A NEW METHOD FOR LOAD-FLOW SOLUTION OF RADIAL DISTRIBUTION NETWORKS

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

Master of Engineering
in
Power Systems & Electric Drives

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CERTIFICATE

I hereby certify that the work which is being presented in the thesis entitled, **"A New Method for Load-Flow Solution of Radial Distribution Networks"**, 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 Dr. Smarajit Ghosh and refers other researcher's works which are duly listed in the reference section.

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

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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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A journey is easier when you travel together. Interdependence is certainly more valuable than independence.

The real spirit of achieving a goal is through the way of excellence and perpetual discipline. I would have never succeeded in completing my task without the cooperation, encouragement and help provided to me by various personalities.

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ABSTRACT

Distribution systems hold a very significant position in the power system since it is the main point of link between bulk power and consumers. The growing awareness of the consumers and the increasing competition in power sector has made it a must deal that the system should operate at its best possible conditions. This thesis presents a fast and efficient method for load-flow analysis of radial distribution networks. The proposed method is based on set theory and is fast. The proposed method handles any type of node numbering. The effectiveness of the method is shown by considering an example of 69-node radial distribution network and solving it for constant load, constant current, constant impedance, composite as well as exponential load modeling.

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NOMENCLATURE

NB : Total number of the nodes
LN1 : Total number of the branch (LN1 = NB − 1)
jj : Branch number
m1 : Receiving end node
m2 : Sending end node
PL(i) : Real power load of ith node
QL(i) : Reactive power load of ith node
|V(i)| : Voltage magnitude of ith node
R(jj) : Resistance of the branch–jj
X(jj) : Reactance of the branch–jj
Z(jj) : Impedance of the branch–jj
I(jj) : Current flowing through branch–jj
P(m2) : Total reactive power load fed through node m2
Q(m2) : Total reactive power load fed through node m2
∠δ(m2) : Voltage angle of the node m2
LP(jj) : Reactive power loss of branch–jj
LQ(jj) : Reactive power loss of branch–jj
IS(jj) : Sending end node of branch–jj
IR(jj) : Receiving end node of branch–jj
IL(i) : Load current of node-i
kV : Kilovolts
kW : Kilowatts
kVAr : Amount of reactive power

CHAPTER-1

INTRODUCTION

1.1 PREFACE

Power system engineering is undoubtedly the oldest and most conventional of the various aspects of electrical engineering. In spite of this fact no other sector of modern technology is currently experiencing a more dramatic revolution in terms of both technology and industrial structure. But none of these changes alter the basic complexity of electric power system behavior, or reduce the challenge that power system engineers have always faced in designing an economical and stable system that operates as intended and shuts down in a safe and non catastrophic mode when something fails unexpectedly.

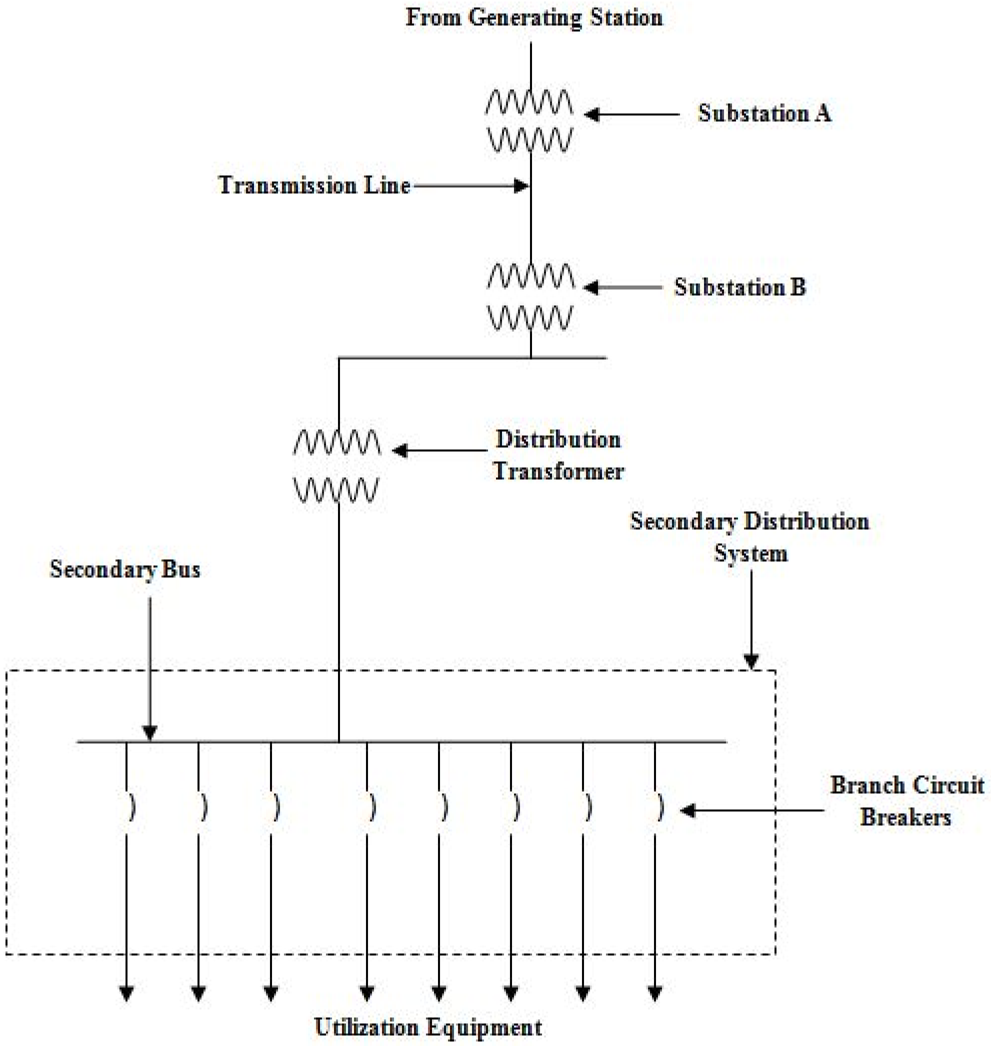
Power system may be broadly classified into three categories i.e. generation, transmission and distribution. This thesis keeps its concern over load-flow analysis of distribution system, so distribution system is discussed in detail in the following section.

1.2 ELECTRICAL POWER SYSTEM

The process of generating, distributing, and controlling the large amounts of power required for a municipality or geographic area is highly complex. However, each system, regardless of its complexity, is composed of the same basic elements with the same basic goal: Deliver ac power where it is needed by customers. In general power system may be broadly classified into three categories:

- Generation
- Transmission
- Distribution

1.2.1 TYPICAL POWER NETWORK: An understanding of basic design principles is essential in the operation of electric power systems. Although there is no typical diagram for electric power system but a schematic representation is necessary for understanding basic design principles of the system. Following diagram shows a one-line diagram of a typical electrical power generation, transmission, and distribution system.



1.1 Single Line Diagram of Typical Electric Power Generation, Transmission and Distribution

1.2.2 ELECTRIC POWER GENERATION: Electrical energy is generated by conversion of energy available in different forms such as kinetic energy of blowing winds, water head and nuclear energy etc. A generator is a machine that transforms mechanical energy into electric power. Prime movers such as engines and turbines convert thermal or hydraulic energy into mechanical power. Thermal energy is derived from the fission of nuclear fuel or the burning of common fuels such as oil, gas, or coal. The alternating current generating units of electric power utilities generally consist of steam turbine generators, gas combustion turbine generators, hydro (water) generators, and internal-combustion engine generators.

1.2.2.1 Prime Movers: The prime movers used for utility power generation are predominantly steam turbines and internal-combustion machines. High-pressure/high-temperature and high-speed (1800 to 3600 rotational speed (rpm)) steam turbines are used primarily in large industrial and utility power generating stations. Internal-combustion machines are normally of the reciprocating-engine type. The diesel engine is the most commonly used internal-combustion machine, although some gasoline engines are also used.

1.2.2.2 Generators

- **Generator Capacity**: Turbine units can be built for almost any desired capacity. The capacity of steam turbine driven generators in utility plants ranges from 5 MW to 1000 MW. Most of the installed steam turbine generators are rated less than 500 MW. Gas turbine generators for electric power generation generally have capacities ranging from 100 kW to 20 MW (but are used in multiple installations). The applications of gas turbine generators include both continuous and peak load service. Diesel engine generator sets have capacities ranging from 500 kW to 6500 kW. These units are widely used in auxiliary or standby service in portable or stationary installations, but they may be used as the primary power source in some locations. Smaller units (steam turbine, gasoline, or diesel engine) are also available for special applications or industrial plants.
- **Generator Voltage**: Large generators used by commercial utilities are usually designed with output voltages rated between 11 and 18 kV. Industrial plant generators are normally rated 2.4 kV to 13.8 kV, coinciding with standard distribution voltages. The generated voltage is stepped up to higher levels for long distance power transmission.
- **Generator Frequency**: Power generation in India is standardized at 50 Hz. The standard frequency is 60 Hz in most western countries. Generators operating at higher frequencies are available for special applications.

1.2.2.3 Voltage and Frequency Control

- **Voltage Control**: The terminal voltage of a generator operating in isolation is a function of the excitation on the rotor field winding. The generator output terminal voltage is normally maintained at the correct level by an automatic voltage regulator that adjusts the field current.
- **Frequency Control**: Electrical frequency is directly proportional to the rpm of the rotor which is driven by the prime mover. Because of this relationship, prime movers are controlled by governors that respond to variation in speed or frequency. The governor is connected to the throttle control mechanism to regulate speed, accomplishing frequency control automatically.

1.2.2.4 Parallel Operation of Generators: Large power plants normally have more than one generator in operation at the same time. When generators are to be paralleled, it is necessary to synchronize the units before closing the paralleling circuit breaker. This means that the generators must be brought to approximately the same speed, the same phase rotation and position, and the same voltage. Proper synchronization is accomplished with the aid of a synchro-scope, an instrument which indicates the difference in phase position and in frequency of two sources. Paralleling of generators is accomplished either manually or automatically with one incoming unit at a time.

1.2.2.5 DC Generation: The requirement for direct current power is limited largely to special loads; for example, electrochemical processes, railway electrification, cranes, automotive equipment, and elevators. Direct current power may be generated directly as such, but is more commonly obtained by conversion or rectification of AC power near the load.

1.2.3 POWER TRANSMISSION SYSTEM: The transmission system is the bulk power transfer system between the power generation station and the distribution center from which power is carried to customer delivery points. The transmission system includes step-up and step-down transformers at the generating and distribution stations, respectively. The transmission system is usually part of the electric utility's network. Power transmission systems may include sub-transmission stages to supply intermediate voltage levels. Sub-transmission stages are used to enable a more practical or economical transition between transmission and distribution systems.

1.2.3.1 Transmission Voltage: Usually, generated power is transformed in a substation, located at the generating station, to 46 kV or more for transmission. Standard nominal transmission system voltages are: 69 kV, 115 kV, 138 kV, 161 kV and 230 kV. Some transmission voltages, however, may be at 23 kV to 69 kV, levels normally categorized as primary distribution system voltages. There are also a few transmission networks operating in the extra-high-voltage class (345 kV to 765 kV).

1.2.3.2 Transmission Lines: Transmission lines supply distribution substations equipped with transformers which step the high voltages down to lower levels. The transmission of large quantities of power over long distances is more economical at higher voltages. Power transmission at high voltage can be accomplished with lower currents which lower the I^2R (Power) losses and reduce the voltage drop. The consequent use of smaller conductors requires a lower investment. Standard power transmission systems are 3-phase, 3-conductor, overhead lines with or without a ground conductor. Transmission lines are classed as unregulated because the voltage at the generating station is controlled only to keep the lines operating within normal voltage limits and to facilitate power flow.

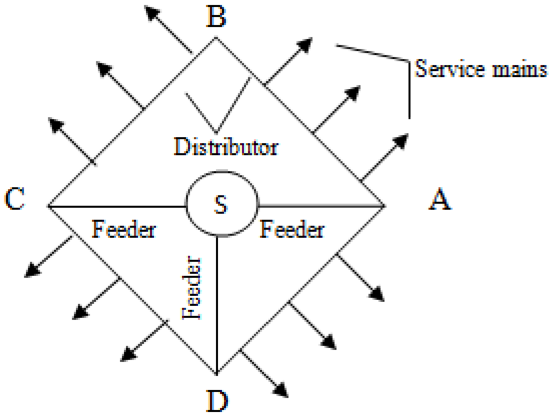
1.2.4 DISTRIBUTION SYSTEM

Distribution system may be defined as a tying system between the transmission and consumer service points. In general, the distribution system is the electrical system between the substation fed by the transmission system and the consumers' 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.

