system. Major classifications are by insulation, size, stranding, material, impedance, and ampacity. Lines without an insulated cover are called bare conductors and all other lines are referred to as insulated conductors. Insulated conductors are further classified into covered conductor, tree wire, spacer cable, and aerial cable.

Covered conductor and tree wire have a thin covering of insulation that cannot withstand phase to ground voltages, but reduce the probability of a fault if vegetation bridges two conductors. Spacer cable has increased insulation that allows conductors to be arranged in a small triangular configuration. Aerial cable has fully rated insulation capable of withstanding phase to ground voltages.

Most lines consist of steel strands surrounded by aluminium strands. Referred to as Aluminium Conductor Steel Reinforced (ACSR), this wire type uses steel to achieve high tensile strength and aluminium to achieve high conductivity at a low weight.

Table 1.1. Common types of overhead lines

Conductor Name	Resistance (Ω/km)	Reactance (Ω/km)	Impedance (Ω/km)	Area (mmsq)	Current (Amp)
Squirrel	1.3740	0.3200	1.396	20.71	125
Gopher	1.0980	0.3100	1.100	25.91	148
Weasel	0.9116	0.3080	0.953	31.27	160
Ferret	0.6795	0.2980	0.738	41.87	190
Rabbit	0.5449	0.2910	0.614	52.21	218
Mink	0.4565	0.2850	0.536	62.32	236
Beaver	0.3841	0.2795	0.484	74.07	260
Racoon	0.3656	0.2765	0.464	77.83	270
Otter	0.3434	0.2752	0.437	82.85	281
Cat	0.3020	0.2725	0.406	94.21	300
Dog	0.2745	0.2695	0.383	103.60	320
Leopard	0.2193	0.2625	0.340	129.70	375
Wolf	0.1844	0.2410	0.310	154.30	455
Lynx	0.1810	0.2330	0.290	179.00	495
Panther	0.1760	0.2280	0.260	207.00	540

1.4.1 Typical Configurations of primary distribution system

Some typical primary distribution system configurations are shown in Figure 1.4. The simplest primary distribution system consists of independent feeders with each customer connected to a single feeder. Since there are no feeder interconnections, a fault will interrupt all downstream customers until it is repaired. This configuration is called a radial system and is common for low-density rural areas where more complex systems are cost prohibitive. A slightly more common configuration connects two feeders together at their endpoints with a normally open tie switch. This primary loop increases reliability by allowing customers downstream of a fault to receive power by opening an upstream switch and closing the tie switch. The only customers that cannot be restored are those in switchable section where the fault occurred.

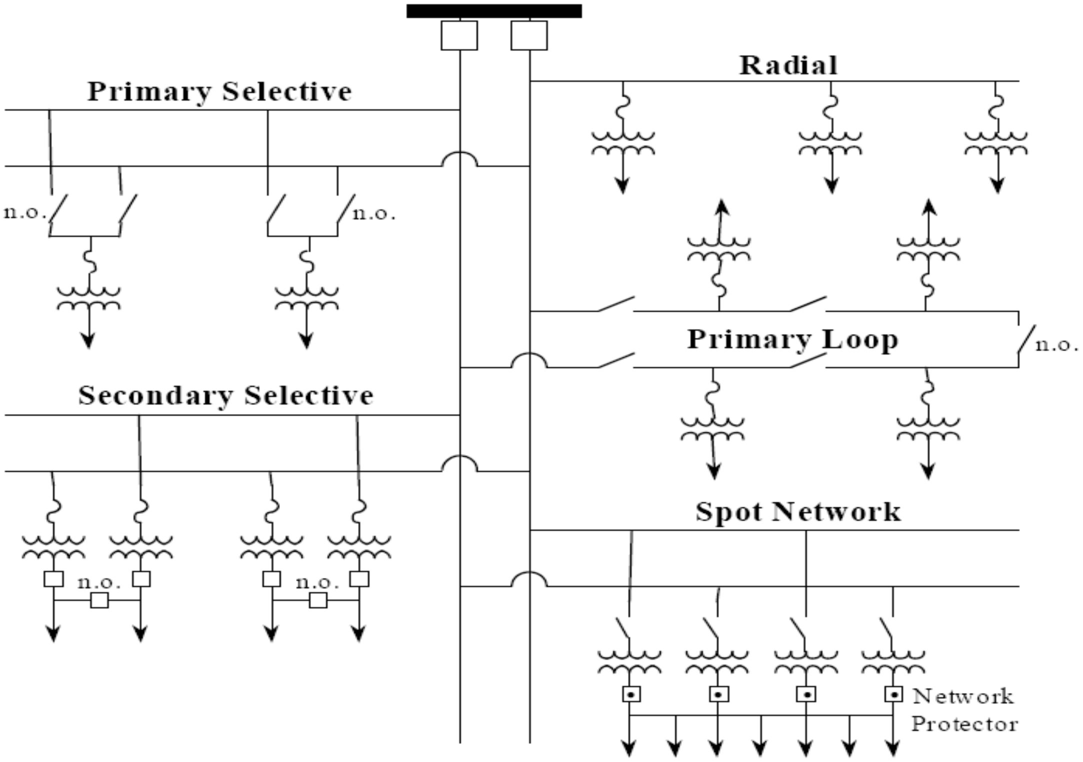

Figure 1.4. Typical Primary Distribution Systems.

1.5 SECONDARY DISTRIBUTION SYSTEMS

Secondary systems connect distribution transformers to customer service entrances. They can be extremely simple, like overhead service drop, and extremely complex, like a secondary network.

Customers are connected to distribution systems via service drops. In the US, service is typically 1Φ 3-wire 120/240V, 3 Φ 4-wire 120/208V, or 3 Φ 4-wire 277/480V. Customers close to a distribution transformer are able to have service drops directly connected to transformer secondary connections. Other customers are reached by routing a secondary main for service drop connections. These two types of service connections are shown in Figure 1.5.

Systems utilizing secondary mains are characterized by a small number of large distribution transformers rather than a large number of small distribution transformers. This can be cost effective for areas with low load density and/or large lot size, but increases Ohmic losses and results in higher voltage drops. Increased line exposure tends to reduce reliability while fewer transformers tend to increase reliability.

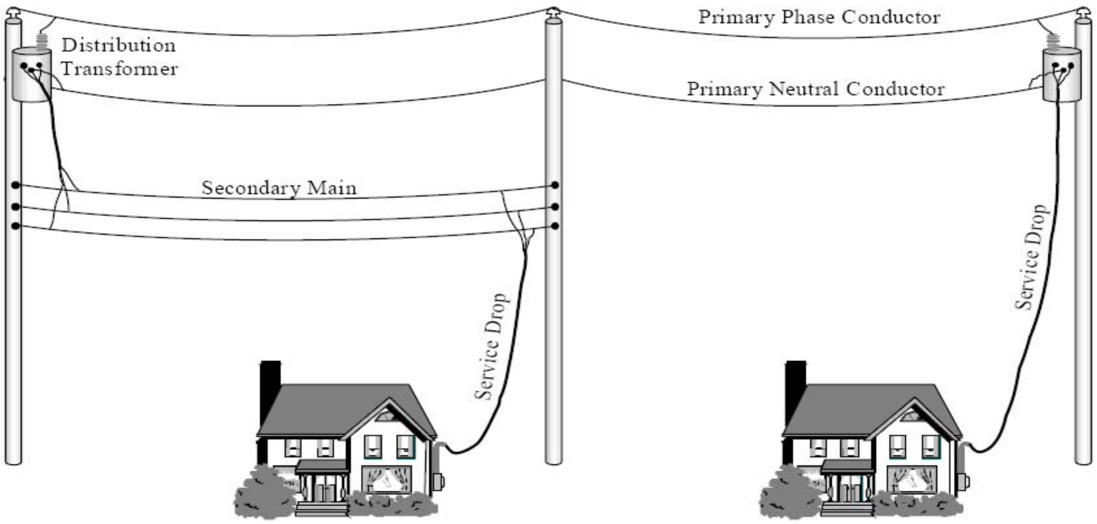

Figure 1.5. Service Drops in Distribution System

1.6 LITERATURE REVIEW

Distribution planning is the art of spending money today so that it will have lasting value in the future. If done properly, distribution planning will proactively identify all of the construction projects that will satisfy present and future stakeholder expectations for the lowest possible cost at an acceptable level of risk. Done properly, this is a large and complicated task that requires detailed distribution system models and computer analysis tools [2].

Distribution system planning requires two basic capabilities: capacity analysis and reliability analysis. The ability to correctly balance these two aspects of feeder performance is greatly increased through the use of a common modelling environment [4]

1.6.1 Load Flow Analysis

There are various methods for solving load flow problems of the distribution network. An earlier approach of radial system power flow analysis utilizes linear network theory by approximating all constant power loads as admittances calculated corresponding to assumed bus voltages. Network reduction techniques are used to get an equivalent circuit and new bus voltages are calculated by unfolding the network. The process is iterative and repetitive till convergent. Next proposed solution took advantage of the structure of the radial system and is referred to as ladder network approach. In this method iterations are started with estimates of ending reverse voltages and an reverse trace there is then performed for determining the various bus voltages leading to a calculated value of the source voltage. New estimates for the ending bus voltages are determined based on the mismatch between the calculated and specified source voltage. Iteration are continued till specified source voltage is achieved with in accuracy limit. General load flow method of Newton however has the disadvantage of complexity in program, higher memory requirement and more calculation time

The ladder method [5] uses a reverse trace towards the source when the nodes voltages are calculated by simple addition of voltage drop and then applying a correction to account for the given magnitude of the source voltage. If lateral are present there are sub-iterations on each lateral in each main iteration.

The tree form of solution method [6] adopts a nomenclature of branch and node, which gives the branches a number that coincide with one of the end nodes of the same, which allows the representation of the network by a single vector. A branch can be considered to be oriented towards the source node. To solve the load flow the tree formed by all the branches shall be followed in a systematic form starting from the last node and ending at source node. The solution algorithm can be summerized as first reading the network data, parameters topology and voltage magnitudes at source nodes, then assuming voltage magnitudes for rest of nodes and estimate of initial load. Doing upstream iteration from end to source node, calculate the equivalent load for each node, considering power losses too, now in downstream iteration using final voltages, recalculate losses, and check for difference in losses for tolerance. This method can be extended to the load flow calculation of unbalanced system. This method also includes the possibility to define load dependent on voltage, which is a realistic form of representing loads at distribution voltage levels.

Direct solution method [7-9] uses tree structure of distribution system, unique set of equations are developed by applying Kirchhoff's law and inserting source bus in all equations (with loads as constant impedances), a system of N load nodes, will only have N equations. This method adopts a new scheme developed for economy in storage and computation aspect. The main lines through source node are numbered first towards end node. After that, groups of lateral lines, nearest to source node are numbered. The sublateral with fewest numbers of further connected sub-laterals is assigned a higher level. In a N number load node system, there will he impedance matrix of $n*n$ dimension in which self impedance of i^{th} loop is the summation of all impedances through which current of i^{th} load node flows. Off diagonal terms will be impedance of section which is common to both i and j node. This method is basically for balanced radial system but can also be extended for meshed and unbalanced networks by converting them into equivalent radial systems. The advantage of this method is that convergence is never a problem.

In compensation based method for weakly meshed systems [9], an inter connected system is first broken in the line sections at a number of points called breakpoints to convert the network into radial one, then solved by KVL and KCL. The breakpoint currents are calculated using multiport compensation method. The numerical efficiency decreases as the number of break points increase. This method is capable of solving radial and weakly meshed distribution networks with upto several thousand line sections and nodes. Only a few iterations are required for the solution of network using this power flow technique.

The power summation method [10] solves single phase model which is used for the balanced three phase system. The source voltage being given, a reverse trace of distribution system is first made and the section loads and system losses supplied at each bus are calculated using fiat voltage profile. A forward trace is next executed and voltage magnitude is calculated. Then convergence is checked for further iteration. When multiphase model is used the mutual couplings between phase conductors in a section are modeled as current dependent voltage sources in series with self impedance of the phases Loads other than the balanced types are first converted into equivalent constant power loads in each phase during reverse trace and lumped with the actual constant power load of the phase. Three phase unbalanced star connected impedance type loads with isolated neutral can be convened into equivalent delta. Solution algorithm has all steps like other methods of reverse and forward traces.

The dist flow method [11] algorithm stats with starting initial iteration by using total real and reactive loads as initial power injection, then summing the losses to find equivalent R and X for single line system. The new power injection is calculated and tolerance is checked for difference of real power. Finally other parameters like voltage etc. are calculated from power losses and power injection.

The D.C. load flow method [12] assumes that all bus voltages are known and equal to 1.0 p.u. This method is least accurate but simple and fast. The A.C. balanced load flow [12] incorporates the well known methods as Gauss-Seidel, Newton-Rapson and fast decoupled method.