- **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 tapping 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.
- **Distributor** *:* A distributor is a conductor from which tapping 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.

- **Service mains:** A service mains is generally a small cable which connects the distributor to the consumer's terminals.



1.2 Elements of Distribution System

1.2.4.1 Primary Distribution Systems: The transmission system voltage is stepped-down to lower levels by distribution substation transformers. The primary distribution system is that portion of the power network between the distribution substation and the utilization transformers. The primary distribution system consists of circuits, referred to as primary or distribution feeders, which originate at the secondary bus of the distribution substation. The distribution substation is usually the delivery point of electric power in large industrial or commercial applications.

1.2.4.1.1 Nominal System Voltages: Primary distribution system voltages range from 2,400 V to 69,000 V. Some of the standard nominal system voltages are:

Volts	Phase	Wire
4,160Y/2,400	Three	Four
4,160	Three	Three
6,900	Three	Three

12,470Y/7,200 12,470	Three Three	Four Three
13,200Y/7,620 13,200	Three Three	Four Three
13,800Y/7,970 13,800	Three Three	Four Three
24,940Y/14,400 34,500	Three Three	Four Three
69,000	Three	Three

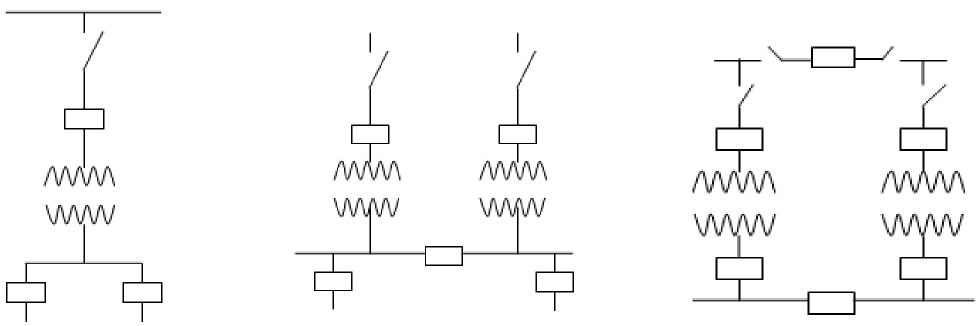
Table 1.1: Nominal System Voltages for Primary Distribution System

The primary distribution voltages in widest use are 12,470 V and 13,200 V, both three wire and four wire. Major expansion of distribution systems below the 15 kV nominal level (12 kV-14.4kV) is not recommended due to the increased line energy costs inherent with lower voltage systems.

1.2.4.1.2 Distribution Substations: A substation consists of one or more power transformer banks together with the necessary voltage regulating equipment, buses, and switchgear.

Substation Arrangement: A simple substation arrangement consists of one incoming line and one transformer. More complicated substation arrangements result when there are two or more incoming lines, two or more power transformers, or a complex bus network. Some typical distribution substation arrangements are shown in Figure 1.3. Specific sections are identified as follows:

a) A primary section provides for the connection of one or more incoming high-voltage circuits. Each circuit is provided with a switching device or a combination switching and interrupting device.
b) A transformer section includes one or more transformers with or without automatic load-tap-changing (voltage regulating) capability.
c) A secondary section provides for the connection of one or more secondary feeders. Each feeder is provided with a switching and interrupting device.



(a) (b) (c)

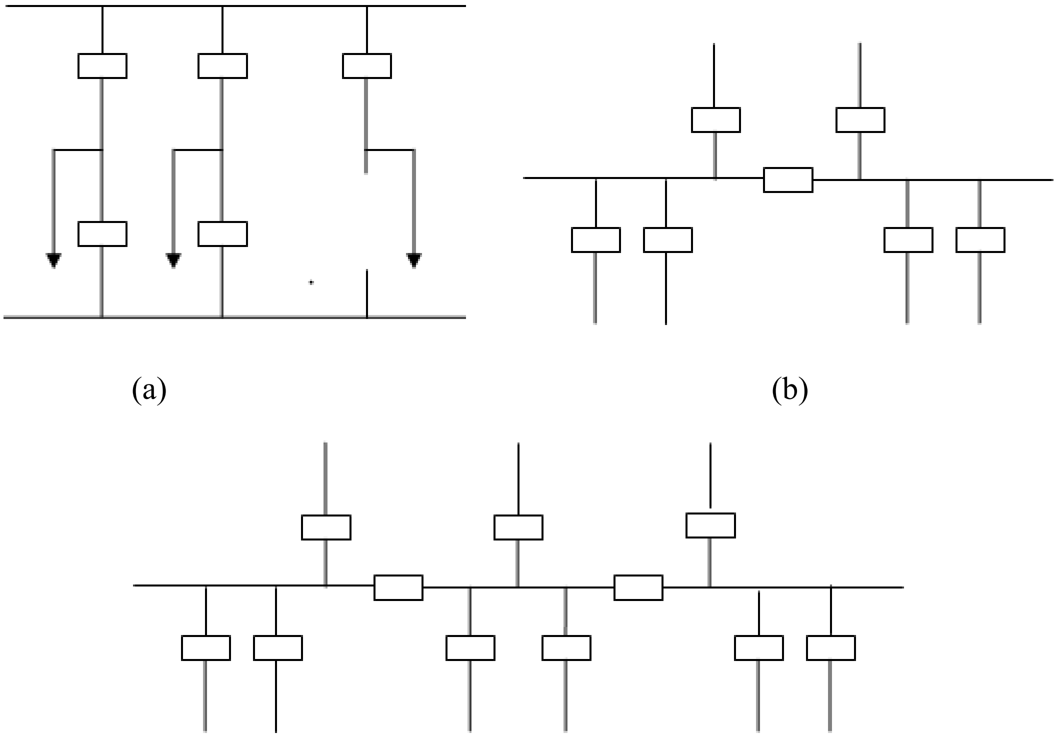
Figure 1.3 Typical Distribution Substation Arrangements

Substation Bus Arrangements: A bus is a junction of two or more incoming and outgoing circuits. The most common bus arrangement consists of one source or supply circuit and one or more feeder circuits. The numerous other arrangements and variations are mainly intended to improve the service reliability through the bus to all or part of the load during scheduled maintenance or unexpected power outages. Typical bus arrangements are shown in Figure 1.4.

The arrangements are normally referred to as:

a) Double-bus
b) Two-source sectionalizing bus
c) Three-source sectionalizing bus
d) Star or synchronizing bus

When two sources are used simultaneously, but must not be operated in parallel, a normally open bus-tie circuit breaker is interlocked with the source circuit breakers. This permits serving both bus sections from one of the sources when the other is not available. For normally parallel sources, a single straight bus may be used. It is preferable, however, to use a normally closed bus-tie circuit breaker to split the system so that service continuity can be retained on either section when the other section is out of service.



(a)

(b)

(c)

Figure 1.4 Typical Bus Arrangements

Substation Operation. Substations may be attended by operators or designed for automatic or remote control of the switching and voltage regulating equipment. Most large new substations are either automatic or remotely controlled.

a) In an automatic substation, switching operations are controlled by a separately installed control system. Major apparatus, such as transformers and converting equipment, may be placed in or taken out of service automatically. Feeder circuit breakers, after being opened, can be reclosed by protective relays or by the control system.
b) Remote control substations are often within a suitable distance from attended stations. In such cases pilot-wire cables provide the communication link to receive indications of circuit breaker or switch positions and to transmit control adjustments, as required. Microwave radio, telephone lines, and carrier current are often used for remote-control links at distances beyond the economic reach of pilot wire systems.

Types of Systems: There are two fundamental types of primary distribution systems; radial and network. Simply defined, a radial system has a single simultaneous path of power flow to the load. A network has more than one simultaneous path. Each of the two types of systems has a number of variations. The following paragraphs discuss the functions and characteristics of the simpler feeder arrangements.

a) Tie Feeder: The main function of a tie feeder (as shown in figure 1.5) is to connect two sources. It may connect two substation buses in parallel to provide service continuity for the load supplied from each bus.

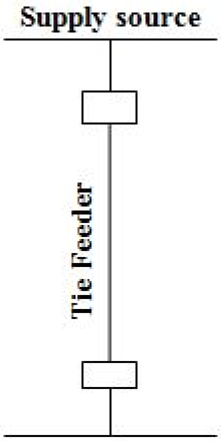


Figure 1.5 Arrangement of a Tie Feeder

b) Loop Feeder: A loop feeder has its ends connected to a source (usually a single source), but its main function is to supply two or more load points in between. Each load point can be supplied from either direction; so it is possible to remove any section of the loop from service without causing an outage at other load points. The loop can be operated normally closed or normally open. Most loop systems are, however, operated normally open at some point by means of a switch. The operation is very similar to that of two radial feeders.

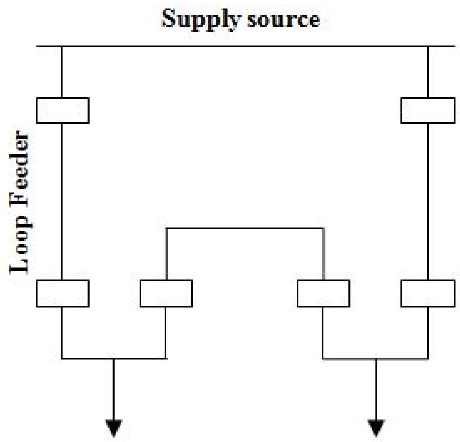


Figure1.6 Arrangement of a Loop Feeder

c) Radial Feeder. A radial feeder connects between a source and a load point, and it may supply one or more additional load points between the two. Each load point can be supplied from one direction only. Radial feeders are most widely used because the circuits are simple, easy to protect, and low in cost.

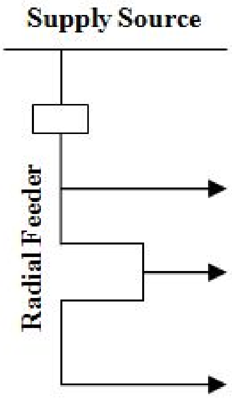


Figure1.7 Arrangement of a Radial Feeder

d) Parallel Feeder. Parallel feeders connect the source and a load or load center and provide the capability of supplying power to the load through one or any number of the parallel feeders. Parallel feeders provide for maintenance of feeders (without interrupting service to loads) and quick restoration of service when one of the feeders fails.

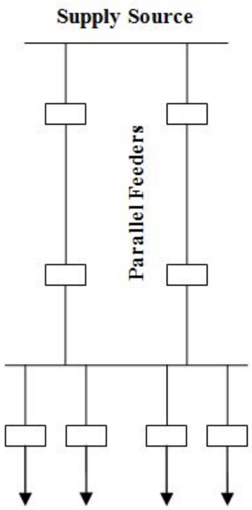


Figure 1.8 Arrangement of a Parallel Feeder

There are other more complex systems, such as the primary network (interconnected substations with feeders forming a grid) and dual-service network (alternate feeder to each load). These systems, however, are simply variations of the two basic feeder arrangements.

1.2.4.2 Secondary Distribution System: The secondary distribution system is that portion of the network between the primary feeders and utilization equipment. The secondary system consists of step-down transformers and secondary circuits at utilization voltage levels. Residential secondary systems are predominantly single-phase, but commercial and industrial systems generally use three-phase power.

1.2.4.2.1 Secondary Voltage Levels: The voltage levels for a particular secondary system are determined by the loads to be served. The utilization voltages are generally in the range of 120 to 600 V. Standard nominal system voltages are:

Volts	Phase	Wire
120,120/240	Single, Single	2,3
208Y/120	Three	4
240	Three	3
480Y/277, 480	Three, Three	4, 3
600	Three	3

Table 1.2: Nominal System Voltages for Secondary Distribution System

In residential and rural areas the nominal supply is a 120/240 V, single-phase, three-wire grounded system. If three-phase power is required in these areas, the systems are normally 208Y/120V or less commonly 240/120V. In commercial or industrial areas, where motor loads are predominant, the common three-phase system voltages are 208Y/120V and 480Y/277V. The preferred utilization voltage for industrial plants, however, is 480Y/277 V. Three-phase power and other 480 V loads are connected directly to the system at 480 V and fluorescent lighting is connected phase to neutral at 277 V. Small dry-type transformers, rated 480-208Y/120 or 480-120/240 V, are used to provide 120 V single-phase for convenience outlets and to provide 208 V single- and three-phase for small tools and other machinery.

1.2.4.2.2 Types of Systems: Various circuit arrangements are available for secondary power distribution. The basic circuits are: simple radial system, expanded radial system, primary selective system, primary loop system, secondary selective system, and secondary spot network.

a) Conventional Simple-Radial Distribution System: In the simple-radial system, distribution is at the utilization voltage. A single primary service and distribution transformer supply all the feeders. There is no duplication of equipment. System investment is the lowest of all circuit arrangements. Operation and expansion are simple. Reliability is high if quality components are used, however, loss of a cable, primary supply, or transformer will cut off service. Further, electrical service is interrupted when any piece of service equipment must be de-energized to perform routine maintenance and servicing.

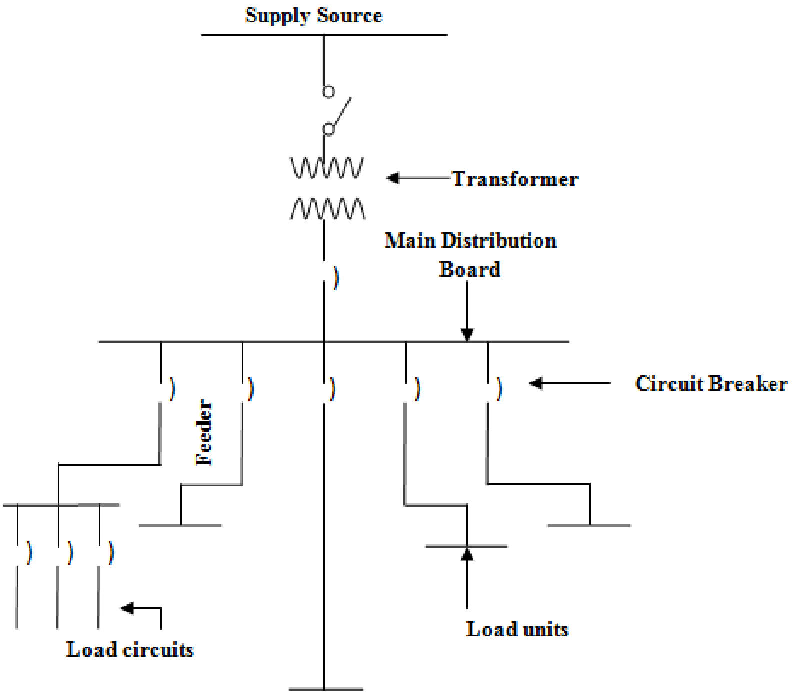


Figure 1.9 Conventional Simple-Radial Distribution System

b) Primary Selective Distribution System: Protection against loss of a primary supply can be gained through use of a primary selective system. Each unit substation is connected to two separate primary feeders through switching equipment to provide a normal and an alternate source. When the normal source feeder is out of service for maintenance or a fault, the distribution transformer is switched, either manually or automatically, to the alternate source. An interruption will occur until the load is transferred to the alternate source. Cost is somewhat higher than for a radial system because primary cable and switchgear are duplicated.

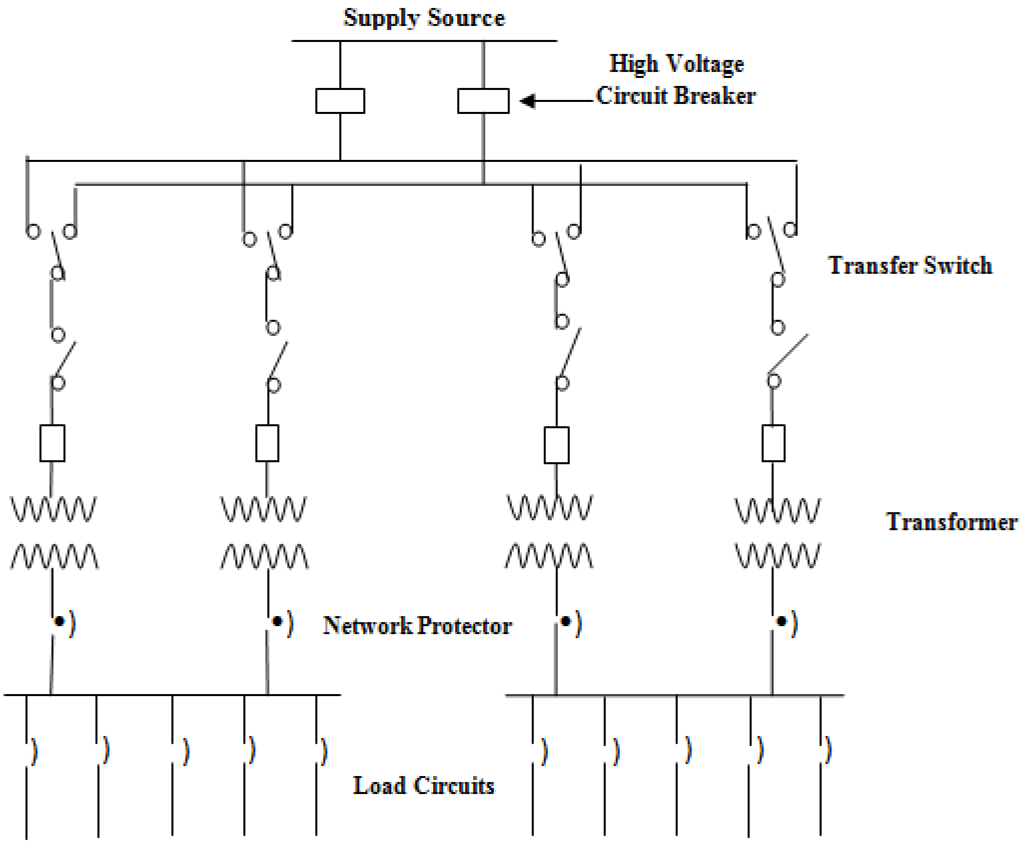


Figure 1.10 Primary Selective Distribution System

c) Secondary Selective-Radial Distribution System: When a pair of unit- substations are connected through a normally open secondary tie circuit breaker, the result is a secondary selective-radial distribution system. If the primary feeder or a transformer fails, the main secondary circuit breaker on the affected transformer is opened and the tie circuit breaker is closed. Operation may be manual or automatic. Normally, the stations operate as radial systems. Maintenance of primary feeders, transformer, and main secondary circuit breakers is possible with only momentary power interruption, or no interruption, if the stations may be operated in parallel during switching. With the loss of one primary circuit or transformer, the total substation load may be supplied by one transformer. In this situation, however, if load shedding is to be avoided, both transformers and each feeder must be oversized to carry the total load. A distributed secondary selective system has pairs of unit substations in different locations connected by tie cables and normally open tie circuit breakers. The secondary selective system may be combined with the primary selective system to provide a high degree of reliability.

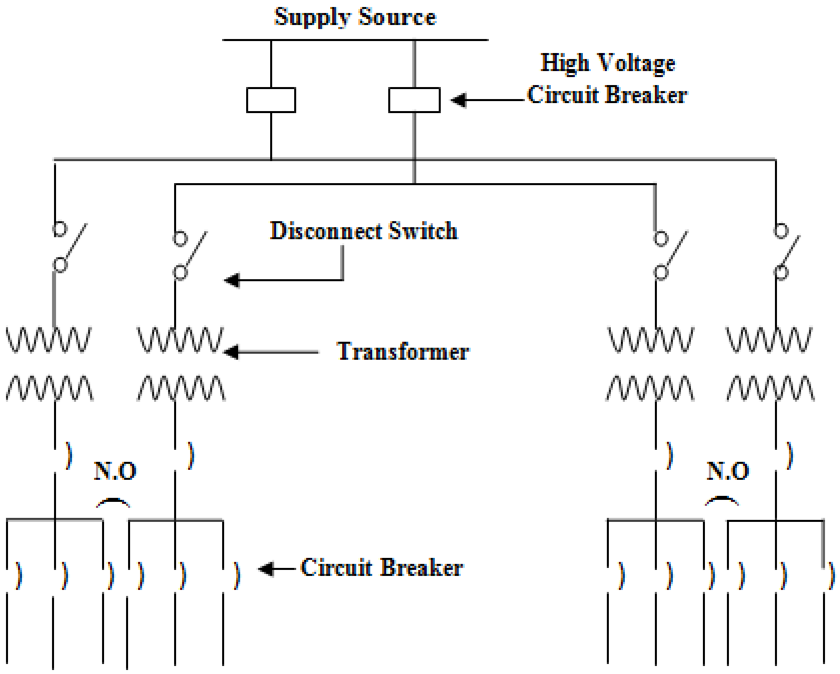


Figure 1.11 Secondary Selective-Radial Distribution System

d) Secondary Network Distribution System: In a secondary network distribution system, two or more distribution transformers are each supplied from a separate primary distribution feeder. The secondary sides of the transformers are connected in parallel through a special type of circuit breaker, called a network protector, to a secondary bus. Radial secondary feeders are tapped from the secondary bus to supply loads. A more complex network is a system in which the low-voltage circuits are interconnected in the form of a grid or mesh.

a) If a primary feeder fails, or a fault occurs on a primary feeder or distribution transformer, the other transformers start to feed back through the network protector on the faulted circuit. This reverse power causes the network protector to open and disconnect the faulty supply circuit from the secondary bus. The network protector operates so fast that there is minimal exposure of secondary equipment to the associated voltage drop.

b) The secondary network is the most reliable for large loads. A power interruption can only occur when there is a simultaneous failure of all primary feeders or when a fault occurs on the secondary bus. There are no momentary interruptions as with transfer switches on primary selective, secondary selective, or loop systems. Voltage dips which could be caused by faults on the system, or large transient loads, are materially reduced.

c) Networks are expensive because of the extra cost of the network protector and excess transformer capacity. In addition, each transformer connected in parallel increases the available short-circuit current and may increase the duty rating requirement of secondary equipment.

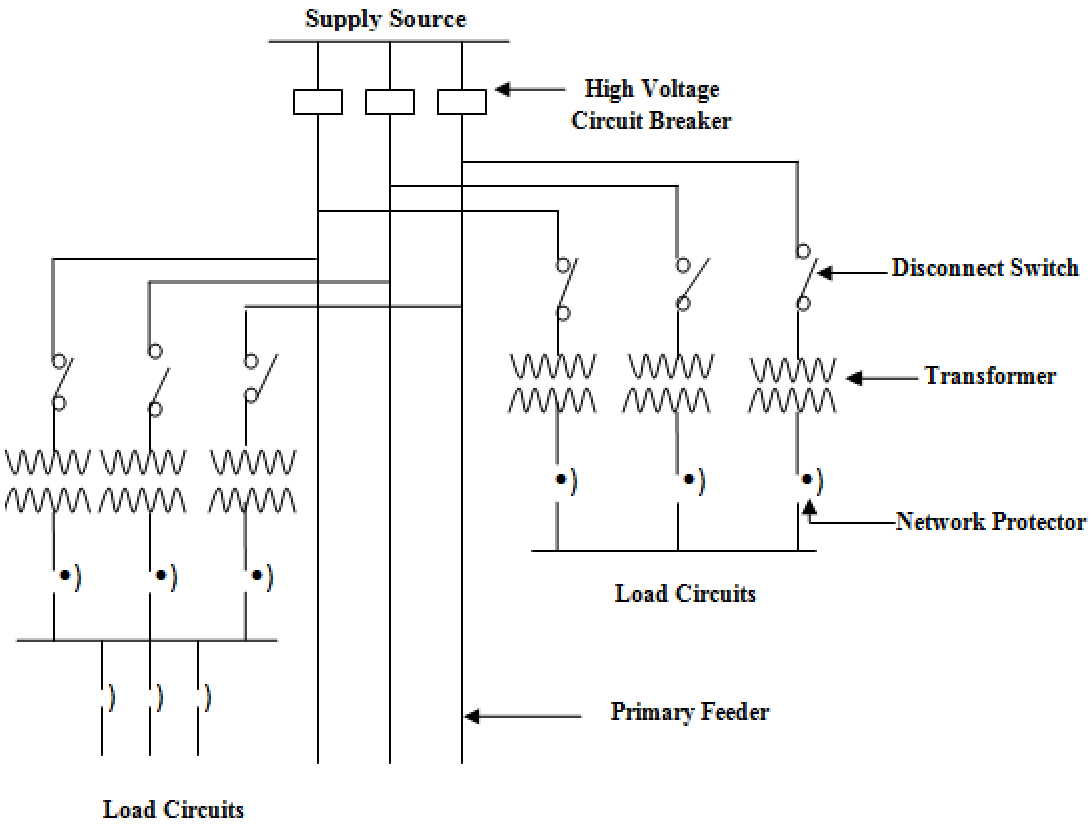


Figure 1.12 Secondary Network Distribution System

e) Secondary Banking: The term banking means to parallel, on the secondary side, a number of transformers. All of the transformers are connected to the same primary feeder. Banking is usually applied to the secondaries of single-phase transformers, and the entire bank must be supplied from the same phase of the primary circuit. All transformers in a bank are usually of the same size and should have the same nominal impedance.

a) The advantages of banking include: reduction in lamp flicker caused by starting motors, less transformer capacity required because of greater load diversity, and better average voltage along the secondary.
b) Solid banking, where the secondary conductors are connected without over-current protection, is usually not practiced because of the obvious risks.