Tree-phase unbalanced distribution power flow [13] uses traditional Newton-Raphson algorithm in a rectangular coordinate systems. The jacobian matrix can be decoupled both on phases as well as on real and imaginary pans. An exact three phase distribution load-flow program can be executed with minimum data preparation. The method is robust and is insensitive to line parameters. This method requires less memo and exhibits steady iteration number.

Fast decoupled power flow [14] is an effective solution method for general unbalanced radial distribution system. The models developed consider lines, switches, transformers, shunt capacitors, cogenerators and several types of loads. This method significantly reduces the number of power flow equations as compared with conventional formulation. The reduced number of power flow equations comes out to be equal to number of laterals present. This method exploits the radial topological and numerical structure of the radial network. Due to the reduced number of equations and the fact that the jacobian is approximated by a constant upper triangular matrix. It is significantly faster than conventional Gauss and Newton methods.

1.6.2 Allocation of Shunt Capacitors

Application of shunt capacitors on distribution system for power factor improvement started in 1940s. Neagle and Samson [15] considered the loss reduction from capacitors installed on primary feeders. In this method the peak power requirement was minimized. Cook [16] developed a formula for calculating loss reduction as afforded by shunt capacitor application, minimizing energy loss taking into account time variation of the load. Schmill [17] studied that the optimum location, sizing and timing of capacitor banks on feeders with uniformly distributed loads and randomly varying spot loads to evaluate reduction in costs of active and reactive losses without taking into account voltage regulation problem. He suggested a procedure of moments of the loads with respect to feeders resistances or reactance to calculate optimum ratings and locations of N-capacitor banks installed on a distribution feeder.

Carlisle et Al. [18] 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. Increased competition in the industry has created a renewed interest in improving efficiency by reducing these losses

Chang [19] represented feeders by a number of line segments feeding combination of concentrated and uniformly distributed loads, and developed a method for locating and sizing capacitors on primary feeders by maximizing total return due to reduction in peak power losses and energy losses against costs of capacitor banks. Later he developed generalized equations for calculating power and energy loss reduction in a feeder, considering both concentrated and uniformly distributed loads.

Bae [20] developed an analytical method for the calculation of the power loss reduction by applying a number of shunt capacitors of same size, to a uniformly loaded feeder for a constant reactive load level. The formulae for the calculation of yearly average energy loss reduction for assumed reactive load distribution in terms of the beta function was derived.

Grainger et al. [21, 22] suggested comprehensive methods for solving the problem of allocation of fixed as well as switched capacitors on radial distribution feeders. They considered the maximization of net savings on a weighted sum of energy loss savings and peak power savings less cost of installed capacitors. This method included the equal area criterion assuming the constant voltage profile along the feeder main and a voltage dependent model solved by iterative procedure to obtain optimum size and location of fixed capacitors on straight radial distribution feeders. They also developed an iterative solution procedure for the allocation of switched capacitors along with fixed capacitors and suggested a real time switching scheme for the application of switched capacitors.

Ponnavaikko and Rao [23] suggested a method for an optimal choice of fixed and switched capacitors on randomly and discretely loaded radial feeders. The objective function consisting of cost saving due to energy loss reduction and release in other system capacitors less cost of capacitor bank i maxirnised, subject to voltage rise constraint during off peak hours. The load growth, growth in load factor and increase in cost of energy is considered in their model.

Haung et al. [24] solved the capacitor placement problem in a radial distribution system using Tabu search approach. The capacitor placement problem considers practical operating constraints of capacitors, load growth, capacity of feeder and upper and lower bound constraints of voltage at different load levels to minimize investment cost of capacitors and system energy loss. A sensitivity analysis method is used to select the candidate installation locations of the capacitors to reduce the search space of the problem. The Tabu search strategy is built upon a descent mechanism of a search process. The descent mechanism biases the search towards points with lower objective function values.

1.6.3 Conductor Sizing

Funk Houser [25] solved the conductor gradation problem through an enumeration procedure. Walkden [26] suggested a method for the design of low voltage distributors from cables of different sizes by minimizing volume of conductor and taking voltage regulation as limiting factor with uniformly distributed load and solved it by an analytical method based on study made by Davies [28]. Ponnavaikko and Rao [29] made an attempt for optimal distribution system planning through conductor gradation by developing a method based on dynamic programming approach for straight radial distribution feeder considering the aspect of non uniform loading conditions.

1.7 OBJECTIVE OF THE THESIS

The objective of the present thesis work is to plan the radial distribution network by using multiple cross-section conductors and by allocation of shunt capacitor. The conductor gradation is reduces the cost of distribution system and capacitor placement improves the distribution network.

In this thesis work, conductor gradation has been done by current density based method and RCV index method and capacitor placement has been done by coggin approach.

1.8 ORGANIZATION OF THE THESIS

Chapter 1- This chapter contains the brief introduction to electrical power system, distribution system, configuration of distribution system, literature review, and objective of the thesis work.

Chapter 2- This chapter contains the overview of distribution system planning and some of its different methods.

Chapter 3- This chapter gives the introduction to the load flow analysis to the distribution system power flow, solution methodology, algorithm and flow chart for the load flow.

Chapter 4- This chapter gives the introduction to optimal conductor size selection, optimization problem, solution methodology, introduction to capacitor placement in radial distribution system, flow chart and algorithm for capacitor placement.

Chapter 5- This chapter shows the result of the thesis work.

Chapter 6- This chapter gives the conclusion and future scope of the thesis work.

CHAPTER 2

DISTRIBUTION NETWORK PLANNING

2.1 OVERVIEW

Power system planning is essential to meet the growing demand of electricity. Increasing demand for electric power combined with a scarcity of resources has put a burden on the system planner for optimizing the capital investment and running costs of the power system. The distribution system constitutes a significant part of the total power system. The capital expenditure incurred in distribution systems from 40 percent of the total expenditure.

The distribution system operates at low voltage level and is extensive; it is prone to have more energy losses compared to other parts of the system. While quantifying the losses in the power system, it has been observed that the distribution system losses constitute a major part of losses, ranging from 75 to 80 percent of the total system losses [2]. It is evident from studies [4] that 99 percent of consumer outages are attributable to distribution systems. This brings about the realization that accurate planning techniques are essential for distribution systems. Also any haphazard planning of distribution system may further increase the losses in the system. Moreover the cost of energy in maximum at the distribution level in a power system, therefore haphazard planning may also lead to serious economic problems to the power utility. The above facts again justify the need for the proper planning strategies of the distribution systems, to provide an adequate the reliable supply to its consumers at a reasonable economic cost.

In the distribution system planning, service quality and economy are the main considerations. The service quality means, to supply power to the consumer at the specified voltage, which in turn depends on the voltage regulation, tap setting of transformers and voltage received at the source station. The system planner has a very little control on these variables except for the voltage regulation in the feeder. Design of a distribution system with high voltage regulation may result in more distribution losses and consequently higher voltage level at the substation as compared to an alternative design of low voltage regulation. The design of distribution systems based on high voltage regulation may result in higher recurring expenditure and low initial investment. On the contrary a system with low voltage regulation will have less expenditure and more initial investment. The source voltage and the desired voltage at the consumer point further control the voltage regulation. If the voltage at the consumer end is also fixed to provide a good quality of service, the voltage regulation for the distribution system will also be fixed, on which the other dependent variable parameters of the distribution system will depend. These parameters are feeder voltage, size and feeder length etc. Hence the optimization of these parameters is virtually essential for distribution system planning. The basic independent variables, on which these parameters depend are load, power factor and load distribution etc.

In distribution system mostly the feeders are radial in configuration, either straight or branched. Hence the loading of the feeder is in a decreasing order from feed point to end point of the feeder. This inherent feature of the feeders provides the possibility of multi conductor cross section configuration for a feeder by way of making provision for low size of conductor cross section towards the far ends of the feeder, in number of stages subject to availability of size in the inventory. The proper choice of multi-conductor cross section for radial feeders in the distribution system improves the system economy without affecting technical requirements of the system.

After finding out the routing of feeders it needs to be analysed to find out the various electrical parameters under different loading conditions of the system. Thus a load flow study forms an important part of power system analysis. It is necessary for planning, economic operation and control of an existing system. In addition, distribution systems extend to wide areas and contain a very large number of elements, like substations, line sections, loads of different types etc. The distribution system comprises of many feeders operating radially in normal operating conditions. Therefore in the distribution system analysis a repeated number of calculations are often required, because of large number of alternative solutions that must be examined.

The distribution system is operated radially and therefore the voltage at the end node on a particular feeder is likely to be low as compared to that at the start node. Thus maintenance of the system voltage at a certain acceptable limit is one of the important control schemes in a distribution system. The voltage profile of the distribution system can be improved by the installation of shunt capacitor. The provisions of excessive shunt compensation or fixed shunt compensation for full load, at off peak hours may result in undesirable high voltages in the system. Thus the economic benefits of the capacitor depend mainly on where and what capacities of the capacitors nearer to the load points yields maximum benefit. Hence probable locations of capacitor installation are the load points on the feeder. Thus it is essential to make proper choice of the number, size and location of the capacitor banks along the radial feeder to achieve maximum economy.

2.2 DIFFERENT METHODS FOR PLANNING OF DISTRIBUTON NETWORK

There are various methods exist for the planning of distribution system. Some of them are explained below:

2.2.1. Branch and Bound Method

A significant number of studies have been devoted to optimization the distribution system using different computational methods, and the Branch and Bound algorithm of the linear programming methods has been employed to find an optimal solution to design problem.

Considering a close loop network consisting of number nodes so it seems that the possible variants will be $\frac{(n-1)!}{2}$. The branch and bound method is an effective math device, as it is based on implicit systematic enumeration of feasible solution set and it provides us with the optimal solution. The set of feasible solution is successively divided (branched) into smaller subsets.

If minimum of cost of the distribution network is our aim, then for each subset the lower bound (called simply bound) for all solution of this subset is calculated. Branching proceeds until sets with single solutions are obtained. After each division we eliminate all these subsets for which bound are greater than the cost of any solution. The best actual solution is optimal if there is no more subsets to be branched more.

The efficiency of this methodology depends on two important factors: the branching rule or the principle of branching, and the bound calculation bases. However, the exact efficiency improvement is very hard to pin down. It cannot be mathematically represented, as it's differs for each different problem. And the designers (design engineers) sometimes have different opinions for different reasons for the same problem and so they carry out different configurations. This makes the task more sophisticated.

2.2.2. Branch-Exchange Algorithm

The branch exchange technique, applied for the reconfiguration of distribution network, basically converts a radial network into a meshed network by connecting the tie lines. The radial structure is restored again by opening some other lines of the network so as to minimize an objective function. The exact form of the objective function being dependent upon the purpose of reconfiguration. In the proposed algorithm branch exchange technique is implemented by forming one loop only at a time. Two types of branch exchanges are performed

I. Branch exchange within each distribution zone – called intrazone branch exchange.
II. Branch exchange between the adjacent distribution zones called interzone exchange.

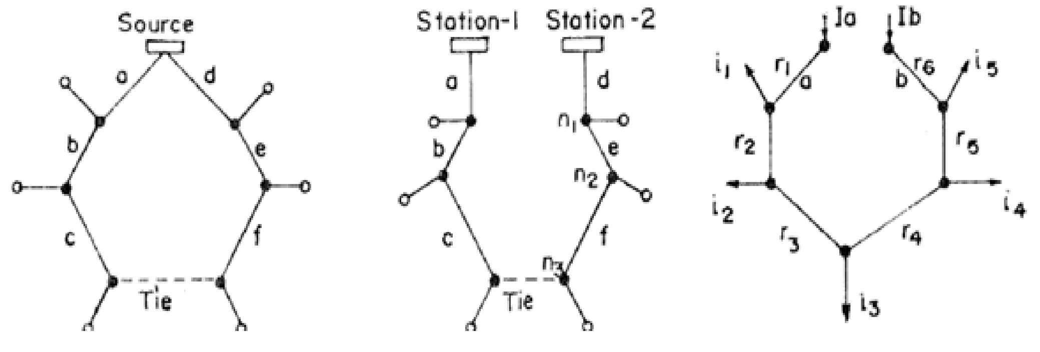

Fig. 2.1 A Loop Interconnection Branch-Exchange and Optimal Flow Pattern

Intrazone exchange and interzone exchanges are performed repeatedly. A set of interzone and intrazone branch exchanges constitute an iteration of the algorithm. The branch exchange continues till the system cost or limit violation can be minimized. When the optimum solution is obtained for the selected substations, we check the optimality of the substation capacity. If the optimum is not reached a new solution is obtained by reducing the number of substation by one. The substation to be closed for the next solution is determined on the basis of the cost per KVA of the substations. Cost per KVA is calculated as: (cost of the substation + cost of feeders + cost of energy loss) / Total KVA load of the substation. The substation having the maximum cost per KVA is closed and a new optimum network configuration is obtained with the selected substations. This process is repeated till a cost reduction is achieved by reducing the number of substation. A complete load flow is performed after each successful branch exchange. Since the number of successful branch exchanges is generally much less than the number of exchanges attempted, number of full load flows are not many. It may be noted here that the solution obtained from radial load flow has to be changed every time when a branch exchange is attempted. This however, does not need full load flow and can be obtained very easily by minor modifications of the available load flow results.