1.3 LOAD-FLOW

1.3.1 Introduction

The load-flow calculation for electrical systems is one of the most studied topics in literature since a good knowledge on the system's state is the basis for the correct management of any control and design problem.

In order to obtain a reliable power system operation under normal balanced three phase steady state conditions, it is required to have the followings:

1. Generation supplies the load demand and losses
2. Bus voltage magnitudes remain close to rated values
3. Generator operates within specific real and reactive power limits
4. Transmission lines and transformers are not overloaded

The so called, steady state in reality, is the one which is subjected to small disturbances such that the variables defining the state fluctuate between different steady values. That in which some specified characteristics of a condition, such as value, rate, periodicity, or amplitude, exhibits only negligible change over an arbitrarily long period of time. In simple understanding, a steady state is a relative constant condition without major changes. In power engineering, the power flow study (also known as load-flow study) is an important tool involving numerical analysis applied to a power system to determine and examine above mentioned requirements.

Load-Flow is defined as the computational procedure required to determine the steady state operating characteristics of a power system network. The aim of power flow calculations is to determine the steady state operating characteristics of a power transmission/generation system for a given set of loads. 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. The program computes the voltage magnitude and angle at each bus in a power system under balanced three phase steady state conditions. Once they are calculated, real and reactive power flows for all equipment interconnecting the buses, as well as equipment losses are also computed. In addition to that, power flow program can also be used to study power systems under disturbance/contingency conditions. So a set of load-flow program written is able to compute:

1. voltage magnitude and phase angle at each bus in a power network system
2. real and reactive power flows for all equipment interconnecting the buses
3. equipment losses

Unlike traditional circuit analysis, a power flow study usually uses simplified notation such as a one-line diagram and per-unit system. Some assumptions are made before carrying the load-flow analysis of a particular system. Some of those are given below:

- Power system is assumed to be a balanced three phase system. The transmission system is represented by its positive phase sequence network of linear lumped series and shunt branches.
- The generators are assumed to be three phase balanced voltage sources and only the generator positive voltages are present. The internal impedance of the generators is not included in the system model.
- The generators are shown as constant P-V models i.e. as the injected powers into the system.
- The load on each bus is assumed to be three phase balanced load.

- Each bus of the system is described by four parameters: P, Q, |V| and δ. Two of the parameters are known and other two parameters are not known.

1.3.2 Formulation of the Load-flow Problem

Load-flow studies are based on a nodal voltage analysis of a power system. As an example, consider the very simple system represented by the single-line diagram in Fig. 1.12. Here two generators (1 and 2) are interconnected by one transmission line and are separately connected to a load (3) by two other lines. If the phasor currents injected into the system are I_1, I_2 and I_3 and the lines are modeled by simple series admittances, then it is possible to draw the equivalent circuit for one representative phase of the balanced three-phase system, as shown in Fig. 1.13

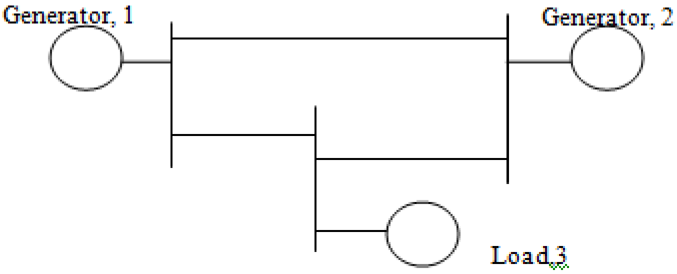


Figure 1.12 Single Line Diagram of a Simple Example Power System

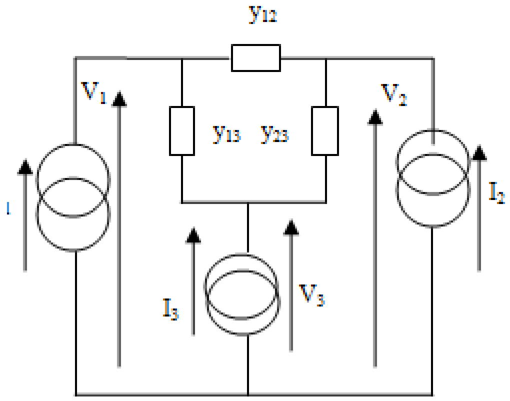


Figure 1.13 Equivalent Circuit for Single Phase

1.3.3 Stages and Data for Load-flow Studies

There are three required stages explained here to perform load-flow studies.

1) Single line diagram of power system: The starting point for a load-flow problem is a single-line diagram of the power system, from which the input data for computer solutions can be obtained and the three types of buses can be assigned.

2) Input data: bus data, transmission line and transformer data. The bus input data gives information about the bus number, the type of bus, the voltage, phase angle, generator power (PG and QG), load power (PL and QL) and reactive power limits (Qmax and Qmin). At each bus except the swing/slack, the net real power (P) into the network must be specified. The power drawn by a load is negative power input to the system. The other power inputs are from generators and positive and negative power entering over interconnections. In addition, at these buses either the net flow of reactive power into the network (PQ load bus) or the magnitude of the voltage (PV bus) must be specified; that is at each bus a decision is required whether the voltage magnitude or the reactive power flow is maintained constant. The usual case is to specify the reactive power at load buses and voltage magnitude at generator buses.

3) Four variables are associated with certain bus k:

- Voltage magnitude (V_k)
- Phase angle (δ_k)
- Net real power (P_k)
- Reactive power (Q_k)

Two of these are specified and two are unknowns. Power delivered to bus k is separated into generator (G) and load (L) terms, as

$$P_k = PG_k - PL_k$$

$$Q_k = QG_k - QL_k$$

1.3.4 Types of Buses

(1) Swing/slack bus: This is a reference bus where the voltage and the phase angle are specified. Typically it is assigned to $V_1 \angle \delta_1 = 1 \angle 0$. The swing/slack bus is the only bus at which the power is not specified. Net power flows cannot be fixed in advance at every generating bus because the network power losses are not known until the study has been completed. The generators at the swing bus supply the difference between the specified real power into the system at the other buses and the total system output plus

losses. The power flow computes the real power P_1 and reactive power Q_1. The swing bus designation is bestowed upon the stiffest buses in the network, traditionally Power company or Utility buses.

(2) Load bus: P_k and Q_k are input data. Most buses are load buses. The power flow program computes the voltage V_k and phase angle δ_k. Due to the fact that the real and reactive powers are specified at a given load bus, the load bus is also known as PQ bus.

(3) Voltage controlled bus: P_k and V_k are the input data. The load-flow program then computes reactive power Q_k and phase angle δ_k. Examples are buses to which generators, switched shunt capacitors or static var systems are connected. The voltage controlled bus such as a generator bus is also known as a PV bus. Maximum and minimum var limits QG_{kmax} and Qg_{kmin} that the equipment can supply are also input data.

So to recapitulate the things the load-flow solution can indeed be considered as a primary objective or as an intermediate step towards the evaluation of the behavior of these systems in terms of stability, faults diagnosis, optimal dispatch, regulation, etc. The development of large size high voltage networks, as well as the primary importance of the energy transmission from the generation plants to the final customers, have driven the power systems research towards the development of load-flow solution methods for high voltage systems. As it is known, the load's nature considered for high voltage systems brings into the load-flow equations nonlinearities; their solution can be attained only by means of iterative methods. The convergence of these methods is not always guaranteed and, moreover, reaching a good solution often requires large calculation times. The increasing power of calculation systems, together with the increasing networks sizes, have kept open the problem of the research of faster and faster methodologies for the load-flow solution, for which the Newton-Raphson method, Gauss-Siedal method ,the decoupled Stott-Alsac method, parallel calculation and artificial intelligence derived techniques have been used .

However the methods above mentioned systems have shown good convergence for every kind of transmission systems but show either slow convergence or no convergence at all for most of the distribution systems.

1.3.5 Load-flow for Distribution Systems

The operation and planning studies of a distribution system require a steady-state condition of the system for various load demands. Distribution networks have recently acquired a growing importance because their extension has quite increased and also because their management has become quite complex. Distribution automation at low costs indeed has brought in the opportunity to offer higher quality service by means of the implementation of new operation functions. Knowing exactly the systems state at distribution level is again fundamental for automated systems management. Unfortunately the techniques widely known and used at High Voltage level cannot be straightforward applied to distribution systems. This is because the distribution systems are ill-conditioned systems i.e. the systems which show large oscillations in the results by small perturbations. Since Low Voltage lines have a high R/X ratio. This high R/X ratio factor of the distribution systems makes them ill conditioned and so the need of new and efficient method for the analysis of distribution system arises. The analysis of distribution systems is an important area of activity as distribution systems is the final link between a bulk power system and consumers.

In the past few years, the developments of automated distribution systems solutions have increased considerably. With the development of the microcomputer, the requirement of distribution substation-owned computer programs has become a necessity. However, the choice of a solution method for the practical application is difficult. It requires a careful analysis of comparative advantages and disadvantages of those methods available in respect to storage, computation speed, and convergence criterion. As discussed above, radial distribution network has a high R/X ratio. Due to this, conventional Newton-Raphson and fast decoupled load-flow methods fail to converge. Many other researchers have suggested modified versions of conventional load-flow methods with a high R/X ratio. Accordingly, there are a number of reported studies in the literature specially designed for solution of power flow problem in radial distribution systems (RDS). Methods developed for the solution of ill-conditioned radial distribution systems may be divided into two categories. The first group of methods is based on the forward-backward sweep process for solution of ladder networks. On the other hand, the second group of methods is utilized by proper modification of existing methods such as Newton-Raphson.

Distribution systems usually fall into the category of ill-conditioned power systems for generic Newton-Raphson like methods with its special features, such as radial or weakly meshed topologies, high R/X ratio of the distribution lines, unbalanced operation and loading conditions, non-linear load models and dispersed generation, etc. Numerous efforts have been made to develop power flow algorithms for distribution systems. The following are the most typical ones:

a) Forward and backward sweep methods or ladder networks theory:

These methods take advantage of a natural feature of the radial networks, i.e., there is a unique path from any given bus to the source. The general algorithm consists of two basic steps: forward sweep and backward sweep. Essentially, the ladder network method treats the radial system as two basic element types: the network natural elements (impedance) and voltage control current sources (system loads) at each load node. The forward sweep is mainly a voltage drop calculation from the sending end to the far end of a feeder or a lateral; and the backward sweep is primarily a current summation based on the voltage updates from the far end of the feeder to the sending end. Then by using KVL and KCL, the voltage drop can be obtained. Load-flow equations' are essentially solved by a Newton-Raphson approach which makes this method complex and costly. Sometimes the influence of the load distribution would cause slow convergence.

Generally, the above ladder network methods have the following advantages:

- quite robust for heavy loads;
- less sensitive to the high R/X ratio;
- simple formulation;
- more suitable to reflect the dependency of the node voltage on the load level, which is a distinguishing characteristic of distribution systems.

The limitation is that these methods are only suitable for one source and a simple tree structure. Load distribution and tree structure still influence the convergence speed.

b) Compensation-based open loop distribution power flow for weakly meshed networks

Some distribution systems have weakly meshed structures. Because of the interconnection of the system branches, the methods mentioned in the previous section would not be suitable. Because of the high R/X ratio, Newton-Raphson like methods would not be adaptable either. The method first converts the multiple-source mesh network into an equivalent single-source radial type network by setting dummy nodes for the break points at distributed generators and loop connecting points. Then the traditional ladder network method can be applied for the equivalent radial system. Following each of the iterations of the equivalent radial system, the power injected at the breaker points must be updated by an additional calculation through a reduced order impedance matrix. The disadvantages of the above methods are:

- the structure analysis of the system is complex. Sometimes a heuristic method must be used to decide where the break points are. So the adaptability of this method is not good enough.
- load conditions at the break points have great influence on the power flow solutions. Heavy loading loops and weak power sources (dispersed generation) in meshed systems may cause difficulties for the convergence speed and accuracy.

c) Using current injection in Newton-Raphson and Newton-Raphson like methods to solve power flow problems for large distribution systems

As discussed earlier, with the expansion of distribution systems strong connection loops exist in modern distribution networks. When using the Newton-Raphson method for such networks, how to obtain the equivalent network of the rest of the system becomes very important. In distribution systems, equivalent impedance methods, which are popular in transmission systems, are no longer suitable because of the load behaviors. Then load current injection becomes a good choice. This method is still based on the nodal model. The formulas are complex, and the computation cost is high as well, especially when the system load model is voltage sensitive.

1.4 OBJECTIVE OF THE THESIS

The objective of the thesis is to propose a load-flow technique based on set theory for solution of radial distribution networks.

1.5 ORGANIZATION OF THE THESIS WORK

Chapter 1 presents the introduction of distribution system, load-flow, objectives of the research and organization of the thesis work.

Chapter 2 presents the review of the literature on load-flow analysis of radial distribution system and scope of the work in load-flow analysis of radial distribution networks.

Chapter 3 presents the load-flow analysis of radial distribution networks. The assumption, solution methodology, load modeling, algorithms, examples and results.

Chapter 4 presents the summary of conclusions and the future scope of further research work.

References present the list of previous papers published by researchers in load-flow, and planning of power distribution system that have been surveyed by the author and also the books in this area.

Appendix A shows the line data and load data of 69 node radial distribution network available in [9].

CHAPTER 2

LITERATURE SURVEY

2.1 REVIEW OF LITERATURE

Load-flow analysis of any power system network has always been the top most concern of power engineers. Load-flow analysis of distribution system is an important area of activity as it is the final link between bulk power systems and consumers. A few methods have been reported in the literature for load-flow analysis of distribution system.

Power flow is the most fundamental numerical algorithm for power system analysis. In 1967, **Tinney** and **Hart** [1] developed the classical Newton based power flow solution method. Later work by **Stott** and **Alsac** [2] made the fast decoupled Newton method as well as its various alternatives a kind of standard power flow method for EMS systems. Many other applications have been developed based on the Newton formulation since then. Even though the fast decoupled Newton method works well for transmission systems, its convergence performance is poor for most distribution systems due to their high R/X ratio which deteriorates the diagonal dominance of the Jacobian matrix. For this reason, several non-Newton type of methods have been presented. Those methods consisted of back/forward sweeps on a ladder system. The formulation and the algorithm of those methods were different from the Newton's power flow method, which made those methods hard to be extended to other applications, such as the state estimation and the optimal power flow, in which the Newton method seemed more appropriate.

Iwamoto and Tamura [3] presented an algorithm based on the modification of conventional Newton-Raphson method for the solution of ill-conditioned power systems but this method was quite time consuming and complex.

Tripathy *et al.* [4] presented a Newton like method for solving ill-conditioned power systems. Their method showed voltage convergence but could not be used efficiently for state estimation or optimal power-flow calculations.

Kersting [5] developed a technique for solving the load-flow problem in radial distribution networks based on ladder network theory in the iterative routine. This solution was complicated and had many assumptions for a typical distribution system, which was rarely a pure ladder network. In other words the method was not designed to efficiently solve for meshed networks. Also **Stevens *et al.***[6] demonstrated that the ladder based technique was very fast but did not guarantee convergence.

Shirmohammadi *et al.*[7] presented a new compensation-based power flow method for the solution of weakly meshed distribution and transmission networks. This technique solved radial distribution networks with the help of direct voltage application of Kirchoff's laws and presented a branch-numbering scheme to enhance numerical performance of the solution method. This method undoubtedly was more efficient than the Newton-Raphson power flow technique when used for solving radial and weakly meshed distribution and transmission networks but needed a rigorous data preparation.

Renato [8] presented method for obtaining load-flow solution of radial distribution networks computing the electrical equivalent for each node summing all the loads of the network fed through the node including losses and then starting from the source node, voltage of each receiving-end node was computed.

Baran *et al*.[9] presented a forward method in 1989. In this method, the sending end voltage became the main concern of the system convergence. Voltage drop and the information on system structure had been considered in the forward sweep. The voltage-sensitive load current could be included in the system model. However, this method still had disadvantages. Oriented from ladder network concepts, the 'branch flow equations' were essentially solved by a Newton-Raphson approach which made this method complex and costly. Sometimes the influence of the load distribution would cause slow convergence.

Luo *et al.* [10] presented a compensation method for weakly meshed networks. This method started from a network structure analysis to find the interconnection points. Then it broke those interconnection points using the compensation method so that the meshed system structure could be changed to simple tree-type radial system. This method was also suitable for the system with multiple voltage control buses. This method had some disadvantages such as the structure analysis of the system was complex. Sometimes a heuristic method must be used to decide where the break points are. So the adaptability of this method was not good enough. The other disadvantage being load conditions at the break points have great influence on the power flow solutions. Heavy loading loops and weak power sources (dispersed generation) in meshed systems may cause difficulties for the convergence speed and accuracy.

Goswami and Basu [11] presented an approximate method for solving radial and meshed distribution networks. Their method had the advantages of a no convergence problem, a guaranteed accurate solution for any realistic distribution system, and the ease with which composite loads could be represented. The disadvantages were difficulty in numbering the nodes and branches, and that no node in the network was the junction of more than three branches.

Chiang [12] presented three different algorithms for solving radial distribution networks. The decoupled and fast decoupled distribution load-flow algorithms presented by Chiang were similar to that of Baran and Wu. However, the very fast decoupled distribution load-flow presented by Chiang was very attractive because it did not require any Jacobian matrix construction and factorization.

Jasmon and Lee [13] presented a load-flow technique for every branch, which lead to a pair of quadratic equations relating power flows at both ends with the voltage magnitude at the sending end for the voltage stability analysis of radial networks.

Das *et al.* [14] presented a load−flow method using power convergence with the help of coding at the lateral and sub lateral nodes for large system that increased complexity of computation. Their method worked only for sequential branch and node numbering scheme. They had calculated voltage of each receiving−end node using forward sweep. They had taken the initial guess of zero initial power loss presented to solve radial distribution networks (RDN). It solved the simple algebraic recursive expression of voltage magnitude and all the data were stored in vector form. The algorithm used the basic principle of circuit theory. This method had the advantage that all data could be stored in vector forms, thus saving an enormous amount of computer memory.

Haque [15] presented a new approach for meshed networks with more than one feeding node. The method first converted the multiple-source mesh network into an equivalent single-source radial type network by setting dummy nodes for the break points at distributed generators and loop connecting points. Then the traditional ladder network method could be applied for the equivalent radial system. Following each of the iterations of the equivalent radial system, the power injected at the breaker points must be updated by an additional calculation through a reduced order impedance matrix. The method had the same disadvantages as of the method presented by Luo et al. in their paper [10].

Lin and Teng [16] proposed a phase decoupled load-flow method in which fast convergence was ensured, by means of the Newton-Raphson algorithm; branch currents could be used as state variables. Keeping into account the mutual relations between each phase's parameters, some simplifications were introduced so as to obtain from the Jacobian matrix, three sub-Jacobian constant matrices.

Nguyen [17] presented a new algorithm based on the extension of Newton-Raphson method and its Jacobian in complex form that was used for the solution of three phase (or unsymmetrical) power flow analysis of both transmission or distribution systems under unsymmetrical operating conditions. This method gave the solutions in whole phasor format which made it suitable for applications such as voltage quality analysis and power quality improvement. Jacobian matrix increased the memory requirement of this method.

Expositos and **Ramos** [18] presented a method to solve the power flow problem in radial networks. In the presented formulation, the load-flow equations were written in terms of new variables resulting in a set of 3N equations (2N linear plus N quadratic) for a network with N+l buses. A computationally efficient solution scheme based on the Newton-Raphson method was presented and some simplifications were discussed.

Lin *et al.* [19] presented an exact three-phase fast decoupled power flow solution for radial distribution system. This method used traditional Newton-Raphson algorithm in a rectangular coordinate system. The Jacobian matrix of the presented method could be decoupled both on phases as well as on real and imaginary parts. In addition, the memory requirement of the traditional fast decoupled load-flow could be reduced to only one-sixth. The need of the complicated mutual coupling terms could be avoided. It was even possible to solve the distribution system with line conductances only. That is, an exact three-phase distribution load-flow program could be executed with minimum data preparation to substantially off-load the burden of distribution engineers.

Ghosh and Das [20] presented a load−flow method for solving radial distribution networks by evaluating only a simple algebraic expression of receiving end voltages. In this method, the authors assumed an initial flat voltage for all nodes. Then, by numbering the nodes beyond each branch, they calculated the loads and charging currents, followed by the branch currents. The modified nodal voltages were recalculated, as were the losses. Evaluating the difference between new and previous voltage values and then comparing it with an accepted tolerance verified the convergence for this method. The method was simple and had good and fast convergence, and could be used for composite load modeling, if the composition of the loads was known. The main drawback of this method was that it stored nodes beyond each branch. This method calculated current for each branch by adding load currents of nodes beyond the respective branch.

Augugliaro *et al.* [21] presented a fast converging method for the load-flow analysis of radial distribution networks. This method was based on an iterative algorithm with some special procedures to increase the convergence speed. The bus voltages were considered as state variables. It used a simple matrix representation for the network topology and branch current flow management.

Aravindhababu *et al.* [22] presented a simple and efficient branch-to-node matrix-based power flow (BNPF) for radial distribution systems but this method was unsuitable for extension to optimal power flow for which the NR method seems to be more appropriate. In that method any presence of sub laterals complicated the matrix formation.

Afsari *et al.* [23] presented a load−flow method based on estimation of node voltage and assuming the loads of the nodes of lateral and their sub lateral were concentrated at the originating node of the feeder. They had tried to reduce the computation time only. But the computation became very complex when the number of laterals and sub-laterals increased.

Mekhamer *et al.* [24] used the equations developed by Baran and Wu for each node of the feeder but with a different procedure. In this method the load-flow problem was solved by considering the laterals as a concentrated load of the main feeder. Once the voltage of the main feeder calculated, the first node voltage of each lateral was put equal to the voltage of the same node on the main feeder. The node voltages of the lateral were then calculated using Baran and Wu equations. The convergence criterion was made upon the active and reactive power fed through the terminal nodes of laterals and main feeder.

Ranjan and Das [25] had presented a simple and efficient method to solve radial distribution network. Their method solves the simple algebraic recursive expression of voltage magnitude and all the data were stored in vector form thus saving computer memory. The algorithm used the basic principle of circuit theory.

Eminoglu and Hocaoglu [26] presented a simple and efficient method to solve the power low problem in radial distribution systems. The presented method took into account voltage dependency of static loads, and line charging capacitance. The method was based on the forward and backward voltage updating by using polynomial voltage equation for each branch and backward ladder equation (Kirchoff's Laws). Convergence ability and reliability of the method was compared with the Ratio-Flow method, which was based on classical forward–backward ladder method, for different loading conditions, R/X ratios and different source voltage levels, under the wide range of exponents of loads.

Ghosh and Sherpa [27] presented a method for load-flow solution of radial distribution networks with minimum data preparation. Here the node and branch numbering need not to be sequential like other available methods. This method did not need sending-node, receiving–node and branch numbers if those were sequential. The presented method used the simple equation to compute the voltage magnitude and had the capability to handle composite load modeling. This method used the set of nodes of feeder, lateral(s) and sub lateral(s).

Most recently **Kumar and Arvindhababu** [28] presented an approach of power flow with a view to obtain a reliable convergence in distribution systems. The trigonometric terms were eliminated in the node power expressions and thereby the resulting equations were partially linearised for obtaining better convergence. The method was simpler than existing approaches and solved iteratively similar to Newton-Raphson (NR) technique.

2.2 FUTURE SCOPE OF THE WORK

This thesis aims to propose a load-flow technique for solution of radial distribution networks based on set theory. The proposed method handles any type of node numbering. Since voltage convergence is applied, the proposed method handles easily the composite load modeling. The efficiency of the proposed method is demonstrated by its comparison with the other two methods.[25,27].

CHAPTER -3

LOAD-FLOW ANALYSIS

3.1INTRODUCTION

Load-Flow is defined as the computational procedure required to determine the steady state operating characteristics of a power system network. The aim of power flow calculations is to determine the steady state operating characteristics of a power transmission/generation system for a given set of loads. Given certain known quantities-typically, the amount of power generated and consumed at different locations-load-flow analysis allows one to determine other quantities. As explained in the previous sections that due to the ill conditioned nature of the distribution systems the conventional methods of load-flow analysis used for transmission systems failed to converge. Unlike transmission networks, distribution networks are radial in nature. The distribution networks have high R/X ratio compared to the transmission networks because $X \gg R$ in distribution systems as compared to the transmission systems. So therefore arises need a to develop new load-flow techniques of load-flow analysis which can assure convergence for distribution systems. A lot of work has been done in this area as discussed in the previous chapter.

This thesis aims to develop a new load-flow technique which requires lesser data preparation. This method shows good and fast convergence for any kind of numbering scheme of the nodes and laterals.