2.2.3. Evolutionary Algorithms

Evolutionary algorithms work with a population of individuals (codified solutions), which is able to evolve in a given environment by application of the selection, crossover, and mutation operators. The "elite" or best individuals (solutions) survive during the optimization process. Each individual or "chromosome," represents a complete solution of the network. The chromosomes are integer strings that codify the connection between the nodes of the distribution network.

The first step of an evolutionary algorithm is to generate the initial population. The initial population consists of μ different chromosomes generated randomly, that represent μ different solutions for the configurations in Fig. 2.2.

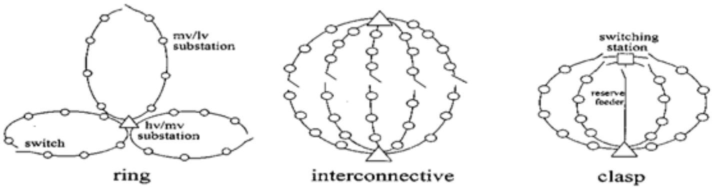

Fig. 2.2 Urban Distribution Network Configuration

A random sampling of this initial population is selected to create an intermediate population, and the crossover and mutation operators are applied to them in order to obtain a new population with λ chromosomes. This process is called a generation and it is repeated until a stop function is decided.

The population of the next generation must have μ chromosomes. These μ chromosomes will be the best (minimal cost function) of the set composed by the μ and λ chromosomes of the previous generation.

CHAPTER 3

LOAD FLOW ANALYSIS

3.1 INTRODUCTION

Load flow is very important and fundamental tool for the analysis of any power system and is used in the operational as well as planning stages. Certain application, particularly in distribution automation and optimization of power system requires repeated load flow solution. In these applications it is very important to solve the load flow problem as efficiently as possible.

The Newton Raphson and the fast decoupled power flow solution techniques and a host of their derivatives have efficiently solved “well behaved” power systems. Researchers however have been aware of the shortcomings of these solution algorithms when they are generally implemented and applied to ill conditioned power systems. Hence commercial power flow packages always modify these algorithms for enhanced robustness. The nature of modification and the degree of improvement obtained vary for different packages. The Gauss-Siedal power flow method, another classical technique, although very robust but is extremely inefficient in solving ill conditioned power system for generic Newton Raphson and fast decoupled power flow algorithms.

3.2 DISTRIBUTION SYSTEM POWER FLOW

Power flow in a distribution system obey physical laws(Kirchoff laws and Ohms law) which became part of the constraints in the capacitor placement problem and the distribution system power flow solution is to be used as a subroutine in every iteration. Therefore, it is essential to have a computationally efficient and numerically robust method for solving the distribution system power flow. By radial distribution system we mean a system which has a single simultaneous path of power flow to the load.

First, a special case distribution system is considered, where there is only one main feeder. To simplify the analysis, the system is assumed to be balanced 3 phase system.

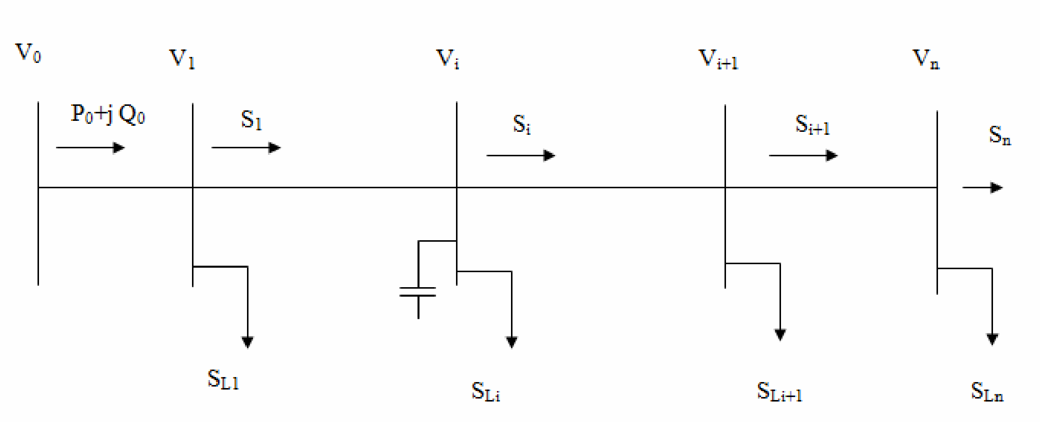

Fig. 3.1 One Line Diagram of Radial Distribution Network

Consider a distribution system consists of a radial main feeder only. As shown in Fig 3.1 comprising n branches/nodes. In the figure $|V_0|$represents the substation bus voltage magnitude and is assumed to be constant. V_0 is assumed as reference voltage and hence $V_0 = |V_0|\angle 0^\circ$. Lines are represented by a series impedance $Z_i=R_i+jX_i$, and loads are treated as constant power sinks $SL_i=PL_i+jQL_i$. Shunt capacitors to be placed at the nodes of the system will be represented as reactive power injections. With this representation, the network becomes a ladder network with nonlinear shunt loads. If the power supplied from the substation $S_0=P_0+jQ_0$ is known, then power and the voltage at the receiving end of the first branch can be calculated as follows.

$$S_1 = S_0 - S_{LOSS\ 1} - S_{L\ 1} \qquad (3.1)$$

$$V_1 < \theta_1 = V_0 - Z_1 I_0 \qquad (3.2)$$

Repeating the same process yields the following recursive formula for each branch on feeder

$$P_{i+1} = P_i - R_{i+1}\frac{\left(P_i^2 + Q_i^2\right)}{|V_i|^2} - P_{Li} \qquad (3.3)$$

$$Q_{i+1} = Q_i - X_{i+1}\frac{\left(P_i^2 + Q_i^2\right)}{|V_i|^2} - Q_{b_{i+1}} + Q_{C_{i+1}} \qquad (3.4)$$

$$V_{i+1} = V_i - Z_{i+1}I_i$$

$$= V_i - Z_{i+1}\frac{S_i^*}{V_i^*}$$

$$|V_{i+1}| = \frac{\left||V_i|^2 - Z_{i+1}S_i^*\right|}{|V_i^*|}$$

$$|V_{i+1}|^2 = \frac{\left|\left(|V_i|^2 - (P_iR_{i+1} + Q_iR_{i+1}) - j(P_iX_{i+1} - Q_iR_{i+1})\right)\right|^2}{|V_i|^2}$$

$$= \frac{[|V_i|^2 - P_iR_{i+1} + Q_iX_{i+1}]^2 + P_iX_{i+1} - Q_iR_{i+1}^2}{|V_i|^2}$$

$$= \frac{|V_i|^4 - 2P_iR_{i+1} + Q_iX_{i+1}|V_i|^2 + P_i^2R_{i+1}^2 + Q_i^2X_{i+1}^2 + P_i^2X_{i+1}^2 + Q_i^2R_{i+1}^2}{|V_i|^2}$$

$$|V_{i+1}|^2 = |V_i|^2 + 2(R_{i+1} + P_i) + \frac{\left(R_{i+1}^2 + X_{i+1}^2\right) + \left(P_i^2 + Q_i^2\right)}{|V_i|^2} \qquad (3.5)$$

where,

- P_i, and Q_i are Real and Reactive power flows in to the sending end of branch i+1 connecting node i and node i+1.
- V_i is bus voltage magnitude at node i.
- Q_{Ci} is reactive power injection from capacitor at node i.

Equations (3.3), (3.4) and (3.5) are called the branch flow equation has the following form

$$X_{0i+1} = f_{0i+1}(X_{0i}, U_{i+1}) \tag{3.6}$$

where

$$X_{0i} = [P_i, Q_i, V_i^2]^T$$

$$U_{i+1} = Q_{C_{i+1}}$$

Note that if there is no capacitor at node i, then U_i does not appear in the equation (3.6). By using notation, we will simply use U as a nc dimensional vector containing the nc capacitors to be sized. i.e.

$$U^T = [U_1 \ldots\ldots U_{nc}] = \left[Q_{C_{n1}} \ldots\ldots Q_{Cn_{nc}}\right] \tag{3.7}$$

We have the following terminal conditions are:

(1) At the substation: let the given substation voltage be V_{sp}.

Then $X_{003} = V_0^2 = \left(V_{sp}\right)^2$ $\quad$ (3.8)

(2) At the end of main feeder

$$X_{0n1} = P_n = 0; \qquad X_{0n2} = Q_n = 0 \tag{3.9}$$

The $3n$ branch flow equation of (3.6) together with the boundary conditions of (3.8) and (3.9) constitutes the system equations and will be referred to as Dist flow equations.

They are of the form

$$G(X_0, U) = 0 \qquad (3.10)$$

Where $X_0 = [X_{00}^T \dots \dots \dots . X_{0n}^T]^T$is the branch variables and U is the capacitor sizes. For a given load profile (i.e. set of demands$P_{Li,}Q_{Li;}i = 1 \dots . . n$) and capacitor sizes (control variable), U, 3(n+10). Dist flow equations can be used to determine the operating point, X_0 of the system.

3.3 GENERAL CASE

For notational simplicity, the lateral branching out from the node K will be referred to as the lateral K and and the node K will be referred to as branching node.

For lateral K with nk branches, the same process of formulation applied to the main feeder can be repeated for the lateral by using line flow equations (3.3), (3.4) and (3.5) and the new terminal conditions$V_{k0} = V_k, P_{kn} = 0, Q_{kn} = 0$, where, we have used the dummy variable V_{k0} for notational simplicity. As a result, we have the following $3(nk + 1)$ equations

$$X_{ki+1} = f_{ki+1}(X_{ki}, U_{ki+1}) \qquad i = 0,1, \dots \dots, nk - 1$$

$$X_{k_{n1}} = P_{kn} = 0; \quad X_{k_{n2}} = Q_{kn} = 0 \qquad i = 0,1, \dots \dots, nk - 1$$

$$X_{k_{03}} = V_{k0}^2 = V_k^2 = X_{k_{03}} \qquad (3.11)$$

3.3.1 Solution of Dist Flow Equations

The Dist Flow equation of a radial distribution system comprises branch flow equations and the associated terminal conditions for each lateral including the main feeder which is treated as the 0^{th} lateral. They are of the following form:

$$X_{k_{i+1}} = f_{k_{i+1}}(X_{k_i}, X_{0k_{i+1}}) \qquad k = 0,1, \dots \dots i \qquad (3.12)$$

$$X_{k0} = X_{0k}\, X_{kn} = X_{kn2} \qquad i = 0,1, \dots \dots, nk - 1 \qquad (3.13)$$

We use these equations to determine the operating point $X_{ki} = [P_{ki}, Q_{ki}, V_{ki}^2]^T$of the system for a given u. But rather than using the above equation to solve for $X_{ki}'s$ directly.

We are going to conceptually reduce the number of equations first and then propose an efficient solution algorithm.

3.3.2 Reduction of Dist Flow Equation

Since the substation voltage, V_0 is given, then only variables need to be determined are $Z_{00} = [P_0\ Q_0]^T$, i.e. the power supplied from the substation. Therefore, Z_0 constitutes the "state" of the system. To eliminate the other variables, X_{0i} from the equations (3.12) and (3.13), we use the terminal conditions at the end of the feeder i.e.

$$P_n = \hat{P}_{0n}(X_{0_{n-1}}) = 0$$

$$Q_n = \hat{Q}_{0n}(X_{0_{n-1}}) = 0 \tag{3.14}$$

And eliminate $X_{0i}'s$ by substituting the branch flow equations recursively for $i = n-1, n-2, \dots, 1$. As a result, we get two equations of the following form.

$$\hat{P}_{0n}(X_{00}, U) = 0$$

$$\hat{Q}_{0n}(X_{00}, U) = 0 \tag{3.15}$$

These two equations can be used to solve Z_{00} for a given$U$.

3.4 ALGORITHM FOR THE DISTFLOW EQUATIONS

The reduced Dist flow equations are of the form

$$H(Z_0, U) = 0 \tag{3.16}$$

and can be used to solve for the state variable Z.

Let us consider solving (3.16) for Z by Newton Raphson for a given U. From an estimated value Z, an iteration step of NR involves three steps.

STEP 1: Calculation of mismatches $H(Z^j)$.

STEP 2: Construction of the system jacobian matrix.

$$J(Z^j) = {}^{\partial H}/_{\partial Z}\Big|_{z=z^{-1}} \qquad (3.17)$$

STEP 3: Solution of the following system of equations to update the states Z.

$$J(Z^j)\partial Z^j = -H(Z^j) \qquad (3.18)$$

Now the mismatches can be calculated as follows. At iteration j, the substation bus voltage V0 is given and the updated values of the substation power P_0, Q_0 are available. Therefore, the recursive branch flow equations (3.8) and (3.9) can be employed to update the variable $X_{0i} = [P_i Q_i V_i^2]^T \; i = 1\ldots\ldots n$ successively along the feeder starting from the substation and proceedings towards the end feeder. When we reach the end of the feeder, the updated variables Pn, Qn will be the mismatches as indicated by the equation (3.14). This procedure is called the forward sweep.

The elements of the system jacobian can be calculated by using the chain rule. For the main feeder case, the jacobian is a 2x2 matrix of the following form.

$$J(Z) = \begin{bmatrix} \frac{\partial \hat{P}_n}{\partial P_0} & \frac{\partial \hat{P}_n}{\partial Q_0} \\ \frac{\partial \hat{Q}_n}{\partial P_0} & \frac{\partial \hat{Q}_n}{\partial Q_0} \end{bmatrix} \qquad (3.19)$$

By using the branch flow equation (3.12) and applying chain rule, $J(Z_{00})$ can be constructed as follows.

$$J = \begin{bmatrix} \frac{\partial \widehat{P}_n}{\partial X_{n-1}} \\ \frac{\partial \widehat{Q}_n}{\partial X_{n-1}} \end{bmatrix} \begin{bmatrix} \frac{\partial X_{n-1}}{\partial X_{n-2}} \cdots\cdots \frac{\partial X_i}{\partial X_{i-1}} \cdots\cdots \frac{\partial X_1}{\partial X_0} \end{bmatrix} \qquad (3.20)$$

$$J_i = \frac{\partial X_i}{\partial X_{i-1}}$$

$$= \begin{bmatrix} 1 - 2R_i \frac{P_{i-1}}{V_{i-1}^2} & 2R_i \frac{Q_{i-1}}{V_{i-1}^2} & R_i \frac{(P_{i-1}^2 + Q_{i-1}^2)}{V_{i-1}^4} \\ -2X_i \frac{P_{i-1}}{V_{i-1}^2} & 1 - 2X_i \frac{Q_{i-1}}{V_{i-1}^2} & X_i \frac{(P_{i-1}^2 + Q_{i-1}^2)}{V_{i-1}^4} \\ -2\left(R_i - Z_i^2 \frac{P_{i-1}}{V_{i-1}^2}\right) & -2\left(X_i - Z_i^2 \frac{Q_{i-1}}{V_{i-1}^2}\right) & 1 - Z_i^2 \frac{(P_{i-1}^2 + Q_{i-1}^2)}{V_{i-1}^4} \end{bmatrix}$$

$$(3.21)$$

Ji is the jacobian of branch flow equation i and will be referred as branch jacobian. Therefore calculation of 2x2 jacobian in equation(3.21) can easily be achieved by the multiplication of the 2x3, 3x3 and 3x2 matrix in equation (3.20). The mismatch can be calculated by generalizing the forward sweep procedure as follows. For lateral K, given the estimated power injected in to the lateral P_{k0}, Q_{k0} and the voltage at the branching node V_k the forward sweep method of the main bus to update the variable $X_{ki} = [P_{ki} Q_{ki} V_{ki}^2]^T$along lateral P_{kn} and Q_{kn} .(To update all the variables and thus obtain all the mismatches, above procedure is applied to all the laterals in an order such the main feeder is updated before the lateral branching out form it.)

Note that mismatches and the jacobian matrix in the proposed method involves only the equivalent of simple algebraic expression and no trigonometric function as opposed to the standard load flow case. Thus computationally the proposed method is efficient and has very good numerical properties and it can be modified to make it computationally even more efficient.

3.5 FLOW CHART FOR LOAD FLOW

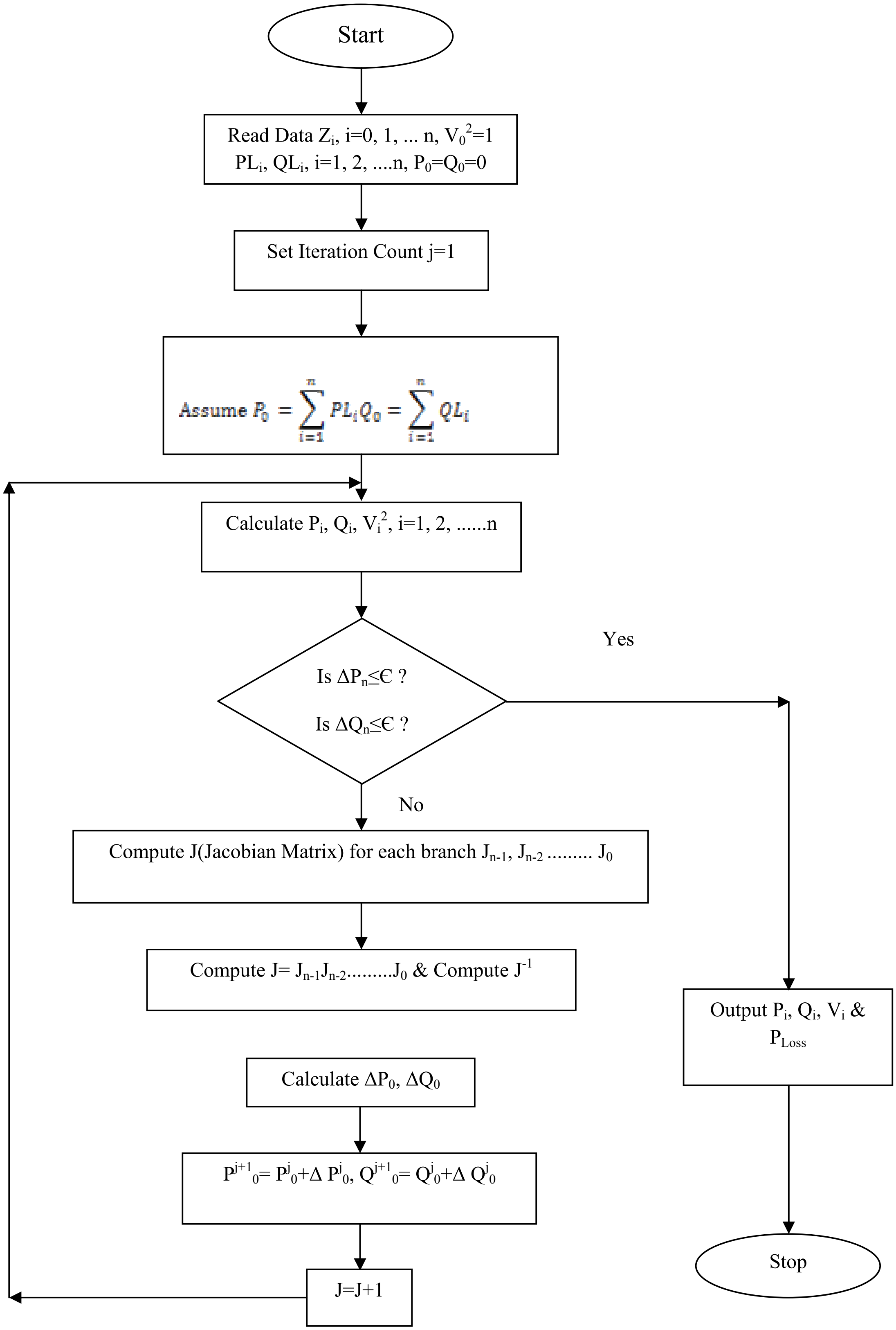

Fig.3.2 Flow Chart for Load Flow

CHAPTER 4

OPTIMAL CONDUCTOR SIZE SELECTION AND CAPACTOR ALLOCATION

4.1 INTRODUCTION

The distribution feeders share a major part of the cost of distribution system. Thus, an optimal design of the distribution feeder is an essential activity of the distribution system planning. The feeders are usually radial in configuration. The currents carried by the distribution feeders are always decreasing in order from source point to far end load point. Therefore, for an economical design of a feeder the various portions of the feeders should be in accordance with the currents carried by them. This necessiates designing the radial feeder using multi-conductor cross sections, so as to minimize the cost of feeder. Thus in this chapter a model for optimal design of multiconductor cross sectional radial feeder has been developed which is a constrained minimization problem.

4.2 PROBLEM FORMULATION

Fig.4.1 shows a typical radial feeder, because of non-uniform loading of the feeders the Feeder has been divided in line sections and loads for analysis purpose. The load points are represented by n nodes (here n = 33) and source point by node 0. The line sequents are recognized by their head node number. For example segments between 0 & 1 and 1 & 2 are represented by 1 and 2 respectively.

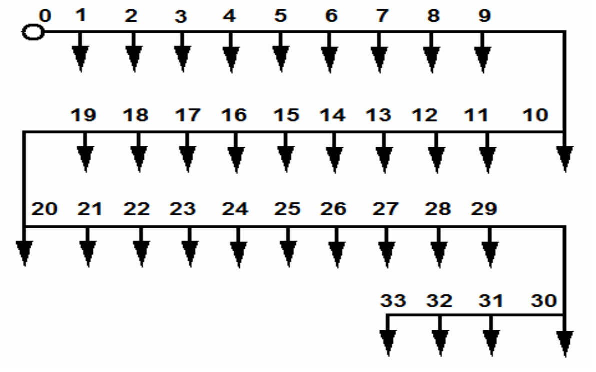

Fig.4.1 A 33-Bus Radial Distribution Feeder [27]

4.2.1 Optimization Problem of Conductor Size Selection

Optimization Problem of Conductor Size Selection The optimization problem of conductor size selection in planning radial distribution systems is to select the conductor sizes with the minimal total cost under the constraints of:

i) Maximum allowable voltage drop,

ii) Demand/supply balance, and

iii) Radial configuration.

For the sake of simplicity, the following conditions apply in this thesis work is:

i) Only a peak load for a planning period of one year is considered.

ii) The feeder configuration is known.

4.2.2 Formulation of the Optimization Problem

The optimization problem can be formulated as the following integer programming problem [1].

4.2.2.1 Objective Function [27]

$$\min C_c = \sum_{k=1}^{b} \left[\frac{\alpha(P_k^2 + Q_k^2)}{A_k} + \beta A_k \right] L_k \tag{4.1}$$

where,

- C_c is a cost to be minimized, which involves the areas of conductor cross sections;
- b is the number of all feeder segments;
- P_k and Q_k and are respectively the real and reactive powers through feeder segment k in the base year ($P_k>0$ and $Q_k >0$);
- A_k is the decision variable for the area of conductor cross-section of feeder segment k, which takes one of the discrete values of cross-section areas for the conductors available in the inventory;
- L_k is the length of feeder segment k;
- β is a constant concerning the variable installation cost of the line, which can be determined from the cost versus conductor cross-section characteristic of the line according to [1];
- α is a constant related to the peak power/energy losses costs, and can be formulated from [1] as follows:

$$\alpha = \frac{26.28\rho\left[\sum_{k=1}^{M}\frac{(1+g)^{2k}(LLF)_k C_k}{(1+r)^k} + (1+g)^{2M}(LLF)_M \sum_{k=M+1}^{N}\frac{C_k}{(1+r)^k}\right]}{V_N^2} \tag{4.2}$$

where,

- ρ is the resistivity of conductor material;
- M is a plan period up to which the line can take load growth;
- g is an annual load growth rate;
- $(LLF)_k$ the loss load factor in the kth year;
- C_k is the cost of energy in the kth year;
- r is an annual discount rate;
- N is the life period of line;
- V_N is the rated phase to phase voltage of distribution line.

Thus, it can be seen that α and β are not fixed parameters for all cases, but dependent on some other technical and economic parameters.