To show the results 69-node radial distribution network with constant power (CP), constant current(CI), constant impedance(CZ), composite as well as exponential load modeling is considered.

3.2 ASSUMPTIONS

While implementing all the discussed methods it was assumed that:

1. Three-phase radial distribution networks were balanced and represented by their single-line diagrams.

2. Charging capacitances are neglected at the distribution voltage level (medium level).

3.3 SOLUTION METHODOLOGY

Figure 3.1 shows the single line diagram of a distribution feeder.

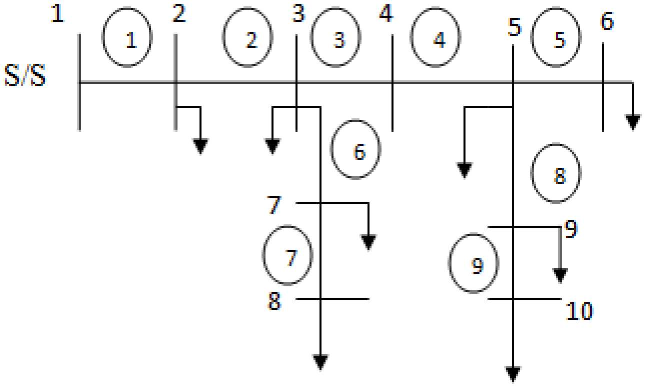


Figure 3.1 Single line diagram of a distribution feeder.

Consider branch 1. The node voltage of the receiving-end node can be written as:

$$V(2) = V(l) - I(1)Z(1) \tag{3.1}$$

Similarly, for branch 2,

$$V(3) = V(2) - I(2)Z(2) \tag{3.2}$$

Substation voltage is taken as 1.00 pu

Since the voltage at the substation V(1) is known, so if I(l) is known, i.e. current of branch 1, V(2) can be easily calculated from eqn.3.1. Once V(2) is known, it is easy to calculate V(3) from eqn. 2.2, if the current through branch 2 is known. Similarly, voltages of nodes 4,5,.....NB can easily be calculated if all the branch currents are known. Therefore, a generalized equation of receiving-end voltage, sending-end voltage, branch current and branch impedance can be defined as

$$V(m2) = V(m1) - I(jj)Z(jj) \tag{3.3}$$

Where *jj* is the branch number

$$m2 = IR(jj) \tag{3.4}$$

$$ml = IS(jj) \tag{3.5}$$

The load current at node m2 is expressed by

$$\mathrm{IL(m2)} = \frac{\mathrm{PL(m2)} - \mathrm{jQL(m2)}}{\mathrm{V^*(m2)}} \tag{3.6}$$

where PL(m2) is the real power load at node m2 and QL(m2) is the reactive power load at node m2.

The real and reactive power losses of branch *jj* are given by:

$$LP(jj) = |I(jj)|^2 R(jj) \tag{3.7}$$

$$LQ(jj) = |I(jj)|^2 X(jj) \tag{3.8}$$

Figure 3.2 shows the Venn diagram of the figure shown in figure 3.1.

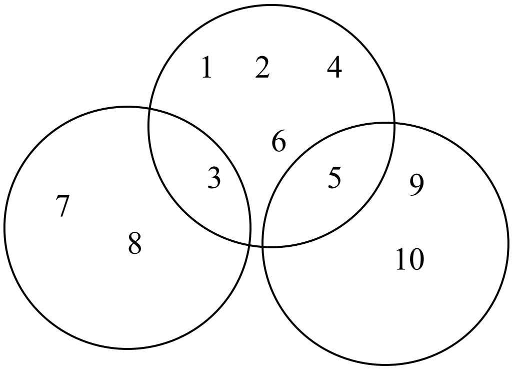


Figure 3.2 Venn diagram of figure 3.1

From Venn diagram the common points of $F \cap L1 = \{3\}$ and $F \cap L2 = \{5\}$ whereas F is the set of nodes of feeder and L is the set of nodes of lateral. From figure 3.1 set of nodes of feeder and lateral are F = {1,2,3,4,5,6}, L1 = {3,7,8} and L2 = {5,9,10} respectively. Fom fig.1 the nodes of feeder and laterals along with their order are shown below:

For feeder:

F(1,1) = 1, F(1,2) = 2, F(1,3) = 3, F(1,4) = 4, F(1,5) = 5, F(1,6) = 6.

Here first number denotes the order of the feeder and second number denotes the order of the node of the set.

For lateral:

L(1,1) = 3, L(1,2) = 7, L(1,3) = 8, L(2,1) = 5, L(2,2) = 9, and L(2,3) = 10.

Here first number denotes the order of the lateral and second number denotes the order of the node of the set.

Total number of feeder plus total number of laterals is defined as

$$\mathrm{TFL} = \sum_{i=1}^{M} \mathrm{TF}(i) + \sum_{j=1}^{N} \mathrm{TL}(j) \tag{3.9}$$

3.4 LOAD MODELING

In distribution systems, because of the voltage-dependent characteristics of load, the constant load model is no longer suitable for accurate power flow analysis. Load models usually can be classified into two main categories: static and dynamic. Since power flow analysis is mainly performed for static states of power systems, only static load is considered here.

Normally, static load can be described using one of the following models:

- Constant power model (constant P and Q), i.e., the load power doesn't vary with the voltage magnitude;
- Constant impedance model (constant Z), i.e., the load power varies with the square of the voltage magnitude;
- Constant current model (constant I), i.e., the load power varies with the voltage magnitude only;
- exponential load model, i.e., the load power varies with the voltage magnitude with an exponential relationship.

Here the load is modeled as polynomial load as:

$$P = P_0(a_0 + a_1V + a_2V^2 + a_3V^{1.38}) \tag{3.10}$$

$$Q = Q_0(b_0 + b_1V + b_2V^2 + b_3V^{3.22}) \tag{3.11}$$

$$a_0 + a_1 + a_2 + a_3 = b_0 + b_1 + b_2 + b_3 = 1$$

where

V is the pu value of the node voltage;

P_0, Q_0 are the real power and reactive power consumed at the specific node under the reference voltage;

a_0, b_0 are the parameters for constant power (constant P and Q) load component i.e. $a_0 = b_0 = 1$ and $a_i = b_i = 0$ for i = 1,2,3;

a_1, b_1 are the parameters for constant current (constant I) load component i.e. $a_1 = b_1 = 1$ and $a_i = b_i = 0$ for i = 0,2,3;

a_2, b_2 are the parameters for constant impedance (constant Z) load component i.e. $a_2 = b_2 = 1$ and $a_i = b_i = 0$ for i = 0,1,3;

a_3, b_3 are the parameters for exponential load component i.e. i.e. $a_3 = b_3 = 1$ and $a_i = b_i = 0$ for i = 0,1,2;

Composite load modeling is combination of CP, CI and CZ.

3.5 ALGORITHM FOR LOAD-FLOW COMPUTATION

The complete algorithm for load-flow computation is show below:

Step 1 : Start

Step 2 : Read line data and load data of the system.

Step 3 : Read base values.

Step 4 : Set ITMAX = 100.

Step 5 : Set V(i,j) = 1.0 + j0.0 for i = 1,2,3……TFL and j = 1,2,3……..TN(i).

Step 6 : Set IT = 1.

Step 7 : Set PL1(i,j) = PL(i,j) and QL1(i,j) = QL(i,j) for i=1,2,3……TFL and j= 1,2,3…..TN.

Step 8 : Using equation (3.10) and (3.11) calculate PL(i,j) and QL1(i,j).

Step 9 : Using equation (3.6) calculate IL(m2) for m2 = 1,2,3……..TN.

Step 10 : Calculate I(I,jj) for i=1,2,…….TFL and jj = 1,2,……TN-1 where $I(i,jj) = \sum_{i=1,jj=1}^{i=TFL,jj=TN-1} IL(i,j)$

Step 11 : Compute $V(i,j+1) = V(i,j) - I(i,jj)Z(i,jj)$ for i=1,2,3……TFL and j= 1,2,3……..TN(i).

Step 12 : Compute $\Delta V^k(i,j) = V^{k-1}(i,j) - V^k(i,j)$.

Step 13 : Arrange $\Delta V^k(i,j)$ in descending order.

Step 14 : Get the highest value of $\Delta V^k(i,j)$.

Step 15 : If $\Delta V^k(i,j) < 0.001$ go to step 18 else go to step 16.

Step 16 : IT = IT+1.

Step 17 : If IT < ITMAX, go to step 7 else go to step 20.

Step 18 : Calculate LP(i,jj) and LQ(i,jj) using equation (3.7) and (3.8) for i=1,2….TFL and jj=1,2,3…….TN-1.

Step 19 : Display the result, go to step 21.

Step 20 : Display ‘SOLUTION CONVERGED’.

Step 21 : Stop.

3.6 EXAMPLE

A 69-node (shown in figure 3.2) example has been considered to show the effectiveness of the proposed method. Base values are 12.66 kV and 100 MVA. Line data and load data for 69-node radial distribution network is shown in Appendix A in table A1 and A2 respectively (as available in [9]).

3.7 RESULTS

Table 3.2 and table 3.4, table 3.6, table 3.8 and table 3.10 show the real power and reactive power loss of each branch.

Table 3.1 compares the total real and reactive power loss for CP, CI, CZ, CC and Exponential load modeling.

Table 3.12 compares the minimum voltage magnitude in pu for CP, CI, CZ, CC and Exponential load modeling.

Table 3.13 compares the iteration number for CP, CI, CZ, CC and Exponential load modeling.

Table 3.14 compares the relative CPU time of the proposed method with other two methods [25,27].

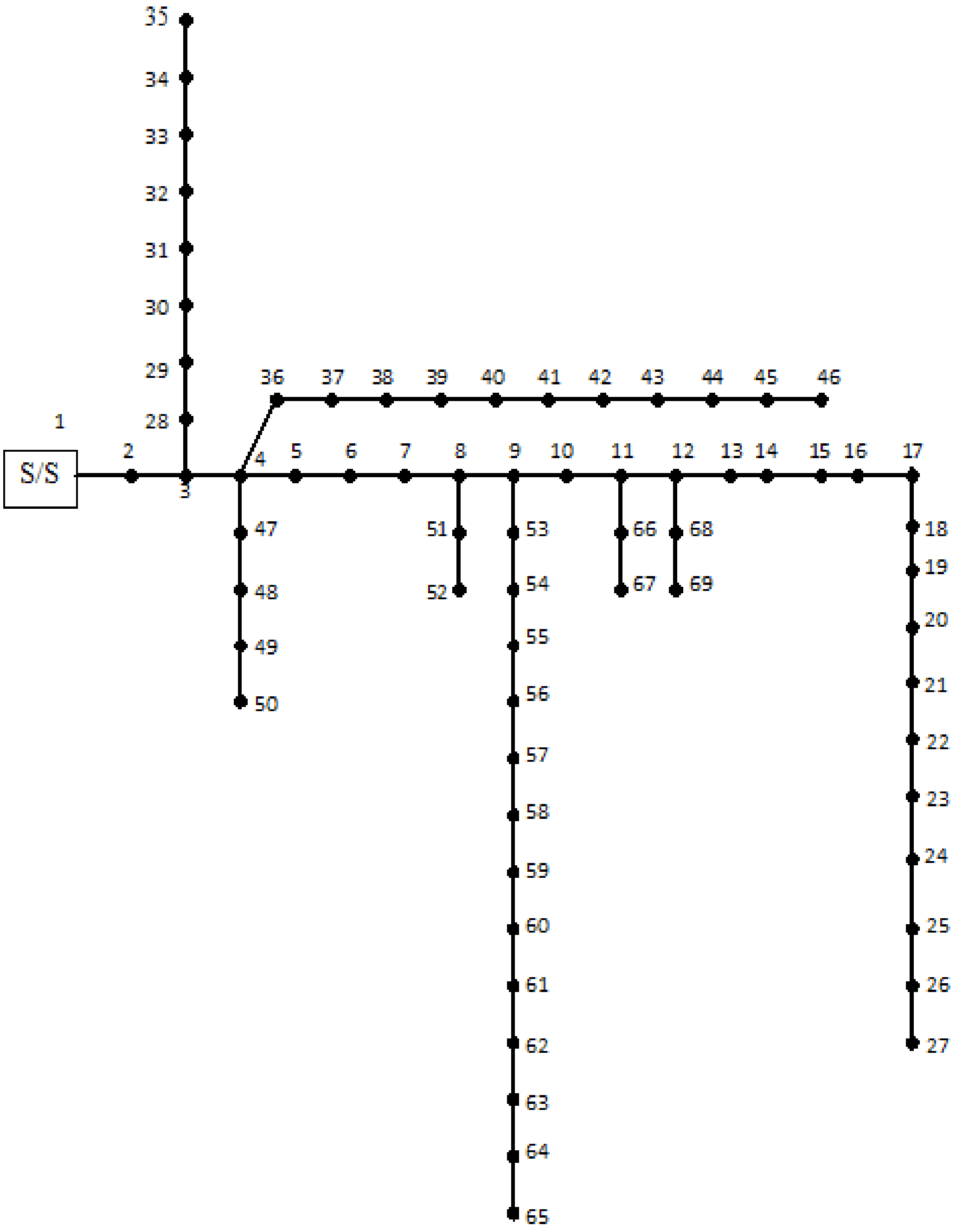


Figure 3.3 69- node radial distribution network

Table 3.1: Voltage Magnitude of Each Node in pu for Constant Power Load Modeling

Node number	Voltage magnitude (pu)	Node number	Voltage magnitude (pu)
1 (S/S)	1.000000	42	0.998551
2	0.999967	43	0.99851
3	0.999933	44	0.9985
4	0.999839	45	0.99841
5	0.999021	46	0.99841
6	0.990087	47	0.99979
7	0.980796	48	0.99855
8	0.978580	49	0.9947
9	0.977447	50	0.99416
10	0.972450	51	0.97855
11	0.971349	52	0.97854
12	0.968191	53	0.97466
13	0.965269	54	0.97142
14	0.962373	55	0.96694
15	0.959505	56	0.96258
16	0.958972	57	0.9401
17	0.958093	58	0.92904
18	0.958084	59	0.92477
19	0.958084	60	0.91974
20	0.957321	61	0.91234
21	0.956839	62	0.91205
22	0.956833	63	0.91167
23	0.956761	64	0.90977
24	0.956604	65	0.90919
25	0.956435	66	0.97129
26	0.956365	67	0.97129
27	0.956346	68	0.96786
28	0.999926	69	0.96786
29	0.999854		
30	0.999733		
31	0.999712		
32	0.999605		
33	0.999349		
34	0.999013		
35	0.998946		
36	0.999919		
37	0.999747		
38	0.999589		
39	0.999543		
40	0.999541		
41	0.998843		

Table 3.2: Real and Reactive Power Loss of Each Branch for Constant Power Load Modeling

Branch number	Real power loss (kW)	Reactive power loss(kVAr)
1	0.074951	0.179883
2	0.074951	0.179883
3	0.194856	0.467655
4	1.936011	2.267678
5	28.230280	14.377387
6	29.337767	14.942168
7	6.892022	3.513286
8	3.373739	1.717664
9	4.769865	1.576560
10	1.013138	0.335007
11	2.187400	0.722881
12	1.282614	0.423387
13	1.243801	0.411026
14	1.204575	0.398034
15	0.223837	0.074005
16	0.320393	0.105942
17	0.002604	0.000886
18	0.104118	0.034420
19	0.066933	0.022025
20	0.107403	0.035497
21	0.000536	0.000176
22	0.005139	0.001699
23	0.011185	0.003698
24	0.006048	0.001999
25	0.002495	0.000825
26	0.000350	0.000116
27	0.000347	0.000851
28	0.002583	0.006317
29	0.005829	0.001927
30	0.001029	0.000340
31	0.005143	0.001700
32	0.012293	0.004126
33	0.010403	0.003439
34	0.000479	0.000158
35	0.001405	0.003450
36	0.015079	0.036872
37	0.017323	0.020235
38	0.005001	0.005840
39	0.000199	0.000232
40	0.048714	0.056915
41	0.020117	0.023511
42	0.002661	0.003102

43	0.000514	0.000648
44	0.006080	0.007665
45	0.000013	0.000017
46	0.023259	0.057463
47	0.582158	1.424953
48	1.631481	3.992005
49	0.115753	0.283187
50	0.001757	0.000896
51	0.000044	0.000015
52	5.781147	2.943734
53	6.711319	3.418475
54	9.124545	4.645748
55	8.789956	4.477784
56	49.683723	16.676857
57	24.488764	8.218125
58	9.505527	3.143511
59	10.670816	3.239109
60	14.026003	7.144279
61	0.112051	0.057061
62	0.134930	0.068674
63	0.661155	0.336765
64	0.041211	0.020990
65	0.002624	0.000797
66	0.000015	0.000005
67	0.023324	0.007709
68	0.000037	0.000013

Table 3.3: Voltage Magnitude of Each Node in pu for Constant Current Load Modeling

Node number	Voltage magnitude (pu)	Node number	Voltage magnitude (pu)
1 (S/S)	1.000000	43	0.998518
2	0.999968	44	0.998509
3	0.999936	45	0.998411
4	0.999848	46	0.998410
5	0.999084	47	0.999798
6	0.990754	48	0.998560
7	0.982090	49	0.994741
8	0.980026	50	0.994200
9	0.978972	51	0.979991
10	0.974154	52	0.979982
11	0.973093	53	0.976424
12	0.970055	54	0.973460
13	0.967257	55	0.969374
14	0.964483	56	0.965387
15	0.961737	57	0.944874
16	0.961227	58	0.934779
17	0.960384	59	0.930873
18	0.960376	60	0.926290
19	0.959931	61	0.919543
20	0.959646	62	0.919280
21	0.959185	63	0.918927
22	0.959179	64	0.917198
23	0.959110	65	0.916676
24	0.958960	66	0.973037
25	0.958799	67	0.973037
26	0.958732	68	0.969736
27	0.958713	69	0.969735
28	0.999929		
29	0.999858		
30	0.999737		
31	0.999715		
32	0.999609		
33	0.999353		
34	0.999018		
35	0.998950		
36	0.999923		
37	0.999751		
38	0.999593		
39	0.999547		
40	0.999545		
41	0.998848		
42	0.998556		

Table 3.4: Real and Reactive Power Loss of Each Branch for Constant Current Load Modeling

Branch number	Real power loss (kW)	Reactive power loss(kVar)
1	0.067705	0.162492
2	0.067705	0.162492
3	0.174678	0.419228
4	1.683517	1.971928
5	24.548492	12.502293
6	25.508469	12.991850
7	5.983242	3.050026
8	2.915603	1.484414
9	4.434904	1.465847
10	0.941392	0.311283
11	2.022315	0.668325
12	1.176562	0.388380
13	1.140558	0.376909
14	1.104336	0.364911
15	0.205210	0.067847
16	0.293591	0.097080
17	0.002385	0.000812
18	0.095303	0.031506
19	0.061266	0.020160
20	0.098308	0.032491
21	0.000490	0.000161
22	0.004701	0.001554
23	0.010233	0.003383
24	0.005532	0.001828
25	0.002282	0.000754
26	0.000320	0.000106
27	0.000347	0.000851
28	0.002580	0.006310
29	0.005818	0.001923
30	0.001027	0.000339
31	0.005134	0.001697
32	0.012272	0.004119
33	0.010382	0.003432
34	0.000478	0.000158
35	0.001403	0.003444
36	0.015048	0.036797
37	0.017282	0.020187
38	0.004989	0.005826
39	0.000198	0.000231
40	0.048561	0.056735
41	0.020053	0.023436

42	0.002652	0.003092
43	0.000512	0.000646
44	0.006060	0.007641
45	0.000013	0.000017
46	0.023018	0.056869
47	0.576136	1.410212
48	1.613364	3.947675
49	0.114405	0.279889
50	0.001682	0.000858
51	0.000042	0.000014
52	4.833170	2.461028
53	5.608976	2.856986
54	7.611742	3.875507
55	7.320890	3.729411
56	41.380074	13.889651
57	20.395952	6.844629
58	7.916867	2.618135
59	8.872423	2.693209
60	11.662147	5.940227
61	0.092768	0.047241
62	0.111650	0.056826
63	0.547084	0.278663
64	0.034067	0.017351
65	0.002476	0.000752
66	0.000014	0.000004
67	0.021849	0.007222
68	0.000035	0.000012

Table 3.5: Voltage Magnitude of Each Node in pu for Constant Impedance Load Modeling

Node number	Voltage magnitude (pu)	Node number	Voltage magnitude (pu)
1 (S/S)	1.000000	42	0.998561
2	0.999969	43	0.998522
3	0.999939	44	0.998514
4	0.999854	45	0.998416
5	0.999134	46	0.998415
6	0.991284	47	0.999805
7	0.983120	48	0.998573
8	0.981176	49	0.994775
9	0.980186	50	0.994237
10	0.975523	51	0.981142
11	0.974496	52	0.981133
12	0.971564	53	0.977825
13	0.968873	54	0.975078
14	0.966206	55	0.971296
15	0.963565	56	0.967607
16	0.963074	57	0.948637
17	0.962264	58	0.939299
18	0.962256	59	0.935687
19	0.961829	60	0.931450
20	0.961555	61	0.925213
21	0.961112	62	0.924969
22	0.961106	63	0.924644
23	0.961040	64	0.923049
24	0.960896	65	0.922567
25	0.960741	66	0.974443
26	0.960677	67	0.974442
27	0.960659	68	0.971254
28	0.999932	69	0.971253
29	0.999860		
30	0.999740		
31	0.999718		
32	0.999611		
33	0.999356		
34	0.999021		
35	0.998954		
36	0.999925		
37	0.999754		
38	0.999596		
39	0.999550		
40	0.999548		
41	0.998852		

Table 3.6: Real and Reactive Power Loss of Each Branch for Constant Impedance Load Modeling

Branch number	Real power loss (kW)	Reactive power loss(kVAr)
1	0.062190	0.149256
2	0.062190	0.149256
3	0.159379	0.382510
4	1.495764	1.752010
5	21.810734	11.107981
6	22.661222	11.541704
7	5.308249	2.705940
8	2.576439	1.311737
9	4.155425	1.373472
10	0.881549	0.291495
11	1.884989	0.622942
12	1.088764	0.359398
13	1.055105	0.348670
14	1.021381	0.337500
15	0.189795	0.062750
16	0.271419	0.089748
17	0.002204	0.000750
18	0.088016	0.029097
19	0.056582	0.018619
20	0.090791	0.030007
21	0.000453	0.000149
22	0.004340	0.001435
23	0.009446	0.003123
24	0.005105	0.001687
25	0.002106	0.000696
26	0.000295	0.000097
27	0.000346	0.000850
28	0.002577	0.006302
29	0.005808	0.001920
30	0.001025	0.000339
31	0.005125	0.001694
32	0.012250	0.004112
33	0.010362	0.003425
34	0.000477	0.000158
35	0.001400	0.003437
36	0.015017	0.036722
37	0.017242	0.020140
38	0.004978	0.005813
39	0.000197	0.000230
40	0.048408	0.056557
41	0.019990	0.023362

42	0.002644	0.003082
43	0.000510	0.000644
44	0.006041	0.007617
45	0.000012	0.000017
46	0.022783	0.056289
47	0.570257	1.395822
48	1.595685	3.904418
49	0.113090	0.276672
50	0.001620	0.000826
51	0.000040	0.000014
52	4.153267	2.114825
53	4.818533	2.454366
54	6.528377	3.323914
55	6.270060	3.194097
56	35.440437	11.895950
57	17.468344	5.862160
58	6.780491	2.242332
59	7.588098	2.303354
60	9.973995	5.080350
61	0.079058	0.040259
62	0.095108	0.048406
63	0.466027	0.237375
64	0.028995	0.014768
65	0.002351	0.000714
66	0.000014	0.000004
67	0.020611	0.006813
68	0.000033	0.000011

Table 3.7: Voltage Magnitude of Each Node in pu for Composite Load Modeling

Node number	Voltage magnitude (pu)	Node number	Voltage magnitude (pu)
1 (S/S)	1.000000	43	0.998524
2	0.999970	44	0.998516
3	0.999940	45	0.998417
4	0.999857	46	0.998417
5	0.999146	47	0.999808
6	0.991237	48	0.998580
7	0.983011	49	0.994793
8	0.981052	50	0.994256
9	0.980054	51	0.981018
10	0.975348	52	0.981009
11	0.974312	53	0.977671
12	0.971351	54	0.974897
13	0.968629	55	0.971077
14	0.965931	56	0.967352
15	0.963260	57	0.947998
16	0.962764	58	0.938466
17	0.961945	59	0.934777
18	0.961936	60	0.930440
19	0.961505	61	0.924133
20	0.961227	62	0.923887
21	0.960780	63	0.923558
22	0.960773	64	0.921944
23	0.960707	65	0.921457
24	0.960561	66	0.974258
25	0.960404	67	0.974258
26	0.960339	68	0.971039
27	0.960321	69	0.971038
28	0.999933		
29	0.999862		
30	0.999741		
31	0.999719		
32	0.999613		
33	0.999357		
34	0.999022		
35	0.998955		
36	0.999926		
37	0.999755		
38	0.999597		
39	0.999551		
40	0.999549		
41	0.998854		
42	0.998562		