4.2.2.2 Constraints [27]

a) Condition for radial configuration

$$b = n - 1 \qquad (4.3)$$

where n is the number of all nodes.

b) Kirchhoff's current law

$$\sum_{k \epsilon Bi} \lambda_k (P_k + jQ_k) = S_i \qquad (i \epsilon N_1) \qquad (4.4)$$

where

- λ_k is 1 or –1 (if P_k enters node i, λ_k is 1; otherwise, λ_k is –1);
- B_i is the set of the line segments directly connected to node i;
- S_i is the load demand at node i;
- N_1 is the set of the nodes excluding the substation node.

c) Node voltage constraints

$$\sum_{k \epsilon Mi} \frac{L_k \left(\frac{\rho P_k}{A_k} + Q_k x \right)}{V_N} \leq \Delta \bar{V} \qquad (i \epsilon N_2) \qquad (4.5)$$

where,

- x is the per-phase, per-kilometer reactance of distribution line, which is assumed constant for a given range of conductor sizes;
- M_i is the set of the feeder segments through which load S_i flows;
- $\Delta \bar{V}$ is the value of maximum allowable voltage drop; N_2 is the set of the end nodes of radial feeders.

4.2.3 Solution Methodology [27]

This practical approach combines two methods, namely an economical current density based method and a heuristic method, and, thus, allows one to efficiently find the cross-section areas. The heuristic method employs an index, the ratio of cost increase to voltage decrease because of the change in conductor size, and thus is called "RCV index method" hereafter. In what follows, the two consecutive methods and their combined usage are, respectively, shown.

4.2.3.1 Economical Current Density Based Method [27]

Given the feeder configuration, the economical current density based method is employed to obtain initially selected cross section areas (referred to as "initial cross-section areas" hereafter) and approximate power flows for all feeder segments, with (4.5) being ignored. The approximate power flows can be found by using the same V_N for all node voltages and the initial cross-section areas. For the problem of conductor sizing, the approximate power flows can result in less computational effort compared to the actual power flows, and also produce satisfactory results. For any line segment k, with its power flows being known, a continuous value $\underline{A_k}$of its cross-section area can be given from (4.1) by

$$\underline{A_k} = \sqrt{\frac{\alpha(P_k^2 + Q_k^2)}{\beta}} \tag{4.6}$$

In what follows, the major points of this method are explained For the feeder segments starting from the far (or end) ones and moving along all the feeder branches toward the substation node, alternate the following activities: i) find their approximate power flows by employing the node power balance method of power flow analyzes and ii) calculate their $\underline{A_k}$'s by (4.6), and then determine their initial discrete cross-section areas which result in less costs between their two optional cross-section areas (whose values are, respectively, next to their corresponding $\underline{A_k}$'s) or which are, respectively, their only available cross-section areas (next to their corresponding $\underline{A_k}$'s). If the initial cross-section areas can satisfy (4.5), an optimal solution has been achieved; otherwise, they should be modified by the following heuristic method, and, for any line segment, the cross-section areas whose values are smaller than that of its initial one, shouldn't be taken into account afterwards.

4.2.3.2 RCV Index Method [27]

Based upon the previously obtained cross-section areas, the RCV index method can be employed

i) To dynamically produce a priority list of the indexes to be defined below, and, thus,

ii) To efficiently find the improved cross-section areas for the line segments in a radial branching feeder so as to meet the requirements of (4.5).

Fig. 4.2 shows a flow chart of this method.

4.2.3.3 Flow Chart of RCV Method [27]

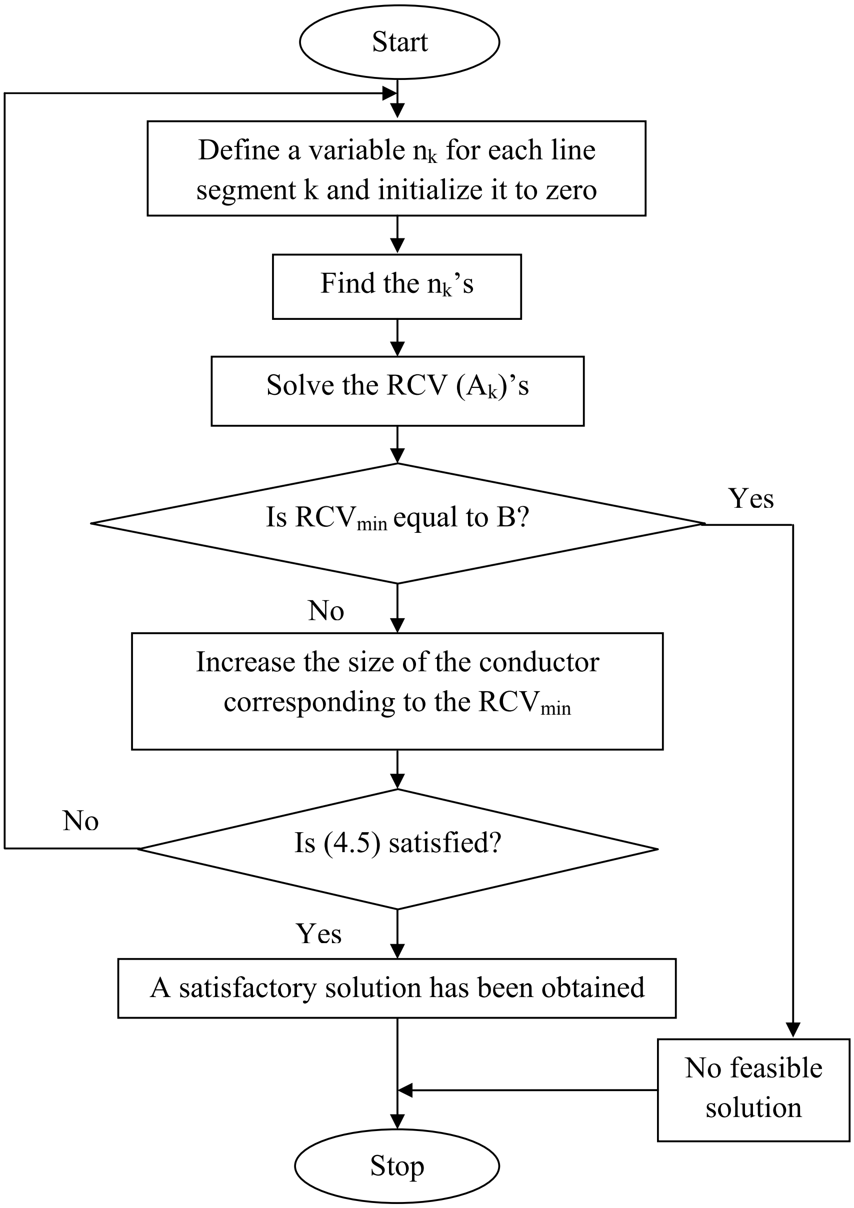

Fig.4.2 RCV Index Method

4.2.3.4 Algorithm for RCV Index Method [27]

Its details in 6 steps can be stated as follows:

Step 1 Define a variable n_k for any line segment k and initialize it to zero.

Step 2 For each end node, find the voltage drop between it and the substation node; if a voltage drop exceeds $\Delta\overline{V}$, increase by 1 the n_k's for the line segments through which the load at the corresponding end node flows.

Step 3 Assume that the cross-section area A_k for any line segment k is replaced with an immediately greater one $A`_k$ available and define a RCV(A_k) index as being directly proportional to the resulting increase in C_c and inversely proportional to both the n_k and the resultant decrease in voltage drop. Therefore, from (4.1) and (4.5), RCV may be given by

$$RCV(A_k) = \frac{[\beta A_k A_k^{`} - \alpha(P_k^2 + Q_k^2)]}{P_k n_k} \tag{4.7}$$

Note that if n_k=0 or there is not any greater available crosssection area compared with A_k, let RCV (A_k)=B(a very large number).

Step 4 If the smallest value RCV_{min} among the existing RCV(A_k)'s equals B, stop with no feasible solution.

Step 5 Replace the cross-section area corresponding to the existing RCV_{min} with an immediately greater one available.

Step 6 If (4.5) still can't be satisfied, go to Step 1; otherwise, stop with a near-optimal solution, namely the existing crosssection areas A_k's.

The proposed approach is an organic combination of the economical current density based method and the heuristic RCV index method, and is applicable to all types of radial feeders in practice.

4.3 ALLOCATION OF SHUNT CAPACITOR

The capacitor placement problem is to determine the location, and size of the capacitor to be placed on the distributed system. The objective is to obtain the location and size of the capacitor such that given objective function is minimized.

The optimal capacitor placement problem as defined above has many parameters, such as, the location, number and cost of capacitors, voltage constraints, and load variation on the system. These parameters determine the complexity of the problem.

Recently these have been some studies to solve the problem in its general form. There are basically three approaches. The first one is dynamic programming type approach by treating the capacitor sizes as discrete variables. The second approach is to combine the conventional analytical method with heuristics. Third approach pioneered by Grainger et al is to formulate the problem as a nonlinear programming problem by treating the capacitor sizes and locations as continuous variables.

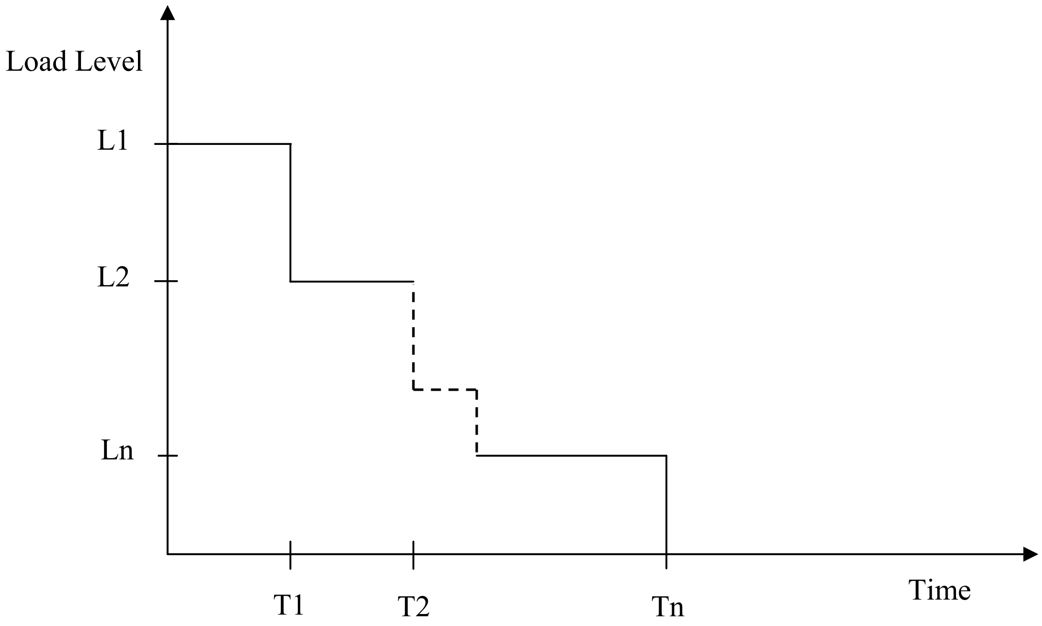

Fig 4.3 Load Duration Curve

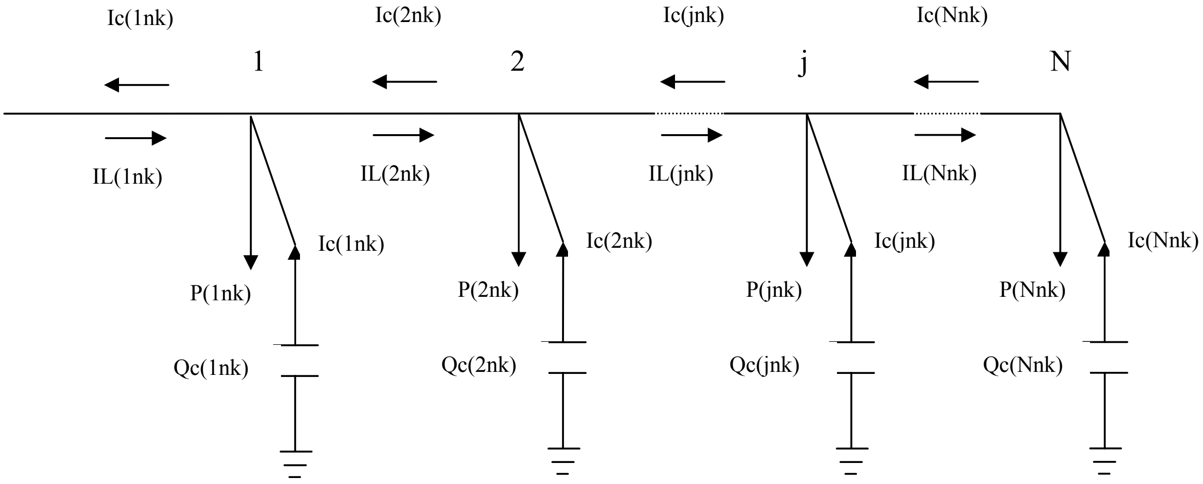

Fig 4.4 Typical Distribution Feeder

Growth of load along with change in cost of energy with time considerably influences the size and location of shunt capacitors to be installed along the feeder. Thus it is imperative to incorporate the effect of growth of load over the planning horizon to obtain realistic results, since with growth in load reactive currents also grow necessitating more capacitive currents to compensate them with the lapse of time.