Table 3.8: Real and Reactive Power Loss of Each Branch for Composite Load Modeling

Branch number	Real power loss (kW)	Reactive power loss (kVar)
1	0.062340	0.149617
2	0.062340	0.149617
3	0.159814	0.383554
4	1.502463	1.759858
5	21.908432	11.157737
6	22.763132	11.593608
7	5.332883	2.718498
8	2.589222	1.318245
9	4.168276	1.377719
10	0.884293	0.292403
11	1.892831	0.625534
12	1.095827	0.361729
13	1.061921	0.350922
14	1.027933	0.339665
15	0.191013	0.063153
16	0.273172	0.090328
17	0.002214	0.000754
18	0.088182	0.029152
19	0.056688	0.018654
20	0.090957	0.030062
21	0.000453	0.000149
22	0.004347	0.001437
23	0.009461	0.003128
24	0.005113	0.001690
25	0.002109	0.000697
26	0.000296	0.000098
27	0.000346	0.000850
28	0.005808	0.006302
29	0.002577	0.001920
30	0.001025	0.000339
31	0.005125	0.001694
32	0.012250	0.004112
33	0.010362	0.003425
34	0.000477	0.000158
35	0.001401	0.003438
36	0.015018	0.036724
37	0.017244	0.020142
38	0.004978	0.005813
39	0.000198	0.000230
40	0.048415	0.056565
41	.019993	0.023366
42	0.002644	0.003083

43	0.000510	0.000644
44	0.006042	0.007618
45	0.000012	0.000017
46	0.022785	0.056293
47	0.570304	1.395939
48	1.595830	3.904774
49	0.113101	0.276699
50	0.001621	0.000826
51	0.000040	0.000014
52	4.178988	2.127921
53	4.848616	2.469689
54	6.570112	3.345163
55	6.310939	3.214922
56	35.671501	11.973510
57	17.582237	5.900380
58	6.824698	2.256952
59	7.639059	2.318824
60	10.040981	5.114470
61	0.079618	0.040545
62	0.095795	0.048756
63	0.469394	0.239091
64	0.029215	0.014880
65	0.002351	0.000714
66	0.000014	0.000004
67	0.020626	0.006818
68	0.000033	0.000011

Table 3.9: Voltage Magnitude of Each Node in pu for Exponential Load Modeling

Node number	Voltage magnitude (pu)	Node number	Voltage magnitude (pu)
1 (S/S)	1.000000	43	0.998517
2	0.999968	44	0.998509
3	0.999936	45	0.998410
4	0.999847	46	0.998410
5	0.999077	47	0.999797
6	0.990680	48	0.998558
7	0.981946	49	0.994737
8	0.979865	50	0.994196
9	0.978803	51	0.979830
10	0.973966	52	0.979821
11	0.972901	53	0.976228
12	0.969851	54	0.973232
13	0.967040	55	0.969103
14	0.964254	56	0.965073
15	0.961495	57	0.944345
16	0.960983	58	0.934143
17	0.960136	59	0.930197
18	0.960128	60	0.925565
19	0.959681	61	0.918746
20	0.959395	62	0.918479
21	0.958932	63	0.918122
22	0.958925	64	0.916374
23	0.958856	65	0.915846
24	0.958706	66	0.972846
25	0.958543	67	0.972845
26	0.958476	68	0.969531
27	0.958457	69	0.969530
28	0.999929		
29	0.999857		
30	0.999736		
31	0.999715		
32	0.999608		
33	0.999352		
34	0.999017		
35	0.998950		
36	0.999922		
37	0.999751		
38	0.999592		
39	0.999546		
40	0.999544		
41	0.998848		
42	0.998556		

Table 3.10: Real and Reactive Power Loss of Each Branch for Exponential Load Modeling

Branch number	Real power loss (kW)	Reactive power loss(kVar)
1	0.068501	0.164403
2	0.068501	0.164403
3	0.176892	0.424541
4	1.711073	2.004205
5	24.950312	12.706935
6	25.926382	13.204699
7	6.082432	3.100589
8	2.965631	1.509885
9	4.469410	1.477252
10	0.948788	0.313728
11	2.039418	0.673977
12	1.187627	0.392032
13	1.151333	0.380469
14	1.114800	0.368369
15	0.207155	0.068490
16	0.296390	0.098005
17	0.002408	0.000820
18	0.096225	0.031810
19	0.061859	0.020355
20	0.099259	0.032805
21	0.000495	0.000163
22	0.004747	0.001569
23	0.010333	0.003416
24	0.005586	0.001846
25	0.002304	0.000762
26	0.000323	0.000107
27	0.000347	0.000851
28	0.002581	0.006310
29	0.005819	0.001924
30	0.001027	0.000339
31	0.005135	0.001697
32	0.012274	0.004120
33	0.010384	0.003433
34	0.000478	0.000158
35	0.001403	0.003444
36	0.015051	0.036804
37	0.017287	0.020192
38	0.004991	0.005828
39	0.000198	0.000231
40	0.048576	0.056753

41	0.020059	0.023444
42	0.002653	0.003093
43	0.000512	0.000646
44	0.006062	0.007643
45	0.000013	0.000017
46	0.023043	0.056929
47	0.576742	1.411697
48	1.615189	3.952143
49	0.114541	0.280222
50	0.001690	0.000861
51	0.000042	0.000014
52	4.937270	2.514035
53	5.730026	2.918644
54	7.777884	3.960098
55	7.482258	3.811615
56	42.292179	14.195808
57	20.845522	6.995499
58	8.091372	2.675845
59	9.070159	2.753232
60	11.922057	6.072614
61	0.094894	0.048324
62	0.114218	0.058133
63	0.559669	0.285073
64	0.034855	0.017752
65	0.002490	0.000756
66	0.000015	0.000004
67	0.021999	0.007271
68	0.000035	0.000012

Table 3.11: Comparison of Total Real and Reactive Power Loss for CP, CI, CZ, CC and Exponential Load Modeling

Type of load	Total real power loss (kW)	Total reactive power loss(kVAr)
Constant power	224.933838	102.129272
Constant current	191.444748	87.767311
Constant impedance	167.115631	77.302193
Composite	168.058014	77.701637
Exponential	195.111176	89.339142

Table 3.12: Comparison of Minimum Voltage Magnitude in pu for CP, CI, CZ, CC and Exponential Load Modeling

Type of load	Node number	Minimum voltage(pu)
Constant power	65	0.909191
Constant current	65	0.916676
Constant impedance	65	0.922567
Composite	65	0.921457
Exponential	65	0.915846

Table 3.13: Comparison of Iteration Number for CP, CI, CZ, CC and Exponential Load Modeling

Type of load	Iteration number
Constant power	5
Constant current	2
Constant impedance	5
Composite	4
Exponential	3

Table 3.14 Comparison of Relative CPU Time of the Proposed Method with Other Two existing Methods [25,27] for Composite Load Modeling.

Methods	CPU time
Proposed	1.0
Ranjan *et al.*[25]	1.36
Ghosh *et al.* [27]	1.1

CHAPTER-4

CONCLUSIONS & FUTURE SCOPE

4.1 CONCLUSIONS

In this thesis work a new and efficient method has been proposed for load-flow analysis of ill-conditioned power systems. This method is based on set theory and shows fast convergence. An example of 69-node radial disttribution network [9] has been considered to show the effectiveness of the proposed method. This mrthod is quite effective in handling the composite load and has shown satisfactory convergence for constant power, constant current, constant impedance, composite as well as exponential load modeling. The superiority of the method in terms of speed has been illustrated by comparing it with two of the other existing methods.

4.2 FUTURE SCOPES OF THE WORK

The future scope of the work consists of:

1. Optimal load-flow calculations for unbalanced systems.
2. Fuzzy load-flow analysis
3. Load-flow analysis using Genetic Algorithm

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APPENDIX A

Table A.1 Line Data of 69 Node Radial Distribution Network

Branch Number	Sending end	Receiving end	Branch Resistance (Ω)	Branch Reactance (Ω)
1	1	2	0.0005	0.0012
2	2	3	0.0005	0.0012
3	3	4	0.0015	0.0036
4	4	5	0.0251	0.0294
5	5	6	0.3660	0.1864
6	6	7	0.3811	0.1941
7	7	8	0.0922	0.0470
8	8	9	0.0493	0.0257
9	9	10	0.8190	0.2707
10	10	11	0.1872	0.0619
11	11	12	0.7114	0.2351
12	12	13	1.0300	0.3400
13	13	14	1.0440	0.3450
14	14	15	1.0580	0.3496
15	15	16	0.1966	0.0650
16	16	17	0.3744	0.1238
17	17	18	0.0047	0.0016
18	18	19	0.3276	0.1083
19	19	20	0.2106	0.0696
20	20	21	0.3416	0.1129
21	21	22	0.0140	0.0046
22	22	23	0.1591	0.0526
23	23	24	0.3463	0.1145
24	24	25	0.7488	0.2475
25	25	26	0.3089	0.1021
26	26	27	0.1732	0.0572
27	3	28	0.0044	0.0108
28	28	29	0.0640	0.1565
29	29	30	0.3978	0.1315
30	30	31	0.0702	0.0232
31	31	32	0.3510	0.1160
32	32	33	0.8390	0.2816
33	33	34	1.7080	0.5646
34	34	35	1.4740	0.4873
35	3	36	0.0044	0.0108
36	36	37	0.0640	0.1565
37	37	38	0.1053	0.1230

38	38	39	0.0304	0.0355
39	39	40	0.0018	0.0021
40	40	41	0.7283	0.8509
41	41	42	0.3100	0.3623
42	42	43	0.0410	0.0478
43	43	44	0.0092	0.0116
44	44	45	0.1089	0.1373
45	45	46	0.0009	0.0012
46	4	47	0.0034	0.0084
47	47	48	0.0851	0.2083
48	48	49	0.2898	0.7091
49	49	50	0.0822	0.2011
50	8	51	0.0928	0.0473
51	51	52	0.3319	0.1114
52	9	53	0.1740	0.0886
53	53	54	0.2030	0.1034
54	54	55	0.2842	0.1447
55	55	56	0.2813	0.1433
56	56	57	1.5900	0.5337
57	57	58	0.7837	0.2630
58	58	59	0.3042	0.1006
59	59	60	0.3861	0.1172
60	60	61	0.5075	0.2585
61	61	62	0.0974	0.0496
62	62	63	0.1450	0.0738
63	63	64	0.7105	0.3619
64	64	65	1.0410	0.5302
65	11	66	0.2012	0.0611
66	66	67	0.0047	0.0014
67	12	68	0.7394	0.2444
68	68	69	0.0047	0.0016

BASE kV = 12.66 and BASE MVA = 100

Table A.2 Load Data of 69-Node Radial Distribution Network

Node No.	PL(kW)	QL(kVAr)	Node No.	PL(kW)	QL(kVAr)
1	00.00	00.00	43	6.000	4.300
2	00.00	00.00	44	00.00	00.00
3	00.00	00.00	45	39.22	26.30
4	00.00	00.00	46	39.22	26.30
5	00.00	00.00	47	00.00	00.00
6	2.600	2.200	48	79.00	56.40
7	40.40	30.00	49	384.7	274.0
8	75.00	54.00	50	384.7	274.0
9	30.00	22.00	51	40.50	28.30
10	28.00	19.00	52	3.600	2.700
11	145.0	104.00	53	4.350	3.500
12	145.0	104.00	54	26.40	19.00
13	8.000	5.000	55	26.00	17.20
14	8.000	5.500	56	00.00	00.00
15	00.00	00.00	57	00.00	00.00
16	45.50	30.00	58	00.00	00.00
17	60.00	35.00	59	100.0	72.00
18	60.00	35.00	60	00.00	00.00
19	00.00	00.00	61	1244.0	888.0
20	1.000	00.60	62	32.00	23.00
21	114.0	81.00	63	00.00	00.00
22	5.000	3.500	64	227.0	162.0
23	00.00	00.00	65	59.00	42.00
24	28.00	20.00	66	18.00	13.00
25	00.00	00.00	67	18.00	13.00
26	14.00	10.00	68	28.00	20.00
27	14.00	10.00	69	28.00	20.00
28	26.00	18.60			
29	26.00	18.60			
30	00.00	00.00			
31	00.00	00.00			
32	00.00	00.00			
33	14.00	10.00			
34	19.50	14.00			
35	6.000	4.000			
36	26.00	18.55			
37	26.00	18.55			
38	00.00	00.00			
39	24.00	17.00			
40	24.00	17.00			
41	1.200	1.000			
42	00.00	00.00			