The loads are always varying in nature. The load variation of a given period can be known from the load duration curve. The Fig.4.3 shows a typical load duration curve. The load level L_1 is assumed to occur till T_1 time, load level L_2 for T_2 time and so on. As the load level changes, the reactive currents also change and the capacitive currents required to compensate them also change leading to different sizes of capacitors to he installed for different time. Because of this reason fixed capacitors are installed for time T_3. For T_2 and T_1 switched Capacitors are needed to be put on service as por the load level.

As far as the location of the capacitors is concerned, as already mentioned above, the most probable location of the capacitors is the load point. So in this thesis work optimum size, in terms of reactive power supplied, of the capacitors installed at load points of the feeder is determined. The Fig.4.4 shows a typical distribution feeder. There are N load points other then the source point and N sections. The maximum inductive current flow through the feeder section j in the year K is represent by I_{Ljk} (j=1, 2 ….. n; k=1, 2…… T), resistance and reactance of the feeder are represented by R_j and X_j(j=1, …… n). Let I_{Cjk} (j=1, …… n) be the capacitor current injected due to installed capacitor bank of capacity Q_{Cjk} at load point j during k_{th} year and I_{Cjk} is the current flowing through feeder section j due to the capacitors connected at load point j to N during k_{th} year.

The problem is to calculate the value of shunt capacitor banks Q_{Cjk} at the distribution feeder load points (j = 1 to N) during the year k (k = 1 to T) so as to maximize the net return due to installation of capacitors. The affect of load growth during the planning period is also taken into account. The effect of voltage rise due to installation of capacitor banks, at load points and source points, during off peak hours is considered as limiting factor.

4.4 SINGLE VARIABLE UNCONSTRAINED OPTIMIZATION APPROACH (COGGIN ALGORITHM)

A large number of multivariable search methods require an unconstrained single variable search building block. Many variations exist for this type of problem. All start from some base point and move towards the optimum based on sequential improvement in the value of the objective function. Step size may be fixed accelerated and decelerated subject to set of rules.

The solution of power flow problems on digital computers has become a standard practice. The aim is to adjust the control variables according to some criterion. The importance of this search technique goes beyond one-dimensional problems in that many n-dimensional search techniques utilize a sequence of one-dimensional searches. It does not involve the use of derivatives, but is quadratic convergent all the same, even in the n-dimensional case. Quadratic convergence is that property of the search technique, which enables a minimum of a quadratic function to be located exactly in a finite number of steps, subject to round-off errors. A quadratic function is fitted into the data (last three points), if minimum is achieved that is the answer, else three point interpolation is repeated with new data.

5.3 FLOW CHART FOR OPTIMUM SIZE (COGGIN APPROACH)

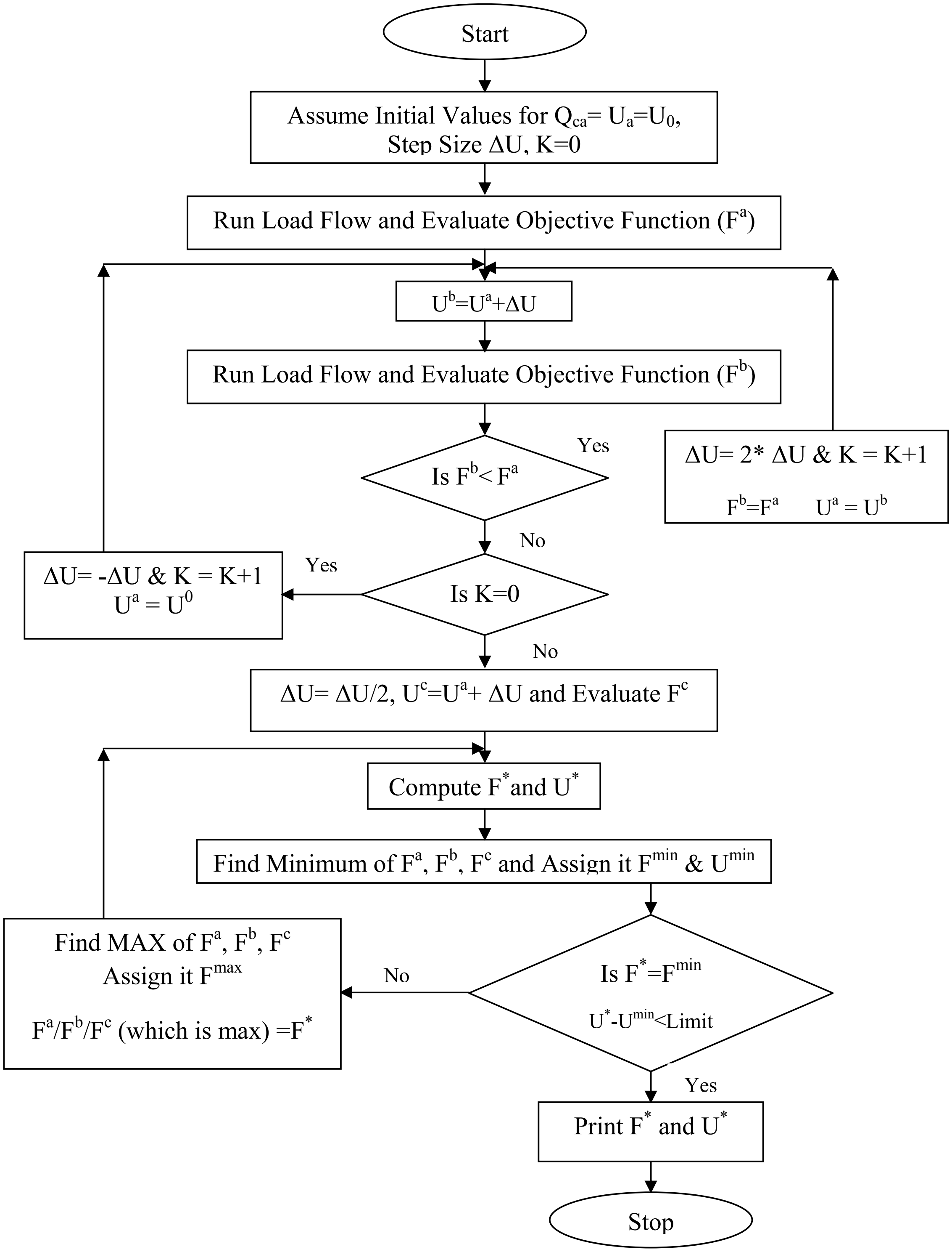

Fig.4.5 Flow Chart for Optimum Capacitor Placement Using Coggin Approach

4.4.2 Algorithm for Optimal Size (Coggin Approach)

The algorithm proceeds as follows:

Step 1. A starting point is chosen and objective function is evaluated.

Step 2. The independent variable is incremented a distance (Δu) and the objected function evaluated again. If a function improvement is obtained the step size is doubled for the next function evaluation. If a function improvement is not obtained on the first step the direction is reversed and the next point is located a distance (Δu) from starting point.

Step 3. After the first step, the size is doubled if the function improvement is obtained and halved if worse function evaluation is obtained.

Step 4. In a local optimum is encountered, the procedure will yield three points(U_k, U_{k-1}, U_{k-2}) straddling the optimum. An additional points, U_{k+1}, is then located:

where ΔU_k, is the current step size. The best three points are then retained.

(Call U_1,U_2,U_3).

Step 5. A quadratic equation, F ,is then curve fitted to the three retained points. The optimum location, U^*, located by setting $\partial F/\partial U=0$, is

$$U^* = \frac{1}{2}\left[\frac{(U_2^2 - U_3^2)f(U_1) + (U_3^2 - U_1^2)f(U_2) + (U_1^2 - U_2^2)f(U_3)}{(U_2 - U_3)f(U_1) + (U_3 - U_1)f(U_2) + (U_1 - U_2)f(U_3)}\right]$$

(4.8)

Step 6. The objective function at U^* is then compared with the best previous point subjected to the convergence limit,

$$|U^* - U_1| \leq limit$$

If the above criterion is satisfied, the procedure stops. If not, the worst point is replaced by U^* and a new quadratic surface fitted and local optimum obtained. This process is repeated until the convergence criterion is satisfied.

CHAPTER 5

RESULT

5.1 RESULTS FOR CAPACITOR PLACEMENT

In this work, for the practical planning of radial distribution network, a 33 bus radial distribution network has been studied. To find the optimal capacitor placement firstly the load flow analysis is performed to the distribution system without any capacitor. The various parameters like active power, reactive power, path loss, voltage and sensitivities, in this case, calculated by load flow technique are shown in table. to improve the efficiency of distributed system the capacitor placement is done by cogging method. To validate the improvement by capacitor placement by coggin method the load flow is performed to distribution system with capacitor placement. The results with capacitors are shown in table.

After allocation of capacitor using coggin logic, the voltage profile of the system is improved and path losses are reduced. Sensitivity is also improved after the capacitor placement.

The output table is shown below. In this all the calculated parameters are shown.

Table 5.1 Load Flow Results without Capacitor Placement

BusNo	Active	Reactive	Pathloss	Voltage	Sensitivity
1	10.834062	5.744821	0.110254	1.000000	0.002422
2	9.701242	2.931232	0.030697	0.991824	-0.000102
3	9.302845	2.265120	0.624550	0.972494	0.0465230
4	8.393231	1.262941	0.498968	0.915416	-0.067226
5	7.55279	0.390262	1.232523	0.890226	-0.078230
6	6.072238	-1.317442	0.526332	0.765682	0.392954
7	5.295883	-1.348062	1.120723	0.698252	0.439224
8	4.165543	-2.243437	2.180247	0.618223	0.821002
9	1.756402	-3.285253	2.340291	0.502102	2.077102
10	1.426143	-4.570424	0.003244	0.646228	0.018921
11	1.391544	-4.783523	0.011023	0.657336	0.002256
12	1.216221	-5.141422	0.384230	0.69532	0.108262
13	0.519207	-5.83071	0.345653	0.7542423	0.065241
14	0.798215	-6.241742	0.982322	0.790338	0.213412
15	1.041228	-7.469002	0.56802	0.896126	0.047134
16	0.312354	-7.926132	1.227934	0.942731	0.108608
17	1.760432	-8.629121	2.929404	0.092443	0.288435
18	1.972302	-10.295442	3.218540	0.221056	-0.056722
19	1.861435	-12.230223	0.0931031	0.460022	-0.020127
20	1.445109	-12.423142	0.01233	0.482323	-0.014302
21	1.289634	-12.795622	0.4522128	0.501224	-0.084404
22	0.523431	-13.621803	0.435610	0.582234	-0.091124
23	0.721204	-14.029760	1.298440	0.604342	-0.282234
24	1.398023	-15.234034	0.613521	0.784026	-0.154142
25	0.487615	-16.223804	1.414202	0.798624	-0.348628
26	1.82016	-17.102455	3.304302	0.911225	-0.917424
27	2.180179	-18.921681	3.686288	1.402902	-1.192682
28	2.106724	-20.982421	0.722383	1.421311	-0.262528
29	1.402182	-21.831923	1.472046	1.392442	-0.582142
30	0.922976	-23.769243	3.320124	1.616562	-1.510212
31	3.163503	-25.781224	3.724563	1.822183	-1.920712
32	1.280821	-26.610623	3.292854	1.962134	-1.782924
33	2.464562	-28.323321	0.000000	0.000000	33.000000

Table 5.2 Load Flow Results without Capacitor Placement Using Coggin Logic

BusNo	Active	Reactive	Pathloss	Voltage	Senstivity
1	10.594577	5.634884	0.103357	1.000000	0.002545
2	9.307543	2.631235	0.010697	0.980812	-0.000098
3	9.062845	2.085180	0.544550	0.967995	0.042403
4	8.091296	1.099094	0.458968	0.895502	-0.066027
5	7.251328	0.260160	1.162568	0.840524	-0.076840
6	5.704759	-0.901878	0.472776	0.710766	0.384956
7	5.045683	-1.340106	1.005572	0.663858	0.438192
8	3.766111	-1.923983	2.099247	0.568245	0.817718
9	1.432864	-3.145295	2.237891	0.474622	2.076172
10	1.196027	-4.460426	0.000000	0.615961	0.016938
11	1.141505	-4.643665	0.006183	0.637824	0.001877
12	0.896322	-5.021341	0.339420	0.672493	0.101660
13	0.222902	-5.650791	0.324154	0.737973	0.063844
14	0.528252	-6.039752	0.956253	0.774372	0.219191
15	0.809001	-7.316699	0.500846	0.880153	0.046054
16	0.024155	-7.896491	1.177979	0.927743	0.100476
17	1.440124	-8.589922	2.789554	0.015221	0.231985
18	1.723430	-10.18595	3.148540	0.196003	-0.042687
19	1.659110	-12.00013	0.073101	0.395471	-0.011067
20	1.295009	-12.293510	0.008308	0.422404	-0.001304
21	1.086701	-12.65453	0.444298	0.463626	-0.072409
22	0.203403	-13.481180	0.421610	0.542736	-0.082861
23	0.452207	-13.929760	1.206490	0.584794	-0.234253
24	1.181283	-15.09349	0.563658	0.706334	-0.138193
25	0.236625	-16.02372	1.351342	0.757876	-0.335263
26	1.498717	-16.93245	3.214734	0.845701	-0.827419
27	1.902316	-18.781460	3.596193	1.044939	-1.132601
28	1.967877	-20.83247	0.612396	1.262612	-0.237973
29	1.121481	-21.6512	1.392978	1.342351	-0.554884
30	0.662497	-23.53993	3.262201	1.538290	-1.454899
31	2.873703	-25.61139	3.644566	1.773213	-1.889765
32	1.004863	-26.43781	3.282832	1.842721	-1.720905
33	2.668969	-28.34693	0.000000	0.000000	33.000000

Graphical output for the capacitor placement and comparison are shown below:

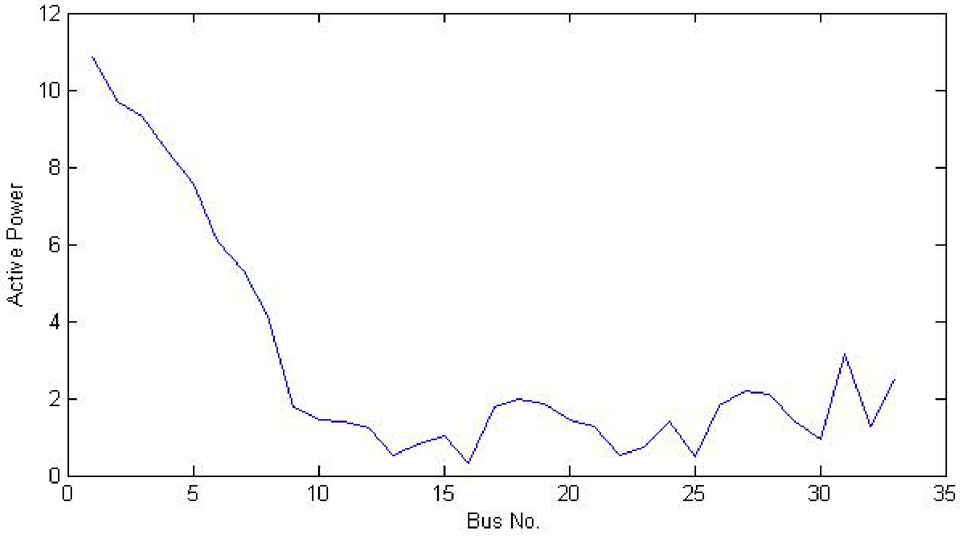

Fig. 5.1 Active Power at Each Node (Without Capacitor Placement)

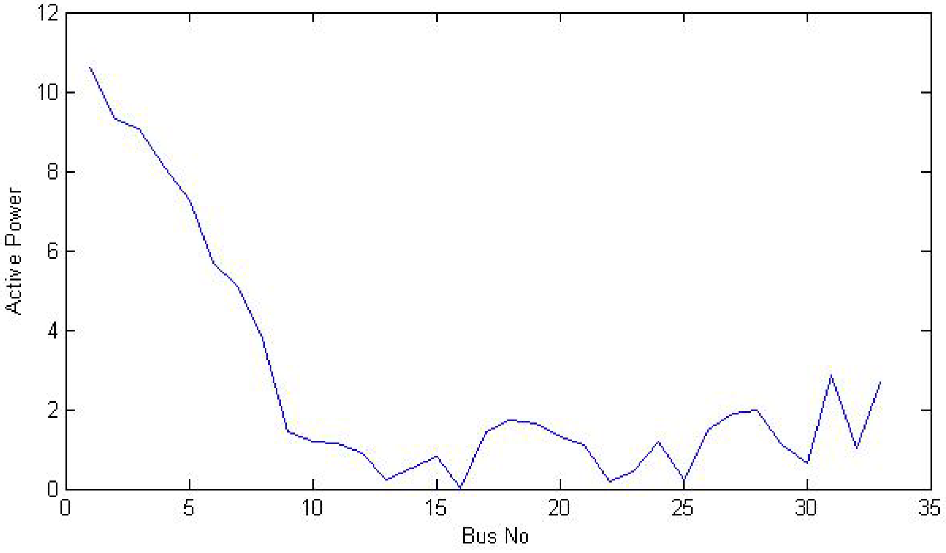

Fig. 5.2 Active Power at Each Node (With Capacitor Placement)

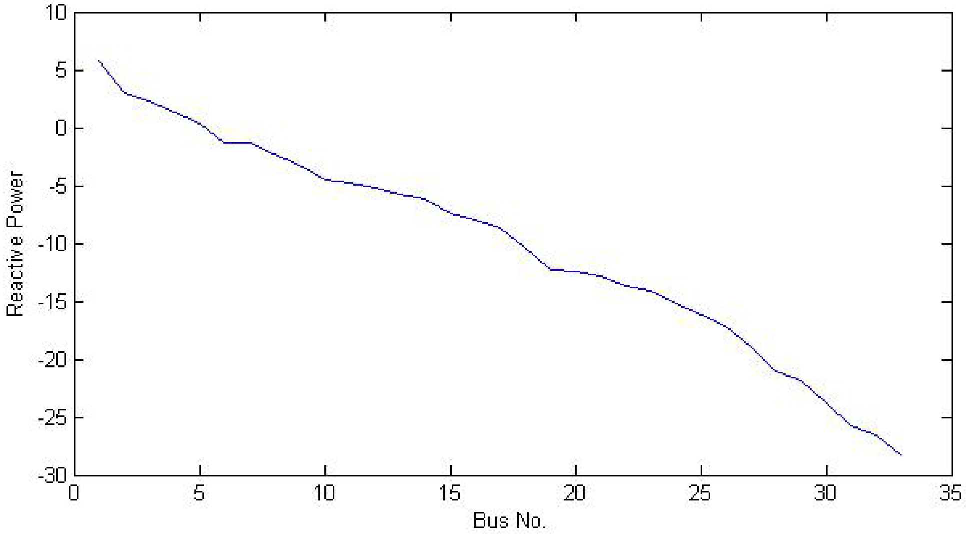

Fig. 5.3 Reactive Power at Each Node (Without Capacitor Placement)

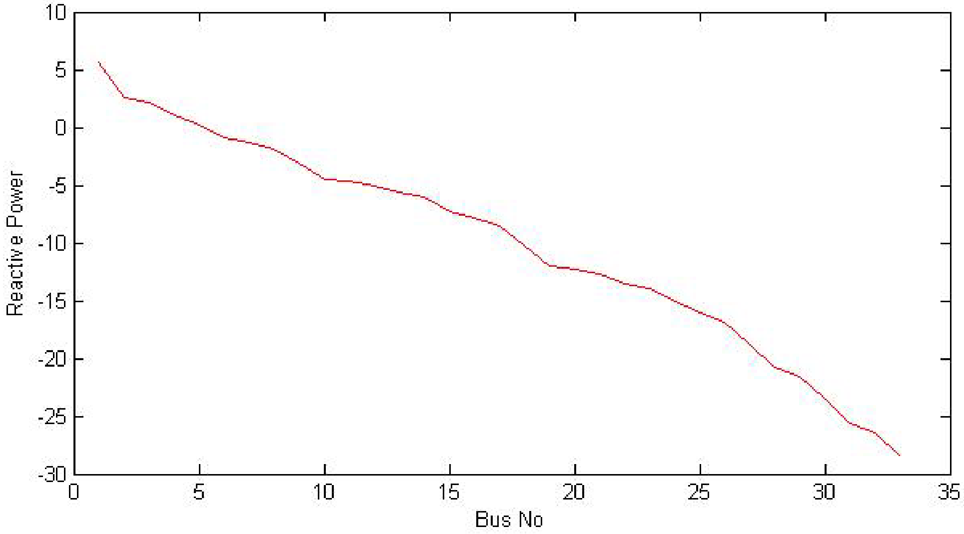

Fig. 5.4 Rective Power at Each Node (With Capacitor Placement)

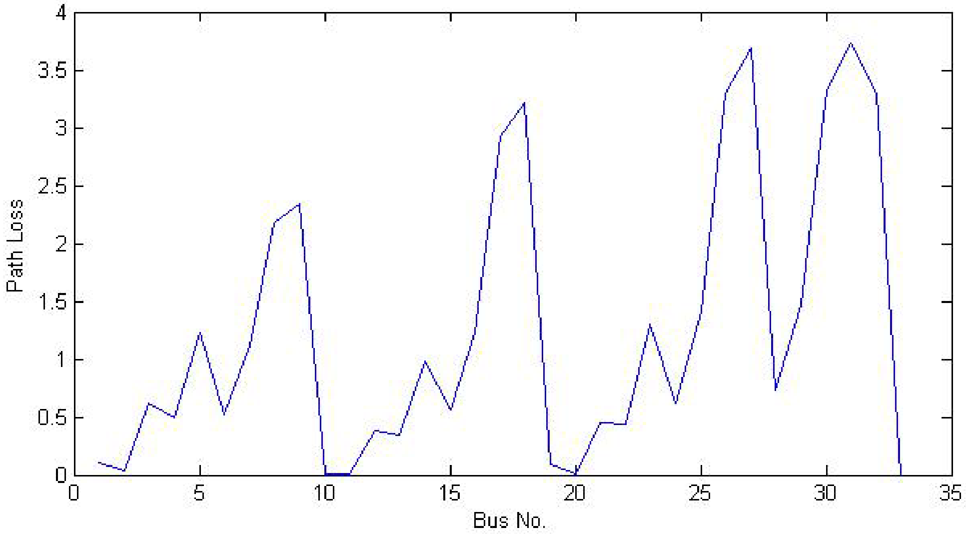

Fig. 5.5 Path Loss at Each Node (Without Capacitor Placement)

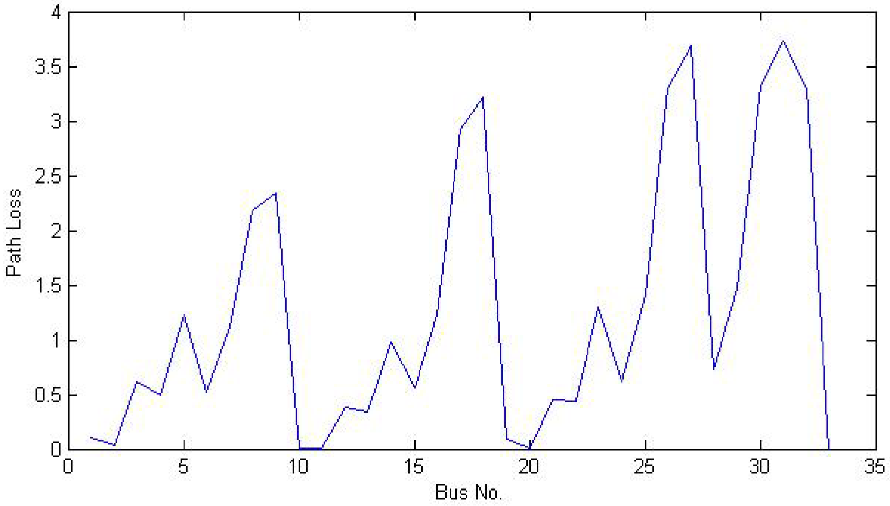

Fig. 5.6 Path Loss at Each Node (With Capacitor Placement)

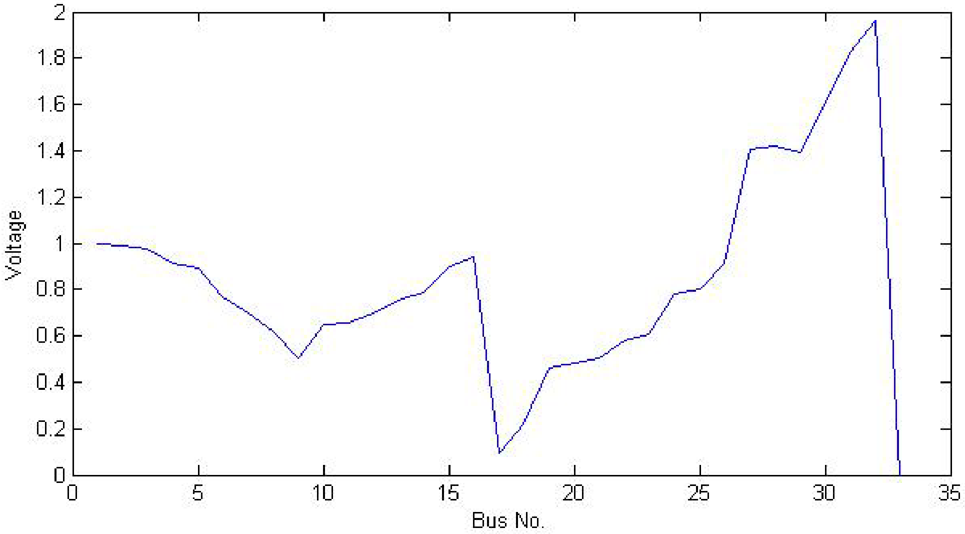

Fig. 5.7 Voltage at Each Node (Without Capacitor Placement)

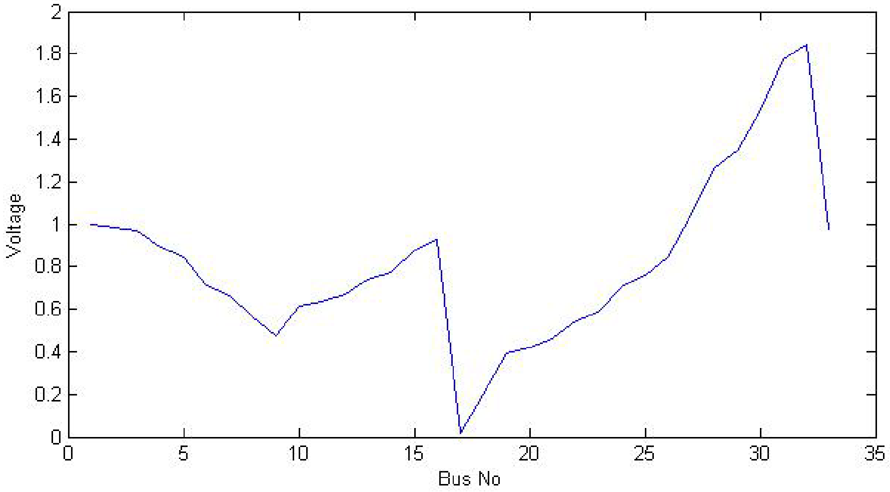

Fig. 5.8 Voltage at Each Node (With Capacitor Placement)

5.2 RESULTS FOR CONDUCTOR GRADATION

Table 5.3 Initial and Final Cross-Section Area of the Conductor

k	Ak	Ak(a)	Ak(b)
1	139.7118	95	150
2	120.1259	95	150
3	85.93280	70	95
4	81.30860	70	95
5	77.93320	70	95
6	44.27560	50	95
7	37.05850	35	70
8	28.99650	25	50
9	22.67960	25	35
10	19.82770	16	25
11	18.14760	16	25
12	14.72060	16	16
13	11.09980	16	16
14	7.11100	16	16
15	4.39650	16	16
16	0.82930	16	16
17	2.73240	16	16
18	13.7528	16	16
19	11.0669	16	16
20	6.64760	16	16
21	3.11900	16	16
22	0.06700	16	16
23	17.2332	25	35
24	27.2386	16	16
25	13.3141	16	16
26	29.2251	25	50
27	27.1518	25	50
28	24.1685	25	50
29	20.8404	25	50
30	16.3550	16	25
31	15.1445	16	25
32	9.7169	16	16
33	2.8910	16	16

Cost (without Grading) = 1138414.6767

Cost with Conductor Grading = 919865.4241

CHAPTER 6

CONCLUSIONS AND FUTURE SCOPE OF WORK

6.1 CONCLUSIONS

In the present work two major areas of distribution system planning i.e. conductor gradation and allocation of shunt capacitor on distribution feeders have been considered. For planning purpose 33-bus system has been considered. The whole system is assumed to be balanced. The interactive part uses Coggin Algorithm and all the standard data is taken as shown in appendix-A. The proposed method selects optimal branch conductors by minimizing an objective function, which is the sum of feeder loss cost, and the feeder cost. In addition, the proposed method keeps the minimum voltage within the prescribed limit and the current flowing through each branch is less than the maximum current carrying capacity of the corresponding branch conductor. The coggin logic for optimal capacitor placement has been used. The method optimises the system and after the conductor gradation, the system becomes economical.

6.2 FUTURE SCOPE OF WORK

The work can be extended by incorporating distribution system expansion planning and feeder network planning. The same work can be further modified by taking the similar network as unbalanced and meshed one.

REFERENCES

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1. Ponnavsikko, M.; Rao, K.S.P., "An approach to optimal distribution system planning through conductor gradation," IEEE Trans. PAS, vol. 101, no. 6, pp. 1735-1742, June 1982.
2. Pabla, A.S., "Electrical Power Distribution Systems". (Book) Tata McGraw-Hill Publishing Company Limited, New Delhi, 1981.
3. Brown, Richard E, "Electric Power Distribution Reliability", Second Edition, (Book). CRC Press, Taylor & Fransis Group, Boca Raton London New York, 2009.
4. Dixon, G.F.L., Hammersley, H., "Reliability and its Cost on Distribution Systems", International Conference on Reliability of Power Supply Systems, IEE Conference Publication No. 148, 1977.
5. Khan, A.H., Broadwater, R.P., Chandrasekaran, A., "A Comparative Study of Three Radial Power Flow Methods", Proceedings of the IASTED International Symposium. HIGH TECHNOLOGY IN THE POWER INDUSTRY, ACTA Press, March, 1998.
6. Renato Cespedes G., "New Method for the Analysis of Distribution Networks". IEEE Transaction on Power Delivery Vol. 5, No. 1, pp. 391 -396, Jan. 1990.
7. Goswami, S.K., Basu, S.K., "Direct Solution of Distribution Systems", IEE proc. C, Vol. 138, No.1, pp. 78-88, Jan. 1991.
8. Goswami, S.K., Basu, S.K., "Power Flow Solution of Weakly Meshed Distribution System Using Direct Solution Technique", IE (I) Journal - EL, Vol. 72. pp. 279-283, February 1992.
9. Goswami, S.K., Basu, S.K., "Storage and Computational Aspects of Direct Solution Technique for Radial Distribution Systems" IE (I) Journal —EL. Vol. 72, pp. 284-290, February 1992.

10. Chen, T.-H.; Chen, M.-S.; Hwang, K.-J.; Kotas, P.; Chebli, E.A., "Distribution system power flow analysis-a rigid approach," Power Delivery, IEEE Transactions on , Vol.6, no.3, pp.1146-1152, Jul 1991
11. Baran, M.; Wu, F.F., "Optimal sizing of capacitors placed on a radial distribution system ," Power Delivery, IEEE Transactions on , Vol.4, no.1, pp.735-743, Jan 1989.
12. Brodsky, Steven F. J.; Wrobel, P. S.; Willis, H. L., "Comparison of Distribution Circuit Voltage Modeling and Calculation Methods," Power Delivery, IEEE Transactions on , Vol.2, no.2, pp.572-576, April 1987
13. Whei-Min Lin; Yuh-Sheng Su; Hong-Chan Chin; Jen-Hao Teng, "Three-phase unbalanced distribution power flow solutions with minimum data preparation," Power Systems, IEEE Transactions on , Vol.14, no.3, pp.1178-1183, Aug. 1999.
14. Zimmerman, R.D.; Hsiao-Dong Chiang, "Fast decoupled power flow for unbalanced radial distribution systems," Power Systems, IEEE Transactions on , vol.10, no.4, pp.2045-2052, Nov. 1995.
15. Neagle, N. M.; Samson, D. R., "Loss Reduction from Capacitors Installed on Primary Feeders," Power Apparatus and Systems, Part III. Transactions of the American Institute of Electrical Engineers, Vol.75, no.3, pp.950-959, Jan. 1956.
16. Cook, R.F., “Analysis of Capacitor Applicatin as Affected by Load Cycle”, AILL Trans. (PAS), Vol. 78, pp. 950-957. October, 1 959.
17. Schmill, J. V., "Optimum Size and Location of Shunt Capacitors on Distribution Feeders," Power Apparatus and Systems, IEEE Transactions on , Vol.84, no.9, pp.825-832, Sept. 1965.
18. Carlisle, J.C.; El-Keib, A.A.; Boyd, D.; Nolan, K., "A review of capacitor placement techniques on distribution feeders ," System Theory, 1997., Proceedings of the Twenty-Ninth Southeastern Symposium on , vol., no., pp.359-365, 9-11 Mar 1997.
19. Chang, N.E., “Locating Shunt Capacitors an Primary Feeders for Voltage Control and Loss Reduction”, IEEE Trans. (PAS) Vol. 88. pp. 1574-1577, October. 1969.

20. Bae, Y.G., “Analytical Method of Capacitor Allocation on Distribution Primary Feeders”, IEEE Trans. (PAS), Vol. 97, pp. 1232-1238, July/August, 1978.
21. Grainger, J.J.; Lee, S.H.; El-Kib, A.A., "Design of a Real-Time Switching Control Scheme for Capacitive Compensation of Distribution Feeders," Power Apparatus and Systems, IEEE Transactions on , Vol.PAS-101, no.8, pp.2420-2428, Aug. 1982
22. Grainger, J.J.; Lee, S.H., "Capacity Release by Shunt Capacitor Placement on Distribution Feeders: A New Voltage-Dependent Model," Power Apparatus and Systems, IEEE Transactions on, Vol.PAS-101, no.5, pp.1236-1244, May 1982.
23. Ponnavsikko, M.; Rao, K.S.P., "Optimal Choice of Fixed and Switched Shunt Capacitors on Radial Distributors by the Method of Local Variations," Power Apparatus and Systems, IEEE Transactions on , Vol.PAS-102, no.6, pp.1607-1615, June 1983
24. Yann-Chang Huang; Hong-Tzer Yang; Ching-Lien Huang, "Solving the capacitor placement problem in a radial distribution system using Tabu Search approach," Power Systems, IEEE Transactions on , Vol.11, no.4, pp.1868-1873, Nov 1996
25. Funk Houser. A.W., “Determining Economical ACSR Conductor Sizes For Distribution System”, AIEE Trans. (PAS). Vol. 74, 479-483, June 1955.
26. Walkden, F.W., "Design of low-voltage distributors," Generation, Transmission and Distribution, IEE Proceedings C, Vol.129, no.3, pp.101-103, May 1982.
27. Zhuding Wang; Haijun Liu; Yu, D.C.; Xiaohui Wang; Hongquan Song, "A practical approach to the conductor size selection in planning radial distribution systems," Power Delivery, IEEE Transactions on , vol.15, no.1, pp.350-354, Jan 2000.
28. Devis. M., “Design of Low Voltage Distributors from Standard Cable Sizes”, Proc. IEEE. Vol. 112(5), pp. 949-956. 1965.
29. Ponnavsikko, M.; Rao, K.S.P., "Optimal Choice of Fixed and Switched Shunt Capacitors on Radial Distributors by the Method of Local Variations," Power Apparatus and Systems, IEEE Transactions on, Vol.PAS-102, no.6, pp.1607-1615, June 1983.

Appendix- A

Table A.1 Segment Data for 33-Segment Feeder [27]

Segment	Node		Length
	From	To	
1	0	1	1.156
2	1	2	2.089
3	2	3	3.392
4	3	4	0.338
5	4	5	1.227
6	5	6	0.516
7	6	7	0.092
8	7	8	0.140
9	8	9	0.156
10	9	10	1.498
11	10	11	0.45
12	11	12	0.499
13	12	13	0.466
14	13	14	0.609
15	14	15	0.500
16	15	16	1.192
17	16	17	0.191
18	17	18	0.255
19	18	19	1.980
20	19	20	0.500
21	20	21	0.104
22	21	22	0.137
23	22	23	1.534
24	23	24	1.228
25	24	25	1.105
26	25	26	0.125
27	26	27	0.500
28	27	28	0.500
29	28	29	0.500
30	29	30	0.500
31	30	31	0.500
32	31	32	0.500
33	32	33	0.500

Table A.2 Node Load Data of the 33-Segment Feeder (kVA) [27]

Node No.	Load
1	19.50
2	32.50
3	103.25
4	52.00
5	32.50
6	48.75
7	81.25
8	48.75
9	13.00
10	13.00
11	29.25
12	107.25
13	32.50
14	65.00
15	13.00
16	65.00
17	45.00
18	19.50
19	32.50
20	71.50
21	65.00
22	32.50
23	32.50
24	156.00
25	6.50
26	32.50
27	32.50
28	32.50
29	65.00
30	32.50
31	130.00
32	117.00
33	32.50